ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

COMPARISON OF PERIODIC REPLACEMENT AND STATE-BASED PREVENTIVE MAINTENANCE. A SIMULATION APPROACH.

Antonio Casimiro Caputo
Department of Mechanical and Industrial Engineering, University of Roma Tre, Roma, Italy
acaputo@uniroma3.it

Pacifico Marcello Pelagagge
University of L'Aquila, L'Aquila, Italy
pacifico.pelagagge@univaq.it

Paolo Salini
University of L'Aquila, L'Aquila, Italy
paolo.salini@univaq.it

Abstract*. In this paper discrete events simulation is used to compare in a consistent manner some state based preventive maintenance policies as opposed to a more traditional constant time policy (i.e. block replacement). A single server workstation is considered to better focus on maintenance policies performances without being affected by the more complex behaviour of a larger scale manufacturing system. Results show that state based policies, although potentially interesting, may be less effective respect to traditional and easier to manage time based policies, except in specific cases which have to be cautiously examined. Thus further research and more detailed investigation is required on this subject.*

Keywords: *state based maintenance, constant time maintenance, discrete events simulation.*

1. INTRODUCTION

Maintenance replacements improve functionality or restore good service of failed equipment. In systems having an increasing failure rate (IFR) preventive maintenance (PM) is also beneficial. This is the results of carrying out "as good as new" replacements which periodically renew the system by bringing it to the initial state thus lowering the average value of failure rate. However, preventive replacements determine additional costs which have to be compared with the reduced corrective maintenance (CM) cost in order to justify their economic convenience. Nevertheless, maintenance may also have adverse effects. In fact, maintenance interruptions may affect equipment availability in a negative manner, i.e. by increasing average value and the standard deviation (σ) of effective process times owing to downtime duration (Hopp and Spearman, 2011). The higher resource utilization and process variability causes, in turn, congestion effects which give rise to queueing phenomena leading to an increase of Work In Process (WIP) and manufacturing lead time. When the economic and operational consequences of the latter performance measures are relevant, maintenance must be planned taking into consideration the side effects of a PM schedule. Usually, when not constrained by production schedules, PM is performed on a time–based manner (Wang, 2002) relying also on guidelines issued by equipment manufacturers or by customary law prescriptions imposing the frequency of replacements or inspections. The two most widely adopted policies are "age based maintenance" and "periodic replacement", also known as "constant time" or "block" replacement. In the former, replacements are carried out at the occurrence of a failure or in a preventive manner after a prescribed time interval T_P has occurred from the last replacement. Each maintenance stop brings the system to an "as good as new" condition, meaning that the system is renewed at any maintenance and the failure rate is brought back at the initial value. In the latter, instead, PM is scheduled at times multiples of a predetermined fixed interval T_P, irrespective of possible corrective maintenance actions carried out between any two preventive replacements,. In this policy it is assumed that PM renews the system, while CM leaves unchanged the equipment age, i.e. the machine remains "as bad as old". In both cases the choice of the value for the T_P interval can be made in order to minimize the overall maintenance cost. In fact, given that with short T_P one has high PM costs but low CM costs, while for long T_P the opposite occurs, an optimal value of T_P which minimizes total maintenance cost per unit time may exist, and numerical methods can be used to determine it (Ben-Daya et al., 2000). However, as an alternative to scheduling preventive replacements according to elapsed working time, PM can be also planned based on a preliminary verification of system status which may authorize or not a preventive interruption. This kind of check is absent in time-based policies. Therefore, a number of alternative PM policies have been proposed in the literature (Das and Sarkar, 1999; Gupta et al., 2001; Iravani and Duenyas, 2002; Kaufman and Lewis, 2007; McKone and Weiss, 2002; Van der Duyn Schouter and Vanneste, 1995; Wang, 2000; Wu and Ryan, 2010). Nevertheless, it should be noted that the concept of "verification of system status" may include either "condition based maintenance" (CBM) or any other more loosely defined "state-based maintenance" (SBM). In CBM the preventive intervention is authorized after a verification or a forecast of the level of functional deterioration of the system. In SBM, as intended in this paper, the

ISSN 2176-5480

verification of system status is not necessarily related to functional equipment efficiency, but rather to a property of the entire system, i.e. the number of jobs in a queue, the busy or idle status of the workstation (as happens in "vacation-based policies") or the inventory level downstream the workstation.

Unfortunately, although many different state-based or vacation-based policies have been suggested or can be conceived, there is no agreement in the academic world about their effectiveness. On the contrary, the only agreed result is that state-based policies can behave better or worse than time-based policies or even better or worse than no PM at all according to each specific problem instance. Moreover, works discussing state based policies do not carry out a comparison with alternative policies, or do not make comparisons under consistent assumptions. Therefore, results from one research study are not directly comparable to those of other studies. Finally, when the analysis is carried out using mathematical approaches (i.e. queueing theory, Markov chains, Petri nets) the simplifications required for analytical tractability lead to models having different features which prevent a direct comparison of their results.

In a previous work (Caputo et al., 2011) discrete events computer simulation was used to compare in a consistent manner age replacement maintenance with SBM. As a further step to increase the understanding of SBM and investigating the implied trade-offs, a preliminary exploratory study is carried out in this work to compare, under the same assumptions and operational conditions, either constant time and state-based PM policies. Reference is made to a basic manufacturing system including a single server workstation, in order to focus on the effects of maintenance policies without being distracted by the operational issues of a more complex manufacturing system. Discrete events numerical simulation is adopted as a modelling tool to ensure the required level of detail and realism. The rest of this paper is organized as follows. At first a description of considered maintenance policies is carried out. Afterwards some details about modelling issues are given and then some numerical results are presented and discussed. We aim to provide a methodology for a systematic comparison of maintenance alternatives and discuss some early findings to point out why state-based policies sometimes fail to be a superior alternative to traditional time based maintenance. However, a full parametric analysis comparing alternative maintenance policies under a wide range of operating conditions is outside the scope of this paper, owing to space limitations. This kind of approach, based on a parametric and consistent comparison of maintenance policies, has the prospective goal of developing a performance map or some generalizable guidelines pointing out the conditions under which any kind of maintenance policy can be preferable.

2. REFERENCE POLICIES

In this work the following maintenance policies are considered, with Policy I being a traditional constant time policy included to provide a reference benchmark. In all cases T_P is defined as the user-defined reference time interval for PM planning.

Policy I. Constant time maintenance. Maintenance is carried out in the event of a breakdown (CM) or in preventive manner after a time interval of length T_P has elapsed starting from the previous PM interruption. In case of PM the system is brought back to "as good as new" condition , i.e. the initial value of failure rate is restored, while in case of CM a minimal repair is carried out which leaves the value of the failure rate unchanged.

Policy II. PM whenever server idle after $T_P - \Delta$. This is a state-based policy where PM is carried out at the first time that the workstation is idle (i.e. no jobs in queue) provided that at least a time interval $T_P - \Delta$ has passed from the last preventive interruption. However, in this case too, only PM restores equipment in "as good as new" conditions while CM is made in "as bad as old" manner. After an interruption, even if the machine stays idle, no further preventive interruption is carried out unless a subsequent $T_P - \Delta$ interval has lapsed. Δ is expressed as a time interval being a percentage of the nominal T_P (i.e. $\Delta = T_p \cdot \Delta\%$) and the PM interruption is triggered at the first time the server is idle between $T_P - \Delta$ and $T_P + \Delta$. In case the state condition (i.e. idle equipment) is not verified in the cited time range, the preventive maintenance is done at time $T_P + \Delta$ anyway. This is made to avoid that, in case the machine is highly saturated, the preventive maintenance is never done.

Policy III. PM whenever WIP $\leq$ K after $T_P - \Delta$. This is a state-based policy where PM is carried out at the first time that the workstation has a WIP lower than a predefined threshold of K jobs, provided that this happens after the predefined time interval from the last PM. In this case too, PM is carried out in "as good as new manner" and CM in "as bad as old" manner.

Both Policies II and III have the potential advantage of postponing or anticipating an interruption scheduled when the workstation is busy or temporarily overloaded without forcing jobs already in a long queue to further wait for a preventive interruption. The goal is to wait until some idle time or low WIP period occurs, in the vicinity of T_P, before performing PM. This would save workstation capacity and prevent WIP accumulation (and lead time increase) during PM downtime. In case $\Delta = 0$, PM is postponed as soon as possible (i.e. when the state condition applies) after T_P, but this has the added risk of increasing the likelihood of a failure to occur before the PM takes place. Given that CM in general has higher downtime and higher cost respect PM, a higher WIP accumulation and cost can occur in case of a breakdown, thus offsetting the expected benefit of PM. This is the trade-off implied by the above state-based policies. However, such policies may not be applicable in case of highly utilized workstations, otherwise there is a risk of continuously delaying PM owing to the high number of jobs in queue. In this respect Policy III is less constrained respect Policy II. Conversely, in low saturation systems queues are short and Policies II and III converge to Policy I.

ISSN 2176-5480

3. MODELING ASSUMPTIONS

Discrete events simulation models of the above policies were developed using the Arena programming environment. As already said a deteriorating single server workstation with infinite buffer was considered having an IFR and a Weibull distributed time to failure with a shape parameter of 3 and a scale parameter of 75. System deteriorates only when utilized, therefore failure rate does not increase during interruptions or periods where server is idle. Since downtime is explicitly accounted for there is no possible superposition of PM and CM, i.e. a breakdown can occur only if the server is busy and only if a preventive downtime is over, while PM can not occur in case it is scheduled when server is undergoing a CM. Corrective interruptions are "preemptive" and job processing resumes after the maintenance interruption is terminated. PM interruption is assumed to be "non preemptive", i.e. job processing is not interrupted and PM is carried out only after job processing is terminated or when the state condition is satisfied (i.e. server is idle or WIP < K). A PM interruption always restore the system in "as good as new" condition while a CM interruption implies a minimal repair without system renewal and the value of failure rate remains unchanged. The arrival process of new jobs is Poisson with exponential distribution of interarrival times. Process times are lognormally distributed and a single type of job is processed. The simulation models were run for T_P values ranging from 25 to 300 h, with a value of server utilization in the range 84%÷92% obtained assuming interarrival time of 6 min when average natural process time is 5 min with standard deviation σ = 1 min.

CM Mean Time To Repair ($MTTR_{CM}$) is 10 h with σ = 4 h, while in PM the Mean Time To Repair ($MTTR_{PM}$) is 2 h and σ = 0.5 h. In Policy III is assumed K = 5, 10, 20. Performance measures are estimated as average values over a number of replication suitable to give a confidence level of 90%. Plots of WIP and maintenance cost are provided. Total cost per unit time is computed as a function of T_P by summing the overall maintenance cost per unit time to the cost of WIP as in Eq. (1), where h (€/h) is the unit WIP cost per unit time, WIP is the average Work in Process value, N_P is the average number of performed PM interruptions and N_B is the average number of corrective maintenance interruptions over the simulated time span T. WIP cost is computed assuming a unit value h = 0.5 €/h. This cost does not include WIP holding cost only, but also any other cost related to WIP amount such as space occupation, handling cost, opportunity cost due to lead time increase and so on. CM replacement cost is C_B = 400 € while preventive maintenance cost is C_P = 100 €. Simulated time is T = 3520 h.

$$C_{TOT}(T_P) = \left(\frac{C_P N_P + C_B N_B}{T} \right) + h\, WIP \qquad (1)$$

4. SIMULATION RESULTS

For each test case five simulation runs have been repeated using the discrete event simulator, and average performance values are shown. In order to test state-based policies two set of PM trigger conditions are used for policy II (Δ% = 10% and 20%) and three for policy III (Δ% = 20% with K = 5, 10 and 20 jobs).

Figure 1 and 2 show the cost of corrective maintenance per unit time comparing state-based policies II and III with Policy I respectively. The CM cost per unit time increases progressively as the number of failures grows when the PM becomes less frequent.

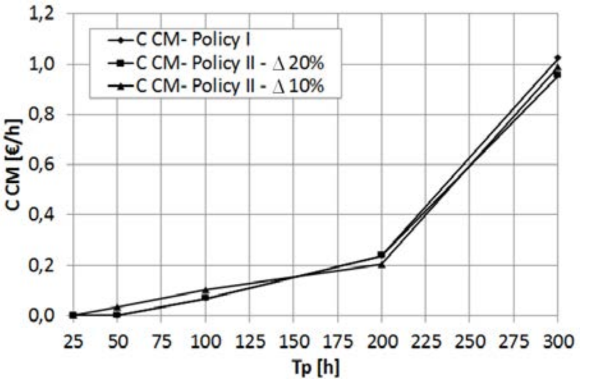

Figure 1:CM cost per unit time (Policies I and II)

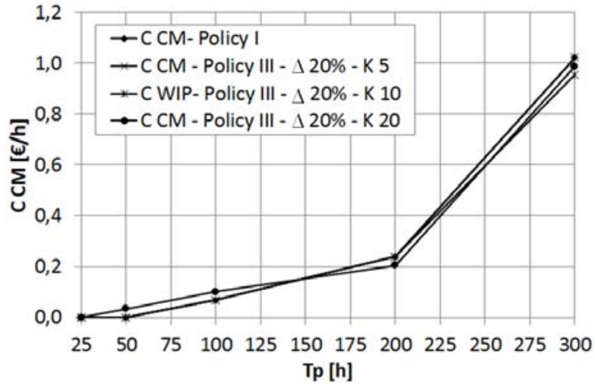

Figure 2:CM cost per unit time (Policies I and III)

If the T_P value is low, policies I, II (with Δ%=20%), and III (with Δ%=20%; K=5 and 10) assume similar trends. When T_P grows state-based policies II and III perform better respect traditional constant time maintenance (Policy I). In fact, when T_P becomes larger the time interval $T_p \cdot \Delta\%$ grows too, and the possibility of matching the state based

ISSN 2176-5480

conditions increases, so Policies II and III may reach better economic results respect to Policy I. For smaller T_P, on the contrary, the additional conditions are not met and the PM is postponed till time $T_P + \Delta$. The PM postponement makes the number of failures bigger and the CM cost grows.

The PM cost is not dependent on the reference policy. In fact, whichever the policy, the time between two preventive maintenances is about T_P and the number of PM is fixed and defined by the time horizon T and T_P. The PM cost per unit time is shown in figure 3. Obviously, the longer the time interval T_P between PM, the lower will be the PM interruption number and their specific cost per unit time.

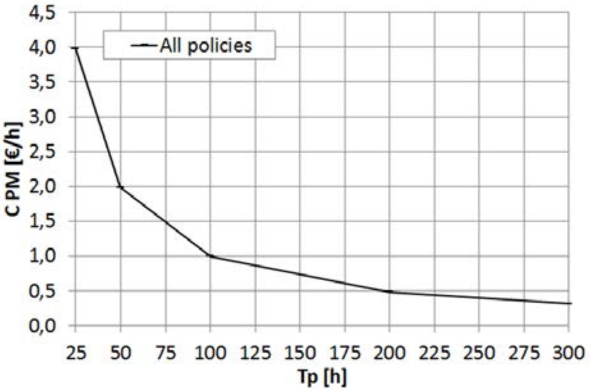

Figure 3: cost of PM per unit time

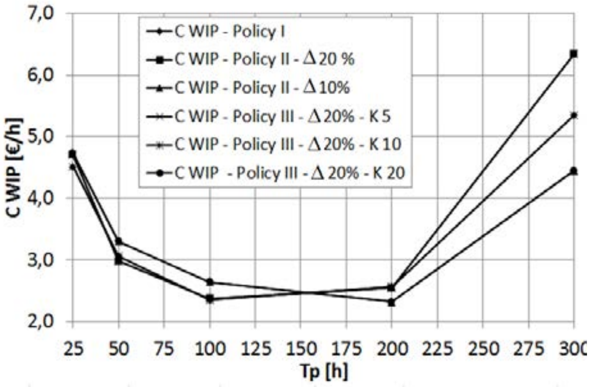

Figure 4: WIP holding cost

Figure 4 shows the average WIP holding cost, which is proportional to the average WIP amount. It is interesting to note that a minimum of WIP occurs. This happens because when T_P is changed the resource saturation, total downtime and resource availability change as well, thus affecting the level of congestion phenomena. As a consequence the excess capacity required to absorb accumulated WIP changes with T_P and a balance between preventive and corrective interruptions may be found so that WIP is minimized. Figure 4 shows that policies II (with Δ%=10%) and III (with Δ%=20% and K 20) have a different minimum respect to other cases. Moreover investigated policies have a benefit in WIP cost thanks to the possibility of making PM when the system is less saturated, thus avoiding WIP accumulation.

Finally, figure 5 shows the total cost per unit time including CM, PM and WIP holding cost. While it is confirmed that an optimal T_P value may exist, this value changes according to the adopted maintenance policy. It is also clear that including WIP cost may affect the optimal T_P interval, provided that WIP cost is high enough to be comparable with maintenance cost. The effect of this change is increasingly relevant the higher is the weight given to WIP control and WIP holding cost. In cases where buffers are limited, or when throughput time should be as low as possible, or where WIP holding cost is significant, the optimal T_P should be evaluated including WIP effects. Figure 5 shows that state-based policies may reduce minimum total cost respect to the traditional time based policy (Policy I), by shifting the PM date near the nominal date and by choosing the time of PM interruption based on WIP level or on the value of machine instantaneous utilization.

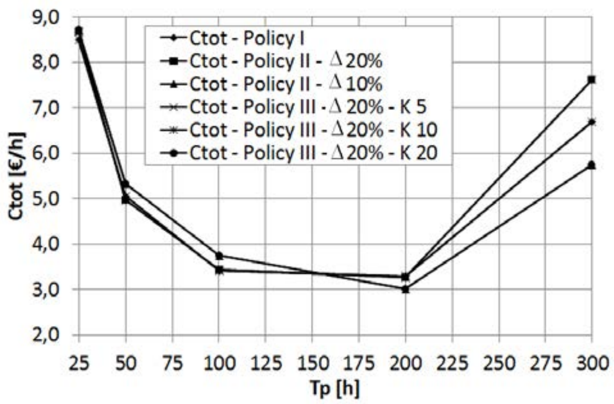

Figure 5: Total cost per unit time

Nevertheless, the results of this preliminary study, which is limited in scope, also point out that although state-based policies have a potential for WIP limitation, they may not be necessarily worthwhile. In fact, given the scarce impact on

ISSN 2176-5480

maintenance cost and the added complexity of SBM management, no real appreciable economic benefit is got unless WIP holding cost is high enough to affect total cost.

This is confirmed by simulation results shown in Table I which compare performances in cases where $MTTR_{CM}$ is reduced from 10 h to 2 h (the same average and σ of PM downtime, or when the Weibull time to failure distribution has the shape parameter reduced from 3 to 1.5, the PM cost is 100 (€/maintenance), the CM cost is 600 (€/maintenance) and the WIP cost is 0.5 (€/h).

Table I. Sensitivity analysis.

MTTR CM = 10 - shape parameter = 3 (Case 1)											
Policy I						Policy II					
TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}	TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}
0,00	140,00	4,70	3,98	0,00	8,68	0,00	140,00	4,31	3,98	0,00	8,28
3,51	70,20	3,35	1,99	0,03	5,37	0,00	70,00	2,87	1,99	0,00	4,86
6,88	35,60	2,60	0,99	0,10	3,69	7,78	35,80	2,56	0,99	0,14	**3,69**
11,66	18,40	2,35	0,48	0,24	**3,07**	19,59	19,20	2,86	0,48	0,38	3,72
61,28	17,20	4,82	0,31	1,06	6,19	52,31	16,20	5,14	0,31	0,89	6,33
MTTR CM = 10 - shape parameter = 1.5 (Case 2)											
Policy I						Policy II					
TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}	TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}
1,77	140,20	4,82	3,98	0,03	8,83	0,00	140,00	4,20	3,98	0,00	8,17
2,00	70,20	3,25	1,99	0,03	5,27	9,36	71,00	3,31	1,99	0,17	5,46
4,06	35,40	2,51	0,99	0,07	3,57	0,00	35,00	2,21	0,99	0,00	3,20
15,82	18,40	2,97	0,48	0,24	3,69	13,78	18,20	2,69	0,48	0,20	3,38
8,16	11,80	2,19	0,31	0,14	**2,63**	3,00	11,40	1,79	0,31	0,07	**2,17**
MTTR CM = 2- shape parameter = 3 (Case 3)											
Policy I						Policy II					
TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}	TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}
0,00	140,00	4,70	3,98	0,00	8,68	0,00	140,00	4,30	1,99	0,00	6,29
1,45	70,20	2,98	1,99	0,03	5,00	0,00	70,00	2,87	0,99	0,00	3,86
1,41	35,60	2,22	0,99	0,10	3,32	1,16	36,00	2,20	0,48	0,17	2,85
1,34	18,40	1,96	0,48	0,24	**2,68**	2,15	18,60	1,85	0,31	0,27	**2,43**
11,18	17,60	2,04	0,31	1,13	3,48	19,09	16,80	3,70	0,31	0,99	5,00
MTTR CM = 2 - shape parameter = 1.5 (Case 4)											
Policy I						Policy II					
TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}	TD	N_T	C_W	C_{PM}	C_{CM}	C_{TOT}
0,15	140,20	4,81	3,98	0,03	8,82	0,00	140,00	4,20	3,98	0,00	8,17
0,23	70,20	3,05	1,99	0,03	5,07	3,64	71,40	2,90	1,99	0,24	5,12
0,78	35,40	2,28	0,99	0,07	3,34	0,00	35,00	2,21	0,99	0,00	3,20
6,13	18,20	2,41	0,48	0,20	3,09	6,31	18,00	2,35	0,48	0,17	3,00
1,76	11,80	1,76	0,31	0,14	**2,21**	0,18	11,40	1,70	0,31	0,07	**2,08**

Legend: TD = Total Downtime (h), N_T = Total number of interruptions (N_P+N_B), C_W = WIP cost (€/h), C_{PM} = PM cost (€/h), C_{CM} = CM cost (€/h), C_{TOT} = Total cost €/h).

Table 1 shows that changing the Weibull shape parameter and the MTTR, Policy II performs better than the traditional time based Policy I, except for Case 1. It must be noted that this is true also without considering the WIP cost for Case 2 and Case 3 (Total cost without WIP cost: 0.45 and 0.72 respectively for Policy I, versus 0.38 and 0.59 for Policy II).

5. CONCLUSIONS

In this work a consistent comparison of some state-based and constant-time maintenance policies was attempted resorting to discrete events simulation of a single server workstation.

Although results of this preliminary work are limited to a specific problem instance, and are not generalizable, there is evidence that only simulation based models allow to realistically capture the complexity of manufacturing systems enabling to fine tune maintenance planning, including either deterioration effects and state-based performance measures, such as WIP levels and machine operational status.

In the considered examples some evidence of the effects that PM timing has on WIP level and maintenance interruptions was found, allowing to better understand the factors which can affect the performances of state-based policies. However, it was also confirmed that state-based policies while being potentially attractive are not always superior to traditional and easier to manage time-based policies. In fact, the benefit of anticipating or postponing preventive interruptions, until WIP is suitably low, is generally offset by a higher number of corrective interruptions which are penalized by longer downtimes and determine an overall increase in average WIP. Nevertheless, a further study on this subject is required before generalizable guidelines and results can be obtained.

6. REFERENCES

Ben-Daya, M., Duffuaa, S.O., Raouf, A., 2000, *Maintenance, Modeling and Optimization*, Springer.

Caputo, A.C., Pelagagge, P.M., Salini, P., 2011, *Comparison of time and state based preventive maintenance policies. A simulation approach*, in Harrison, K.D., Wood, B.M., Evans, D. (Eds.), Advances in Manufacturing Technology XXV, Proc. 9th International Conference on Manufacturing Research ICMR 2011, Glasgow Caledonian University, 6-8 September, ISBN 9781905866564.

Das, T.K., Sarkar, S., 1999, *Optimal preventive maintenance in a production inventory system*, IIE Transactions, Vol. 31, 537-551.

Gupta, D. et al., 2001, *The relationship between preventive maintenance and manufacturing systems performance*, European Journal of Operations Research, Vol. 132, pp. 146-162.

Hopp, W.J., Spearman, M.L., 2011, *Factory Physics*, Waveland Press.

Iravani, S.M.R., Duenyas, I., 2002, *Integrated maintenance and production control of a deteriorating production system*, IIE Transactions, Vol. 34, pp. 423-435.

Kaufman, D.L., Lewis, M.E., 2007, *Machine maintenance with workload considerations*, Naval Research Logistics, Vol. 54, pp. 750-766.

McKone, K.E., Weiss, E.N., 2002, *Guidelines for implementing predictive maintenance*, Production and Operations Management, Vol. 11, No. 2, pp. 109-124.

Van der Duyn Schouten, F:A, Vanneste, S.G, 1995, *Maintenance optimization of a production system with buffer capacity*, European Journal of Operations Research, Vol. 82, pp. 323-338.

Wang, H., 2002, *A survey of maintenance policies of deteriorating systems*, European Journal of Operations Research, Vol. 139, pp. 469-489.

Wu, X., Ryan, S.M., 2010, *Value of condition monitoring for optimal replacement in the proportional hazards model with continuous degradation*, IIE Transactions, Vol. 42, pp. 553-563.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.