Condition Based Maintenance: simulation and optimization

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Abstract: - In this paper we propose a model of a productive system subject to a condition based maintenance policy which has to be optimized by modifying the maintenance thresholds to reach the lowest level of global system cost. After a wide literature review, a simulation approach is proposed that take in count all the cost related both to production and to maintenance. At the end of the paper we propose a parametric study to determine how some critical parameters (mainly costs) can influence the achievement of the system and the maintenance policy to be adopted.

Key-Words: - condition based maintenance, maintenance policy, simulation, optimization

1 Introduction
The goal of this paper is to study a production system that has a Condition Based Maintenance (CBM) policy through the meaning of a simulation model.
There are many works that have been developed in the recent years about the condition based maintenance, and we try with this contribution to build a model that has quite no limitations in the representation of the complexity of a production system and of the several variables of the maintenance management.

2 State of art
As seen, it’s been conducted a wide review of the scientific literature about the condition based maintenance studies.

<table>
<thead>
<tr>
<th>reference</th>
<th>AUTHORS</th>
<th>PAPER TITLE</th>
<th>Mathematical (m)</th>
<th>Simulative (s)</th>
<th>discrete (d)</th>
<th>continuous (c)</th>
<th>multi-parameter (m)</th>
<th>monoparameter (f)</th>
<th>wear resistance (r)</th>
<th>stochastic (st)</th>
<th>deterministic (d)</th>
<th>perfect inspections (yes)</th>
<th>opportunistic inspection (yes)</th>
<th>threshold (yes)</th>
<th>Partial inspections (yes)</th>
<th>Opportunistic replacement (yes)</th>
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<td>19</td>
<td>Grall, Berenguer, Dieulle</td>
<td>a cbm policy for stochastically deteriorating systems</td>
<td>m</td>
<td>c</td>
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<td>21</td>
<td>Kececioglu, Feng Bin Sun</td>
<td>a general discrete time dynamic programming model for the opportunistic replacement policy and its application to ball bearing systems</td>
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<td>d</td>
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The result is represented by 28 mathematical or simulative models about CBM. Each of them has got different characteristics that have been carefully evaluated to understand which could be the most important topics of a new model.
We have identified some main characteristics of the models that are shown in Table 1, where “x” represent just a paper for which the characteristic doesn’t make sense.
In the last part of the table are shown some papers with models about the optimal sizing of an interoperalional buffer; in these cases there are no characteristics that have been mentioned.
<table>
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<td>26</td>
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<td>27</td>
<td>Liao, Elayed, Chan</td>
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<td>28</td>
<td>Van der Duy, Shouten, Vanneste</td>
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<td>29</td>
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<td>optimal continuous wear limit replacement with wear dependent failure</td>
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<td>33</td>
<td>Newby, Dagg</td>
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<td>34</td>
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<td>36</td>
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<td>37</td>
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<td>38</td>
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<td>Guizzi, Santillo, Zeppoli</td>
<td>Condition Based Maintenance: Implementation and optimization of a two-unit serial system model with multi-threshold policy</td>
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<td>42</td>
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<td>43</td>
<td>W. Wang, W. Zhang</td>
<td>An asset residua life prediction model based on expert judgments</td>
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<td>44</td>
<td>Montoro-Carloza, Delia, Perez-Ocon Rafael</td>
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<td>45</td>
<td>Kahle</td>
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<td>46</td>
<td>L. Wang, J. Chu, W. Mao</td>
<td>A condition-based order-replacement policy for a single-unit system</td>
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<td>47</td>
<td>I. Zequeira, E. Valdes, Berenguer</td>
<td>Optimal buffer inventory and opportunistic preventive maintenance under random</td>
<td>m c 1 w s yes no yes yes yes yes No</td>
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3 The model

3.1 The physical model

The choice of a simulation approach gives the chance to represent the production system and the CBM policy with a very responsive reality model. In fact, we can notice that the complexity of this kind of system can be represented by a mathematical model with a set of equations, only when it’s simplified by a certain number of constraints, that could not be representative of the real system.

In our model, the wear has been identified as an obsolescence parameter instead of a resistance parameter, while the wear process is designed as a continuous process and not discrete.

According to quite all the studies, we have modeled the wear process as a gamma process. The failure probability is modeled through a weibull distribution, that is not led by the time, as usual, but by the wear parameter, according to the real phenomenon.

In most of the papers we examined, one component is considered in failure only when its wear parameter goes over a certain threshold, usually identified by $L$. While this idea is in line with the CBM conception, it seems to be something very far from the real experience. We know that failures, even if they are more likely to occur when wear parameter is high, can anyway be revealed also at any time and at any wear level.

That’s why we used a weibull distribution that can also give failures on components at any time of their lifecycle.

In our model there is a series of several machines working, with the possibility to put an interoperational buffer between them.

For each machine we have three maintenance thresholds which lead the decision system:

1. preventive maintenance threshold
2. opportune maintenance threshold
3. alarm threshold

The first two thresholds tell the system to make maintenance immediately to prevent the failure and the system stop.

The last thresholds tell the system to evaluate the possibility to reduce the period between inspections. With this kind of model we can evaluate the interactions between different machines due to the series. In particular, the opportune threshold, that is always lower than the preventive one, give the possibility to make a maintenance intervention on a machine even if it hasn’t reached yet the preventive threshold but there is a global stop of the system to make maintenance on other machines.

In this case we should have an economic convenience to work on that machine, resetting its lifecycle, because we opportunistically use the stop of the whole system to work on several machines.

The economic convenience in this case is related to the high cost of each system stop (setup cost, production loss etc.), due to the fact that the machine are in series and so we have to stop all of them to repair one of them.

3.2 The simulation model

Using a simulation approach, we have to limit the model to a certain number of components of the series.

Anyway we can use the software Arena to model any number of components series.

The model has two different logics:

- production logics
- maintenance logics

The production logics is the way we model the production system that is responsible for the machines wearing process, So it will determine the wear increments and the failure likelihood.

The maintenance logic is the way we use to model the maintenance process, characterized by inspection phases to determine the status of machines and by the different maintenance processes.
For any event of production or maintenance process, the model calculates the related cost (example: production of each piece, inspection, maintenance intervention, buffer etc.). Moreover, the model is able to calculate the free machine cost. A cost related to the time is associated to the global cost, whenever a machine is not working: being stopped because of a system stop, because there is a maintenance intervention on it or even if there is a stop of another machine in the series that doesn’t give pieces to work with. The production process has been modeled in Arena in modules; every machine is represented by a sub-model that can be repeated as many times as the real system.

The wear parameter is increased through an “Assign” module (Fig. 1) at predetermined time intervals, that have been fixed at one minute to simulate the continuous nature of this parameter and to allow the failure of the machine during the manufacturing of a piece.

The failure is determined by a “decide” module and it sends a message to the maintenance model to activate an intervention (Fig. 2). So it’s not needed to have inspections to know if there is a failure, as in many models that have been studied before.

The maintenance process is characterized by periodic inspections to determine the status of each machine wear, that has been determined by production. After the inspection, the model can decide if a maintenance intervention is needed or if it’s necessary to anticipate the next inspection. The decision is taken by the comparison between the machine wear, taken from inspection, and the thresholds that have been fixed to determine the maintenance policy. Moreover, the inspection process has been modeled as imperfect, so that the wear parameter is known with a certain degree of error due to a gauss distribution that affects the measure, according to the possibility that there is always an error in each measuring process.

4 The model optimization

Once defined the model, it has been used to understand the achievement of a particular production system and also to determine the optimal thresholds to be fixed to reach the lower global cost, taking into account both the cost of production and the cost of maintenance.

There have been launched a lot of optimization with the OptQuest module of Arena, to search the best maintenance policy, depending on different system configurations. First of all, we used the inspection cost as a parametric variable to understand which would be the thresholds, and so the maintenance policies, depending on the cost of inspection.

The result is represented by the graph in Fig. 4, in which we used an a-dimensional parameter \( \rho_{isp} \), given by the ratio between the cost of a single inspection on a machine and the cost of a preventive maintenance.

The graph shows the convenience to reduce the number of inspections (by increasing the alarm threshold) related to the increasing of the cost of any inspection, and this is very easy to understand. This lead to a lower threshold of preventive maintenance to prevent the failures anyway. So that when you reduce your inspections you have to pay...
your ignorance about the wear, increasing the number of preventive maintenance intervention to avoid the failures.

Fig. 4: Trend of the thresholds depending on ρ

In fig. 5 the graph shows the achievement of the model depending on the failure cost. As we could expect, all the thresholds decrease when the failure cost is higher. The higher is the impact of a failure, the higher is the number of inspections and of preventive maintenance to make.

Fig. 5: Trend of the thresholds depending on ρ

Finally, in fig. 6, we have the trend of thresholds depending on free machine cost. At the beginning, the free machine cost is zero, all the thresholds are quite the same. It means that the model suggest us to don’t use the condition based maintenance at all. In fact, if there is no cost related to the not working machine, there is also not so much convenience to make many inspections and many preventive maintenance.

The higher is the free machine cost, the higher will be the impact of a series system stop, so that we will need more inspections (lower alarm threshold) and more opportune maintenance (lower opportune threshold).

Fig. 6: Trend of the thresholds depending on ρ

The graphs analysis shows the achievement of the model to determine the best maintenance policy, that is the one that leads to the lowest level of global cost, by setting the right level of thresholds.

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