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Effects of maintenance policies on the productivity of flexible manufacturing cells

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Abstract

Flexible manufacturing cells (FMCs) often operate with increasing failure rate due to extensive utilization and wear-outs of equipment. While maintenance plans can eliminate wear-out failures, random failures are still unavoidable. This paper discusses a procedure that combines simulation and analytical models to analyze the effects of corrective, preventive, and opportunistic maintenance policies on productivity of a flexible manufacturing cell. The production output rate of an FMC, which is a function of availability, is determined under different maintenance policies and mean time between failures.

Keywords: Maintenance; Reliability; FMC; Simulation

1. Introduction

Maintenance analysis is an important issue since the cost of maintenance in industrial facilities can go up to 15–40% of total production costs as reported by Sheu and Krajewski [1]. The trend toward increased automation has forced the managers to pay even more attention to maintain the complex equipment and to keep them in available state. While many maintenance related studies have been carried out on traditional automated systems, very few research can be found related to the effects of maintenance policies and failure rates on the operation of a flexible manufacturing system (FMS) and a flexible manufacturing cell (FMC) which is a subset or a smaller version of FMS. It is well known that during the extended useful life of an FMC, it will experience more wear and tear than a traditional machine operating over the same period of time. This is because, as indicated by Vineyard and Meredith [2], an FMC will typically operate at 70–80% utilization while a traditional machine may operate at as low as 20% utilization. The result is that an FMC may incur four times more wear and tear than a traditional machine. The effect of such an accelerated usage on system performance is not well known yet. However, it is fully realized that the accelerated usage of an FMC would result in higher failure rates, which in turn would necessitate and increase the importance of maintenance and maintenance related activities.

Traditionally it is known that the probability of failure would increase as a machine is aged, and that it would sharply decrease after a planned preventive maintenance is implemented. However, the amount of reduction in failure rate, due to the introduction of preventive maintenance (PM) has not been fully studied. In particular, it would be desirable to know the performance of a FMC before and after the introduction of a PM. It is also desired to know the type and the rate at which a preventive maintenance should be scheduled. In general there are two types of PM policies, namely, age-based and block-based preventive

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maintenance. The implementation of a PM could be at scheduled times (scheduled PM) or at other opportunities (opportunistic PM), which arise when the equipment is stopped due to other reasons. If the equipment is maintained only when it fails, it is called a corrective maintenance (CM) policy. Two other maintenance policies that could be seen in the literature are age and block replacement policies. In both cases, a PM is scheduled and carried out on the equipment. The difference is in the timing of the PMs. In the aged-based policy, if a failure occurs before the scheduled PM, the PM is rescheduled from the time the corrective maintenance is carried out on the equipment. In the block-based policy, on the other hand, the PM is always carried out at scheduled times regardless of the time equipment fails or the time a corrective maintenance is carried out. The best policy has to be selected for a given system with respect to its failure, repair, and maintenance characteristics. Depending on the availability of past data, costs should be taken into consideration in selecting the best policy.

The existing body of theory on system reliability and maintenance is scattered over a large number of scholarly journals belonging to a diverse variety of disciplines. In particular, mathematical sophistication of preventive maintenance models has increased in parallel to the growth in the complexity of modern manufacturing systems. Extensive research work has been published in the areas of maintenance modeling, optimization, and management. Dekker [3] presented an excellent review of maintenance optimization models. Cho and Parlar [4] presented surveys of maintenance models for multi-unit systems. Valdez-Florez and Feldman [5] also presented a survey of maintenance models for repair, replacement, and inspection of systems subject to stochastic deterioration. Vatn et al. [6] developed a generalized model based on influence diagrams for determination of an optimal maintenance schedule in a production system. Sheu and Krajewski [1] presented a decision model, based on simulation and economic analysis, for corrective maintenance policy evaluation. Almost all of the maintenance models try to find a balance between costs and benefits of maintenance for a machine.

Waeyenbergh et al. [7] and Waeyenbergh and Pintelon [8] have discussed detailed procedures, knowledge-based concepts, and frameworks in maintenance policy development and implementation in industry. Komonen [9] presented a cost model of industrial maintenance for profitability analysis. Lin and Chien [10] discuss the maintenance system design problems in flexible manufacturing systems. Very little literature is found on maintenance-related issues of flexible manufacturing cells. Gupta et al. [11] experimentally studied the interrelationship between downtimes and uptimes of CNC machines. They concluded that downtimes had dynamic influence on the uptimes of CNC machines with a delay effect. Kennedy [12] argues several issues related to maintenance of flexible manufacturing systems. However, no models are presented. Milne [13] presented a condition monitoring system to increase the availability of FMS and stand alone flexible machines. The system includes automatic data collection, statistical data analysis, advanced user interface, expert system, and maintenance planning. Lin et. al. [14] developed a closed queuing network model to optimize the number of standby units and the repair capacity for an FMS, which is referred to as maintenance float policy. Sun [15] presented a simple simulation model of an FMS, which is operated under various maintenance policies. He tried to study the effects of maintenance policies by observing the time to failure, time to repair, and the maintenance times generated by simulation. However, he did not incorporate into the simulation model the effects of preventive maintenance on machine failure times. Vineyard and Meredith [2] studied the effects of various maintenance policies on the failures of an FMS in actual operation. They have used the actual failure data and simulated the system under different maintenance policies without providing a mathematical relation between equipment failures and maintenance operations. They have set up a randomized block design and used multiple comparisons to determine the effects of different maintenance policies on different types of failures. Savsar [16,17] presented stochastic models for a FMC and obtained FMC availability assuming no preventive maintenance is performed. Further study is needed to evaluate the effects of preventive maintenance policies on FMC availability and to determine the amount of reduction in equipment failure frequency due to maintenance.

This paper presents analytical and simulation models to determine the performance of a flexible manufacturing cell operated under random failures and different maintenance policies. It is assumed that the FMC can be subjected to a purely corrective maintenance policy, a corrective maintenance combined with a preventive maintenance policy, or a preventive maintenance implemented at different opportunities. Since an FMC operates with an increasing failure probability due to wear-outs, its hazard rate is partitioned into a constant rate representing random failures and an increasing rate representing wear-out failures. In effect, the stream of mixed failures during the system operation cycle is separated into two types: (i) purely random failures due to chance causes; (ii) time-dependent failures due to equipment usage and wear-outs. The effects of preventive maintenance policies (scheduled and opportunistic), which are introduced to eliminate wear-out failures of a flexible manufacturing cell, are investigated by analytical and simulation models. This separation was possible by assuming uniform time between failures with hazard rate increasing by time. In particular, effects of various maintenance policies on system performance are investigated under different mean time between failures, as well as different maintenance and repair-related parameters.

2. Maintenance policies in FMC

Most of the previous studies, which deal with maintenance modeling and optimization, have concentrated on

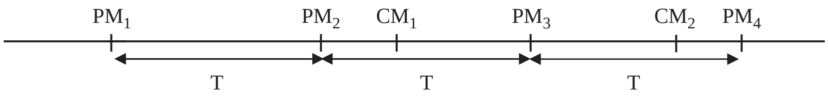

Fig. 1. Illustration of PM operations under block-based policy.

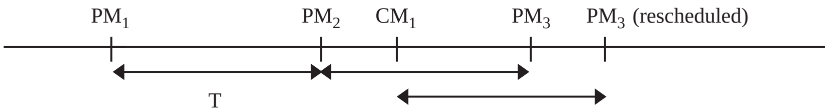

Fig. 2. Illustration of PM operations under age-based policy.

finding an optimum balance between the costs and benefits of preventive maintenance. Two well-known maintenance policies originating from the past research are called *age and block replacement models*. In both models, a PM is scheduled to be carried out on the equipment. The difference is in the timing of the PMs. In the *aged-based model*, if a failure occurs before the scheduled PM, the PM is rescheduled from the time the corrective maintenance is carried out on the equipment. In the *block-based model*, on the other hand, the PM is always carried out at scheduled times regardless of the time of equipment failures and the time the corrective maintenance is carried out. Several other maintenance models, based on the above two concepts, have been discussed in the literature. Most of the studies concentrate on the maintenance modeling of traditional equipment with the assumption that time to failure follows Weibull distribution. In this paper, we have implemented and evaluated five maintenance policies on an FMC. This resulted in six distinct cases as described below.

1. *No maintenance policy*: In this case, a fully reliable FMC with no failures and no maintenance is considered. The cell is assumed to be fully reliable and no maintenance is performed.

2. *Corrective maintenance only policy* (*CMP*): The FMC receives corrective maintenance only when any equipment fails. Time between equipment failures is assumed to follow a certain distribution, which was initially assumed to be uniform distribution. The idea behind using uniformly distributed time between failures is that the total failure rate can mathematically be separated into two components; namely, failures due to random chances and the failures due to wear-outs. This facilitates the analysis when preventive maintenance is introduced to eliminate wear-out failures as described in the next case.

3. *Block-based PM with CM policy* (*BBP*): In this case, the equipment is subjected to a preventive maintenance at the end of each shift to eliminate the wear-out failures during the shift. Regardless of any CM operations between the scheduled two PMs, the PM operations are always carried out as scheduled at the end of the shifts without affecting the production schedule. This policy is evaluated under different mean time between failure and repair cases. Fig. 1 illustrates this maintenance process. Each PM operation is carried out at the end of the shift as scheduled, without regard to the CM operations.

4. *Age-based PM with CM policy* (*ABP*): In this policy, the preventive maintenance is scheduled at the end of the shift, but it changes as the equipment undergoes a corrective maintenance. Suppose that the time between PM operations is fixed as T hours. If after performing a particular PM operation, the equipment fails and a CM is carried out before the next PM, then the next PM is rescheduled T hours from the time the repair for the CM is completed. This is based on the logic that, when a CM is carried out the need for the next PM is eliminated and thus, it must be rescheduled T time units from the time the CM is carried out. If the scheduled PM time arrives before a failure occurs, The PM will be carried out as scheduled. Fig. 2 illustrates this process.

5. *Opportunity-triggered PM with CM policy* (*OTP*): In this policy, PM operations are carried out only when they are triggered by the failure mechanism. In other words, if a failure that requires CM occurs, it also triggers the PM operation. Thus, the corrective maintenance as well as the preventive maintenance is applied to the machine together at the time of a failure. This is called triggered preventive maintenance. Since the equipment is already stopped and some parts are already maintained for the CM, it is expected that the PM time would be reduced in this policy. We assign a certain percentage of reduction in the PM operation. In this case, a 50% reduction was assumed to be reasonable.

6. *Conditional opportunity-triggered PM with CM policy* (*COP*): In this policy, PM is performed on each machine at either scheduled times or when a specified opportunistic condition based on the occurrence of a CM arises. The maintenance management can define the specified condition. In our study, specific condition is defined as follows: If a machine fails within the last quarter of a shift, i.e., within the last 25% of the shift time before the time of next PM, the next PM will be combined with the CM for this machine. In this case, the PM scheduled at the end of the shift would be skipped. On the other hand, if a machine failure occurs before the last quarter of the shift time, only CM is

introduced to the machine and its PM is performed at the end of the shift as it was scheduled. This means that the scheduled PM will be performed only for those machines that did not fail during the last quarter of the shift time.

The maintenance policies described above are compared under similar operating conditions by using simulation models with analytical formulas incorporated into the model to be described below. The FMC production rate, which was the performance measure for the system, is determined under each maintenance policy. A general mathematical formulation will be described in the next section, which illustrates the separation of random failures from the wear-out failures when maintenance is introduced.

3. Mathematical formulation

Following is a mathematical procedure to separate random failures from the wear-out failures. This separation is needed in order to be able to see the effects of maintenance on the productivity and availability of a cell when simulating the system.

Let $f(t)=$ probability distribution function (pdf) of time between failures.

$F(t)=$ cumulative probability distribution function (cdf) of time between failures.

$R(t)=$ reliability function (probability that the equipment survives by time t).

$h(t)=$ hazard rate (or instantaneous failure rate).

Albino et al. [18] have indicated that the hazard rate $h(t)$ can be considered as constituting of two components, the first due to random failures and the second due to wear-out failures as follows:

$$h(t)=h_1(t)+h_2(t). \tag{1}$$

Since the equipment failures are either due to chance causes or wear-outs, reliability of the equipment, which is the probability that equipment survives by time t, can be expressed as follows:

$$R(t)=R_1(t)R_2(t), \tag{2}$$

where $R_1(t)$ is the reliability due to chance causes (or random failures), $R_2(t)$ the reliability due to wear-outs, $h_1(t)$ the hazard rate due to random failures, $h_2(t)$ the hazard rate due to wear-out failures.

Since the hazard rate due to random failures is independent of time and therefore constant, we let $h_1(t)=\lambda$. Thus, the reliability of the equipment due to random failures with constant hazard rate would be as follows:

$$R_1(t)=\mathrm{e}^{-\lambda t}, \tag{3}$$

$$h(t)=\lambda+h_2(t). \tag{4}$$

It is known that

$$h(t)=f(t)/R(t)=f(t)/[1-F(t)]=\lambda+h_2(t), \tag{5}$$

$$h_2(t)=h(t)-h_1(t)=f(t)/[1-F(t)]-\lambda, \tag{6}$$

$$R_2(t)=R(t)/R_1(t)=[1-F(t)]/\mathrm{e}^{-\lambda t}, \tag{7}$$

$$h_2(t)=f_2(t)/R_2(t), \tag{8}$$

$$f_2(t)=h_2(t)R_2(t)=\left[\frac{f(t)}{1-F(t)}-\lambda\right]\left[\frac{1-F(t)}{\mathrm{e}^{-\lambda t}}\right] = \frac{f(t)}{\mathrm{e}^{-\lambda t}}\,\frac{-\lambda}{\mathrm{e}^{-\lambda t}}[1-F(t)] \tag{9}$$

or

$$F_2(t)=1-R_2(t)=1-\frac{1-F(t)}{\mathrm{e}^{-\lambda t}}=\frac{\mathrm{e}^{-\lambda t}-R(t)}{\mathrm{e}^{-\lambda t}},$$

$$f_2(t)=\frac{\mathrm{d}F_2(t)}{\mathrm{d}t}. \tag{10}$$

These derivations show that, total time between failures, $f(t)$ can be separated into two distributions, time between failures due to random causes $[f_1(t)]$ and time between failures due to wear-outs $[f_2(t)]$. Since the failures due to random causes could not be eliminated, we must concentrate on the failures due to wear-outs in order to eliminate them by appropriate maintenance policies. By the procedure described above, it is possible to separate the two types of failures and develop the best maintenance policy to eliminate the wear-out failures. This separation is analytically possible for uniform distribution. However, it is not possible analytically for other distributions. It is assumed that when a preventive maintenance policy is implemented, failures due to wear-outs are eliminated and only failures due to random causes remain. These random failures are assumed to follow exponential distribution with constant hazard rate since they are completely random with unknown causes and effectively the memoryless property of exponential is applicable.

For uniformly distributed time between failures, t, in the interval $0<t<\mu$, probability distribution function of time between failures without introduction of PM is given by

$$f(t)=1/\mu. \tag{11}$$

If we let $\alpha=1/\mu$, then, reliability is given as $1-\alpha t$ and the total failure rate is given as

$$h(t)=f(t)/R(t)=\alpha/(1-\alpha t). \tag{12}$$

Let us assume that hazard rate due to random failures is a constant given by $h_1(t)=\alpha$, then the hazard rate due to wear-out failures could be determined by

$$h_2(t)=h(t)-h_1(t)=\alpha/(1-\alpha t)-\alpha = \alpha^2 t/(1-\alpha t). \tag{13}$$

The corresponding time to failure probability density functions for each type of failure rate is

$$f_1(t) = \alpha \times e^{(-\alpha t)}, \quad 0 < t < \mu, \tag{14}$$

$$f_2(t) = \alpha^2 \times t \times e^{(\alpha t)}, \quad 0 < t < \mu. \tag{15}$$

The reliability function for each component would be is as follows:

$$R_1(t) = e^{(-\alpha t)}, \quad 0 < t < \mu, \tag{16}$$

$$R_2(t) = (1 - \alpha t) \times e^{\alpha t}, \quad 0 < t < \mu, \tag{17}$$

$$R(t) = R_1(t) \times R_2(t). \tag{18}$$

When the PM is introduced, failures due to wear-outs are eliminated and thus the machinery fails only due to random causes, which are exponentially distributed as given by $f_1(t)$. Sampling for the time to failures in simulations is thus based on exponential distribution with mean μ and a constant failure rate of $\alpha = 1/\mu$. In case of CM without PM, in addition to the random failures, wear-out failures are also present and thus the time between equipment failures is uniformly distributed between 0 and μ as given by $f(t)$. The justification behind this assumption is that uniform distribution implies an increasing failure rate with two components, namely, failure rate due to random failures and failure rate due to wear-out failures as given by $h_1(t)$ and $h_2(t)$, respectively. Initially when $t = 0$, failures are due to random effect with a constant rate $\alpha = 1/\mu$. As the equipment operates, wear-out failures come into play and thus the total failure rate $h(t)$ increases with time t. Sampling for the time between failures in simulation is based on a uniform distribution with mean $\mu/2$ and an increasing rate, $h(t)$.

4. Simulation modeling of FMC maintenance policies

In order to analyze the performance measures of FMC operations under different maintenance policies, simulation models are developed for the fully reliable cell and for each of the five maintenance-related policies described above. Simulation models are based on SIMAN language [19]. SIMAN was selected since it offers high flexibility and facilitates modeling of manufacturing systems with various manufacturing-related programming blocks.

4.1. FMC case example

In order to experiment with the mathematical models and the simulation programs, an example FMC case as illustrated in Fig. 3 is considered. As it is seen in the figure, a mixture of parts arrives to the FMC on a cart or pallet. The automated guided vehicle (AGV) selects the parts and loads/unloads them to appropriate machines according to the processing requirements and the sequence programmed. Each part is operated on a different sequence of machines. As the operations are completed, parts are placed on output pallet to be moved out of the cell. Table 1 presents the distance between the elements of the FMC. The speed of the AGV is set at 175 ft/min. Three types of parts enter the system. Table 2 presents the sequence of operations and the processing time on each machine for each part type. Parts arrive to the system on pallets containing 8 units: 4 of type 1, 2 of type 2, and 2 of type 3 every 2 h. This combination was fixed in all cases of simulation to eliminate the effects of randomness in the arriving parts on the comparisons of different maintenance policies.

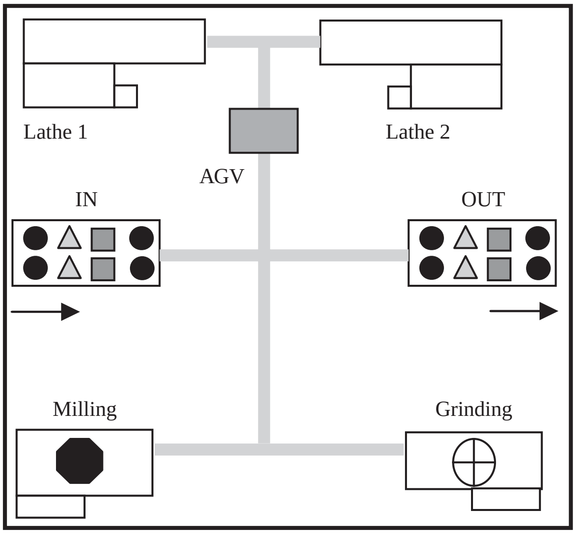

Fig. 3. Flexible manufacturing cell.

Table 1
Distance matrix (in ft)

	In	Lathe	Mill	Grind	Out
In	—	100	75	100	40
Lathe	—	—	150	175	155
Mill	—	—	—	50	90
Grind	—	—	—	—	115
Out	—	—	—	—	—

Table 2
Processing time and operation sequence of parts

Part type	Lathe (L)	Milling (M)	Grinding (G)
1 (L-M-G)	Norm(30,5)	Norm(15,3)	Unif(10,15)
2 (M-G-L)	Norm(25,8)	Tria(2,10,15)	Norm(10,2)
3 (G-L)	Unif(5,10)		Norm(15,3)

4.2. Simulation experiments

Several simulation experiments are carried out to study the performance of FMC operations under different maintenance policies. The performance measure considered was the production output rate during the simulation period. In order to be able to compare different maintenance policies and to determine their effects on FMC performance, the case of fully reliable cell is also included in our study. A simulation model was also developed for the fully reliable cell in addition to five simulation models developed for unreliable cells with five maintenance policies. Thus, a simulation model was developed for each of the six cases as: (a) a FRC; (b) a cell with CMP; (c) a cell with BBP; (d) a cell with ABP; (e) a cell with OPT; (f) a cell with COP.

Each simulation experiment was carried out for the operation of the production cell over a period of 1 month (20 working days and 8 h per day or a period of 9600 min). In the case of PM introduction, it was assumed that PM time of 30 min (or 15 min when combined with CM) is added to 480 min at the end of each shift. Ten simulation replicates are made and the performance measure, the average production output during the month, was obtained for each case. Other simulation related parameters are given for each experiment.

5. Simulation results

Results of five simulation experiments are presented here. Each experiment investigates effects of different set of FMC parameters and operating conditions on the cell production rate under each of five maintenance policies.

5.1. Experiment 1

In the first experiment, times between failures are assumed to be uniform distributed between 0 and T for all machines in the FMC. In the absence of any preventive maintenance, a machine can fail anytime from 0 to T. However, when a PM is introduced, wear-out failures are eliminated; only the failures due to chance causes remain, which have constant hazard rate and thus follow exponential distribution with mean time between failures equal to T. In this experiment, the value of T is varied from 500 to 4000 min, in increments of 500 min. Repair time is assumed to be normal with mean 100 and standard deviation of 10 min for all machines. If PM is introduced on a machine, it is assumed that the PM is done at the end of each shift and it takes 30 min for each machine. If PM is triggered by the CM and done at this opportunity, PM time reduces to half, i.e., 15 min, since it is combined with the CM tasks. Production output results for each case are shown in Fig. 4 under different policies. The production output rate is the average of 10 simulation runs and is calculated as the average of the sum of all products produced during the month. The fully reliable cell demonstrates maximum possible production output (P_i) and is used as a base to compare other maintenance policies. As it is seen from Fig. 4, performing only CM without any PM is the worst policy of all. On the other hand, the best policy appears to be the opportunity triggered maintenance policy (policy 5 or OTP), ignoring minor random fluctuations. Between the age- and block-based policies, the age-based policy (policy 4 or ABP) performed better. Among all the policies with PM, block-based policy (policy 3 or BBP) appears to be the worst policy. As the mean time between failures (MTBF increases, all of the policies reach a steady-state level with respect to operational availability, but the gap between them is almost the same at all levels of MTBF. In case of CM only policy, the production output rate sharply increases at the initial increase of MTBF from 500 to 1000 min.

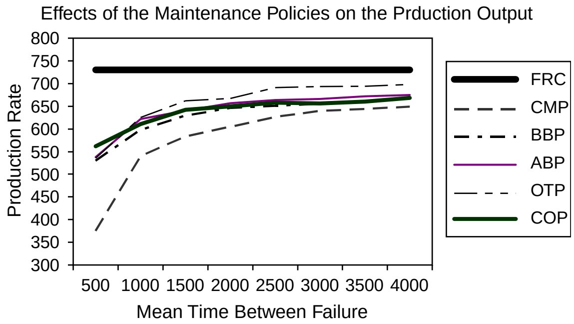

Fig. 4. Production output rate under different policies.

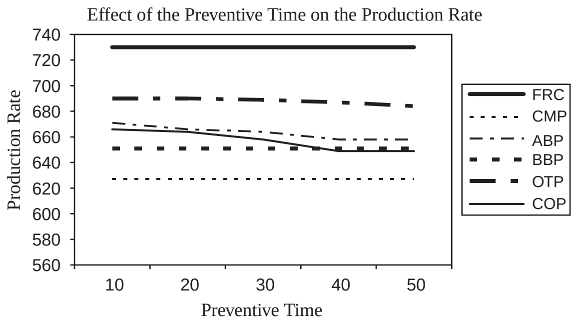

Fig. 5. Effects of variable PM time on FMC production rate.

5.2. Experiment 2

The second experiment investigates the effects of different PM times changing from 10 to 50 min at increments of 10 min on the FMC performance with various maintenance policies. The results are shown in Fig. 5. Increasing PM time has no effect on fully reliable cell and the cell with CMP. BBP was not also affected, since the maintenance is carried out at the end of the shift when the equipment

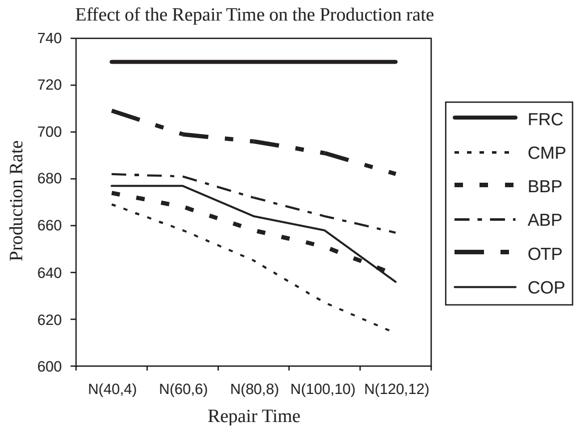

Fig. 6. Effects of repair time on FMC production rate.

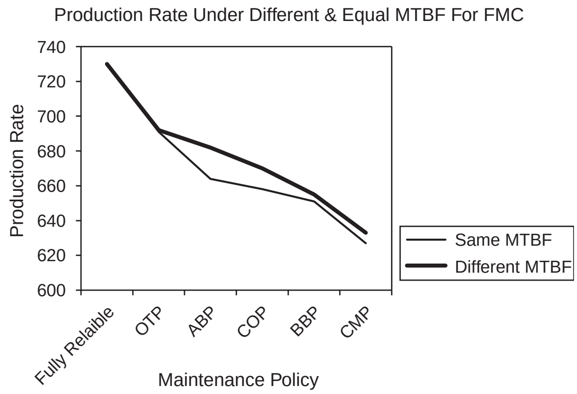

Fig. 7. Comparisons of maintenance policies under equal and different MTBF.

is not used for production. The largest effect was on COP followed by ABP and OTP. As the PM was increased, line productivity was naturally decreased in these cases. The decrease in production rate was about 2.5%.

5.3. *Experiment 3*

The third experiment investigates the effects of maintenance policies on cell production rate under different repair times, which were normally distributed with mean ranging from 40 to 120 and standard deviation from 4 to 12. The same FMC parameters, as in the first experiment, were used. The results are presented in Fig. 6. The largest reduction in production rate was in CMP and smallest was in OTP. The reduction varies from about 3.8% for OTP to about 8.3% in CMP. Thus a three times increase in mean repair time results in less than 9% decrease in production rate for the CMP policy, which seems to be the mostly affected policy by the failures, since no PM is introduced.

5.4. *Experiment 4*

In this experiment, FMC equipments were assigned different mean time to failures and the effects of maintenance policies were investigated under different equipment failure patterns. The time between failures was still assumed to be uniform, which reduces to exponential distribution when PM is introduced. While all the cell parameters were kept the same as in experiment 1, the following mean time to failure (MTTF) values were assigned to the equipment.

$$\text{Lathe: MTTF} = 2500; \quad \text{Mill: MTTF} = 4000;$$
$$\text{Grind: MTTF} = 3500.$$

Mean repair time was kept as before at MTTR = Normal(100, 10) in all cases. PM time was set at 30 time units. The goal of this experiment was to compare the case when all equipment has similar failure patterns (MTTF = 2500 time units for all machines, as analyzed in experiment 1) to the case when equipment failure patterns are different and thus there is interaction between failure patterns of equipment (different MTBF for each machine as stated above for this experiment).

The FMC production rates under different maintenance policies for this experiment are compared to the results of experiment 1 and summarized in Fig. 7. As it is seen from the figure, CMP policy was the worst in both cases, i.e., the case when the MTBF are the same and the case when MTBF is different for all machines, and the OTP was the best among the maintenance policies. Fully reliable cell was of course with the highest production rate as expected. The results in the figure show that there was no significant difference between the case of similar failure pattern and different failure patterns of equipment in the case of block-based and OTP maintenance policies. Some variation was observed in other policies. However, the general trend is similar in both cases considered with somewhat more variation in the case of equal MTBF values.

5.5. *Experiment 5*

This experiment further investigates the effects of changing equipment failure patterns on cell performance with the five cases as shown in Table 3. The mean time between failures was assumed to follow different range of patterns for each machine in the cell. In particular, MTBF was changed from 500 to 4000 for the Lathe, from 800 to 6400 for the Mill, and from 700 to 5600 for the Grinding machine. All other cell parameters were set as in the first experiment. Simulation results for this experiment are summarized in Fig. 8. The difference between the maintenance policies was almost consistent for all cases. OTP was the best and CMP was the worst policy consistently. The difference between the CMP and the other maintenance policies significantly reduces as the time between failures increases.

Table 3
Different equipment failure patterns for comparing maintenance policies

Case	MTBF		
	Lathe	Mill	Grind
1	500	800	700
2	1000	1600	1400
3	2000	3200	2800
4	3000	4800	4200
5	4000	6400	5600

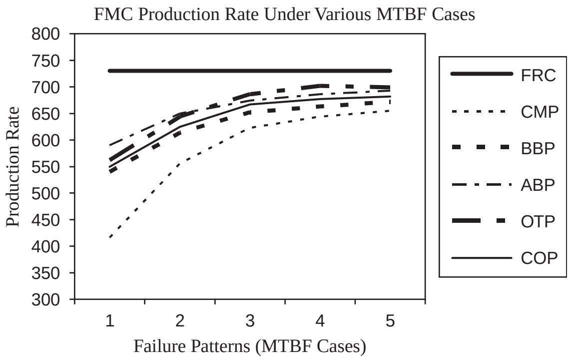

Fig. 8. Effects of maintenance policies under different MTBF.

6. Concluding remarks

This research was undertaken to determine the effects of various maintenance policies on the operational capability (production output rate and availability) of flexible manufacturing cells (FMC). Flexible manufacturing cells are operated at higher usage rates than the traditional equipment since they are flexible and can allow manufacturing of a wide variety of parts. Therefore, they are vulnerable to more wear and tear during their useful life. Maintenance is considered extremely important under such conditions. However, no detailed study can be found in the literature on the effects of maintenance policies on the operational condition of FMC.

Five distinct maintenance policies were identified and their effects on production rate, which is a direct outcome of availability, are analyzed by using mathematical formulation of failure rates and simulation modeling. Using SIMAN simulation package, six simulation programs were developed (one for the fully reliable FMC and one for each of the five maintenance policies implemented on the FMC). The results of the analysis of several experiments show that maintenance of any form has significant effect on production output rate or the availability of the FMC. However, the type of maintenance applied is important and should be carefully studied before implementation. The implication of this research is that any FMC system under consideration must be analyzed with respect to several maintenance policies and the best policy should be selected before blindly implementing a policy. As it is seen from the analysis above, the best policy in all cases appears to be opportunity-triggered maintenance policy (OTP) and the worst policy is the corrective maintenance policy (CMP) case, which is operate-to-failure and then repairs case. One important consideration that is not incorporated into the present study is related to the cost aspects. Cost data were not available during the course of this research. Future studies can be carried out on the cost aspects of various policies if such data are available. The best cost saving policy can be determined depending on the specified parameters related to the repair costs and the preventive maintenance costs. In order to perform such a study, one has to collect all maintenance related costs for the system under consideration. Other possible maintenance policies must be studied and compared to those presented in this study. Combinations of several policies are also possible in the same FMC system. For example, while a machine is maintained by one policy, another machine could be maintained by a different policy. These aspects of the problem need further investigation.

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