Impact of Preventive Maintenance on the Service Level of Multi-stage Manufacturing Systems with Degrading Machines

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Abstract: In manufacturing systems, preventive maintenance plays a fundamental role in keeping and improving the operational condition of machines and the output product quality. However, preventive maintenance policies affect the available productive time of the system. This directly influences the lot completion time and delivery dates of customer orders. Therefore the choice of preventive maintenance policies needs to be taken by jointly considering the actual condition of machines and the impact of these policies on the service level of the system. This paper proposes an analytical approach for the analysis of the impact of preventive maintenance on the service level of manufacturing systems characterized by degrading machines. The actual degradation state of critical machines is inferred from condition monitoring information gathered by sensor networks. The results obtained from the application of the method to a real industrial case in the aeronautics industry show that the decisions on the optimal maintenance policies depend on both the actual status of machines and the target lot completion time, thus paving the way to new service level oriented maintenance policies.

Keywords: Manufacturing systems, Performance evaluation, Preventive Maintenance, Degradation

1. INTRODUCTION

Multi-stage manufacturing systems consist of processing machines, material handling and other equipment which can gradually deteriorate and are subject to failure during operations. Therefore, manufacturers need to plan and carry out maintenance of critical resources in order to avoid the production in critical degradation states, while ensuring the desired availability of resources Das et al. (2007). Effective maintenance planning is one of the essential activities to achieve high productivity and cost efficiency in advanced manufacturing systems Ni and Jin (2012). Indeed, a robust maintenance and production planning plays a fundamental role in meeting key customer requirements such as production completion dates and product quality. Thus, planning and decision making in complex manufacturing systems shall be supported by advanced manufacturing systems engineering tools.

In the literature, maintenance policies are usually classified into two main groups, namely corrective maintenance(CM) and preventive maintenance (PM). Under the corrective maintenance policy machines are operated until failure. Then, a corrective repair is performed to bring back machines to operational conditions. Preventive maintenance instead consists in investigating the specific degradation behavior of critical machines' components and in stopping the machine and replacing the components before a critical failure occurs. Therefore, PM reduces the time to carry on the maintenance activity at the risk of substituting components with useful residual life and of affecting the availability of resources. Preventive Maintenance policies can be characterized as Time-based or Age-based maintenance (TBM), where maintenance is performed at certain time intervals, or condition-based maintenance (CBM), where maintenance is performed when the state of the machine reaches specific critical or undesired degradation conditions that require a repair Celen and Djurdjanovic (2012). Both the TBM and CBM techniques have their unique principles, procedures, and implications for real industrial practice. In CBM, maintenance decisions are based on the inference on the partially observable machine degradation states, usually supported by condition monitoring (CM) systems. This inference can be based on various process monitoring variables, such as vibration, temperature, power consumption, and acoustic emissions Ahmad and Kamaruddin (2012) or on multi-sensor data fusion. Therefore, a suitable Condition monitoring (CM) system, where signals are continuously gathered using specific sensors and properly analyzed, is an essential part of CBM policies Campos (2009).

In the literature, preventive maintenance policies are usually modeled and optimized at single stage level, thus neglecting their impact on the production logistics performance of the multi-stage system as a whole. However, in

practice, preventive maintenance activities interfere with the operations of machines, thus affecting their productive time and the completion times of the customer orders. This undermines the efficiency of the preventive maintenance policies on the whole system, by prioritizing local improvement actions which might be detrimental at system level Yang et al. (2008). The importance of a joint consideration of preventive maintenance decisions and production logistics performance has been recently stressed in Colledani et al. (2014). In Colledani and Tolio (2012) the authors developed a model of a multi-stage asynchronous serial line where machines are subject to deterioration. While going through deteriorated states, increasing failure rate and decreasing yield are observed. The authors showed that in multi-stage systems, while selecting the optimal maintenance thresholds, the solutions obtained by neglecting the system dynamics are always sub performing in terms of effective production rate and always overestimate the length of maintenance cycles. These recent works are mainly focused on the analysis of the interaction among preventive maintenance policies and first order performance measures of the system, such as the average system throughput and the average work in progress. However, the impact of preventive maintenance policies on the service level of the system on a short term time horizon has never been considered in the past. If properly controlled, preventive maintenance operations can potentially reduce the variance of the output, thus increasing the service level, paving the way to a robust joint maintenance and production planning approach.

The objective of this paper is to propose a method for the analysis of the impact of preventive maintenance on the service level of degrading manufacturing systems, that jointly consider alternative CBM maintenance policies, stopping the machine at different critical stages, and production due-date performance of the system. Insights on this fairly new research area are gathered by numerical results. Moreover, the relevance of the proposed approach is demonstrated on a real Flexible Manufacturing System (FMS) for the production of complex titanium parts in the aeronautic sector. The paper is structured as follows: in Section 2, the modeling assumptions are introduced. In Section 3, the methodology for modeling degrading machines is described. Section 4 presents the analytical method for evaluating the target performance measures of the system. Section 5 presents the real case study results and the system behavior. Conclusion are given in Section 6.

2. SYSTEM MODELING

2.1 Main Modeling Assumptions

Although the proposed methodology can be applied to any manufacturing system topology and number of stages, due to space limitation in this paper the attention will be focused on serial, buffered two-machine systems. The flow of material in the system is modeled as a discrete flow of parts. Each machine M_i, $i = 1, 2$, is characterized by a set of states S_i with dimensionality N_i. The dynamics of each machine in these states is captured in the transition probability matrix T_i that is a N_ixN_i matrix. Moreover, a quantity reward vector μ_i is considered, with dimen-

sionality N_i and binary entries: $\mu_i^j = 1$ if the machine is operational and it processes 1 part per time unit while in state j; $\mu_i^j = 0$ if the machine is down and it does not process parts in state j. The generic state indicator for this system assumes the form $s = (b, \alpha_1, \alpha_2)$, where b is the number of parts in the buffer and α_i assumes values in the set S_i . In total $(B + 1) \times N_1 \times N_2$ states exist. For each machine, the states are partitioned into up states (the machine is operational), denoted as U, and down states (the machine is not operational), denoted as D. Because of such partitioning, the transition probability matrix of M_i, denoted with T_i, can be divided into blocks as follows

$$T_i = \begin{vmatrix} \bar{P}_i & P_i \\ R_i & \bar{R}_i \end{vmatrix} \qquad (1)$$

where, considering machine i, the block $\bar{P}_i$ contains the transition probabilities among the up states, $\bar{R}_i$ among the down states, P_i from up states to the down states (leading to a break down) and R_i from down states to up states (leading to a repair).

We further assume that, in each time slot, the state of the machine is determined at the beginning of the time unit and the buffer content is changed accordingly at the end of the time unit. Operational Dependent Transitions are assumed, i.e. a machine cannot make transitions to other states if it is starved or blocked. The Blocking Before Service (BBS) mechanism is assumed. Therefore, when a buffer is full (empty) its upstream (downstream) machine is blocked (starved) and it can only be in the up state. This means that states $(B-1, D, U)$ and $(1, U, D)$ are transient states. The transition matrix of DTMC associated with the system, denoted with Q, can be built by blocks by using Kronecker products. In order to give an example, we provide Table 1 which describes the upper left corner of the transition matrix. The symbol $\otimes$ denotes the Kronecker product operator which is used in this context to describe the parallel evolution of the two machines. Let us discuss just two blocks of Table 1 in detail. The block that contains the transitions that lead from the states in $(1, D, D)$ to the states in $(0, D, U)$ is given by $\bar{R}_1 \otimes R_2$ because if the first machine remains down (described by $\bar{R}_1$) and the second machine gets repaired (R_2) then the buffer becomes empty. The block that provides the transitions from $(0, D, U)$ to $(1, U, U)$ is given by $R_1 \otimes I$ because in this case the first machine gets repaired (R_1) and the second machine maintains its up state (I) since it is starved.

2.2 Machine Degradation Model with CBM

In this paragraph, the general machine modeling framework introduced in the previous section is used to capture the behavior of unreliable machines going through progressive degradation states. Degradation can be due to the wear of tools, fixtures, or machine components. Degradation is a progressive process that increases the probability of breakdown over time. The state-transition diagram of the Markov model for degrading machines adopted in this paper is represented in Figure 1, where states $l = 1, 2, .., L$ denote the operational states and state CM denotes the breakdown state, where corrective maintenance is required to bring the machine back to its as good as new condition. In practice, these states may correspond to specific physical machine or tool conditions, or they