Spare part returns in stochastic deteriorating manufacturing system under a condition-based maintenance policy: Simulation-based Genetic Algorithm approach

H. Boudhar*, M. Dahane,** N. Rezg*

*Laboratoire de Génie Industriel et Production de Metz (LGIPM Laboratory)
1, route d'Ars Laquenexy CS65820 57078 - Metz Cedex 3. France
*Université de Lorraine, France (e-mail:hamza.boudhar, nidhal rezgj@univ-lorraine.fr)
** National School of Engineering (ENIM), Metz, France (e-mail: dahane@enim.fr)

Abstract: This paper deals with the problem of spare part returns and its impact on the degradation of a production unit. The main motivation in this context is how to reuse a recovered spare part and at what level (quality) the remanufacturing action should be performed. The manufacturing under study consists of one failing and repairable machine. Our objective is to determine the decision thresholds $ds$ and $dr$ based on the inspected degradation level $d(t)$. Failure occurs when the degradation level exceeds the critical threshold $d_{max}$. When the degradation level exceeds $dr$, a preventive maintenance action is performed. $ds$ is threshold to manage the spare part order policy.

Keywords: Spare part, reuses options, degradation, maintenance, simulation-based genetic algorithm.

1. INTRODUCTION AND LITERATURE REVIEW

The reliability of degrading systems is managed by engineers through Condition-Based Maintenance (CBM), which is one of many alternative policies for the maintenance (Cheng et al., 2012). The CBM is a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. Thus, CBM is very promising, with a balance between the security and the economy by avoiding unnecessary preventive maintenance actions (Jardine et al., 2006). CBM aims to inspect and quantify the degradation at regular intervals, so that the system can be repaired or replaced preventively before it fails in a catastrophic manner (Cheng et al., 2012).

Moreover, the failure mechanism has a dominant role in the choice of the maintenance policy. There is failure models based on the lifespan, and failure models based on degradation. The lifespan model is a failure system represented by a random variable, estimating the time between the start of operation and the failure (Park et al., 2000). This type of model is usually studied either by a maintenance strategy based on age, with a compromise between corrective maintenance and scheduled maintenance, or through a strategy called block, which is based more on systematic maintenance. Whereas the degradation model is not reduced to two possible states for the system, operation and failure, it introduces intermediate states, less degraded and more degraded. The adopted maintenance strategies for this failure model depend on the class of degradation model. The discrete degradation model is often used for systems, which pass from one state to other increments with jumps. In literature, this type of degradation is modeled in different ways, like semi Markov process, ((Yeh., 1996), (Moustafa et al., 2003), etc). Markov chains (Neves et al., 2011), etc). The degradation model is characterized by a continuous knowledge of the distribution of increments between two successive times. The evolution of degradation between the two moments is related to a random value (Grall et al., 2002), (Barata et al., 2002), (Dieulle et al., 2003), (Wang et al., 2008, 2009).

The degradation level is determined by the inspections performed on the machine. According to the inspected degradation level, decisions are taken for potential maintenance actions. In the literature, we find two possible inspection approaches, a continuous control, for which the level of degradation is known at each instant in time (Lam and Yeh., 1994), (Barata et al., 2002), (Moustafa et al., 2003), or a periodic inspection carried out at specific time intervals, it reveals the degradation level of the machine at the time of the inspection without a traceability of degradation at previous times (Lam and Yeh., 1994), (Grall et al., 2002), (Dieulle et al., 2003), (Wang et al 2008), (Neves et al., 2011).

The maintenance actions can be of different nature and different quality. The nature of maintenance is directly related to the state of the machine, it can be preventable, if the degradation of the machine does not exceed the failure threshold, as it can be corrective in nature, if the machine is considered as failed. However, whatever the nature of maintenance chosen, it is carried out in three possible quality levels, minimal, imperfect and perfect. Generally, minimal and imperfect maintenance consist of a direct intervention on the machine. That intervention will never make the machine as good as new. While perfect maintenance will make the machine as good as new and it’s usually performed with a
replacement during the intervention. In this perspective, there are multiple and diverse researches done in the field. We found (Moustafa et al., 2003) who used preventative maintenance with minimal repair or replacement. (Lam and Yeh, 1994) used preventative replacement with age and corrective replacement in case of failure. In other works such as those of (Barata et al., 2002) (Grall et al., 2002) (Dieulle et al., 2003) (Wang et al., 2008) (Neves et al., 2011) where the authors have opted for a conditional maintenance with preventative replacement and corrective replacement upon failure, for Barata et al., (2002) an imperfect preventative maintenance is performed if the deterioration reaches a certain level.

The replacement requires spare parts drawn from a stock managed by an order placed with a delivery time. This delivery time is considered either fixed (Chalbi and Ait-Kadi, 2001) or random (Sheu and Chien, 2004), with different storage strategies, depending on the number of replacement parts and the number of machines.

Our study is based on works of Barata et al. (2002) and Wang et al. (2008). In these works a condition-based maintenance is adopted. Wang et al. (2008) consider a production unit with a stochastic degradation. The maintenance action requires single type spare parts. Our objective is to determine the optimal decisions according to maintenance, spare parts order, inspection and spare parts remanufacturing/policies minimizing the generated total costs.

The rest of the paper is organized as follows: Section 2 presents the problem statement. In this section a complete description of the considered system is detailed based on the formulation of the maintenance, order, inspection and remanufacturing/replacement policies. The proposed approach is presented in section 3. Section 4 is dedicated to present an illustrative example, and conclusions are summarized in section 5.

2. PROBLEM STATEMENT

Table 1 summarizes the notations used in this paper:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ci</td>
<td>Inspection unit cost</td>
</tr>
<tr>
<td>CUs</td>
<td>Storage unit cost</td>
</tr>
<tr>
<td>CUp</td>
<td>Delay unit penalty</td>
</tr>
<tr>
<td>Cr</td>
<td>Remanufacturing unit cost</td>
</tr>
<tr>
<td>Cpr</td>
<td>Preventive maintenance unit cost</td>
</tr>
<tr>
<td>Ccr</td>
<td>Corrective maintenance unit cost</td>
</tr>
<tr>
<td>Cci</td>
<td>Order cost of one part of quality l, l ∈ {0, 1, 2, 3}</td>
</tr>
<tr>
<td>dmax</td>
<td>Maximum degradation threshold (complete degradation state)</td>
</tr>
<tr>
<td>dr</td>
<td>Degradation threshold of replacement</td>
</tr>
<tr>
<td>ds</td>
<td>Degradation threshold of order</td>
</tr>
<tr>
<td>T</td>
<td>Inspection period</td>
</tr>
<tr>
<td>Tmiss</td>
<td>Total duration of the mission</td>
</tr>
<tr>
<td>ldel</td>
<td>Delivery time</td>
</tr>
</tbody>
</table>

The system under consideration consists of one randomly degrading machine M. The machine M is subject to a random corrective maintenance and a preventive maintenance plan described in the maintenance policy section. The maintenance action requires the replacement of the spare part by another part from the stock S1. After each replacement (due to corrective or preventive maintenance), the used spare part is recovered and put into the stock S2. The recovered parts are controlled and examined by the maintenance service in order to be classified in two different sets: spare parts for reuse and spare parts for disposal (end of lifecycle).

A second classification is required to class the used spare parts under several subsets according to their degradation level (Figure 1).

Fig. 1. System description

The machine degradation at any time t is an increasing stochastic process given by the following expression:

\[d(t) = d(t-1) + (2 \zeta)\]

where \(\zeta \in [0,1]\) is a uniform random variable.

The following assumptions are proposed based on industrial practice:
- The spare part under study is considered as the main part on the machine.
- The replacement action requires one part (from stock S1) and generates one part (to stock S2).
- The degradation level of the spare part determines the quality of this part.
- The new spare parts are provided by a direct supplier. Their nominal degradation rate \( d(0) = 0 \).
- The spare parts of other qualities are provided by the maintenance service after the remanufacturing actions. The remanufactured parts have a degradation rate \( d(0) > 0 \).
- A periodic inspection program is performed to inspect and quantify the machine’s degradation level.

The degradation level of the spare part determines the action to perform (corrective maintenance, preventive maintenance and order), according to the decision thresholds \( (d_{\text{max}}, dr, ds) \).

When the inspected degradation level exceeds the threshold \( d_{\text{max}} \), the machine \( M \) is considered down and the spare part is replaced.

In the case of degradation level inspected between thresholds \( dr \) and \( d_{\text{max}} \) the spare part is replaced preventively. If the degradation level exceeds the threshold \( dr \), an order is launched for a new spare part.

\[
\begin{align*}
&d(t) = ds(t) + dr(t) + d_{\text{max}} \\
&d_{\text{max}}(0) = 0, \quad dr(t) > 0, \quad ds(t) > 0,
\end{align*}
\]

Fig. 2. Machine degradation thresholds

The spare part quality is defined based on the degradation level. Thus, when the part is new, its quality is 0, otherwise the part is of quality 1, 2, 3 or 4. Quality 4 determines a high degraded part: if the degradation level of the part belongs to the zone \( Z_i = [N_i, N_{i+1}] \) then the part quality is \( i \), \( i = 0, \ldots, 4 \), \( N_0 = 0 \), \( N_4 = d_{\text{max}} \), \( N_i = \infty \), \( N_i < N_{i+1} \).

\[\Phi_i \text{ is realized if } N_i < N_{i+1}.\]

2.1 Maintenance policy

- Corrective maintenance

A failure occurs when the degradation level exceeds the threshold \( d_{\text{max}} \). The failure is detected after the inspection of the degradation and it generates a corrective maintenance action, which consists of replacement of the main spare part of the machine \( M \).

After a corrective maintenance, the recovered spare part is necessarily of quality 4 (extreme degradation). In this case, the spare part cannot be reused and it is not possible to perform the remanufacturing action: the spare part is intended for disposal.

- Preventive maintenance

When the inspected degradation level exceeds the threshold \( dr \) and does not exceed \( d_{\text{max}} \) the spare part is preventively replaced. A preventive maintenance action consists of replacement of the main spare part. This allows reusing the part with or without remanufacturing action.

These maintenance actions (either corrective or preventive maintenance) are performed at the instants of inspection but are conditioned by the availability of the ordered part.

2.2 Inspection policy

The degradation level is known at the time of inspection. The inspection actions are carried out under a periodic plan (i.e. each period \( T \)).

The inspection Policy is based on a continuity of inspection periods, with a cancellation of inspection activities between the instant we place the order and the arrival of the spare part.

2.3 Order policy

If no order has been placed during the previous inspection, and the inspected degradation level exceeds the threshold \( ds \) \( (d(t) \geq ds) \), then an order of one spare part is placed. This spare part is required for the replacement to be performed at the inspection that follows the arrival of the ordered part.

The delivery time \( t_{\text{del}} \) of the spare part depends on the quality of the ordered part.

Let \( \varphi \) be the duration between the instant of the spare part ordering and the current time and \( \Phi \) the order state.

So, we have three possible states:

\[\begin{align*}
\Phi_1 &:\text{ no spare part is ordered} \\
\Phi_2 &:\text{ the spare part is ordered since } t_{\text{del}} \text{ unit time} \\
\Phi_3 &:\text{ the part has arrived since } \varphi = t_{\text{del}} \text{ unit time}
\end{align*}\]

Therefore, the value of the variable \( \varphi \) can belong to one of these states \( (\Phi_1, \Phi_2, \Phi_3) \).

2.4 Replacement and remanufacturing policy

The choice of the part to order is made when the inspected degradation level exceeds the threshold \( ds \) \( (d(t) \geq ds) \). The maintenance service decides either to order a new part from the supplier or reuse one of the recovered parts (after remanufacturing actions) available in \( S_2 \).

The remanufacturing action aims to enhance the quality of the spare part. Remanufacturing options can be summarized as follows:

- If the chosen spare part is of quality 1: no remanufacturing action is possible.
- If the chosen spare part is of quality 2: the spare part quality can be improved to quality 1.
• If the chosen spare part is of quality 3: the spare part quality can be improved to quality 1 or quality 2.

When spare part arrives (directly from the supplier or from the maintenance service), it is put into stock $S1$. The stock $S1$ consists of two stock areas $S1a$ and $S1b$: - $S1a$ is a stock of new spare parts (not previously used), provided directly by a supplier. - $S1b$ is a stock of remanufactured spare parts (repaired).

We consider the same storage cost for $S1a$ and $S1b$.

According to (1) the quality of the operating spare part (the part used by the machine), (2) the inspected degradation level and (3) the availability of spare parts, several decisions can be made:

$t = 0$: 
Case 1: the spare part to be used is new. In this case, $d(0)=0$ and no action is planned. 
Case 2: the spare part to be used is remanufactured. In this case, the degradation level $d(0)$ is inspected. Possible actions are planned with respect to the different decision thresholds $ds$, $dr$ and $dmax$.

$t > 0$: 
Case 3: if $0 \leq d(t) < ds$ no order is placed. 
Case 4: if $ds \leq d(t) < dr$ 
- if $\varphi \in \Phi_1$ (i.e. no order is placed): an order is placed and all inspections are cancelled until the arrival of the ordered spare part. 
- if $\varphi \in \Phi_2$: the ordered spare part has not arrived and the inspections are still cancelled. 
- if $\varphi \in \Phi_3$: the ordered spare part has arrived. It has been put in $S2$ since the instant $\varphi - t_{del}$. 
Case 5: if $dr \leq d(t) < dmax$ 
- if $\varphi \in \Phi_1$ (i.e. no order is placed): an order is placed and all inspections are cancelled until the arrival of the ordered spare part. 
- if $\varphi \in \Phi_2$: the ordered spare part has not arrived and the inspections are still cancelled. 
- if $\varphi \in \Phi_3$: the ordered spare part has arrived and has been put in stock until the next inspection. 
Case 6: if $d(t) \geq dmax$ 
- if $\varphi \in \Phi_1$ (i.e. no order is placed): an order is placed and all inspections are cancelled until the arrival of the ordered spare part. 
- if $\varphi \in \Phi_2$: the ordered spare part has not arrived and the inspections are still cancelled. 
- if $\varphi \in \Phi_3$: the ordered spare part has arrived and has been put in stock until the next inspection. 

As long as the part has not been replaced, a penalty cost is generated for each time unit spent in the failure state (because $d(t) \geq dmax$)

3. PROPOSED APPROACH

Our objective is to determine the degradation thresholds $dr$ and $ds$ and the maintenance duration $T$ minimizing the total cost $CT$.

The total cost $CT$ consists of the inspection cost, preventive maintenance cost, corrective maintenance cost, storage cost, and penalty cost. The total cost is given by the following expression:

$$CT = \sum_{t=0}^{\infty} PiCi + \sum_{j} PsCs + \sum_{j} PpCp + \sum_{j} y_j Cr + \sum_{j} PprCpr + \sum_{j} PcrCcr + \sum_{j=0}^{3} x_j Cc$$

Thus, our problem can be formulated as follows:

$$\text{Min } CT$$

Subject to:

$$\sum_{j=0}^{3} x_j = 1 \quad \forall \ j = 1\ldots NR.$$  
$$\sum_{j=1}^{3} k_j x_j > y_j \quad \forall \ j = 1\ldots NR.$$  

where 

$$x_j = \begin{cases} 
1 & \text{if the quality } l \text{ is selected for the replacement } j \\
0 & \text{Sinon} 
\end{cases}$$

$l \in \{0, 1, 2, 3\}$ 

$$y_j = \text{quality remanufactured of the part chosen for replacement } j.$$  

$$t_{s_j} : \text{Storage time before replacing}$$  
$$t_{p_j} : \text{Downtime penalty of the cycle } j$$  
$$P_i : \text{Probability to perform an inspection}$$  
$$P_s : \text{Probability of storing a part}$$  
$$P_p : \text{Probability of exceeding dmax}$$  
$$P_{pr} : \text{Probability to perform a preventive maintenance}$$  
$$P_{cr} : \text{Probability to perform a corrective maintenance}$$

Fig. 3. Simulation model
To resolve our problem we propose a simulation-based genetic algorithm approach. The simulation module aims to calculate the total cost of each chromosome. The simulation is based on discrete event techniques. The manufacturing system states are described through the degradation decision thresholds and the value of the variable $\varphi$. Transitions between two states can be degradation, inspection, or the arrival of an ordered spare part. Figure 3 illustrates model states and transitions.

The genetic algorithm module is illustrated by the figure 4.

The “reproduction” step is based on genetic operators to maintain the genetic diversity. Each new population is generated with the standard genetic operators: Single-point crossover with selection of the best generated chromosomes (80%) and random mutation (20%).

A solution (chromosome) consists of the degradation thresholds $ds$ and $dr$. The implemented chromosome is based on a real number coding. Each solution is composed of two real values. The first part gives the ratio between $dr$ and $d_{\text{max}}$. The second part gives the ratio between $ds$ and $dr$. Figure 5 gives an example where $dr=0.7\times d_{\text{max}}$ and $ds=0.6\times dr$.

4. ILLUSTRATIVE EXAMPLE

The following input data were used to illustrate our study to determine the decision thresholds minimizing the total cost: $T_{\text{miss}}=150\mu t$, $d_{\text{max}}=10$, $t_{v}=3\mu t$ for new spare part and $t_{v}=0$ for reused spare part (quality 3), $C_{t}=8\mu t$, $C_{pr}=50\mu t$, $C_{cr}=100\mu t$, $C_{U}=3\mu t$, $C_{e}=80\mu t$, $C_{Up}=50\mu t$.

Two numerical examples are presented to illustrate the relationship between the spare returns quality and the system degradation. For both examples, several inspection periods are examined.

In the first example, the replaced spare part is always new. Consequently, the used spare parts are not recovered and no remanufacturing action is possible. In this case, the optimal inspection period is $T=4$. The decision threshold to perform preventive replacement is $dr=0.6\times d_{\text{max}}$. The decision threshold to launch the spare part order is $ds=0.6\times dr$. Thus, the optimal thresholds are $dr=6$ and $ds=3.6$ associated with expected cost $CT=2620\mu t$. (Figure 6)

Table 2 illustrates the number of replacement and the obtained decision threshold $dr$ and $ds$ with the expected total cost $CT$.

<table>
<thead>
<tr>
<th>Number of replacements</th>
<th>$CT,(\mu t.10^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>3.05</td>
</tr>
<tr>
<td>16</td>
<td>2.71</td>
</tr>
<tr>
<td>17</td>
<td>2.62</td>
</tr>
<tr>
<td>16</td>
<td>2.70</td>
</tr>
<tr>
<td>16</td>
<td>3.02</td>
</tr>
<tr>
<td>13</td>
<td>3.47</td>
</tr>
<tr>
<td>11</td>
<td>3.86</td>
</tr>
<tr>
<td>10</td>
<td>4.31</td>
</tr>
</tbody>
</table>

In the second example, the replaced spare part is always remanufacturing. Spare parts are recovered and reused in quality 3.

Figure 7 illustrates the variation of the total cost with the inspection duration. In this case, the expected total cost $CT$ decrease with the duration of inspection interval. This can be explained by the increase of the number of replacements. Note that replacements are performed because of the
degradation level, which exceeds the decision thresholds $dr$ and $d_{max}$.

![Graph showing Total Cost variation with inspection duration.](image)

Fig. 7. Total Cost variation with inspection duration. Case 2: remanufactured spare part

Table 3 illustrates the number of replacement and the obtained decision threshold $dr$ and $ds$ with the expected total cost $CT$ when the quality of placed spare part is 3.

**Table 3. Number of replacements and decision thresholds**

<table>
<thead>
<tr>
<th>Case 2: remanufactured spare part</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CT (mu.10^5)$</td>
</tr>
<tr>
<td>Number of replacement</td>
</tr>
<tr>
<td>$dr$ ratio (%)</td>
</tr>
<tr>
<td>$ds$ ratio (%)</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

In this study we have proposed a condition based maintenance policy in a spare part returns context. We study a stochastic degrading manufacturing system, which consists on a single failing and repairable production unit.

Our objective is to determine the decision thresholds $ds$ (to manage the spare part order policy) and $dr$ (to manage the preventive replacement) based on the inspected degradation level $d(t)$. Two numerical examples illustrate the dependence between the inspection interval duration, the decision thresholds and the expected total cost. The first example shows that the use of new spare part is more economically interesting to the fixed data. In the second one, we could see that decision thresholds $ds$ and $dr$ do not depend on the inspection interval duration when used spare parts are remanufactured (quality 3).

REFERENCES


