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A Stochastic Model for Analysis of Manufacturing Modules

M. Savsar and Majid Aldaihani
Kuwait University, College of Engineering & Petroleum, Industrial and Management Systems Engineering, P.O. Box 5969 Safat 13060 Kuwait

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Abstract: In this paper, a stochastic model, which describes the states of a manufacturing system by a set of differential equations, is developed. These equations are changed into a set of difference equations at steady state and then solved by MAPLE software to analyze performance measures of flexible manufacturing modules under different operational conditions. A manufacturing module consists of one or more flexible machines, a loading and unloading robot, and a part transfer pallet. Flexible machines are subject to frequent failures due to their high utilizations. Therefore, models are needed to determine the effects of various factors on system performance as well as the best maintenance and repair policies which optimize manufacturing system performance. The model presented in this paper can be useful for operation managers and engineers to analyze a given machining system.

Keywords: Stochastic Modeling, Failures, Limited Repair, Flexible Manufacturing.

1. Introduction

Manufacturing systems are designed into units called manufacturing modules, which consist of one or more machines, served by robots for loading and unloading of parts, and pallets or conveyor systems for batch material handling operations (see figure 1). Machines used in these modules are flexible and can handle a variety of parts. Therefore, they are called Flexible Machining Modules (FMM). Several FMM may be combined into larger systems entitled Flexible Manufacturing Systems (FMS). These systems are widely used in industry to process variety of parts to achieve high productivity in production environments with rapidly changing product structures and customer demand. There are various types of flexible manufacturing modules for discrete part machining. In addition to discrete part machining, there are different types of Computer Numerical Control (CNC) punching press systems, which are also configured as flexible modules. A CNC press with a special loading and unloading device for handling sheet metals and pallet handling equipment to move the batch of sheet metals into and out of the system forms a CNC press module.

There are several factors and parameters that affect performance of manufacturing modules. Since FMM systems are subject to failures due to high utilization of equipment, repair capacity and repair policy are important factors that affect productivity of an FMM and utilization of its components. Analysis of these systems involve with stochastic input parameters and stochastic results. Some stochastic mathematical models have been developed for FMM systems in relation to the effects of different parameters on system performance. Wang and Wan (1993) studied

Corresponding Author: msavsar@ gmail.com; m.aldaihani@ ku.edu.kw

the dynamic reliability of a FMS based on fuzzy information. Yuanidis et al. (1994) used a heuristic procedure called group method of data handling to asses FMS reliability with minimal data available. Han et al. (2006) analyzed FMM reliability through the method of fuzzy fault tree based on triangular fuzzy membership. Khodabandehloo and Sayles (2007) investigated the applicability of fault tree analysis and event tree analysis to production reliability in FMS and concluded that event tree analysis was more effective in solving this problem. Henneke and Choi (1990), Savsar and Cogun (1993), and Cogun and Savsar (1996) have presented stochastic and simulation models for evaluating the performance of reliable FMM and FMS with respect to system configuration and component speeds, such as machining rate, robot and pallet speeds. Koulamas (1992) and Savsar (2000) have looked into the reliability and maintenance aspects and presented stochastic models for the FMM, which operate under stochastic environment with tool failure and replacement consideration. They developed Markov models to study the effects of tool failures on system performance measures for a FMM with a single machine served by a robot for part loading/unloading and a pallet for part transfers. There are several other studies related to the reliability analysis of manufacturing systems. Butler A. C. and Rao, S. S. (1993) use symbolic logic to analyze reliability of complex systems. Their heuristic approach is based on artificial intelligence and expert systems. Black and Mejabi (1995) have used object oriented simulation modeling to study reliability of complex manufacturing equipment. They present a hierarchical approach to model complex systems. Simeu-Abazi, et. al. (1997) uses decomposition and iterative analysis of Markov chains to obtain numerical solutions for the reliability and dependability of manufacturing systems. Adamyan and He (2002) present a methodology to identify the sequences of failures and probability of their occurrences in an automated manufacturing system. They used Petri nets and reachability trees to develop a model for sequential failure analysis in manufacturing systems.

Aldaihani and Savsar (2005) presented a stochastic analytical model and obtained numerical solutions for a reliable FMM with two machines served by a single robot. Later, Savsar (2008) reconsidered this model and developed a closed form solution, which could be used easily to evaluate FMM performance without the need for extensive computation. These performance measures are compared to the previous results obtained for the FMM with a single robot. Abdulmalek, Savsar, and Aldaihani (2004) presented a simulation model and analysis for tool change policies in a FMM with two machines and a robot, based on ARENA simulation software. Aldaihani and Savsar (2008) Savsar and Aldaihani (2008) have further extended the previous models and developed stochastic models for unreliable FMM systems with two unreliable machines served by a robot and a pallet system. Closed form analytical solutions are obtained and FMM analysis is performed for different performance measures and selected module operations. The results are also compared to reliable FMM system.

In this paper, we have analyzed effects of various factors, including corrective maintenance capacity and repair crew allocation policy on the performance of a manufacturing module with two machines. In particular, stochastic models are used to compare productivity of a module under three different corrective maintenance or repair policies. These policies are as follows: (i) One repair crew is used for each machine with a repair rate of μ for each crew and each machine; (ii) One repair crew is used for both machines with a repair rate of μ for the single repair crew; (iii) One repair crew is used for both machines with a repair rate of 2μ for the single repair crew. In the following section, a stochastic model is developed for a single repair case and FMM performance measures are compared to double repair crew case using a previously developed model by Savsar and Aldaihani (2008). Based on the comparisons, best repair capacity is determined for the FMM systems considered. The model and the results can be useful for design engineers as well as operational managers in production and repair maintenance planning.

2. Operation of the Manufacturing Module

Operation of the FMM system is illustrated in figure 1. An automated pallet handling system delivers a batch of n different parts into the module. The robot reaches to the pallet, grips a blank, moves it to the first machine and loads the blank. While machine 1 operates on the part, the robot reaches the pallet, grips a second part and moves it to the machine 2 and loads it. Next, robot reaches to the machine which finishes its operation first, unloads the finished part and loads a new part. The loading/unloading operation continues in this way with the preference given to the machine which finishes its operation first. After the machining operations of all parts on the pallet are completed, the pallet with n finished parts moves out and a new pallet with n blanks is delivered into the module automatically. Machines are unreliable and fail during the operations. It is assumed that there is a single repair crew, which can repair one machine at a time. Therefore, if the second machine fails while the first is under repair, the second machine has to wait for the repairman to start repair operation. Time to failure and time to repair are assumed to follow exponential distribution. Due to the introduction of different parts into the FMM, failures of machines, and random characteristics of system operation, processing times as well as loading/unloading times are random, which present a complication in studying and modeling module performance.

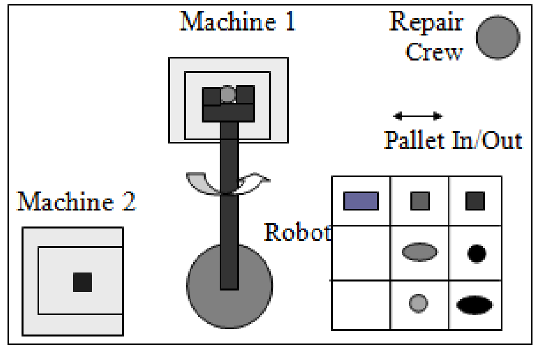

Figure 1. A Flexible Manufacturing Module

3. Stochastic Model of the FMM

In order to analyze the FMM system presented above, a Markovian model is developed based on stochastic transitions between various states of the system. First a set of notations are defined to describe the state of the system and related parameters:

$S_{ijkl}(t)$ = state of the FMM at time t

$P_{ijkl}(t)$ = probability that the system will be in state $S_{ijkl}(t)$

i =number of incomplete parts in FMM (on the pallet)

j = state of the production machine 1 (j=0 if the machine is idle; j=1 if the machine is operating on a part; j=2 if the machine is waiting for the robot; j=3 if the machine is under repair; and j=4 if the machine is waiting for repairman)

k = state of the production machine 2 (j=0 if the M/C is idle; j=1 if the machine is operating on a part; j=2 if the machine is waiting for the robot, j=3 if the machine is under repair; and j=4 if the machine is waiting for repairman)

l = state of the robot (l=0 if the robot is idle; l=1 if the robot is loading/unloading machine 1 ; and l=2 if the robot is loading/unloading machine 2)

l_m = initial loading rate of the robot for machine m (m=1,2) (parts/unit time)

u_m = final unloading rate of the robot for machine m (m=1,2) (parts/unit time)

z_m = combined loading/unloading rate of the robot for machine m (m=1,2)

w = pallet transfer rate (pallets/unit time)

λ_m= failure rate of production machine m ($1/\lambda_m$ = mean time between failures)

μ_m= repair rate of the production machine m ($1/\mu_m$ = mean machine repair time)

v_m= machining rate (or production rate) of machine

m (parts/unit time)
n = pallet capacity (fixed number of parts/pallet)
Q_c = FMM performance measure; production output rate in terms of parts/unit time.

Flow diagram in figure 2 illustrates the flows between different system states an respective rates. Using the fact that the *net flow* rate at each state is equal to the difference between the rates of *flow in* and *flow out*, a set of differential equations are obtained for the FMM system. For example, for the states (n,001) and (n-1,301), rates of change with respect to time t are given by:

$dP_{n,001}(t)/dt = (w)P_{0,000}-(l_1)P_{n,001}$
$dP_{n-1,001}(t)/dt = l_1P_{n,001} + \mu_1 P_{n-1,302} - (v_1 + l_2 + \lambda_1) P_{n-1,102}$

Similarly, a set of differential equations is constructed for 33+11(n-3) system states. At steady state, $t\rightarrow\infty$; $dP(t)/dt\rightarrow 0$ and the differential equations change into a difference equations. The resulting difference equations for all states are given by equation sets 1-3 below. The first set, consisting of 15 equations, describe the states with 0, n, n-1, and n-2 parts

$$
\begin{aligned}
& w\, P_{0,000} - l_1 P_{n,001} = 0 \\
& l_1 P_{n,001} + \mu_1 P_{n-1,302} - (v_1 + l_2 + \lambda_1) P_{n-1,102} = 0 \\
& \lambda_1 P_{n-1,102} - (l_2 + \mu_1) P_{n-1,302} = 0 \\
& v_1 P_{n-1,102} - l_2 P_{n-1,202} = 0 \\
& \lambda_2 P_{n-2,110} + \mu_1 P_{n-2,340} - (v_1 + \lambda_1 + \mu_2) P_{n-2,130} = 0 \\
& l_2 P_{n-1,102} + \mu_1 P_{n-2,310} + \mu_2 P_{n-2,130} - (v_1 + v_2 + \lambda_1 + \lambda_2) P_{n-2,110} = 0 \\
& l_2 P_{n-1,302} + \lambda_1 P_{n-2,110} + \mu_2 P_{n-2,430} - (v_2 + \lambda_2 + \mu_1) P_{n-2,310} = 0 \\
& \lambda_1 P_{n-2,130} - \mu_2 P_{n-2,430} = 0 \\
& \lambda_2 P_{n-2,310} - \mu_1 P_{n-2,340} = 0 \\
& v_2 P_{n-2,011} - z_1 P_{n-2,021} = 0 \\
& v_1 P_{n-2,110} + l_2 P_{n-1,202} + \mu_2 P_{n-2,031} - (v_2 + z_1 + \lambda_2) P_{n-2,011} = 0 \\
& v_1 P_{n-2,130} + \lambda_2 P_{n-2,011} - (z_1 + \mu_2) P_{n-2,031} = 0 \\
& v_2 P_{n-2,310} + \lambda_1 P_{n-2,102} - (z_2 + \mu_1) P_{n-2,302} = 0 \\
& v_2 P_{n-2,110} + \mu_1 P_{n-2,302} - (v_1 + z_2 + \lambda_1) P_{n-2,102} = 0 \\
& v_1 P_{n-2,102} - z_2 P_{n-2,202} = 0
\end{aligned}
\qquad (2)
$$

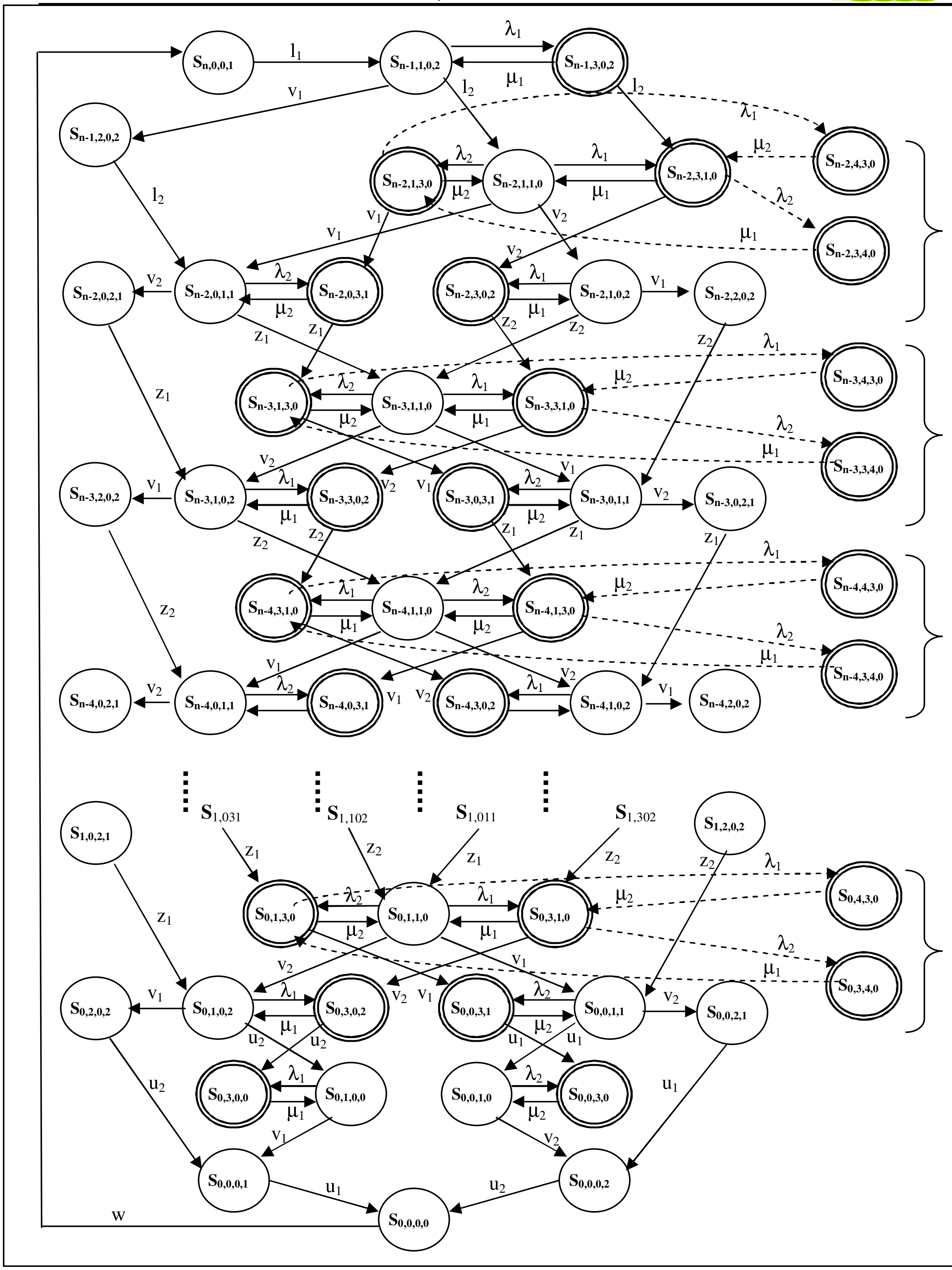

Figure 2. Probability transition flow diagram for the FMM with two unreliable machines.

$$z_1 P_{x+1,031} + \lambda_2 P_{x,110} + \mu_1 P_{x,340} - (v_1 + \lambda_1 + \mu_2) P_{x,130} = 0$$
$$z_1 P_{x+1,011} + z_2 P_{x+1,102} + \mu_1 P_{x,310} + \mu_2 P_{x,130} - (v_1 + v_2 + \lambda_1 + \lambda_2) P_{x,110} = 0$$
$$z_2 P_{x+1,302} + \lambda_1 P_{x,110} + \mu_2 P_{x,430} - (v_2 + \lambda_2 + \mu_1) P_{x,310} = 0$$
$$\lambda_1 P_{x,130} - \mu_2 P_{x,430} = 0$$
$$\lambda_2 P_{x,310} - \mu_1 P_{x,340} = 0$$
$$v_1 P_{x,102} - z_2 P_{x,202} = 0$$
$$v_2 P_{x,110} + z_1 P_{x+1,021} + \mu_1 P_{x,302} - (v_1 + z_2 + \lambda_1) P_{x,102} = 0$$
$$v_2 P_{x,310} + \lambda_1 P_{x,102} - (z_2 + \mu_1) P_{x,302} = 0$$
$$v_1 P_{x,130} + \lambda_2 P_{x,011} - (z_1 + \mu_2) P_{x,031} = 0$$
$$v_1 P_{x,110} + z_2 P_{x+1,202} + \mu_2 P_{x,031} - (v_2 + z_1 + \lambda_2) P_{x,011} = 0$$
$$v_2 P_{x,011} - z_1 P_{x,021} = 0 \qquad \text{for } x = 1,2,\ldots, n\text{-}3$$

$$z_1 P_{1,031} + \lambda_2 P_{0,110} + \mu_1 P_{0,340} - (v_1 + \lambda_1 + \mu_2) P_{0,130} = 0$$
$$\mu_1 P_{0,310} + \mu_2 P_{0,130} - (v_1 + v_2 + \lambda_1 + \lambda_2) P_{0,110} + z_1 P_{1,011} + z_2 P_{1,102} = 0$$
$$z_2 P_{1,302} + \lambda_1 P_{0,110} + \mu_2 P_{0,430} - (v_2 + \lambda_2 + \mu_1) P_{0,310} = 0$$
$$\lambda_1 P_{0,130} - \mu_2 P_{0,430} = 0$$
$$\lambda_2 P_{0,310} - \mu_1 P_{0,340} = 0$$
$$v_1 P_{0,102} - u_2 P_{0,202} = 0$$
$$v_2 P_{0,110} + z_1 P_{1,021} + \mu_1 P_{0,302} - (v_1 + u_2 + \lambda_1) P_{0,102} = 0$$
$$v_2 P_{0,310} + \lambda_1 P_{0,102} - (u_2 + \mu_1) P_{0,302} = 0$$
$$v_1 P_{0,130} + \lambda_2 P_{0,011} - (u_1 + \mu_2) P_{0,031} = 0$$
$$v_1 P_{0,110} + z_2 P_{1,202} + \mu_2 P_{0,031} - (v_2 + u_1 + \lambda_2) P_{0,011} = 0$$
$$v_2 P_{0,011} - u_1 P_{0,021} = 0$$
$$u_2 P_{0,302} + \lambda_1 P_{0,100} - \mu_1 P_{0,300} = 0$$
$$u_2 P_{0,102} + \mu_1 P_{0,300} - (v_1 + \lambda_1) P_{0,100} = 0$$
$$u_1 P_{0,011} + \mu_2 P_{0,030} - (v_2 + \lambda_2) P_{0,010} = 0$$
$$u_1 P_{0,031} + \lambda_2 P_{0,010} - \mu_2 P_{0,030} = 0$$
$$v_1 P_{0,100} + u_2 P_{0,202} - u_1 P_{0,001} = 0$$
$$v_2 P_{0,010} + u_1 P_{0,021} - u_2 P_{0,002} = 0$$
$$u_1 P_{0,001} + u_2 P_{0,002} - w P_{0,000} = 0$$

The system consists of 33+11(n-3) equations and equal number of unknowns. For example, for n=4, number of system states, as well as number of equations, is 33+11(4-1)= 66 and for n=10, it is 33+11(10-3)= 110. It is possible to obtain an exact solution for this system of equations given by PT=0, where P is the state probabilities vector to be determined and T is the probability transition rate matrix. It is known that all the equations in PT=0 are not linearly independent and thus the matrix T is singular, which does not have an inverse. We must add to the sets of equations above the normalizing condition given by equation (4) below, which assures that sum of all state probabilities is 1, by eliminating one of them.

$$\sum_{i=0}^{n}\sum_{j=0}^{2}\sum_{k=0}^{2}\sum_{l=0}^{2} P_{ijkl} = 1 \tag{4}$$

While it may be possible to obtain a closed form solution for this system of equations, it requires extensive manipulation of equations and involves large number of variables that may be extremely difficult, if not impossible. However, exact solutions can be obtained by software that are used to solve linear set of equations. We have solved this system of equations by using MAPLE software which allows symbolic solution to the system. Equations are entered as they are given above and the program solves them symbolically. This facilitates solution since it is not necessary to extract the matrix each time from the equations and enter it for solution. In the following section, we present some numerical results obtained for the system considered.

4. Case Examples and Analysis of Results

This section presents numerical results for a case problem with different parameters and compares the results of various systems operated under different conditions and different repair rates. Parameter values for the unreliable FMM system with a single repair crew are shown in table 1. The same parameters are also used for the double repair crew case with the exception of the repair rate, which is used for each repair crew as will be shown in the figures below. Values given in the table are the mean values for various parameters in the case examples. It should be noted that the mean is the inverse of the rate in each case. System of equations given in the previous section is solved for the given parameters to obtain several performance measures. Figure 2 shows the production output rate, for the FMM system with a single repair crew, as a function of the pallet capacity (n) for two different pallet transfer rates of w=5 and w=20 pallets/time unit. As it is seen from the figure, production rate increases with increasing pallet capacity as well as the pallet transfer rates as expected. While the rate of increase is higher initially, it levels off at higher values of n. When n exceeds 12 units, the effects of pallet capacity on production rate reduces and levels off as it reaches to n=20.

Table 1. Parameter values for the unreliable FMM system (single repair crew)

Operation time per part	$1/v_m$ = 1 time unit, m=1, 2 (for machines 1,2)
Robot loading time for the first part	$1/l_m$ = 0.05 time units, for machines m=1, 2
Robot load/unload time for subsequent parts	$1/z_m$ = 0.1 time units, m=1, 2
Robot unloading time for the last part	$1/u_m$ = 0.05 time units, m=1, 2
Mean time to failure for machine m	$1/\lambda_m$ = 100 time units (Failure Rate=0.01)
Mean time to repair the machine m	$1/\mu_m$ = 10 time units (Repair Rate =0.1)
Pallet transfer rate	w = 5 and w=20 pallets/time unit
Pallet capacity	n=2,….20 units

Figure 3 shows the effects of repair rate on FMM production rate under single (1RM) and double (2RM) repairman cases for a pallet capacity of n=10 parts.. Repair rate is set equal to 0.1 repairs/time unit for the single repairman as well as for each one of double repairmen. Since the machines would not wait for repair in case of double repairmen, production output rate would be higher than single repairman case. As it can be seen in the figure, production rate increases with respect to the repair rate as expected. However, the difference between the two cases diminishes.

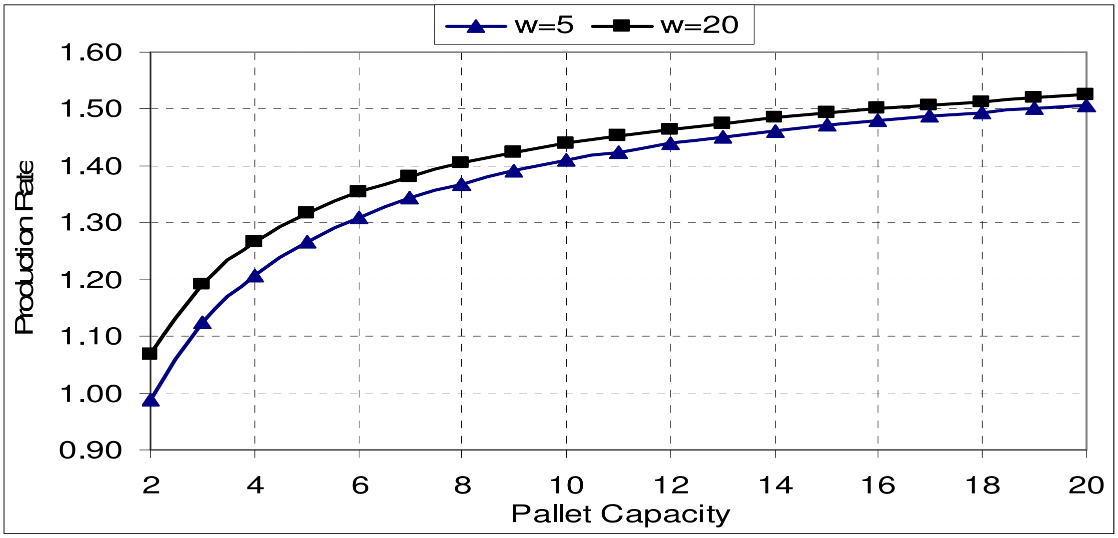

Figure 3. Effects of pallet capacity (n) and pallet transfer rate (w) on FMM production rate.

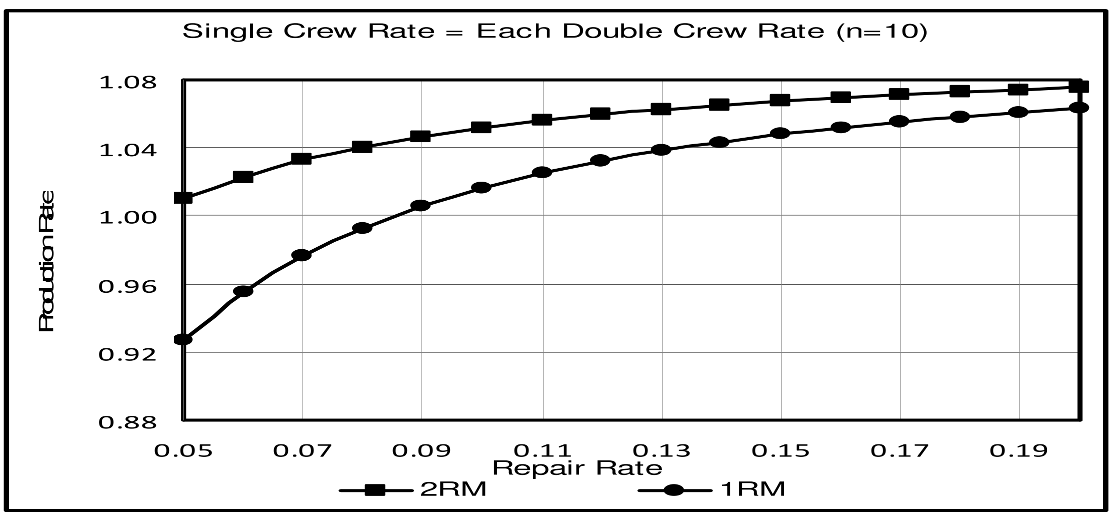

Figure 4. Effects of repair rate on production rate of FMM with double (2RM) and single repairman (1RM) for pallet capacity of n=10 parts.

Figure 4 shows average machine utilizations as a function of repair rate for single and double repair crews. Average machine utilizations show the same trend as the production rate. As it is seen from figure 3 and 4, an FMM system with two machines and two repair crews performs better than the same FMM with a single repair crew. The difference in production rates and average machine utilizations between the two cases is much higher at lower repair rates than at higher repair rates. Here, it is assumed that the single repair crew has a repair rate that is equal to the rate of each of double repair crews. For example, if in the case of single repair crew the repairman has a repair rate of 0.05 repairs/time unit, the repair rate for each of double crew members is also assumed to be equal to 0.05 repairs/time unit.

In figure 5 and 6, double repair crew is compared to single repair crew when the single repair crew has a repair rate that is equal to the total repair rates of double repair crew. Effectively, we assumed that if each of two repairmen has a repair rate of 0.05, the single repairman has a rate that is equivalent to the sum of the two, i.e., 0.10 in this case. This assumption can also be thought of pooling the repair capacity of two into a single crew. It is interesting to observe that the pooled single repair crew policy performs better than double repair crew policy in improving FMM production rate as well as average machine utilizations. These are interesting results from the models presented which are not obvious otherwise. It is important for the maintenance engineers to utilize a policy that increases system performance. Finally, figure 8 compares the effects of machine failures on FMM production rate for the single repairman case, double repairmen case, and single repairman with pooled repair rate case that is equal to the total of double repairmen. While the production rate decreases with increasing failure rates as expected, the pooled repair policy again performed much better than other two cases.

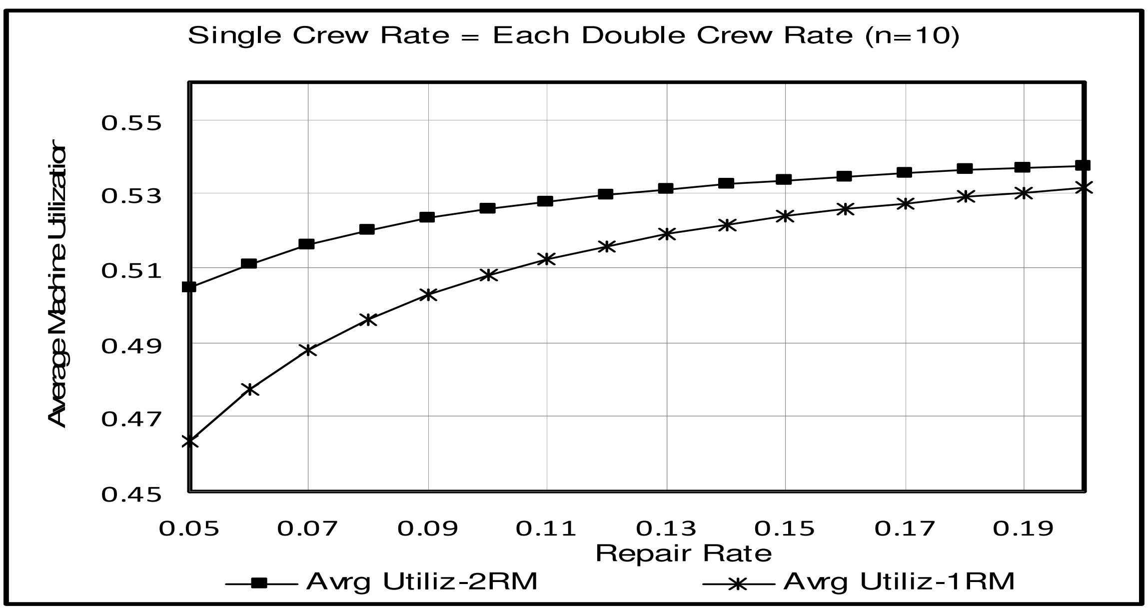

Figure 5. Effects of repair rate on average machine utilizations of FMM with single and double repairmen (RM) for n=10 parts.

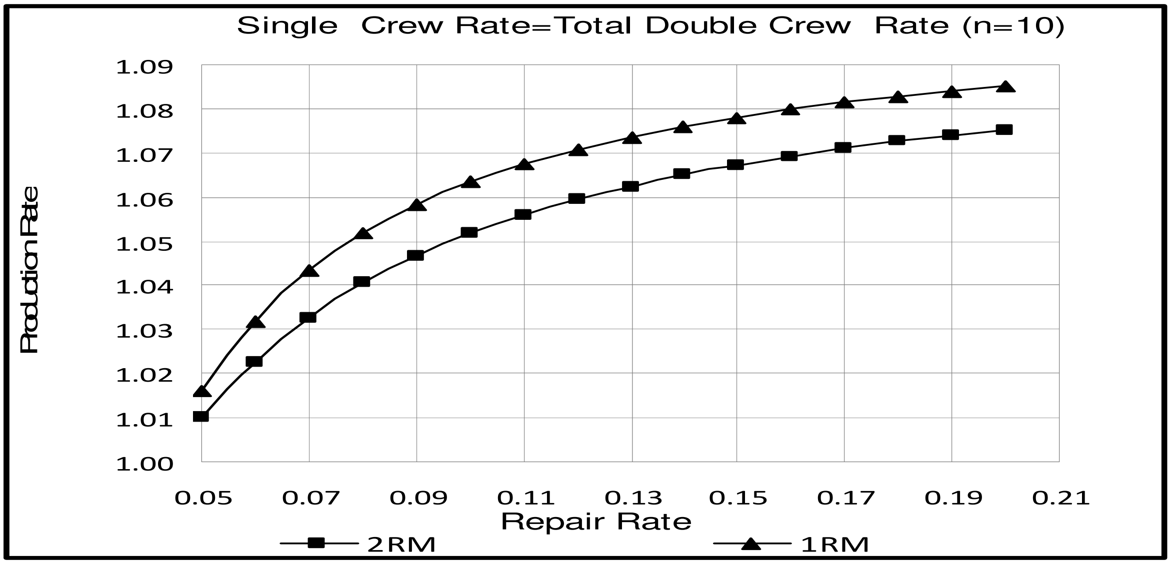

Figure 6. Effects of repair rate on production rate of FMM with double and single repairman (RM) with pooled repair rates for n=10.

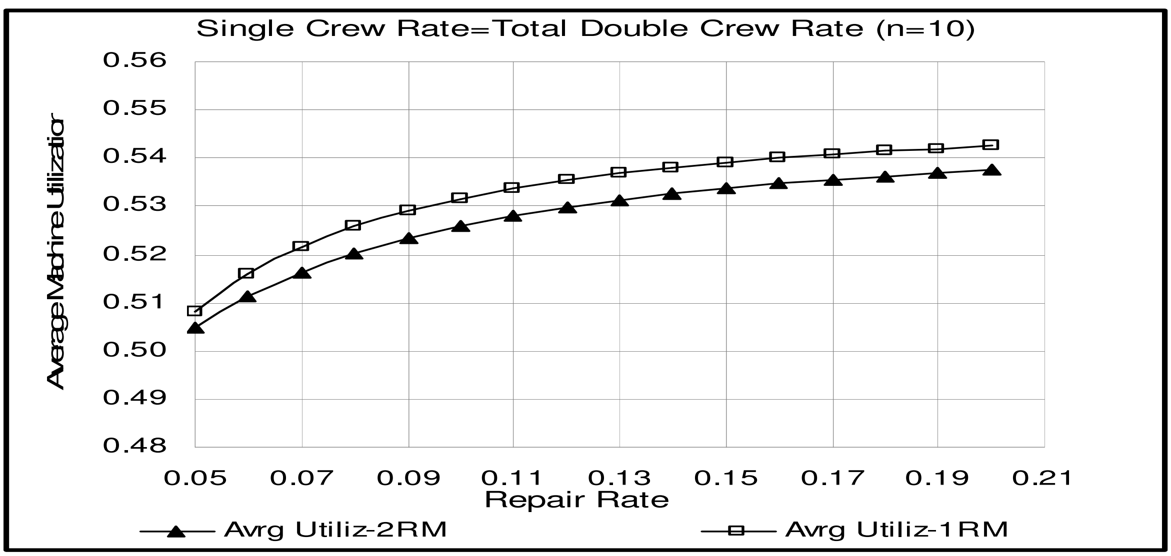

Figure 7. Effects of repair rate on average machine utilizations of FMM with double and single repairman (RM) with pooled rates for n=10.

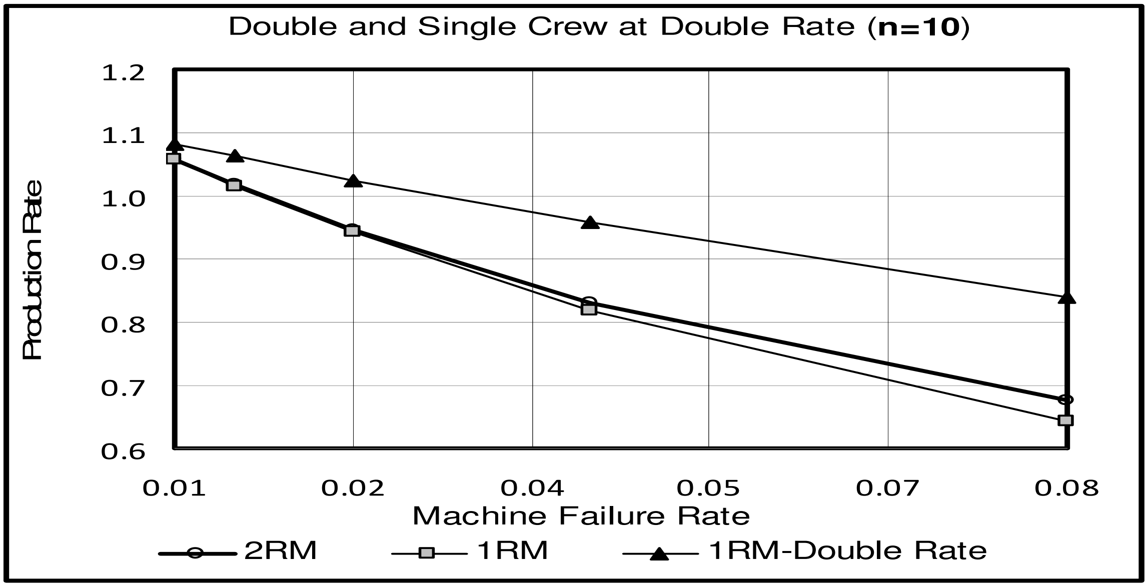

Figure 8. Effects of failure rate on production rate of FMM with single and double repairmen (RM) and single repairman with pooled rate for n=10.

5. Design of Experiments

In order to determine statistical significance of the effects of various factors and their interactions on FMM performance, experimental design was utilized to analyze the results obtained from the model. In particular four factors, as shown in table 1, were selected for the factorial design and their effects were investigated by analysis of variance (ANOVA). While pallet capacity, repair rate, and failure rate had four levels, repair policy had three levels. Response variable was the production rate of the FMM.

Table 1. Four factors and the levels considered in the design of experiment.

Factors	**Levels**			
A: Pallet Capacity (n)	2	6	**10**	**20**
B: Repair Rate	.005	.010	.020	.040
C: Failure Rate	.05	.10	.15	.20
E: Repair Policy	Double Repair Crew	Single Repair Crew	Single Repair Crew Doubled Rate	

Analysis of variance results given in table 2 show the effects of significant factors on FMM production output rate. As it is seen in the ANOVA table, the Model F-value of 367.39 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicated that the model terms were not significant and thus not included in the ANOVA table. In this specific case, the pallet capacity (factor A) had the highest effect on FMM production rate, followed by repair rate (factor B) and failure rate (factor C). Repair policy (factor D) also had significant effect, but not as much as the other three factors.

Interaction BC had much higher effect than interaction BD. Other interactions were not significant and therefore not included in the model here. R-Squared and adjusted R-Squared were 0.98 indicating the suitability of the model. A regression model, which relates the production rate to coded factor levels, is also given below. These results may be very useful for the operation and maintenance engineers in improving and managing FMM systems.

Production Rate= 0.92-0.18*A[1]+5.617E-003*A[2]+0.060*A[3]
+0.074*B[1]+0.042*B[2]-0.013*B[3]
-0.092*C[1]+4.425E-004*C[2]+0.036*C[3]
-0.018*D[1]0.023*D[2]
+0.057*B[1]C[1]+0.028*B[2]C[1]-0.016*B[3]C[1]
+1.247E-003*B[1]C[2]+1.841E-003*B[2]C[2]+1.020E-003*B[3]C[2]
-0.023*B[1]C[3]-0.011*B[2]C[3]+6.260E-003*B[3]C[3]
+0.011*B[1]D[1]+5.217E-003*B[2]D[1]-3.375E-003*B[3]D[1]
+0.015*B[1]D[2]+8.030E-003*B[2]D[2]-3.247E-003*B[3]D[2]

Table 2. Analysis of variance table (significant factors and interactions)

Source of Variation	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	4.16	26	0.16	367.39	< 0.0001
A: Pallet Capacity (n)	2.29	3	0.76	1754.77	< 0.0001
B: Repair Rate (μ)	0.87	3	0.29	666.30	< 0.0001
C: Failure Rate (λ)	0.62	3	0.21	472.67	< 0.0001
D: Repair Policy (Single/Double)	0.16	2	0.081	185.64	< 0.0001
BC Interaction Effect	0.17	9	0.019	43.44	< 0.0001
BD Interaction Effect	0.047	6	7.872E-003	18.09	< 0.0001
Residual	0.072	165	4.351E-004		
Cor Total	4.23	191			

6. Conclusions

Today, manufacturing firms are under pressure to produce a variety of products using the same production equipment or manufacturing set up in order to meet the changing demand and reduce the costs. To achieve this goal, flexible manufacturing equipment has been introduced and is becoming inevitable part of manufacturing systems. The most common type of flexible manufacturing set ups are flexible manufacturing modules, which are gaining wide acceptance in today's dynamic manufacturing environment. In order to get full benefit from these systems, they have to be analyzed in detail before implementation as well as during their operations. While mathematical modeling and analysis of traditional machining and production systems have been subject of extensive research over the past several years, FMM systems have not received the same amount of attention and not as many researches are seen on modeling of FMM systems.

Stochastic model and the solutions obtained in this paper could be used to analyze and optimize the productivity and other performance measures of an FMM under various repair and corrective maintenance policies. Several interesting results are obtained from the analysis that could not be seen otherwise. In particular, the model results showed that by using a single-repairman crew with a pooled rate of 2μ instead of using two-repairmen crew, each with a rate of μ (i.e., two repairmen working together on a machine instead of each being assigned to a machine), FMM productivity could be improved. The model also showed that by simple managerial policies with no additional resources, it was possible to improve system performance. Using the model presented in this paper, best parameter combinations can be determined for a given FMM system. In addition to the best repair policy, best machining rates, best robot loading and unloading rates, best pallet capacity, and best pallet transfer rates can be determined for a given FMM with specific characteristics. Furthermore, the results show that reliability and availability analysis of the FMM system can be determined based on different failure characteristics of the machines in the system. It is possible to optimize machine repair rates, based on other system parameters, to achieve maximum production output rates and other performance measures. Operation managers can use these analysis and results to determine optimum maintenance plans for their systems.

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M. Savsar is Professor of Industrial Engineering at College of Engineering & Petroleum, Kuwait University. He has authored more than 150 publications in international journals and conference proceedings in the areas of reliability, quality and maintenance modeling, flexible manufacturing systems, just-in-time production control, and facilities planning and layout He edited a book on Quality Assurance and Management and authored several book chapters. He received the best researcher award at Kuwait University and best paper awards in several symposiums. He obtained his B.Sc. degree from Karadeniz Technical University in Turkey in 1975, his M.Sc. and PhD. Degrees from the Pennsylvania State University, USA in 1978 and 1982 respectively in the areas of Industrial Engineering & Operations Research. He worked as an engineer, a researcher and a faculty member in several institutions including a fiber board factory in Turkey; The Pennsylvania State University, USA; Anadolu University, Turkey; King Saud University, Saudi Arabia; and Kuwait University. He was chairman of the Department of Industrial & Management Systems Engineering at Kuwait University during 2006-2010. He is a senior member of Institute of Industrial Engineers (IIE), a member of Institute for Operations Research and Management Science (INFORMS), New York Academy of Sciences, Society of Manufacturing Engineers, Turkish Society of Operations Research, and Turkish Society of Mechanical Design and Production. He is on editorial boards of several journals and also on scientific committees of several conferences.

M. M. Aldaihani is an Associate Professor and Chairman of Industrial and Management Systems Engineering at Kuwait University. He received his BS in Petroleum Engineering from Kuwait University and his MS and PhD in Industrial and Systems Engineering from the University of Southern California. His research interests focus on modeling and optimization, vehicle routing, production and scheduling, and analysis of flexible manufacturing systems. He was awarded the Kuwait University Award of Excellence of Teaching in 2006. He is a member of Institute for Operations Research and Management Science (INFORMS), Institute of Industrial Engineers (IIE) and Kuwait Society for Engineers (KSE).