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A multi-level maintenance policy for a multi-component and multifailure mode system with two independent failure modes

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ABSTRACT

This paper studies the maintenance modelling of a multi-component system with two independent failure modes with imperfect prediction signal in the context of a system of systems. Each individual system consists of multiple series components and the failure modes of all the components are divided into two classes due to their consequences: hard failure and soft failure, where the former causes system failure while the later results in inferior performance (production reduction) of system. Besides, the system is monitored and can be alerted by imperfect prediction signal before hard failure.

Based on an illustration example of offshore wind farm, in this paper three maintenance strategies are considered: periodic routine, reactive and opportunistic maintenance. The periodic routine maintenance is scheduled at fixed period for each individual system in the perspective of system of systems. Between two successive routine maintenances, the reactive maintenance is instructed by the imperfect prediction signal according to two criterion proposed in this study for the system components. Due to the high setup cost and practical restraints of implementing maintenance activities, both routine and reactive maintenance can create the opportunities of maintenance for the other components of an individual system. The life cycle of the system and the cost of the proposed maintenance policies are analytically derived. Restrained by the complexity from both the system failure modelling and maintenance strategies, the performances and application scope of the proposed maintenance model are evaluated by numerical simulations.

1. Introduction

In the past several decades, failure models were discussed and studied concentrating on the single component system and single failure mode. However in recent years, due to the complexity of system configurations and the diversity of failure modes of the practical industrial systems, such as wind turbines and aircrafts, multi-component system modelling with multiple failure modes is drawing increasing attention even though it leads to additional difficulties. On the one hand, interactions (such as economic dependency, stochastic dependency, and structural dependency) between components complicate the failure modelling and scheduling of maintenance. On the other hand, the complexity and effectiveness of optimizing procedure including formulations and simulations for such system are extensively more difficult than these of the single component system. Although many maintenance models have been proposed for single-component systems, they cannot be applied directly on multi-component system due to the economic dependency among the components, see in [1,2]. Besides, different failure modes and their effects on the system increase the modelling complexity of system performance as well as the maintenance scheduling. Moreover, it is interesting to notice that condition monitoring information has been gradually taken into account maintenance modelling. For the system whose failure mechanisms are considerably complex, the availability level of condition monitoring information decides which maintenance strategy could be established. In an offshore wind farm, where the wind turbines operate in harsh and unstable environment with low accessibility, the benefits of reliable maintenance strategy with limited available information are worthy to be studied. The introduction section firstly depicts the existing achievement of maintenance models for multi-component systems; secondly, it emphasizes some literature concentrating on the different failure modes with their definition; thirdly, it draws forth

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Nomenclature

Notation

C_{hi}	ith hard component
C_{si}	ith soft component
(α_i, λ_i)	shape parameter and scale parameter of Weibull distribution of component i
δ	*precision*, describing the proximity of the signal to the time of the actual failure
η	*accuracy*, the probability of not detecting potential failure before actual failure
ε	evaluate the closeness between the abnormal signal and the next routine maintenance
τ	time interval of routine maintenance
EC^i_{im}	expected cost for reactive maintenance without delay
EC^i_{wd}	expected cost for reactive maintenance with delay
q_1	age threshold, deciding the functional component that can take the opportunity to be maintained
t_{fi}	component life of hard component i
D_{li}	design life of component i
A_{li}	age of component i
s_i	moment of the abnormal signal of component i
$\xi_i(t)$	age of component i at time t
$f_i(\cdot)$	Weibull pdf
$f_{Si}(\cdot\|t_i)$	conditional pdf of abnormal signal of C_{hi} given the actual failure may occur at t_i
$f_i^{t_f}(\cdot\|s_i)$	conditional pdf of life given abnormal signal occurs at s_i
t_{fi}	lifetime of component $C_{\cdot i}$
$R_i(\cdot\|t)$	survival function of component $C_{\cdot i}$ given it functions at time t
$H_{subs.}$	subsystem consists of the other components exclusive the mentioned component
Y_i	ith replacement cycle of the hard components
$J_i(t) = \lceil \frac{t}{\tau} \rceil$	maximum number of routine maintenance actions experienced by hard component C_{hi} during time interval t
$T_k = \sum_{j=1}^{k} Y_k$	the time of the kth maintenance of the system
$A_{i,j}$	the jth replacement cycle of component C_{hi}
$a_{i,n_i} = \sum_{j=1}^{n_i} A_{i,j}$	the time of the n_ith replacement of component C_{hi}
$N_i(t) = \sum_{j=1}^{\infty} \mathbb{1}_{\{a_{i,j} \le t\}}$	renewal function
$A^P_{i,j}$	for component $C_{\cdot i}$, its jth maintenance is preventive maintenance
$A^C_{i,j}$	for component $C_{\cdot i}$, its jth maintenance is corrective maintenance
$A^O_{i,j}$	for component $C_{\cdot i}$, its jth maintenance is opportunistic maintenance
C^h_{im}	total cost caused by hard components during time interval t
$B_{i,j}$	jth replacement cycle of soft component C_{si}
$N^S(t) = \sum_{j=0}^{\infty} \mathbb{1}_{\{T_j < t\}}$	counting process of the reactive maintenance times
$N^\tau(t) = \sum_{j=0}^{\infty} \mathbb{1}_{\{j\tau < t\}}$	counting process of the routine maintenance times
$b_{i,k} = \sum_{j=1}^{k} B_{i,j}$	time of kth maintenance of soft component C_{si}
$K_i = \lceil \frac{Y_i}{\tau} \rceil$	maximum number of routine maintenances experienced by soft component C_{si} during Y_i
N^t_i	number of soft failures during T_i
$C_{im}{}^s$	total cost caused by soft component during time interval t

the information used for failure modelling and decision making in the existing literature. Then based on the background of the offshore wind farm, we will introduce the practical and theoretical significance of the proposed model.

In [3] the authors presented an overview of the three main groups of maintenance models for multi-component system in the existing literature: the block replacement models, group maintenance models, and opportunistic maintenance; meanwhile they emphasized the potential shortcoming of applying the regular maintenance policies directly on multi-component system, such as the low availability. To avoid these shortcomings, some researchers took maximization availability as decision criteria to optimize the decision parameters. In [4] a multi-component system is maintained by imperfect repair and perfect maintenance for each component. The periodic preventive maintenance intervals are optimized among the components according to the availability criteria by dynamic programming. In [5] the maintenance cost is dependent on the degradation state and the optimal preventive maintenance interval yielding minimal downtime is solved by integer programming. Some other researchers focused on proposing some practical maintenance strategies to maintain the availability at a given threshold. In [6] the authors considered a two-unit series system which can share the setup cost when they both need inspection or replacement. Then to coordinate inspection/replacement the opportunistic maintenance chance and inspection are scheduled separately firstly and then compromised altogether according to a given criteria. In [7] the authors considered a multi-component series system where each component is scheduled to be maintained according to its own period and the opportunistic maintenance is informed according to the expected cost. In [8] the authors studied the opportunistic maintenance of the system which is composed of multiple nonidentical and life-limited components with both economic and structural dependencies and they extended the optimization rule to improve the efficiency of decision-making. In [9] the authors studied a multi-component system with two maintenance actions: imperfect maintenance and replacement, by minimizing total cost and maximizing overall system reliability by metaheuristic solution methods and generational genetic algorithm. In [10] the authors studied the maintenance policies for a multi-component system with failure interactions and scheduled opportunistic maintenance by decomposing the system into mutually influential single-component systems. In [11] the role of opportunistic maintenance for multi-component system is specially pointed out. In [12] the authors studied a multi-component system with economic dependencies by solving a NP-complete dynamic grouping strategy. In [13] the authors considered the system-level and component-level periodic inspection-based maintenance polices and solved theoptimization problem for the component-level policy by the simulation based optimization approach with stochastic approximation. In [14] the authors emphasized the expensive maintenance setup cost and optimized the periodic maintenance by two levels: the component and the overall system according to the independency assumption with the aim of reducing the setup cost.

For a multi-component system, several failure modes can simultaneously affect on the system. Lin et al. introduced the concept of two categories of failure modes: maintainable failure and non-maintainable failure in [15]. They assumed that preventive maintenance (PM) can reduce the hazard rate of the maintainable failure modes but cannot change the hazard rate of the non-maintainable failure modes. The mentioned PM is more