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Implementing a Preventive Maintenance Planning Model on an Ageing and Deteriorating Production System

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Abstract

This research article employs a mathematical model to boost the efficiency of the preventive maintenance planning model for an industrial production system. This study focuses on using real data of an industrial Lathe machine to test the effectiveness of the Preventive Maintenance model and its effect on both reliability and maintainability of the machine. The model is tested for different scenarios/cases by changing one of the main parameters during each calculation. These scenarios/cases are developed by using different values of failure rates to calculate the steady state probability at normal machine operation. This would allow us to calculate the best

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suitable scheduling time for Preventive Maintenance and improving the reliability of the lathe machine. The timing of the preventive maintenance is important to reduce system's failure and its corrective maintenance. The proposed model helps us to find a good and calculated suitable time, when the preventive maintenance work can be performed rather than having a corrective maintenance action to take place on the lathe machine. This model supports the industrial plant for sustainability and cost effectiveness with good calculated timing of effective Preventive Maintenance. Therefore, protecting high failure rates in order to decrease the probability of the lathe machine failure and to increase the life-time of the system using the proposed Preventive Maintenance model. Similarly, increasing the reliability would also increase the operational life cycle by reducing down-time during operations, hence dropping the total expenses by improving the availability..

Keywords

Maintenance Policy, Maintenance, Reliability, Replacement, Optimization, Deteriorating Systems, Production Systems, Case Study.

Introduction

There are mainly two types of maintenance; Corrective (CM) and Preventive Maintenance (PM). Preventive Maintenance (PM) is one of the most important and cost-effective way to improve the availability of any machine within a production system. To perform PM successfully, considerations should be made using the calculation of the probability of the system to operate normally (availability of the machine), the probability of the system to be repaired periodically (maintainability) and the probability of failure for a system. In general, PM activity helps to improve the reliability of a machine and the performance of the overall system. Implementing of a well planned preventive maintenance model can help to reduce the corrective maintenance efforts and its related cost for a production system. The maintenance team within a plant is responsible for running PM activities routinely to avoid unwanted shutdowns because of the system failure.

Production Plant operations are always dependent of the system's unit failure, which could lead an overall system down-time associated with lot of financial losses and penalties in some cases. Avoiding preventive maintenance may lead

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to an unplanned system downtime, which can be due to many possible reasons such as installation or breakdown of equipments, amendment of work orders, and lack of raw-materials and/or resources including skilled manpower. In this study, we aimed to maximize the usefulness of the preventive maintenance model in order to avoid such losses. It is recommended to take early actions to reduce the possibilities of system failure. This would allow the system to operate with high availability (up-time) and reliability. One way of doing this is to schedule preventive maintenance periodically, to avoid system failure or downtime/breakdown of a unit. Preventive maintenance reduces the number of failures and minimizes the chances of system failure.

A production system at an Indian industrial plant at Greater Noida is selected to demonstrate this study. In particular, the lathe machine is a significant unit in the production plant. Real-time preventive maintenance data was used to apply and study the proposed model. The lathe machine is considered to be a vital unit in the production plant. Moreover, the main objective of this study was to maximize the effectiveness of the preventive maintenance. In this article, we would be discussing some of the factors and considerations that affect the effectiveness of the preventive maintenance model. Scheduling preventive maintenance can be both a short-term and/or long term process which includes maintaining information about the maintenance in a logbook.

The important characteristic of a successful maintainability for a system is often determined by the equipment's design used in the system. A set of maintenance procedures, duration of repair time is also based on equipment's design. One of the main characteristic for maintainability is the mean time to repair (MTTR). Short repair times are more desirable to achieve and maintain high availability for a system/machine. The main objective of every preventive maintenance action is to reduce the probability of failures and system downtime. Preventive maintenance also has financial aspects of increasing availability for a production system and can direct contribute towards company's income and sustainability. For our case, the role of an effective preventive maintenance model (PMM) is to achieve significant availability of lathe machine for production. This is absolutely true and possible that the PMM impacts on both the reliability and maintainability of a machine/system, when it is well planned and executed. The right preventive maintenance plan including periodic on-condition monitoring, is always responsible for maintaining a unit of equipment in its running state and also in decreasing its MTTR. This would not only detect failure for a machine/system but also and gives an opportunity to repair and/or replace the faulty part on time, thus avoiding the unplanned downtime.

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To improve the preventive maintenance activity, which is being performed on the lathe machine, first the performance of the individual lathe machine should be measured accurately. This would cut the costs incurred from unnecessary preventive maintenance and would also improve the plant's overall efficiency. Preventive maintenance program may also increase lathe machine's efficiency, increase performance levels and reduce costs in most of the cases of system failure. Preventive Maintenance's effectiveness can also be improved through identifying the associated financial benefits that any performance improvements would bring.

Reliability is the probability of a machine that will achieve a required function under specific conditions for a definite period of time. These conditions includes physical environment, mechanical, thermal, electrical conditions, etc. Higher reliability brings comparatively fewer failures and ease of maintainability for a system that means the system is effectively operating. Availability is related to both frequency of operation and duration of downtime for a machine/system. Accordingly, the avail-ability goal should be converted into reliability as well as maintainability requirements in terms of reasonable failure rates and downtime hours. The concepts of reliability and maintainability and its practical application to an Industrial plants often requires certain metrics and measures [35] to be calculated before planning a preventive maintenance model.

In this paper, section 2 elaborate the summary of existing literature of the research work carried out in the field of Preventive Maintenance (PM), section 3 would define the proposed mathematical model for Preventive Maintenance (PM), section 4 would elaborate the application of the preventive maintenance (PM) model on CNC lathe machine utilized by an industrial production system, also would explain about the results on four different scenarios based on four main parameters, section 5 would conclude this research article.

Literature Review

The Preventive Maintenance Planning Models, Techniques and Policies have been extensively studied, experimented and documented in the past. Barlow and Hunter (1960) [1], Nakagawa (1979) [2], Singh (1989) [3] have computed the state probabilities of a complex production system in their research articles. Zhao (1994) [4] have developed a generalized availability model in their research for repairable components within a production system. In a research by Edward

A. Silver et al. (1995) [5], a preventive maintenance with limited historical data is presented. In a research by Russell D. Meller et al. (1996) [6], results of preventive maintenance on overall system cost and its buffer size is discussed. Zhang (1996) [7] have studied the stochastic behaviour of an (N+1) unit stand by production system. M.A.J. Smith et al. (1997) [8] in their article have discussed the uptime, downtime and costs associated in the preventive maintenance of 1 out of n systems. I. Gertsbakh et al. (1997) [9] in their article have discussed a selection for the most suitable time scale for preventive maintenance in diverse environments. In a research by K.K. Lai et al. (2000) [10] a case study on practices of preventive maintenance and replacement for engines is presented. In a research by D. Gupta et al. (2001) [11], defines the relationship between preventive maintenance and manufacturing system performance. In a research by Ruey Huei Yeh et al. (2001) [12] an optimal Preventive maintenance warranty policy for repairable products is presented. In a research by Sophie Bloch-Mercier et al. (2002) [13], B. S. Dhillon (2002) [33] and Ibrahim A. Kattan et al. (2010) [34] have presented a preventive maintenance policy with consecutive monitoring procedure for a Markov deteriorating system. In a research by Hongzhou Wang (2002) [14] a survey of maintenance policies of deteriorating systems is presented. Grail et al (2002) [15] presented a preventive maintenance technique for a gradually deteriorating single unit production systems. In a research by Muh-Guey Juang et al. (2004) [16] a Bayesian method on adaptive preventive maintenance problem is presented. In a research by Timothy S. Vaughan, (2005) [17] on failure replacement and preventive maintenance spare parts ordering policy is presented. In a research by N. Sortrakul et al. (2005) [18] have presented the use of Genetic algorithms in an integrated single-machine preventive maintenance planning and production scheduling. In a research by J. Jaturonnatee et al. (2006) [19] an optimal preventive maintenance through corrective minimal repair of leased equipments have been discussed. Mohanta et al. (2006) [20] have presented an intelligent computational method for preventive maintenance of a captive thermal plant. Todinav (2007) [21] have presented a new method for optimizing the topology of engineering production systems based on reliability allocation based on cost. Kumar et al (1991) [22], Garg and Singh (2005) [23], Singh (2007) [24] and similarly some other writers also have applied reliability technologies to various Industrial and production systems to obtain good results. In a research by E.H. Aghezzaf et al. (2007) [25] integrated production and preventive maintenance planning model is presented. In a research by Yeh Lam, (2007) [26] a geometric process maintenance model with preventive repair is presented. In a research by El-Houssaine Aghezzaf et al. (2008) [27] have presented an integrated production planning and preventive maintenance technique for deteriorating production systems. In a research by Seong-Jong Joo (2009) [28] a dynamic approach of scheduling preventive maintenance for modular designed components is presented. In a research by Chin-Tai Chen, (2011) [29] a dynamic preventive maintenance strategy for a multi-state aging and deteriorating production system is presented. In a research by Ruey Huei Yeh et al. (2011) [30] a preventive-maintenance policy for leased products considering all aspects of applicable maintenance costs is discussed. In a research by Chung-Ho Wang et al. (2011) [31] have discussed a technique to minimize series-parallel system's periodic preventive maintenance cost using improved particle swarm optimization. In a research by Julien Rabatel et al. (2011) [32] have presented a detection of anomaly point in sensor monitoring data for preventive maintenance. This summary of literature review on previously published research articles on preventive maintenance is taken from the survey article (2013) [48].

Model for Preventive Maintenance

Markov Model for Preventive Maintenance as we would discuss in this section represents a system/equipment/facility that can either fails completely or undergoes a routine preventive maintenance after every specific period of time, as shown in figure 1. This model is extracted from the following references [33], [36], [42], [43] and [44].

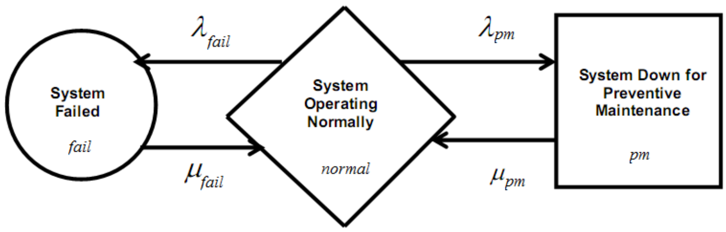

Figure 1: *State Transition Diagrams for the PM Markov Model [33, 36, 42, 43, 44, 45]*

Input Variables and Assumptions

This PM Markov Model helps to predict the system's probabilities for its availability, down for its maintenance, down due to failure. The following assumptions are made for this PM Model:

1. System have a constant preventive maintenance, repair and failure rates,

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2. System becomes well functional just after its repair or preventive maintenance.

The rates illustrated in Table 1 represents the current condition of the Lathe Machine.

The **input variables** used in this model are as follows:

S = state of the system/equipment, for $S = normal$ (system is operating normally), $S = fail$ (system failure), $S = pm$ (system is down due to preventive maintenance).
$P_S(t)$ = Probability of a system/equipment to be in S^{th} state at time t, for $S = normal, fail, pm$
λ_{fail} = failure rate of a system/equipment
μ_{fail} = repair rate of a system/equipment
λ_{pm} = rate of a system/equipment down for preventive maintenance
μ_{pm} = rate of a system/equipment preventive maintenance performance
Av = rate of availability for system/equipment.

Mathematical Model Formulation

The equations for the State Transition Diagram for the PM Markov Model as shown in figure 1 can be expressed as following:

$$\frac{dP_{normal}(t)}{dt} + (\lambda_{fail} + \lambda_{pm}) = (\mu_{fail} * P_{fail}(t)) + (\mu_{pm} * P_{pm}(t)) \tag{1}$$

$$\frac{dP_{pm}(t)}{dt} + (\mu_{pm} * P_{pm}(t)) = (\lambda_{pm} * P_{normal}(t)) \tag{2}$$

$$\frac{dP_{fail}(t)}{dt} + (\mu_{fail} * P_{fail}(t)) = (\lambda_{fail} * P_{normal}(t)) \tag{3}$$

Solving equations 1, 2 and 3, at $t = 0$, keeping $P_{normal}(0) = 1$ and $P_{pm}(0) = P_{fail}(0) = 0$, we gets:

$$P_{normal}(t) = \frac{\mu_{pm} * \mu_{fail}}{c_1 * c_2} + \left[\frac{(c_1 + \mu_{pm})(c_1 + \mu_{fail})}{c_1(c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(c_2 + \mu_{pm})(c_2 + \mu_{fail})}{c_2(c_1 - c_2)}\right] e^{c_2 t} \tag{4}$$

$$P_{fail}(t) = \frac{\lambda_{fail} * \mu_{pm}}{c_1 * c_2} + \left[\frac{\lambda_{fail} * c_1 + \lambda_{fail} * \mu_{pm}}{c_1(c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(\mu_{pm} + c_2)\lambda_{fail}}{c_2(c_1 - c_2)}\right] e^{c_2 t} \tag{5}$$

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$$P_{pm}(t) = \frac{\lambda_{pm} * \mu_{fail}}{c_1 * c_2} + \left[\frac{\lambda_{pm} * c_1 + \lambda_{pm} * \mu_{fail}}{c_1(c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(\mu_{fail} + c_2)\lambda_{pm}}{c_2(c_1 - c_2)}\right] e^{c_2 t} \tag{6}$$

where,

$$c_1, c_2 = \frac{-Av \pm [Av^2 - 4(\mu_{pm} * \mu_{fail} + \lambda_{fail} * \mu_{pm} + \lambda_{pm} * \mu_{fail})]^{1/2}}{2} \tag{7}$$

$$Av \equiv (\mu_{fail} + \mu_{pm} + \lambda_{fail} + \lambda_{pm}) \tag{8}$$

$$c_1 + c_2 = -Av \tag{9}$$

$$c_1 c_2 = (\mu_{pm} * \mu_{fail} + \lambda_{pm} * \mu_{fail} + \lambda_{fail} * \mu_{pm}) \tag{10}$$

When, time t becomes very large, the steady state probabilities of the system/equipment would become:

$$P_{normal} = \frac{\mu_{fail} * \mu_{pm}}{c_1 * c_2} \tag{11}$$

$$P_{pm} = \frac{\lambda_{pm} * \mu_{fail}}{c_1 * c_2} \tag{12}$$

$$P_{fail} = \frac{\lambda_{fail} * \mu_{pm}}{c_1 * c_2} \tag{13}$$

Output Variables

The following output variables are calculated using the PM Markov Model [33, 36, 42, 43, 44, 45] by changing one input parameter at a time and keeping the rest of the input parameters to a constant value:

$P_{normal}(t)$ = Probability of a system/equipment to work normally at time t,
$P_{pm}(t)$ = Probability of a system/equipment down due to preventive maintenance at time t,
$P_{fail}(t)$ = Probability of a system/equipment failure/breakdown at time t,
P_{normal} = Steady state probability of a system/equipment to work normally (steady state availability),
P_{pm} = Steady state probability of a system/equipment down due to preventive maintenance,
P_{fail} = Steady state probability of a system/equipment failure.

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Implementation of the Model and Analysis of Results

The historical data related to PM for the CNC lathe machine is obtained from one Manufacturing unit of Subros Limited, Noida. The CNC Lathe machine at the Subros Manufacturing plant, operates for 24 hours per day, seven days a week. The rates mentioned in the Table 1, shows the current condition of the CNC Lathe Machine, based on last one year PM data.

Table 1: *Various parameters for the CNC Lathe Machine*

Variables	Rate (per month)
λ_{pm} (Rate of system being down for PM)	**0.1111** (downtime because of PM once every 9 months)
λ_{fail} (System's failure rate)	**0.0833** (downtime because of failure every 12 months)
μ_{pm} (PM performance rate)	**0.3333** (downtime of 24 hours every 3 months)
μ_{fail} (CM/Repair performance rate)	**0.1666** (downtime of 24 hours every 6 months)

The following steps are involved in the implementation of the mathematical model to obtain the effective PM solution for the CNC Lathe Machine:

1. `Step 1`: Steady state probability for the CNC lathe machine operating in a normal state (P_{normal}) can be calculated using equation 11.
2. `Step 2`: Steady state probability for the CNC lathe machine down for preventive maintenance (P_{pm}) can be calculated using equation 12.
3. `Step 3`: Steady state probability for the CNC lathe machine down because of system failure for repair action ($P_{failure}$) can be calculated using equation 13.

The above mentioned implementation steps have been used to develop four cases/scenarios to test the validity/effectiveness of the model.

First Case/Scenario

Implementation

Calculated the values of P_{normal} (Availability), P_{pm} and P_{fail} by keeping the constant values of λ_{pm}, μ_{fail} and μ_{pm} as per the table 1, and varying the value

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of λ_{fail} (system failure rate). The calculated values are shown in the table 2 and the graph is plotted in figure 2.

Table 2: *Results of the case/scenario with varying system failure rate (λ_{fail}).*

μ_{fail}	μ_{pm}	λ_{fail}	λ_{pm}	P_{normal}	P_{pm}	P_{fail}
0.1666	0.3333	0.0453	0.1111	0.6230	0.2077	0.1694
0.1666	0.3333	0.0473	0.1111	0.6183	0.2061	0.1756
0.1666	0.3333	0.0493	0.1111	0.6138	0.2046	0.1816
0.1666	0.3333	0.0513	0.1111	0.6093	0.2031	0.1876
0.1666	0.3333	0.0533	0.1111	0.6049	0.2016	0.1935
0.1666	0.3333	0.0553	0.1111	0.6005	0.2002	0.1993
0.1666	0.3333	0.0555	0.1111	0.6001	0.2000	0.1999
0.1666	0.3333	0.0573	0.1111	0.5962	0.1987	0.2051
0.1666	0.3333	0.0593	0.1111	0.5920	0.1973	0.2107
0.1666	0.3333	0.0613	0.1111	0.5878	0.1959	0.2163
0.1666	0.3333	0.0633	0.1111	0.5837	0.1946	0.2218
0.1666	0.3333	0.0653	0.1111	0.5796	0.1932	0.2272
0.1666	0.3333	0.0673	0.1111	0.5756	0.1919	0.2325
0.1666	0.3333	0.0693	0.1111	0.5717	0.1906	0.2378
0.1666	0.3333	0.0713	0.1111	0.5678	0.1893	0.2430
0.1666	0.3333	0.0733	0.1111	0.5639	0.1880	0.2481
0.1666	0.3333	0.0753	0.1111	0.5601	0.1867	0.2532
0.1666	0.3333	0.0773	0.1111	0.5564	0.1855	0.2582
0.1666	0.3333	0.0793	0.1111	0.5527	0.1842	0.2631
0.1666	0.3333	0.0813	0.1111	0.5490	0.1830	0.2679
0.1666	0.3333	0.0833	0.1111	0.5455	0.1818	0.2727
0.1666	0.3333	0.0853	0.1111	0.5419	0.1806	0.2775
0.1666	0.3333	0.0873	0.1111	0.5384	0.1795	0.2821
0.1666	0.3333	0.0893	0.1111	0.5349	0.1783	0.2867
0.1666	0.3333	0.0913	0.1111	0.5315	0.1772	0.2913
0.1666	0.3333	0.0933	0.1111	0.5282	0.1761	0.2958
0.1666	0.3333	0.0953	0.1111	0.5248	0.1749	0.3002
0.1666	0.3333	0.0973	0.1111	0.5215	0.1738	0.3046
0.1666	0.3333	0.0993	0.1111	0.5183	0.1728	0.3089
0.1666	0.3333	0.1013	0.1111	0.5151	0.1717	0.3132

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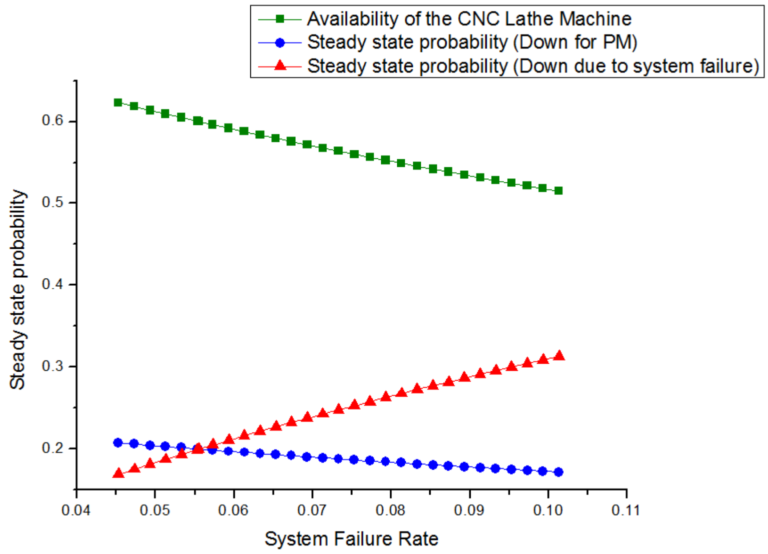

Figure 2: *Results of the case/scenario with varying system failure rate (λ_{fail}).*

Analysis

1. The availability of the CNC lathe machine is decreasing with the increase in the failure rate.

2. The increase in failure rate of the CNC Lathe Machine indicates that the machine is highly prone to failures; decrease in the failure rate indicates that the machine is less prone to failures.

3. The steady state probabilities of system being in a normal operating condition and of system down for preventive maintenance are inversely proportional to the system's failure rate.

4. PM activity can only be effectively carried out when the probability of system's failure rate is smaller than the probability of system being under preventive maintenance. At a point at the failure rate (λ_{fail}) of 0.0555, the probability of system's failure rate becomes equal than the probability of system being under preventive maintenance, after this point the chances of system's failure becomes more. Thus the PM of the CNC lathe machine should be performed before the failure rate of $\lambda_{fail} = 0.0555$.

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Second Case/Scenario

Implementation

Calculated the values of P_{normal} (Availability), P_{pm} and P_{fail} by keeping the constant values of λ_{fail}, μ_{fail} and μ_{pm} as per the table 1, and varying the value of λ_{pm} (rate of a system/equipment down for preventive maintenance). The calculated values are shown in the table 3 and the graph is plotted in figure 3.

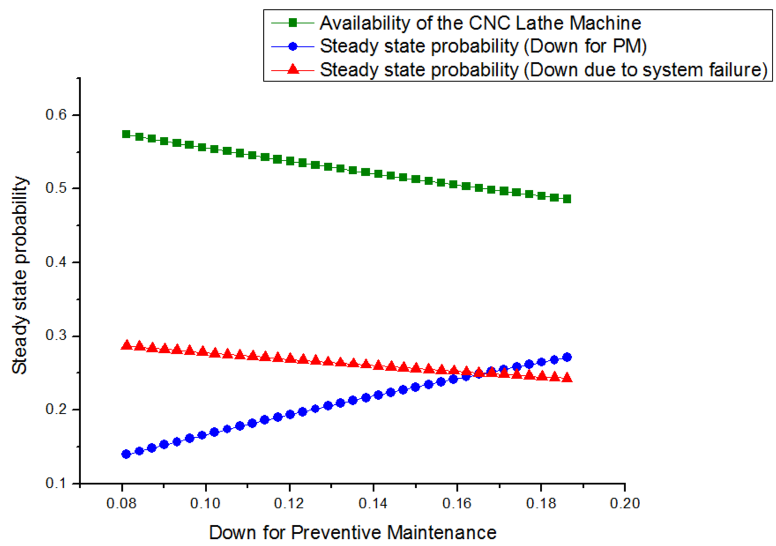

Figure 3: *Results of the case/scenario with varying rate of system being down for preventive maintenance (λ_{pm}).*

Analysis

1. The availability of the CNC lathe machine is decreasing with the increase in the rate of a system/equipment down for preventive maintenance. Availability of the CNC Lathe Machine can be adjusted by changing/choosing the appropriate rate of a system/equipment down for preventive maintenance.

2. The steady state probabilities of system being in a normal operating condition (availability) and of system being down for repair are inversely proportional to the rate of a system/equipment down for preventive maintenance (λ_{pm}).

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3. The increase in rate of system being down for preventive maintenance (λ_{pm}) indicates that the CNC Lathe Machine requires a routine PM activity; decrease in this rate indicates that the requirement of PM activity on the lathe machine is less.

Third Case/Scenario

Implementation

Calculated the values of P_{normal} (Availability), P_{pm} and P_{fail} by keeping the constant values of λ_{pm}, λ_{fail} and μ_{pm} as per the table 1, and varying the value of μ_{fail} (repair rate of a system/equipment). The calculated values are shown in the table 4 and the graph is plotted in figure 4.

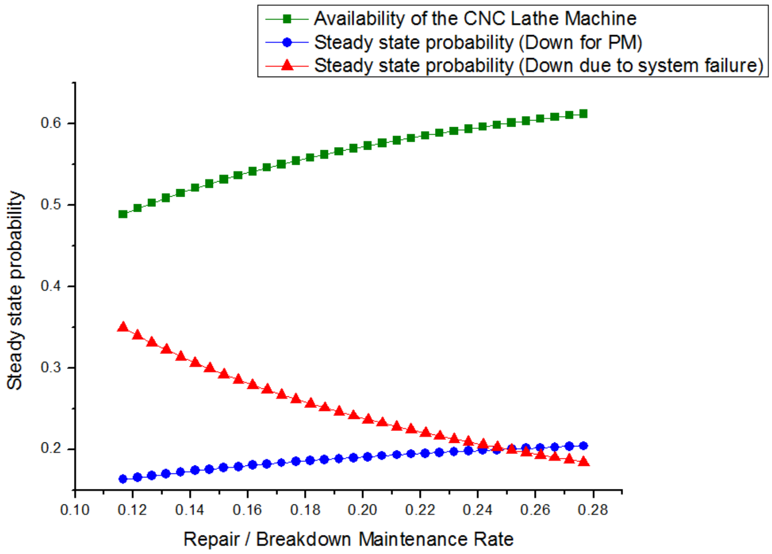

Figure 4: *Results of the case/scenario with varying rate of system being down for repair/breakdown maintenance (μ_{fail}).*

Analysis

1. The availability of the CNC lathe machine increases with the decrease in the probability of system down due to failure, as a result of increase in the repair rate (because of the maintenance activity at this time reduces the probability of machine failure).

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2. The steady state probabilities of system being in a normal operating condition (availability) and of system being down for preventive maintenance are directly proportional (increasing steadily) to the repair rate of a system/equipment (μ_{fail}).

3. The increase in repair rate of the CNC Lathe Machine indicates that the machine should undergo repair/corrective maintenance in order to avoid system's failure; decrease in the repair rate indicates that the machine does not require repair actions.

Fourth Case/Scenario

Implementation

Calculated the values of P_{normal} (Availability), P_{pm} and P_{fail} by keeping the constant values of λ_{pm}, μ_{fail} and λ_{fail} as per the table 1, and varying the value of μ_{pm} (PM performance rate). The calculated values are shown in the table 5 and in the graph plotted in figure 5.

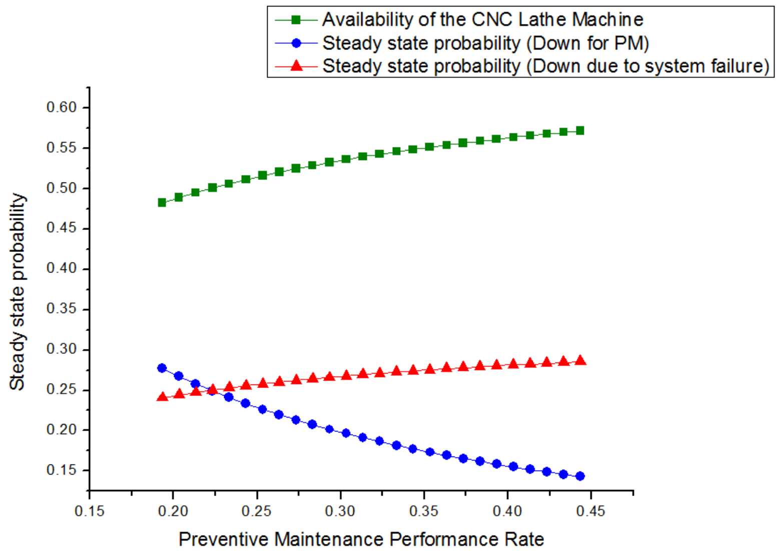

Figure 5: *Results of the case/scenario with varying rate of system's preventive maintenance performance (μ_{pm}).*

Analysis

1. The availability of the CNC lathe machine is increasing with the increase in the rate of preventive maintenance performance (μ_{pm}).

2. The increase in rate of preventive maintenance performance of the CNC Lathe Machine indicates that preventive maintenance of the machine is effectively performed; decrease in this rate indicates that the machine is getting non-effective or even no preventive maintenance.

3. The steady state probabilities of system being in a normal operating condition (availability) and of system's failure are directly proportional (increasing steadily) to the rate of preventive maintenance performance (μ_{pm}).

Conclusion

The following conclusions were made from this study:

1. The correct scheduling of the preventive maintenance is essential to decrease the systems failure and related corrective maintenance.

2. This mathematical model helps to find accurate time, when the preventive maintenance work can be more effective than the corrective repairing of the CNC lathe machine.

3. The most important factor is the availability of the CNC lathe machine which is to be always considered in all calculations.

4. In case the probability of the CNC lathe machine which is operating normally decreases with time, the maintenance team should start making plans and arrangements for preventive maintenance activity on it.

5. The PM activities should be done at least once before the probability of the CNC lathe machine's failure becomes equal or less than the probability of the machine down for PM, so that the effectiveness of preventive maintenance can be achieved and the machine's/system's failure can be prevented.

6. A higher failure rate of the machine would increase the chances of the machine's failure resulting in the reduction of the machine's availability which indicates the need of preventive maintenance to be performed on the machine.

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Table 3: *Results of the case/scenario with varying rate of system being down for preventive maintenance (λ_{pm}).*

μ_{fail}	μ_{pm}	λ_{fail}	λ_{pm}	P_{normal}	P_{pm}	P_{fail}
0.1666	0.3333	0.0833	0.0911	0.5639	0.1541	0.2820
0.1666	0.3333	0.0833	0.0931	0.5620	0.1570	0.2810
0.1666	0.3333	0.0833	0.0951	0.5601	0.1598	0.2801
0.1666	0.3333	0.0833	0.0971	0.5582	0.1626	0.2791
0.1666	0.3333	0.0833	0.0991	0.5564	0.1654	0.2782
0.1666	0.3333	0.0833	0.1011	0.5545	0.1682	0.2773
0.1666	0.3333	0.0833	0.1031	0.5527	0.1710	0.2763
0.1666	0.3333	0.0833	0.1051	0.5509	0.1737	0.2754
0.1666	0.3333	0.0833	0.1071	0.5490	0.1764	0.2745
0.1666	0.3333	0.0833	0.1091	0.5472	0.1791	0.2736
0.1666	0.3333	0.0833	0.1111	0.5455	0.1818	0.2727
0.1666	0.3333	0.0833	0.1141	0.5428	0.1858	0.2714
0.1666	0.3333	0.0833	0.1171	0.5402	0.1898	0.2701
0.1666	0.3333	0.0833	0.1201	0.5375	0.1937	0.2688
0.1666	0.3333	0.0833	0.1231	0.5349	0.1976	0.2675
0.1666	0.3333	0.0833	0.1261	0.5324	0.2014	0.2662
0.1666	0.3333	0.0833	0.1291	0.5298	0.2052	0.2649
0.1666	0.3333	0.0833	0.1321	0.5273	0.2090	0.2637
0.1666	0.3333	0.0833	0.1351	0.5248	0.2127	0.2624
0.1666	0.3333	0.0833	0.1381	0.5224	0.2164	0.2612
0.1666	0.3333	0.0833	0.1411	0.5199	0.2201	0.2600
0.1666	0.3333	0.0833	0.1441	0.5175	0.2237	0.2588
0.1666	0.3333	0.0833	0.1471	0.5151	0.2273	0.2576
0.1666	0.3333	0.0833	0.1501	0.5127	0.2309	0.2564
0.1666	0.3333	0.0833	0.1531	0.5104	0.2344	0.2552
0.1666	0.3333	0.0833	0.1561	0.5080	0.2379	0.2540
0.1666	0.3333	0.0833	0.1591	0.5057	0.2414	0.2529
0.1666	0.3333	0.0833	0.1621	0.5034	0.2448	0.2517
0.1666	0.3333	0.0833	0.1651	0.5012	0.2483	0.2506
0.1666	0.3333	0.0833	0.1681	0.4989	0.2516	0.2495
0.1666	0.3333	0.0833	0.1711	0.4967	0.2550	0.2483
0.1666	0.3333	0.0833	0.1741	0.4945	0.2583	0.2472
0.1666	0.3333	0.0833	0.1771	0.4923	0.2616	0.2461
0.1666	0.3333	0.0833	0.1801	0.4901	0.2648	0.2451
0.1666	0.3333	0.0833	0.1831	0.4880	0.2681	0.2440
0.1666	0.3333	0.0833	0.1861	0.4858	0.2713	0.2429

Table 4: *Results of the case/scenario with varying rate of system being down for repair/corrective maintenance (μ_{fail}).*

μ_{fail}	μ_{pm}	λ_{fail}	λ_{pm}	P_{normal}	P_{pm}	P_{fail}
0.1166	0.3333	0.0833	0.1111	0.4883	0.1628	0.3489
0.1216	0.3333	0.0833	0.1111	0.4955	0.1652	0.3394
0.1266	0.3333	0.0833	0.1111	0.5022	0.1674	0.3304
0.1316	0.3333	0.0833	0.1111	0.5086	0.1695	0.3219
0.1366	0.3333	0.0833	0.1111	0.5146	0.1715	0.3138
0.1416	0.3333	0.0833	0.1111	0.5204	0.1735	0.3061
0.1466	0.3333	0.0833	0.1111	0.5259	0.1753	0.2988
0.1516	0.3333	0.0833	0.1111	0.5311	0.1770	0.2918
0.1566	0.3333	0.0833	0.1111	0.5361	0.1787	0.2852
0.1616	0.3333	0.0833	0.1111	0.5409	0.1803	0.2788
0.1666	0.3333	0.0833	0.1111	0.5455	0.1818	0.2727
0.1716	0.3333	0.0833	0.1111	0.5498	0.1833	0.2669
0.1766	0.3333	0.0833	0.1111	0.5540	0.1847	0.2613
0.1816	0.3333	0.0833	0.1111	0.5580	0.1860	0.2560
0.1866	0.3333	0.0833	0.1111	0.5619	0.1873	0.2508
0.1916	0.3333	0.0833	0.1111	0.5656	0.1885	0.2459
0.1966	0.3333	0.0833	0.1111	0.5691	0.1897	0.2411
0.2016	0.3333	0.0833	0.1111	0.5726	0.1909	0.2366
0.2066	0.3333	0.0833	0.1111	0.5759	0.1920	0.2322
0.2116	0.3333	0.0833	0.1111	0.5790	0.1930	0.2279
0.2166	0.3333	0.0833	0.1111	0.5821	0.1940	0.2239
0.2216	0.3333	0.0833	0.1111	0.5851	0.1950	0.2199
0.2266	0.3333	0.0833	0.1111	0.5879	0.1960	0.2161
0.2316	0.3333	0.0833	0.1111	0.5907	0.1969	0.2124
0.2366	0.3333	0.0833	0.1111	0.5933	0.1978	0.2089
0.2416	0.3333	0.0833	0.1111	0.5959	0.1986	0.2055
0.2466	0.3333	0.0833	0.1111	0.5984	0.1995	0.2021
0.2516	0.3333	0.0833	0.1111	0.6008	0.2003	0.1989
0.2566	0.3333	0.0833	0.1111	0.6031	0.2010	0.1958
0.2616	0.3333	0.0833	0.1111	0.6054	0.2018	0.1928
0.2666	0.3333	0.0833	0.1111	0.6076	0.2025	0.1899
0.2716	0.3333	0.0833	0.1111	0.6097	0.2032	0.1870
0.2766	0.3333	0.0833	0.1111	0.6118	0.2039	0.1843

Table 5: *Results of the case/scenario with varying rate of systems preventive maintenance performance (μ_{pm}).*

μ_{fail}	μ_{pm}	λ_{fail}	λ_{pm}	P_{normal}	P_{pm}	P_{fail}
0.1666	0.1933	0.0833	0.1111	0.4820	0.2770	0.2410
0.1666	0.2033	0.0833	0.1111	0.4886	0.2670	0.2443
0.1666	0.2133	0.0833	0.1111	0.4948	0.2577	0.2474
0.1666	0.2233	0.0833	0.1111	0.5006	0.2491	0.2503
0.1666	0.2333	0.0833	0.1111	0.5060	0.2410	0.2530
0.1666	0.2433	0.0833	0.1111	0.5111	0.2334	0.2555
0.1666	0.2533	0.0833	0.1111	0.5158	0.2262	0.2579
0.1666	0.2633	0.0833	0.1111	0.5203	0.2195	0.2602
0.1666	0.2733	0.0833	0.1111	0.5245	0.2132	0.2623
0.1666	0.2833	0.0833	0.1111	0.5285	0.2073	0.2642
0.1666	0.2933	0.0833	0.1111	0.5323	0.2016	0.2661
0.1666	0.3033	0.0833	0.1111	0.5358	0.1963	0.2679
0.1666	0.3133	0.0833	0.1111	0.5392	0.1912	0.2696
0.1666	0.3233	0.0833	0.1111	0.5424	0.1864	0.2712
0.1666	0.3333	0.0833	0.1111	0.5455	0.1818	0.2727
0.1666	0.3433	0.0833	0.1111	0.5484	0.1775	0.2742
0.1666	0.3533	0.0833	0.1111	0.5511	0.1733	0.2756
0.1666	0.3633	0.0833	0.1111	0.5538	0.1693	0.2769
0.1666	0.3733	0.0833	0.1111	0.5563	0.1656	0.2781
0.1666	0.3833	0.0833	0.1111	0.5587	0.1619	0.2794
0.1666	0.3933	0.0833	0.1111	0.5610	0.1585	0.2805
0.1666	0.4033	0.0833	0.1111	0.5632	0.1552	0.2816
0.1666	0.4133	0.0833	0.1111	0.5654	0.1520	0.2827
0.1666	0.4233	0.0833	0.1111	0.5674	0.1489	0.2837
0.1666	0.4333	0.0833	0.1111	0.5693	0.1460	0.2847
0.1666	0.4433	0.0833	0.1111	0.5712	0.1432	0.2856