Optimal production and preventive maintenance rate in a failure-prone manufacturing system using discrete event simulation

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Abstract: Production control in a failure-prone manufacturing system (FPMS) is studied in the present paper. FPMS are those which are subjected to random breakdown assumption and corrective and preventive maintenance are considered for them too. In order to prevent shortage, buffer is used in these systems. Determining the inventory level of the buffer is one of the most important parameter. Another effective parameter is determining the time of period for preventive maintenance which is important to discover breakdowns before their occurrence and thus minimise the cost of corrective maintenance. The purpose of this paper is to determine the optimal production rate and time of period for preventive maintenance for an FPMS to minimise sum of holding shortage, corrective and preventive maintenance cost. To this end, discrete event simulation is used. Studying the system under conditions where analytical solution is not possible is the most important advantage of simulation method.

Keywords: failure-prone manufacturing system; FPMS; production control; preventive maintenance, discrete event simulation.


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1 Introduction

A manufacturing system of machineries is exposed to breakdown due to some reasons and this decreases the productive capacity. Breakdown of machineries in a manufacturing system can have dangerous consequences and thus a regular maintenance programme to enhance the reliability of machineries seems necessary. Maintenance of machineries is divided into two categories; corrective and preventive classes. Corrective maintenance is performed when machineries are not working and preventive maintenance is related to the time when the system is active and the purpose is to discover and prevent breakdowns before they occur.

A buffer is therefore used to prevent the effect of machine failure on demand, since machines are broken down after one period of functioning in most manufacturing systems. If the buffer inventory in these systems is exhausted before completing the machine maintenance, the system is faced with shortage and on the other hand, high inventory level of the buffer increases maintenance costs. Hence in failure-prone manufacturing systems (FPMS) the purpose is to determine the optimal level of inventory to decrease sum of costs (holding, backlog and maintenance).

2 Literature review

FPMS are a subset of flexible manufacturing systems. This system was proposed by Rishel in 1975 for the first time and was formulated by Olsder and Suri in 1980 as an optimal control problem. Akella and Kumar (1986) presented an analytical solution for single-machine system which produces one product. They used exponential distribution for breakdown and maintenance. Kenne et al. (2007) studied optimal production rate and
maintenance planning for FPMS with multiple machines. Sharifnia (1998) studied FPMS with multiple machines. Many researchers have investigated these systems based on Rishel's work and have shown that a production control policy for such systems is the hedging point policy (HPP). The production rate in HPP is conducted given to the optimal capacity of buffer. If the inventory becomes more than the optimal capacity, no production is accomplished and if the inventory is less than the optimal capacity, then production is conducted with maximum machine rate. If the inventory and the optimal capacity are equal, the machine produces to the extent to satisfy the needs. In 1995, Hu et al. studied FPMS in a state where backordered demand is not allowable and showed that HPP was valid in this state too. Mourani et al. (2008) examined single-machine FPMS with constant demand by considering the transportation time. Bi-section search algorithm and simulation method were used in this article to optimise the system. Aghezzaf and Najid (2008) studied preventive maintenance in FPMS. They intended to determine the time of preventive maintenance for a system composed of several production lines. It was shown that this problem is of NP-hard type and a heuristic method was used to solve it. Rezg et al. (2004) studied a production line consisting of $n$ machines without middle buffers using simulation method. They investigated maintenance of machineries given to their age in this research and genetic algorithm was used to optimise the maintenance time. Sajadi et al. (2011) investigated a network FPMS with constant demand. In this article $m$ dissimilar machines are associated with each other and are led to manufacturing of one product. Mhada et al. (2011) proposed a model for FPMS with fixed demand and distribution of the maintenance time and exponential breakdown. Then they studied occasions when machines are exposed to distribution of the maintenance time and non-exponential breakdown by developing the HPP. Zhou et al. (2010) investigated the optimum time of preventive maintenance for multi-unit series systems. Filliger and Hongler (2005) investigated a system consisting of two failure-prone machines with independent productions and a buffer and stated the optimal production rate of each machine given to the buffer level. Rahim and Shakil (2011) studied the role of preventive maintenance to minimise quality control expenses. They employed tabu search approach to optimise the time of preventive maintenance in their study. Demir et al. (2012) studied buffer allocation in failure-prone production lines where the purpose was to determine optimal size of each buffer to increase efficiency of the system. Lin and Wang (2012) studied preventive maintenance period to minimise the expenses using genetics algorithm method. Series/parallel systems were investigated in this paper and preventive maintenance period was specified for elements of these systems given to reliability of each element by means of genetics algorithm in order to minimise the expenses. Hong et al. (2012) studied choosing the best maintenance policy for different industries. Singholi et al. (2012) examined operation sequencing in flexible manufacturing systems using discrete event simulation method and their purpose was to minimise make span. Chakraborty et al. (2013) determined the threshold level of buffer in manufacturing FPMS. The manufacturing product in this system was considered decomposable and an analytical method was proposed to determine the threshold level of buffer. Bouslah and Gharbi (2013) studied single-machine FPMS for imperfect products. They used a general distribution for breakdown and maintenance of machines. Wee and Widyadana (2013) investigated stochastic preventive maintenance for FPMS. Time of preventive maintenance has probable distribution in this article. The system has been analysed for uniform and exponential distributions.
A single-machine FPMS with constant demand state was studied in this paper and the purpose was to determine optimal production rate and time of preventive maintenance. Therefore, discrete event simulation was employed in the present article for modelling of FPMS and simulated annealing algorithm was used for optimisation of the production rate and time of preventive maintenance. To this end, FPMS was modelled in ARENA simulation software and HPP was applied to control the production. Arbitrary distribution for breakdown and maintenance of machineries can be considered and obtain the optimal production rate using the simulation method.

3 Notations and abbreviations

Throughout this article, the following notations and abbreviations are used.

FPMS  failure-prone manufacturing system
HPP  hedging point policy
$C^+$  holding cost per unit of item per unit of time
$C^-$  backlog cost per unit of item per unit of time
d  demand rate per unit of time
$J$  expected long run average cost
$T_p$  preventive maintenance time for machine
$u$  production rate of machine
$x(t)$  inventory of buffer at time t
$Z^*$  optimal inventory level of buffer.

4 Equations governing failure-prone manufacturing system

State of machine in FPMS is shown with $ζ(t)$ and is as below:

$$ζ(t) = \begin{cases} 
0 & \text{If machine is under maintenance} \\
1 & \text{If machine is in use or idle}
\end{cases} \quad (1)$$

Inventory of the system at any moment is as bellow:

$$x(t) = u(t) - d(t) \quad (2)$$

The production rate is based on the following relation given to the state of machine.

$$u(t) \in \begin{cases} 
0 & \text{if } ζ(t) = 0 \\
[0 \quad u^{\text{max}}] & \text{if } ζ(t) = 1
\end{cases} \quad (3)$$

According to HPP, production rate of machine is obtained through the following relation:
Optimal production and preventive maintenance rate in a FPMS

\[ u(t) = \begin{cases} 0 & x(t) > z^* \\ \mu_{\text{max}} & x(t) + u_{\text{max}} < z^* \\ z - x(t) & \text{otherwise} \end{cases} \] (4)

The buffer inventory in terms of time is as below using relation (4):

**Figure 1** Buffer inventory in terms of time according to HPP

![Buffer inventory in terms of time according to HPP](image)

The purpose is to minimise cost of holding, shortage and maintenance that the target function is shown in relation (5).

\[
J = \lim_{T \to \infty} \frac{1}{T} E \int_0^T [C^+(t)x^+(t) + C^-(t)x^-(t)] \, dt
\] (5)

As there is no analytical solution to minimise the amount of target function shown in relation (5) and also minimise the expenses of corrective and preventive maintenance in complicated states, simulation method was used in this paper.

5 Simulation model

Figure 2 shows the simulation algorithm of FPMS in ARENA software. As it is clear from the algorithm if the time of system is less than the time of breakdown occurrence, the system continues its production given to HPP and if the time of system reaches the time of breakdown occurrence, corrective and preventive maintenance are conducted. Then production starts again. Expenses are calculated in both sections of production and maintenance. Figure 3 shows the model of FPMS in ARENA software.
Figure 2  Simulation algorithm of a failure-prone manufacturing system in arena

Steps of simulation algorithm of the FPMS:

1. determining the costs per unit of item per unit of time such as holding, shortage and maintenance
2. determining breakdown distribution and maintenance distribution
3. manufacturing by considering the HPP
4. studying the occurrence of maintenance time for machines and determining the type of maintenance (corrective and preventive)
5. returning of the machine to the production cycle
6. calculation of costs.
Costs of maintenance and shortage are obtained using the system model in ARENA software by changing the buffer sizes. Therefore, it is possible to determine the optimal level of buffer to minimise sum of costs of maintenance and shortage. Also by changing the time of preventive maintenance it is possible to obtain sum of cost of preventive and corrective maintenance. Hence, the optimal time for preventive maintenance is calculated.

6 Numerical example

The purpose of this example is to determine the optimal inventory level of buffer and time of preventive maintenance for FPMS. Single-machine FPMS is shown in Figure 4. Information of the system is indicated in Table 1.
Table 1  Properties of system

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>60 product per hour</td>
</tr>
<tr>
<td>Max rate of production</td>
<td>75 product per hour</td>
</tr>
<tr>
<td>Holding cost</td>
<td>30</td>
</tr>
<tr>
<td>Shortage cost</td>
<td>100</td>
</tr>
<tr>
<td>Corrective maintenance cost</td>
<td>80</td>
</tr>
<tr>
<td>Preventive maintenance cost</td>
<td>20</td>
</tr>
<tr>
<td>Duration of corrective maintenance</td>
<td>Unif (35,45)</td>
</tr>
<tr>
<td>Duration of preventive maintenance</td>
<td>Constant 20</td>
</tr>
<tr>
<td>Distribution of failure</td>
<td>Weibull (10,200)</td>
</tr>
</tbody>
</table>

In order to determine the simulation time, total cost diagram was first executed in terms of time during 3,500 minutes. As it is obvious in Figure 5, the system reaches a steady state after 2,500 minutes.

Figure 5  Determining the steady state time of simulation (see online version for colours)

The following results were obtained after 2,000 minutes of running the software. Table 2 shows sum of costs in terms of inventory level of the buffer. The relation between inventory level of buffer and sum of costs in terms of $T_p = 150$ and $T_p = 250$ are shown in Figures 6 and 7. As it is observed, the optimal inventory level are obtained equal to $z^* = 6$ and $z^* = 25$ for $T_p = 150$ and $T_p = 250$ respectively. But the optimal inventory level of the
buffer is changed by changing the time of preventive maintenance and thus time of preventive maintenance and inventory level of the buffer must be optimised simultaneously to minimise total cost. To this end, the system was simulated in terms of several inventory levels of buffer as well as different times of preventive maintenance. The obtained results are shown in Figure 6. The relation between time of preventive maintenance and sum of costs in terms of $z = 10$ and $z = 20$ are shown in Figures 8 and 9. Figure 10 displays system inventory during the time.

**Table 2** Total costs in terms of inventory level

<table>
<thead>
<tr>
<th>$Z$</th>
<th>Total cost for $T_p=150$</th>
<th>Total cost for $T_p=250$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>630</td>
<td>1,985</td>
</tr>
<tr>
<td>10</td>
<td>660</td>
<td>1,732</td>
</tr>
<tr>
<td>15</td>
<td>764</td>
<td>1,609</td>
</tr>
<tr>
<td>20</td>
<td>911</td>
<td>1,536</td>
</tr>
<tr>
<td>25</td>
<td>1,057</td>
<td>1,509</td>
</tr>
<tr>
<td>30</td>
<td>1,202</td>
<td>1,530</td>
</tr>
<tr>
<td>35</td>
<td>1,347</td>
<td>1,597</td>
</tr>
</tbody>
</table>

Figure 6 Relation between inventory level of buffer and sum of costs for $T_p = 150$ (see online version for colours)
Figure 7  Relation between inventory level of buffer and sum of costs for $T_p = 250$ (see online version for colours)

Figure 8  Relation between time of preventive maintenance and sum of costs for $z = 10$ (see online version for colours)
Figure 9  Relation between time of preventive maintenance and sum of costs for $z = 20$
(see online version for colours)

Figure 10  Inventory of system during the time (see online version for colours)

Total cost contour in Figure 11 was depicted in terms of the inventory level and time of preventive maintenance and given to the figure the minimum total cost is equal to 699 monetary units. As Figure 10 shows, inventory level of the buffer must be less than 15 or time of preventive maintenance must be between 120 and 160 so that the system has minimum total cost. 3D plot of total cost in terms of inventory level and preventive maintenance time is shown in Figure 12.
7 Conclusions

A FPMS was studied in this paper and optimal production rate and time of preventive maintenance were determined to minimise costs of maintenance and inventory. Considering that analytical solution exists for FPMS only when maintenance and breakdown of machines has exponential distribution (Mhada et al., 2011) utilisation of discrete event simulation method to analyse FPMS given to each arbitrary distribution like uniform distribution and Weibull distribution for maintenance of machines is one of the features of the current paper. It is possible to analyse complex problems of FPMS...
using the simulation method and HPP. To this end, time of the system’s steady state should be determined. Because two parameters of inventory level and time of preventive maintenance should be optimised simultaneously to minimise total expense it is be possible to determine minimum total cost of system, optimal inventory level and time of preventive maintenance by simulation of the system in terms of inventory levels and times of different preventive maintenance and then depict the total cost contour based on the above two parameters. Considering machine breakdown with regard to its age and also examining the system in variable demand are other advantages of this approach.

Acknowledgements

The authors would like to thank the reviewers for their invaluable comments.

References


