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ANALYSIS OF THE PERFORMANCE OF A MANUFACTURING CELL OPERATING UNDER DIFFERENT FAILURE RATES AND MAINTENANCE POLICIES

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ABSTRACT

Flexible manufacturing cells (FMCs) often operate with increasing failure rate due to extensive utilization and wearouts of equipment. While maintenance plans can eliminate wearout 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 availability of a flexible manufacturing cell. The production output rate of an FMC, which is a function of availability, is determined under different time between failure distributions. The effects of various maintenance policies on FMC production rate are simulated and the results are compared.

Keywords: *Maintenance, Reliability, FMC, Failure Rates, Simulation.*

الملخص

تعمل خلايا الانتاج المرن مع معدل الاعطال المتزايد بسبب الاستخدام المكثف والتآكل فى الالات بينما تعمل خطط الصيانة على إلغاء الاعطال إلا أن الأعطال العشوائية لا يمكن تفاديها. هذا البحث يقدم طريقة تجمع بين نموذجى المحاكاة والتحليل ليصل إلى تأثير قرارات الصيانة المتوفرة فى خلايا الانتاج المرن سواء التصحيحية منها أو الوقائية أو صيانة الفرص. كما أن معدل الانتاج فى خلايا الانتاج المرن والمعتمد على توفر الالات (الاتاحية) يتحدد مبيناً على التوزيع احتمالى المختلف لفترة ما بين الاعطال. تأثير القرارات المختلفة على خلايا الانتاج المرن تمت محاكاتها والنتائج تمت مقارنتها فى هذا البحث.

1. INTRODUCTION

The cost of maintenance in industrial facilities has been estimated to be 15-40% of total production costs [Sheu and Krajewski, 1994]. The trend towards 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 an FMC will typically operate at 70-80% utilization while a traditional machine may operate at as low as 20% utilization [Vineyard and Meredith, 1992]. 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 increase the importance of maintenance and 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 a preventive maintenance 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 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. The best policy has to be selected for a given system with respect to its failure, repair, and maintenance characteristics. 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.

Excellent reviews and surveys of maintenance optimization models are presented by [Dekker, 1996], [Cho and Parlar, 1991], and [Valdez-Florez and Feldman, 1989]. [Vatn, et. al., 1996] presented a generalized model based on influence diagrams for determination of an optimal maintenance schedule in a production system. A decision model, based on simulation and economic analysis, for corrective maintenance policy evaluation is presented by [Sheu and

Krajewski, 1994]. Very little literature is found on maintenance related issues of flexible manufacturing cells. [Gupta et. al., 1988] 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, 1987] discussed several issues related to maintenance of flexible manufacturing systems with no models presented. [Milne, 1996] discussed a condition monitoring system to increase the availability of Flexible Manufacturing Systems (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., 1994] developed a closed queuing network model to optimize the number of standby units and the repair capacity for a FMS, which is referred to as maintenance float policy. [Sun, 1994] presented a simple simulation model of a FMS 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. [Vineyard and Meredith, 1992] studied the effects of various maintenance policies on the failures of a 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. [Savsar, 1997, 2000] presented stochastic models for a Flexible Manufacturing Cell (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 of various distribution types. It is assumed that the FMC is subjected to a purely corrective maintenance policy, a corrective maintenance combined with a preventive maintenance policy, and 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 FMC, are investigated by analytical and simulation models. In particular, effects of various maintenance policies on system performance are investigated under various time between failure distributions, including the uniform, normal, gamma, triangular and weibull distributions, as well as different repair and maintenance parameters.

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2. MAINTENANCE POLICIES IN FMC

Most of the previous studies, which deal with maintenance modeling and optimization, have concentrated on finding an optimum balance between the costs and benefits of preventive maintenance. Two well-known maintenance policies originating from the past research are so-called ***age and block replacement models***. In both models, a preventive maintenance (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 a 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 wearout 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 wearout failures during the shift. Regardless of any CM operations between the two scheduled 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 various times between failure distributions. 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 PM 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.

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 is first determined under each policy. Then, using the production rate of the fully reliable cell as a basis, an index is developed for the operational availability, namely the **operational availability index**, (OAI_i) of the FMC system under each policy i. The following formula is used for this purpose: $OAI_i=P_i/P_1$, where P_1=Production rate of the fully reliable FMC and P_i = Production rate of FMC operated under maintenance policy i (i=2,3,4,5,6). A general formulation will be described in the next section for five different times between failure distributions and their implementation with respect to the maintenance policies. The mathematical formulation describes the separation of random failures from the wear-out failures when a maintenance is introduced.

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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.

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., 1992] 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:

$$h(t) = h_1(t) + h_2(t)$$

Since failures are due to chance causes (random causes) and wear-outs, reliability of the equipment, which is the probability, that equipment survives by time t, can be expressed as $R(t) = R_1(t)\ R_2(t)$. $R_1(t)$ = Reliability due to chance causes (or random failures). $R_2(t)$ = Reliability due to wear-outs. $h_1(t)$ = Hazard rate due to random failures. $h_2(t)$ = 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: $R_1(t) = e^{-\lambda t}$, $h(t) = \lambda + h_2(t)$

It is known that

$$h(t) = f(t)/R(t) = f(t)/[1-F(t)] = \lambda + h_2(t)$$

$$h_2(t) = h(t) - h_1(t) = f(t)/[1-F(t)] - \lambda$$

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

$$h_2(t) = f_2(t)/R_2(t)$$

$$f_2(t) = h_2(t)R_2(t) = [\frac{f(t)}{1-F(t)} - \lambda][\frac{1-F(t)}{e^{-\lambda t}}] = \frac{f(t)}{e^{-\lambda t}} - \frac{\lambda}{e^{-\lambda t}}[1-F(t)]$$

or,

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

$$f_2(t) = \frac{dF_2(t)}{dt}$$

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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 for other distributions. Another approach is used for other distributions in simulation.

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: $f(t) = 1/\mu$. If we let $\alpha = 1/\mu$, then, reliability is given as $1- \alpha t$ and the total failure rate is given as $h(t)=f(t)/R(t)=\alpha/(1-\alpha t)$. 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 $h_2(t)=h(t)-h_1(t)=\alpha/(1-\alpha t)-\alpha=\alpha^2 t/(1-\alpha t)$. The corresponding time to failure probability density functions for each type of failure rate would be:

$$f_1(t) = \alpha \times e^{(-\alpha t)} \quad 0 < t < \mu \qquad\qquad f_2(t) = \alpha^2 \times t \times e^{(\alpha t)}, \quad 0 < t < \mu$$

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

$$R_1(t) = e^{(-\alpha t)} \quad 0 < t < \mu, \quad R_2(t) = (1-\alpha t) \times e^{\alpha t}, \quad 0 < t < \mu, \; R(t) = R_1(t) \times R_2(t)$$

When the preventive maintenance (PM) is introduced, failures due to wearouts are eliminated and thus the machinery fails only due to random failures, 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 zero 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 wearout 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, wearout 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).

If the times between failures (TBF) are normally distributed, it is not possible to separate the two types of failures analytically. However, the following procedure is implemented in the simulation model: When no preventive maintenance is implemented, TBF is sampled from a normal distribution with mean μ and standard deviation σ in the simulation model. When PM is implemented, it is assumed that wear-out failures are eliminated and the remaining random failures follow exponential distribution with constant failure rate. Since the PM results in extending the MTBF, it is assumed that the MTBF after introduction of PM changes to $k\mu$. Where, k is a constant varied between 1.5 and 2.5. In the simulation model, TBF are sampled from exponential distribution with mean $k\mu$ for the cases when a PM is introduced.

The cases of gamma, weibull, and triangular distributions are also treated similar to the normal distribution, since the separation of two failure types are not possible analytically in these cases also. For gamma distribution (which is Erlang when α is integer, and exponential when α=1), when no PM is introduced, times between failures are sampled from a gamma distribution with mean time between failures of $\alpha\beta$. If a PM is introduced, times between failures are extended by a constant k. Sampling is made from exponential distribution with mean $k(\alpha\beta)$.Value of k is again varied from 1.5 to 2.5.

In case of weibull distribution, α=Shape parameter and β=Scale parameter. $E(T)= \beta\Gamma(1/\alpha)/\alpha$, and $V(T)= \beta^2[2\Gamma(2/\alpha)-\{\Gamma(1/\alpha)\}^2/\alpha]$. If α=c and $\beta=c(MTBF)/\sqrt{\pi}$. When there is no PM, times between failures are sampled from weibull with parameters, α and β. When PM is introduced, wear-out failures are eliminated and the random failures are sampled from exponential distribution with mean=$k[\beta\Gamma(1/\alpha)/\alpha]$, where α and β are parameters of the Weibull distribution and k is a constant changed from 1.5 to 2.5 in simulation.

Triangular distribution is described by the parameters a, m, and b (i.e., minimum, mode, and maximum). Its mean is given by $E(T)=(a+m+b)/3$ and variance by $V(T) = (a^2+m^2+b^2-ma-ab-mb)/18$. Since the times between failures can be any value starting from zero, we let a=0 and thus m=b/3 from the property of triangular distribution. $E(T)= (m+b)/3 = [b+b/3]/3 = 4b/9 = 4m/3$. If no PM are introduced, time between failures are sampled in simulation from a triangular distribution with parameters (a, m, b) or (0, b/3, b). If PM is introduced, wear-out failures are eliminated and the random failures are sampled from exponential distribution with an extended mean of $k[a+m+b]/3$, where a, m, and b are parameters of the triangular distribution that describes the time between failures. The multiplier k is again varied between 1.5 and 2.5.

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 [Pegden, et. al., 1995], 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 developed, an FMC system as illustrated in Figure 1 is considered. As it is seen in the figure, a mixture of parts arrives to the FMC on a cart or pallet. The 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 feet/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 hours. 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.

Table 1. Distance Matrix (in feet)

	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

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)

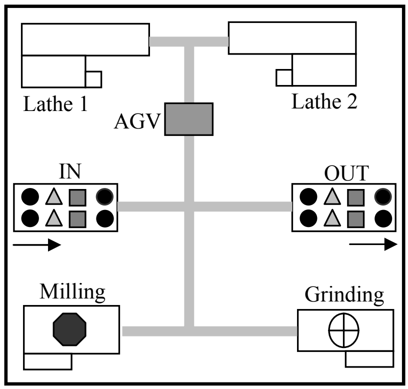

Figure 1. A Flexible Manufacturing Cell

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 Fully Reliable Cell (FRC); (b) A Cell with Corrective Maintenance Policy Only (CMP); (c) A Cell with Block-Based Policy (BBP); (d) A Cell with Age-Based Policy (ABP); (e) A Cell with Opportunity-Triggered Maintenance Policy (OPT); (f) A Cell with Conditional Opportunity-Triggered Maintenance Policy (COP)

Each simulation experiment was carried on for the operation of the production cell over a period of one month (20 working days or 9600 minutes). In the case of PM introduction, it was assumed that PM time of 30 minutes (or 15 minutes when combined with CM) is added to 480 minutes 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

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 MTBF equal to T. In this experiment, the value of T is varied from 500 to 4000 minutes, in increments of 500 minutes. Repair time is assumed to be normal with mean 100 and standard deviation of 10 minutes 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 minutes for each machine. If PM is triggered by the CM and done at this opportunity, PM time reduces to half, i.e., 15 minutes, since it is combined with the CM tasks. Production output results are shown in Figure 2 while Figure 3 shows the operational availability index under different policies.

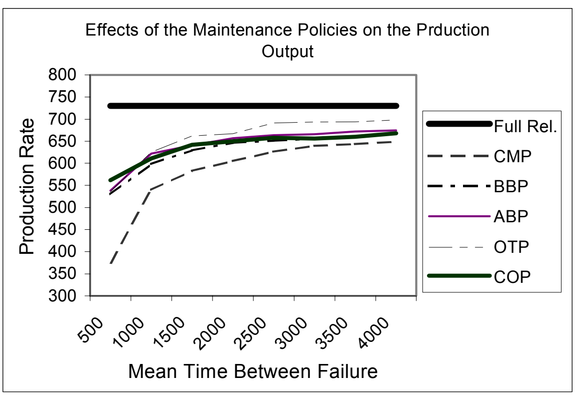

Figure 2. Production output rate under different policies

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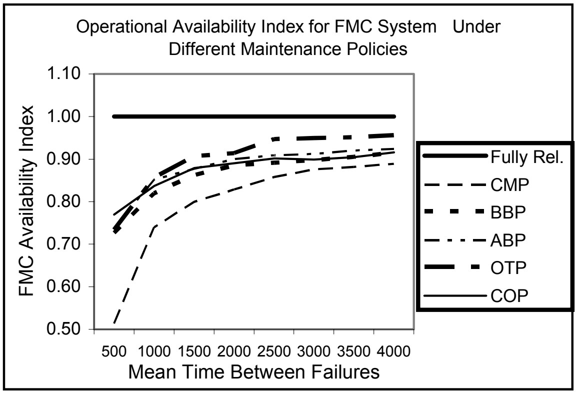

Figure 3. Operational Availability Index under different policies

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. The operational availability index (OAI_i) is defined as: $OAI_i = P_i/P_1$, where P_1=Production rate of the fully reliable FMC and P_i = Production rate of FMC operated under maintenance policy i (i=2,3,4,5,6). As it is seen from Figures 2 and 3, 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 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 as well as the operational availability index sharply increases at the initial increase of MTBF from 500 to 1000 minutes.

The second experiment investigated the effects of different PM times changing from 10 to 50 minutes at increments of 10 minutes on the FMC performance with various maintenance policies. The results are shown in Figure 4. 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 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%.

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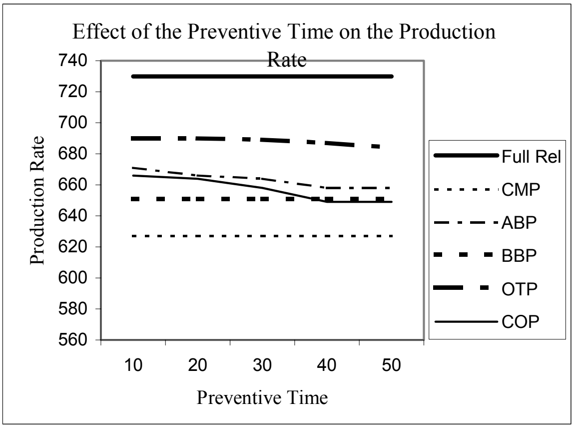

Figure 4. Effects of variable PM time on FMC production rate

The third experiment investigated the effects of maintenance policies on cell production rate under different repair times, normally distributed with mean varied 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 Figure 5. The largest reduction in production rate was in CMP and the 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 mostly affected by the failures, since no PM is introduced.

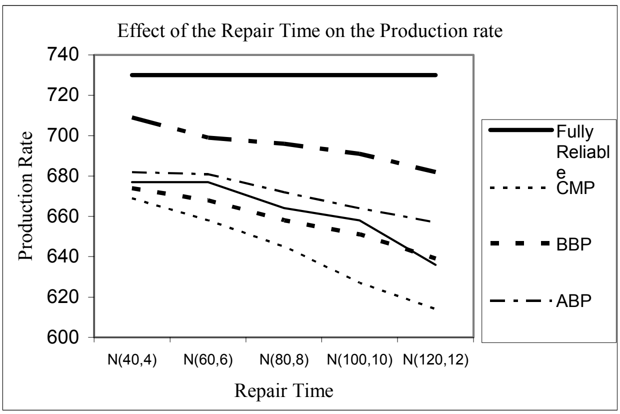

Figure 5. Effects of Repair Time on FMC Production Rate

The fourth experiment investigated the effects of changing equipment failure patterns on cell performance with the 5 cases as shown in Table 3. The mean time between failures was assumed to follow different 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 Figure 6. 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

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

The fifth experiment compared the effects of five times to failure distributions (uniform, normal, gamma, weibull, and triangular) with respect to the corrective maintenance policy (CMP). It should be noted that the other four maintenance policies (with some form of PM to eliminate wear-outs) produce the same results under all distributions since time between failures changes to exponential in any case as it was stated above. Therefore, there is no need to look at each distribution case for these maintenance policies. The parameters of all distributions were set such that the MTBF was the same for all and changed from 500 to 4000 minutes. The results are presented in Figure 7. As it seen in the figure, uniformly distributed TBF result in significantly different FMC production rates as compared the other four distributions, which resulted in very close outputs. This is due to the fact that in uniform distribution, probability of failure is equally likely at all possible values that the random variable can take, while in the other distribution cases probability concentration is around the central value.

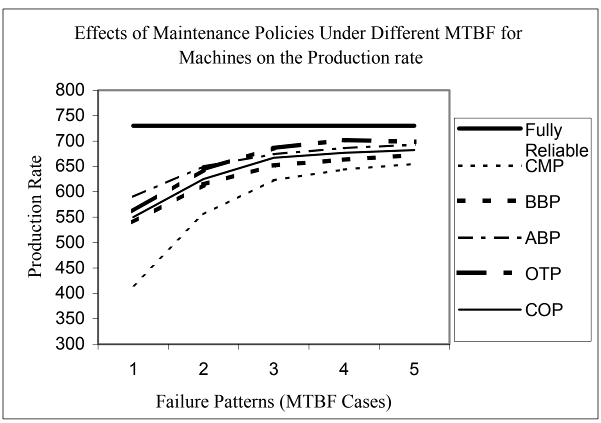

Figure 6. Effects of Maintenance Policies Under Different MTBF

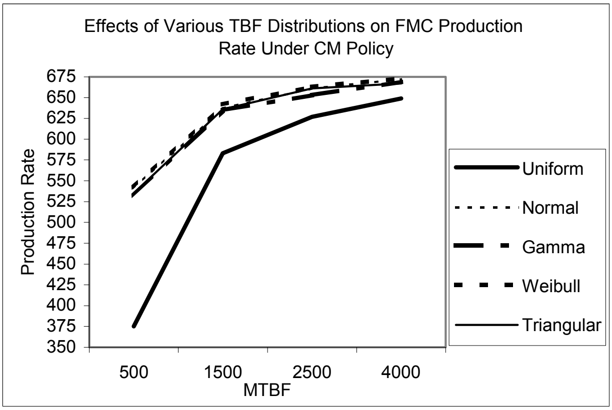

Figure 7. Effects of Various Failure Distributions on FMC Production Rate.

6. CONCLUSIONS

This research was undertaken to determine the effects of various maintenance policies on the operational capability (production output rate and availability) of a FMC. FMCs 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 more vulnerable to 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 performance of FMC.

Five distinct maintenance policies are 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. The results of the analysis of several cases 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. As it is seen from the analysis above, the best policy in all cases was opportunity-triggered maintenance policy (OTP) and the worst policy was the corrective maintenance policy (CMP). Future studies can be carried out on the cost aspects of various policies. The best cost saving policy can be determined depending on the specified parameters related to the repair costs and the preventive maintenance costs. 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 an equipment is maintained by one policy, another equipment could be maintained by a different policy. These aspects of the problem need further investigation.

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