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Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operating units

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ABSTRACT

For continuous operating units such as petrochemical plants, the production loss due to downtime is high, and the economic profitability is conditioned by the implementation of suitable maintenance policy that could increase the availability and reduce the operating costs. In this paper, a preventive maintenance plan approach is proposed for a multi-component series system subjected to random failures, where the cost rate is minimized under general lifetime distribution. The expected total cost is given by corrective and preventive costs, which are related to the components, and by the common costs related to the whole system, especially the production loss during system shutdown. When the system is down, either correctively or preventively, the opportunity to replace preventively non-failed components is considered. A solution procedure based on Monte Carlo simulations with informative search method is proposed and applied to the optimisation of the component replacement for the hydrogen compressor in an oil refinery.

1. Introduction

For continuous operating units, the production loss is often very large when unexpected shutdown occurs. Their economic profitability implies the implementation of suitable maintenance policy which could increase the availability and reduce the operating costs. To underline the consequences of unavailability, it can be mentioned that production losses in chemical plants can range from \$5000 to \$100,000 per hour (Tan & Kramer, 1997). For refineries, the total production losses soar to millions of dollars (Nahara, 1993). In addition, the safety requirements enforce to decrease the failure probability, on a very low level in order to avoid disastrous consequences.

The preventive maintenance (PM) is often carried out to prevent or to slow down the deterioration processes. PM is a scheduled downtime, usually periodical, in which a well-defined set of tasks (e.g., inspection, replacement, cleaning, lubrication, adjustment and alignment) are performed. In oil refining facilities, the problems associated with part replacement are more concerned than other routine maintenance activities such as cleaning and lubricating, from the PM scheduling point of view. This is because the direct costs due to part failure and replacement are usually very high, and the impact of different replacement intervals on the overall maintenance cost is often very sensitive and significant, in addition to the safety requirements.

In a series system, the one-by-one preventive replacements of components improve the global system reliability on the account of its availability, which would be largely penalized, because of frequent shutdowns for component replacements. For multi-component systems, an optimal maintenance policy must take into account the interactions between the various components of the system. These interactions are of three types (Thomas, 1986): economic dependence, structural dependence and stochastic dependence. We are mainly concerned by the *economic dependence* reflecting the influence of component operation/maintenance costs on the overall system costs; in this case, saving in costs or downtime can be achieved when several components are jointly maintained.

The objective of this paper is to develop a preventive/corrective/opportunistic maintenance plan for a multi-component system subjected to high production losses and economic dependence. In the next section, we review the relevant literature, particularly that dealing with multi-component systems. In Section 3, we provide the cost formulation and the maintenance models in several cases; an algorithm allowing for combined preventive/corrective/opportunistic replacement of the system components is also presented. In Section 4, the proposed approach is illustrated by a simple example with two components, allowing to explain the formulation interest and to verify the convergence of the solution procedure. An industrial application is provided in

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Nomenclature

C_0^c	corrective common cost related to the system, to be paid at each repair upon failure
C_0^p	preventive common cost related to the system, to be paid at each time the system undergoes a preventive maintenance.
C_i^c	specific corrective cost, to be paid at each replacement upon failure of component i
C_i^p	specific corrective cost, to be paid at each preventive replacement of component i
$C_{syst,j}^c$	expected total corrective cost of the whole system due to failure of component j
C_{sys}^p	expected total preventive maintenance cost of the whole system
$C_i(\tau_i)$	cost rate for component i (objective function of the mono-component policy)
$C_{mono}(\tau)$	cost rate for the mono-group policy (objective function)
$C(\tau,k_1,\ldots,k_q)$	cost rate for the opportunistic multi-grouping policy (objective function)
τ	basic preventive maintenance interval ($\tau = \min_{i=1,\ldots,q} \tau_i$)
i	subscripts indicating components, $i = 1, 2, \ldots, q$
k_i	integer multiplier of component i
τ_i	time interval (age) between preventive replacements of component i ($\tau_i = k_i\tau$)
q	number of system components
K	the least common multiple of all k_i
τ_k	kth scheduled time instant where preventive replacements take place, $k = 1, 2, \ldots, K$
τ_i^0	initial optimal replacement time interval of component i
k_i^0	initial Integer multiplying factor of component i
t_i	simulated lifetime of component i
t_j	time instant of failure of component i
t_i	simulated time instant of system failure due to the weakest component
N	total number of simulations
s	subscript indicating the simulation number
$I_{F_{k,s}}, I_{R_{k,s}} \in [0, 1]$	binary variables indicating the states of failure or operation, respectively
G_p	group (set) of components to be preventively replaced at a scheduled time instant
G_h	group of non-failed components to be opportunistically replaced during a failure
G_{p_k}	group of components to be preventively replaced at the kth scheduled time instant
G_{p_h}	group of components to be opportunistically replaced at the kth interval $[(k-1)\tau, k\tau]$
$F_i(\cdot)$	cumulative distribution failure (CDF) of component i
$F_{sys}(\cdot)$	cumulative distribution failure of the whole system
$F_{sys,j}(\cdot)$	cumulative distribution failure of the system due to component j
$R_{sys}(\cdot)$	reliability function of the whole system
MTTF	mean time to failure
β	Weibull shape parameter
η	Weibull scale parameter
H_2	hydrogen
HC	hydrocarbon
LPG	liquefied petrol gas

Section 5, where the results show the effectiveness of the proposed approach for practical systems.

2. Literature review

For multi-component systems, when no strong dependence exists between the different components, the traditional single-unit model developed by Barlow and Hunter (1960) can be independently applied to each unit, in order to provide optimal replacement schedule. However, the general case of multi-component systems implies to take account for the interactions between various components. The economic dependence is common in most continuous operating systems, such as oil refineries, chemical processing facilities, mass-production manufacturing lines and power generators (Das, Lashkari, & Sengupta, 2007; Vassiliadis & Pistikopoulos, 2001). For this type of systems, the single shutdown cost is often much higher than the cost of the components to be replaced. Therefore, there is a great potential for cost savings by implementing suitable maintenance policy. A number of studies have reviewed the various maintenance policies for multi-component systems (Cho & Parlar, 1991; Dekker, Wildeman, & Van Der Duyn Schouten, 1997; Thomas, 1986; Wang, 2002). These reviews show that most of the authors use simplified assumptions, or deal with particular systems (special structure is assumed), in order to formulate the decision problem with less mathematical difficulty. From another point of view, most of the developed decision models are based on dynamic programming or Markovian approaches (Bâckert & Rippin, 1985; Lam & Yeh, 1994), which approximate continuous decision variables by finite discrete state decision variables. These restrictions in both maintenance policies and model formulations could affect the optimality of the solutions because of the reduction of the solution space. In addition, discrete state decision models are often difficult to apply to systems with large number of components and different failure distributions.

The common planning approaches used for multi-component manufacturing systems include the group/block replacement models and the opportunistic maintenance models. In the block maintenance policy, an entire group of units or components are replaced at periodic intervals. The interval is decided based on time, cost or both (Dekker et al., 1997; Kardon & Fredendall, 2002; Tam, Chan, & Price, 2006). Performing maintenance periodically can be a costly option because maintenance activities are carried out even though components are in good condition. The concept of opportunistic maintenance comes from the fact that there is the possibility of dependence between the various components of the system. For example, the cost of simultaneous maintenance actions on various components would be less than the sum of the total cost of individual maintenance actions (Huang & Okogbaa, 1996); this is due to the potential savings in the common cost usually termed "set-up cost" in the literature. This is particularly true in the case of series system, where the failure of any component results in stopping the whole system. Therefore, providing the opportunity to carry out preventive maintenance on some components along with replacement of failed components, leads to very small additional cost, compared to separate replacements. Under these conditions, the maintenance decisions for one component depend on the states (ages) of the other components in the system (Rao & Bhadhury, 2000; Van Der Duyn Schouten & Vanneste, 1990).

Several techniques and approaches dealing with multi-component systems are provided in the specialized literature. Dekker and Roelvink (1995) presented a heuristic replacement criterion which is only useful when a fixed group of components is replaced. Huang and Okogbaa (1996) presented a replacement scheduling approach based on the cost boundary condition; they claim that it is more effective than some of the very sophisticated but improperly formulated "optimal" models. Van Der Duyn