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Maintenance Model Implementation on Manufacturing Systems

Nwadinobi, Chibundo Princewill
Department of Mechanical Engineering, Abia State University, Uturu, Abia State

ABSTRACT

In this research, a mathematical model was deployed that improves the effectiveness of maintenance planning for manufacturing systems. It utilizes operational data as obtained from industrial equipment to monitor the reliability and availability of the test equipment. A parametric test was conducted on the model by varying the input parameters to ascertain their effects on the overall system. For each case, varied values of failure rates and repair rates at given states are used to calculate the state probabilies considering the discrete states of the equipment under study. Continuing, this evaluation, gives an insight to the most appropriate maintenance action to undertake at any given time so as to improve on the reliability and availability of the equipment. The prescribed procedure, assists in planning preventive maintenance, which stands preferred to having a corrective maintenance action on manufacturing systems as it makes for increased operational life cycle, cost effectiveness, improving availability and reliability of such systems.

Keywords : Mathematical Model, Manufacturing Systems, Maintenance, Availability, Reliability

I. INTRODUCTION

Maintenance is aimed at extending equipment life time or at least the mean time to the next failure whose repair may be expensive. Again, it is expected that effective maintenance policies should be able to reduce the frequency of system uptime interruptions and the many undesirable consequences of such stoppages. Traditionally, there are mainly two types of maintenance policies, which are corrective maintenance (CM) and preventive maintenance (PM). Maintenance is becoming a critical functional area in most types of organizations and systems including construction, manufacturing, transportation, etc. This increasing role of maintenance is reflected in its high cost, which is estimated to be approximately 30% of the total running cost of manufacturing and construction businesses [1]. Furthermore, it has been observed that next to the energy costs, maintenance costs is the largest part of any operational budget [2,3,4]. As such, planning for maintenance is becoming an essential part of planning for the whole organization [5]. As effective maintenance can extend the equipment life, improve equipment availability, and restore the equipment to a good condition [6].

A survey of the operations and management of today's industries shows that maintenance activities contribute immensely to the success of industrial concerns. Therefore, good maintenance policy can increase availability of equipment by trading off between planned and unplanned downtime, which can cause major disruptions in manufacturing processes [7]. An effective maintenance policy leads to better operational availability and reliability of a system. Well-defined maintenance will ensure optimal performance of the machineries [8]. This will not only improve the quality of goods and services but also satisfy and rather exceed customers' demands [9].

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Furthermore, management of equipment in a manufacturing system is a big challenge. One of the major challenge remains the probability of system failure occurrence and its consequence. Thus, knowledge on the effective management of these equipment can maximize utilization. Maximum benefit or minimal life cycle cost; is achievable through proper maintenance management procedure. And it is said to be a strategy to handle decisions for these systems and to make right decisions on what systems to apply actions to; what actions to apply; how to apply the actions; and when to apply the actions [10]. The aim of this study is to use a predictive maintenance model to determine the equipment condition and predict failures in a more accurate way. This way preventive maintenance actions can be planned before failure. In addition, unnecessary process interruptions can be avoided resulting in decreased maintenance and related costs. To successfully perform the procedure, evaluations of the probability of the system to operate normally (availability), the probability of the system to be repaired (maintainability) and the probability of failure for the system are undertaken at any instant of time. This is to achieve reduced probability of failures and system downtime.

II. METHODOLOGY

The implementation of this study was demonstrated using real-time maintenance data obtained from 7up Bottling Company, Aba Plant. In the production line, the Bottle filling machine was considered being an integral unit on the line. The factors and considerations that affect the effectiveness of the maintenance model developed is considered. A set of input measures which include the total operational period (duration), the no of breakdowns (frequency), the total downtime (duration), mean time between failures (MTBF) of component, and mean time to repair (MTTR) of component of the equipment that influences the failure rate and repair rate were sourced from maintenance data record. Four scenarios were described based on four main parameters used as input variables. The essence of this maintenance model is to achieve significant availability of the Bottle filling machine for production when it is well implemented. This makes for effective condition monitoring which may be continuous or periodic, for maintaining a unit of equipment in its operating state. In this work, the degradation of a component from commissioning to failure is simplified by categorizing the technical condition into four defined stages of degradation (states) using Di to represent each state as illustrated in Figure 1. In state D = 1, a component as-good-as-new. At D = 4, the condition is characterized as critical, and maintenance actions must be taken immediately. State 1 represents an "as good as new" condition (no degradation). State 2 represents "expected" degradation (wear and tear) that normally do require minor maintenance actions (incipient degradation). State 3 represents a condition that normally (sooner or later) would require some preventive maintenance action (severe degradation). State 4 represents a critical condition where corrective maintenance actions should be taken immediately (critical degradation).

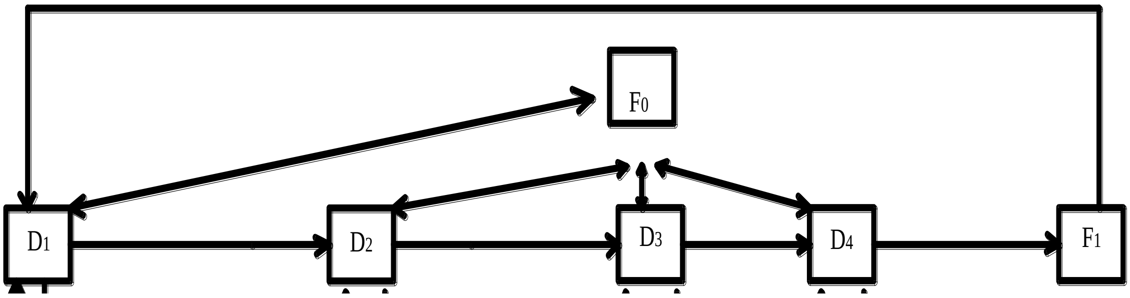

Figure 1. System/Equipment State Space maintenance model

The maintenance planning model state space is as presented in figure 1. There can be random failure F0 or failure due to degradation F1. Considering a failure and repair process of a repairable system, the state probabilities for the process can be determined by equating the rate at which the process leaves a state with the rate at which it enters that state [11], we obtain:

State: Rate at which the process leaves=Rate a which the process enters

Applying the Markov state probabilities solution approach to plan maintenance for the State Transition Diagram as shown in Figure 1. The maintenance model in equations (1) to (3) has its formulation presented in [12]. The three distinct states (Normal state, PM state and CM state) were considered with the associated assumptions that:

The system is periodically inspected. The time of next inspection depends on the system state revealed by the previous inspection.

The proportion of time the process is in each of the states is not a pure birth and death process (since the process can go directly from last state to first state).

The input variables used in this model are as follows: D = the ith system state, D = 1,2 (system at normal operating state), D = 3 (system at PM state), D = 4 (system at CM state); Pi (t) = probability that the system is in state i at time t, for i = 1,2; 3; 4; λcm = system failure rate at CM state, μcm = system repair rate at CM state, λpm = repair rate at PM state, μpm = repair rate at PM state.

The state probability equations for the State Space transition diagram as shown in figure 1 is expressed as following:

$$P_{1,2}(\text{NORMAL STATE}) = \frac{\mu_{cm}\mu_{pm}}{\mu_{pm}\mu_{cm} + \lambda_{pm}\mu_{cm} + \lambda_{cm}\mu_{pm}} \quad (1)$$

$$P_3(\text{PM STATE}) = \frac{\lambda_{pm}\mu_{cm}}{\mu_{pm}\mu_{cm} + \lambda_{pm}\mu_{cm} + \lambda_{cm}\mu_{pm}} \quad (2)$$

$$P_4(\text{FAILURE/CM STATE}) = \frac{\lambda_{cm}\mu_{pm}}{\mu_{pm}\mu_{cm} + \lambda_{pm}\mu_{cm} + \lambda_{cm}\mu_{pm}} \quad (3)$$

These equations can predict system availability, probability of system set for preventive maintenance, and probability of system failure from equations (1), (2) and (3) respectively.

For the parametric evaluation, a constant factor is assumed for the model to forecast future behaviour trends of the system under consideration. A linear trend equation was determined for the given data set. The assumption of a linear trend was to obtain a constant slope of the trend in data points. The slope represents the change in rate per period, was divided by the average number of breakdowns/repairs in the period under review to determine the factor by which time affects state rates.

$$Factor\ by\ which\ time\ affects\ state\ rate = \frac{absolute\ value\ slope\ of\ the\ equation}{average\ number\ of\ breakdowns/repairs\ in\ the\ period\ under\ review} \quad (4)$$

From this equation, the slope gives the rate of change (increase/decrease) in breakdowns/repairs per period.

III. RESULTS AND DISCUSSIONS

The developed models were tested using the breakdown data obtained from a bottling line filler machine. The health condition (deterioration level) of the equipment is classified into three distinct stages of Normal State, PM State and CM/Failure State. The developed Markov State Probability models were applied to the input variables of average failure and repair rates (λpm, λcm, μpm and μcm) for nine years (2007-2015) of these distinct states and the result are as displayed in Table 1.

Table 1. Equipment Input variables and Main State Probabilities (2007-2015)

T1ME	λ_{pm}	λ_{cm}	μ_{pm}	μ_{cm}	$P_{1,2}$ (NORMAL STATE)	P_3(PM STATE)	P_4(FAILURE/CM STATE)
2007	0.0272	0.0268	0.0461	0.0932	0.5324	0.3143	0.1533
2008	0.0214	0.0231	0.0358	0.079	0.5292	0.3163	0.1546
2009	0.0237	0.0279	0.0399	0.0957	0.5301	0.3156	0.1543
2010	0.0250	0.0241	0.0416	0.0818	0.5274	0.3173	0.1553
2011	0.0192	0.0270	0.0313	0.0908	0.5235	0.3206	0.1559
2012	0.0302	0.0253	0.0485	0.0827	0.5189	0.3226	0.1585
2013	0.0204	0.0292	0.0332	0.0950	0.5202	0.3201	0.1597
2014	0.0230	0.0254	0.0366	0.0812	0.5152	0.3238	0.1610
2015	0.0267	0.0234	0.0423	0.0755	0.5151	0.3252	0.1597
AVERAGE	**0.0258**	**0.0241**	**0.0395**	**0.0861**			

In addition, the input variables of average value of failure and repair rates for nine years under review were used to analyze the effect of each input variable on the output/performance parameter as shown in Table 1. Trend factors were calculated using equation (4) to determine the change in rates per period of the data set available. On the basis of this, each analysis examined the effect of each input/operational variable on the output/performance parameters. In each analysis case, all other input variables were kept constant while one is varied and the performance parameters are observed. Hence, we achieve four different cases as outlined in figures 2 to 5 in order to have an optimal decision.

Table 2. Variation of system failure rate at PM state

λ_{pm}	λ_{cm}	μ_{pm}	μ_{cm}	P_{normal} (NORMAL STATE)	P_{pm}(PM STATE)	P_{cm}(FAILURE/CM STATE)
0.0258	0.0241	0.0395	0.0861	0.5173	0.3379	0.1448
0.0616	0.0241	0.0395	0.0861	0.3522	0.5492	0.0986
0.0974	0.0241	0.0395	0.0861	0.2670	0.6583	0.0747
0.1332	0.0241	0.0395	0.0861	0.2150	0.7249	0.0602
0.169	0.0241	0.0395	0.0861	0.1799	0.7697	0.0504
0.2048	0.0241	0.0395	0.0861	0.1547	0.8020	0.0433
0.2406	0.0241	0.0395	0.0861	0.1357	0.8264	0.0380
0.2764	0.0241	0.0395	0.0861	0.1208	0.8454	0.0338
0.3122	0.0241	0.0395	0.0861	0.1089	0.8606	0.0305
0.348	0.0241	0.0395	0.0861	0.0991	0.8732	0.0277
0.3838	0.0241	0.0395	0.0861	0.0909	0.8836	0.0255
0.4196	0.0241	0.0395	0.0861	0.0840	0.8925	0.0235
0.4554	0.0241	0.0395	0.0861	0.0781	0.9001	0.0219
0.4912	0.0241	0.0395	0.0861	0.0729	0.9067	0.0204
0.527	0.0241	0.0395	0.0861	0.0684	0.9125	0.0191
0.5628	0.0241	0.0395	0.0861	0.0644	0.9176	0.0180
0.5986	0.0241	0.0395	0.0861	0.0608	0.9221	0.0170
0.6344	0.0241	0.0395	0.0861	0.0577	0.9262	0.0161

0.6702	0.0241	0.0395	0.0861	0.0548	0.9299	0.0153
0.706	0.0241	0.0395	0.0861	0.0522	0.9332	0.0146

From table 2, the value of λpm was varied at a uniform incremental rate while the other operational variables are kept constant. The calculated values of the performance variables were obtained, and it was observed that the availability (Pnormal) of the machine and its CM state probability was decreasing while the PM state probability was increasing with increase in the failure rate of the equipment in preventive maintenance state (λpm). Whenever this nature of result is obtained from equipment health diagnosis, it implies that the system requires prompt maintenance action (minor maintenance (mM) or intermediate maintenance (IM) or major maintenance (MM)) in order to go back to a desired state. If left unattended to, will soonest fail.

Considering the graphical display in figure 2, it shows that as failure rate (λpm) increases; the normal operating state probability (Pnormal) and Corrective maintenance state probability (Pcm) are inversely proportional while the machine being down for preventive maintenance (Ppm) is directly proportional. With respect to this trend, regular PM action should be undertaken, while a decrease in the rate indicates less PM activities. It was also observed that failure rate effect on the various degradation states were significant at the incipient stage and gets less serious as time goes by. To this end, regular minor maintenance is recommended when the machine is still at as-good-as-new state.

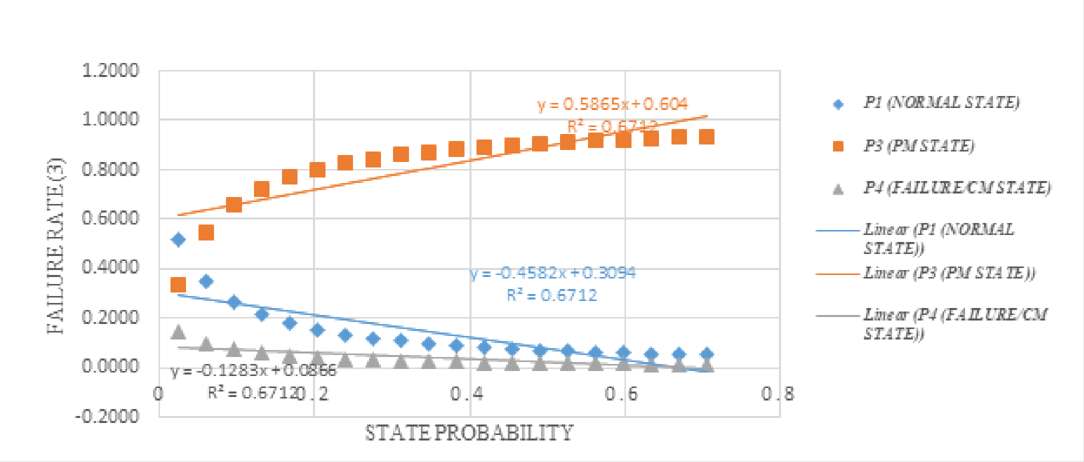

Figure 2. Graphical result for system failure rate at PM state

Table 3. Variation of system repair rate at PM state

λ_{pm}	λ_{cm}	μ_{pm}	μ_{cm}	P_{normal} (NORMAL STATE)	P_{pm}(PM STATE)	P_{cm}(FAILURE/CM STATE)
0.0258	0.0241	**0.0395**	0.0861	0.5173	0.3379	0.1448
0.0258	0.0241	**0.0753**	0.0861	0.6163	0.2112	0.1725
0.0258	0.0241	**0.1111**	0.0861	0.6613	0.1536	0.1851
0.0258	0.0241	**0.1469**	0.0861	0.6870	0.1207	0.1923
0.0258	0.0241	**0.1827**	0.0861	0.7037	0.0994	0.1970
0.0258	0.0241	**0.2185**	0.0861	0.7153	0.0845	0.2002
0.0258	0.0241	**0.2543**	0.0861	0.7239	0.0734	0.2026
0.0258	0.0241	**0.2901**	0.0861	0.7305	0.0650	0.2045
0.0258	0.0241	**0.3259**	0.0861	0.7358	0.0582	0.2060
0.0258	0.0241	**0.3617**	0.0861	0.7401	0.0528	0.2071
0.0258	0.0241	**0.3975**	0.0861	0.7436	0.0483	0.2081
0.0258	0.0241	**0.4333**	0.0861	0.7466	0.0445	0.2090
0.0258	0.0241	**0.4691**	0.0861	0.7491	0.0412	0.2097
0.0258	0.0241	**0.5049**	0.0861	0.7513	0.0384	0.2103
0.0258	0.0241	**0.5407**	0.0861	0.7532	0.0359	0.2108
0.0258	0.0241	**0.5765**	0.0861	0.7549	0.0338	0.2113

0.0258	0.0241	**0.6123**	0.0861	0.7564	0.0319	0.2117
0.0258	0.0241	**0.6481**	0.0861	0.7577	0.0302	0.2121
0.0258	0.0241	**0.6839**	0.0861	0.7589	0.0286	0.2124
0.0258	0.0241	**0.7197**	0.0861	0.7600	0.0272	0.2127

Results from table 3 shows that as the repair rate improves over time, the probability of the equipment being in the normal (good) health state increases while the probability of the machine being in PM state decreases. The implication of this, is that at increasing rate of PM actions, the performance of the equipment remains high and effective. If a reduction in repair rate at this state becomes the case, the machine's availability level reduces implying lack of PM actions.

Again, considering the graphical representation in figure 3, the state probabilities of system being in a normal operating state (Pnormal) and of system being down for Corrective maintenance (Pcm) are directly proportional with the behavior of the input variable while the rate at which machine being down for preventive maintenance (Ppm) is inversely proportional. Also, the graph shows that the effect of repair is significantly observable at the earliest times of the equipment operational life, as the significance reduces over time. When the equipment's health condition is observed stable, the frequency of PM actions should be limited.

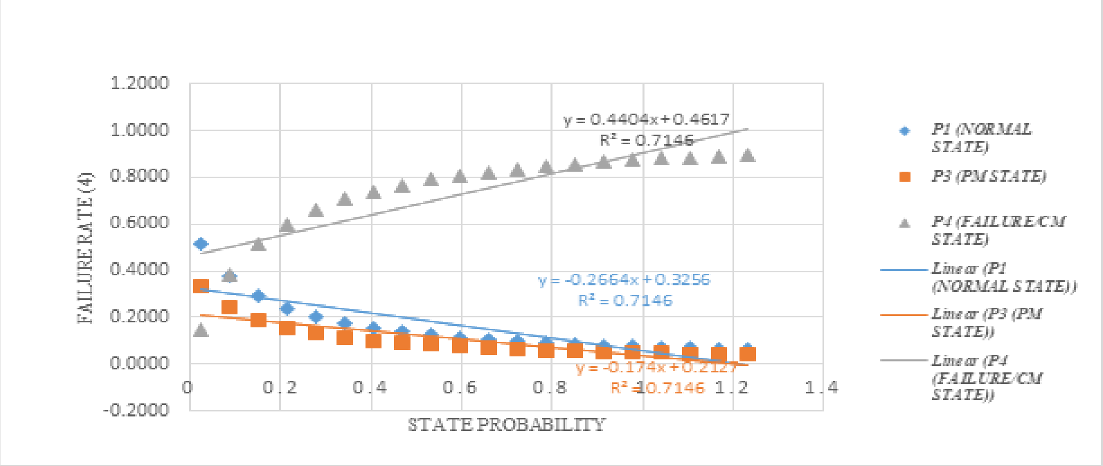

Figure 5. Graphical result for system failure rate at CM state

Table 5. Variation of system repair rate at CM state

λ_{pm}	**λ_{cm}**	**μ_{pm}**	**μ_{cm}**	**P_{normal} (NORMAL STATE)**	**P_{pm}(PM STATE)**	**P_{cm}(FAILURE/CM STATE)**
0.0258	0.0241	0.0395	**0.0861**	0.5173	0.3379	0.1448
0.0258	0.0241	0.0395	**0.1497**	0.5512	0.3600	0.0887
0.0258	0.0241	0.0395	**0.2133**	0.5662	0.3698	0.0640
0.0258	0.0241	0.0395	**0.2769**	0.5746	0.3753	0.0500
0.0258	0.0241	0.0395	**0.3405**	0.5801	0.3789	0.0411
0.0258	0.0241	0.0395	**0.4041**	0.5838	0.3813	0.0348
0.0258	0.0241	0.0395	**0.4677**	0.5866	0.3832	0.0302
0.0258	0.0241	0.0395	**0.5313**	0.5887	0.3845	0.0267
0.0258	0.0241	0.0395	**0.5949**	0.5904	0.3856	0.0239
0.0258	0.0241	0.0395	**0.6585**	0.5918	0.3865	0.0217
0.0258	0.0241	0.0395	**0.7221**	0.5929	0.3873	0.0198
0.0258	0.0241	0.0395	**0.7857**	0.5939	0.3879	0.0182
0.0258	0.0241	0.0395	**0.8493**	0.5947	0.3884	0.0169
0.0258	0.0241	0.0395	**0.9129**	0.5954	0.3889	0.0157
0.0258	0.0241	0.0395	**0.9765**	0.5960	0.3893	0.0147

0.0258	0.0241	0.0395	**1.0401**	0.5965	0.3896	0.0138
0.0258	0.0241	0.0395	**1.1037**	0.5970	0.3899	0.0130
0.0258	0.0241	0.0395	**1.1673**	0.5974	0.3902	0.0123
0.0258	0.0241	0.0395	**1.2309**	0.5978	0.3905	0.0117
0.0258	0.0241	0.0395	**1.2945**	0.5982	0.3907	0.0111

Considering the outcome in Table 5, as the repair rate in state 4 increases, the availability of the machine increases with the decrease in the probability of system down due to failure. This is because the maintenance actions at this time reduces the probability of machine/equipment failure. For the repair rate, an increase indicates that the machine should undergo corrective maintenance/replacement in order to avoid equipment's failure; while a decrease in the repair rate indicates that the machine requires no repair actions at the time under consideration. It was also observed that rate of change over time was reasonably insignificant, implying that at CM state, Major Maintenance or Replacement remains the best maintenance action to be taken to have significant result.

Continuing, observations from figure 5, shows that the state probabilities of system being in a normal operating state (Pnormal) and of the system being in preventive maintenance state (Ppm) are directly proportional with increasing repair rate while the probability of the machine being in Corrective maintenance state (Pcm) is inversely proportional. From this, as maintenance takes place there is improvement on the health condition of the equipment been diagnosed.

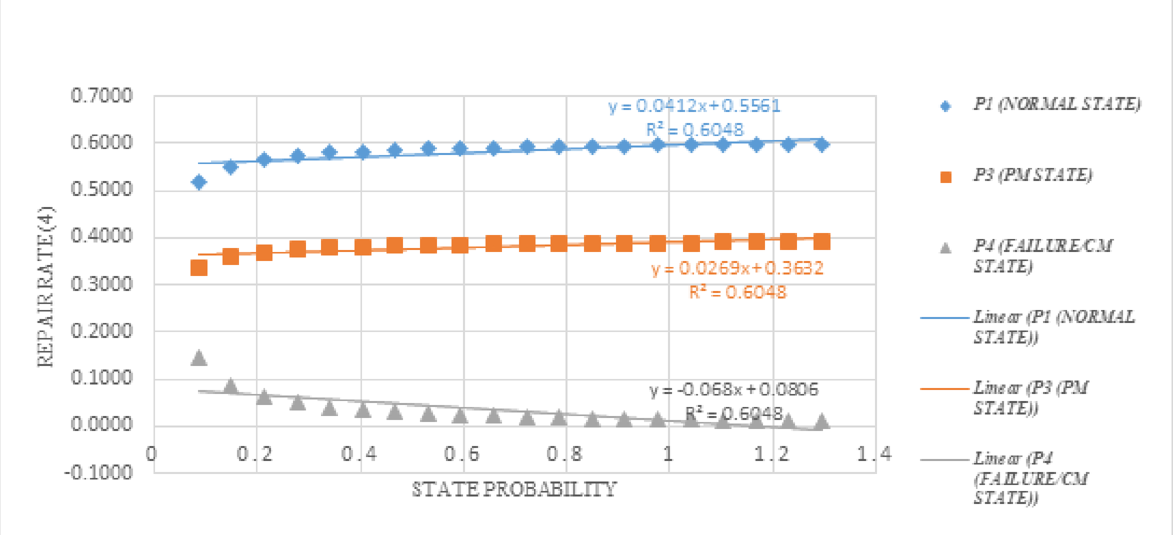

Figure 5. Graphical result for system repair rate at CM state

IV. CONCLUSION

In this paper a predictive maintenance model is presented which is based on a four state definition of the technical conditions of a manufacturing system. This is a clearly simple, systematic prediction model readily applicable to the industrial situation. It is intended to assists maintenance engineers and technicians to know the maintenance action to take at a given time based on the measure of the state of the system. The results obtained from the test of the practicability of the model were encouraging with the machine failures being predicted before they occur. It was evident that the prediction accuracy of the model was dependent on the quality of the input variables measurements. Furthermore, when machine availability decreases with time, the maintenance team should start making plans for suitable maintenance action. It is expected that the developed model will be applied to maintenance situations so as to realistically predict the health state of the machine with machine availability prioritized.

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