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An effective approach to reducing strategy space for maintenance optimisation of multistate series–parallel systems

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ABSTRACT

Maintenance optimisation of series–parallel systems is a research topic of practical significance. Nevertheless, a cost-effective maintenance strategy is difficult to obtain due to the large strategy space for maintenance optimisation of such systems. The heuristic algorithm is often employed to deal with this problem. However, the solution obtained by the heuristic algorithm is not always the global optimum and the algorithm itself can be very time consuming. An alternative method based on linear programming is thus developed in this paper to overcome such difficulties by reducing strategy space of maintenance optimisation. A theoretical proof is provided in the paper to verify that the proposed method is at least as effective as the existing methods for strategy space reduction. Numerical examples for maintenance optimisation of series–parallel systems having multistate components and considering both economic dependence among components and multiple-level imperfect maintenance are also presented. The simulation results confirm that the proposed method is more effective than the existing methods in removing inappropriate maintenance strategies of multistate series–parallel systems.

1. Introduction

Maintenance optimisation of series–parallel systems is an important research topic and has attracted strong research interest from many pioneering researchers in the last two decades [1–5]. Many practical industrial systems can be regarded as series–parallel systems. A typical example is a production line in a manufacturing factory. A production line can have multiple production phases. Each phase can have several production units organised in parallel to enhance the performance of the system [6,7]. These production units can have multiple performance levels according to their actual degradation states. Therefore, performance of a series–parallel system is a function of the degradation state of its components. Moreover, there are various types of dependence, such as economic dependence, structure dependence, and stochastic dependence, among the components [8]. A system-level maintenance strategy, which is a combination of the component-level maintenance strategies, is thus needed to reduce the component degradation and to enhance the production rate of a system. However, the system-level strategy space of a typical series–parallel system is often large, which poses a problem for system maintenance optimisation. For example, there are more than six million possible combinations of component-level maintenance strategies for the case study described in Ref. [9], even though the system contains only 14 components and has less than five degradation states for each component.

The heuristic algorithm is often employed to find a cost-effective system-level maintenance strategy when the strategy space is large. Huang and Wang [10] used the genetic algorithm to optimise the imperfect maintenance strategy of a multistate system. In their paper, the component degradation process was described by a non-homogeneous continuous-time Markov model. The genetic algorithm was also employed by Liu and Huang [11] to solve the selective maintenance problem of a series–parallel system under imperfect maintenance. Their work [11] was further extended by Pandey et al. [12] who employed a hybrid model to describe the effects of imperfect maintenance. In a later publication, Pandey et al. [13] developed a more complex maintenance optimisation problem by considering multistate components in the system. The differential evolution algorithm was employed in both Refs. [12,13] to solve the maintenance optimisation problem. The genetic algorithm was also employed by Vu et al. [14] in their study of maintenance planning and dynamic grouping problem of complex systems with either positive or negative economic

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Nomenclature

UGF	universal generating function
ACO	ant colony optimisation
N	number of subsystems in the series–parallel system
N_n	number of components in subsystem n
N_{PRO}	number of possible production rate levels of the series–parallel system
$N_{PRO,n}$	number of possible production rate levels of subsystem n
$N_{PRO,\overline{n}}$	number of possible production rate levels of the system excluding subsystem n
$N_n(i, j')$	number of components in state i, when subsystem n is in state j'.
K_n	number of states of components in subsystem n
$\boldsymbol{\theta}$	the parameter vector of the maintenance strategy for the series–parallel system
$\boldsymbol{\theta}_{\mathbf{n}}$	the parameter vector of the maintenance strategy for subsystem n
$\theta_{PR,n}$	the preventive replacement threshold of a component in subsystem n
$\theta_{OP,n,w}$	the threshold of the imperfect opportunistic maintenance that can improve the condition of a component in subsystem n from state i to state $(i-w)$
$\boldsymbol{\theta}_{\overline{\mathbf{n}}}$	the parameter vector of the maintenance strategy for the system excluding subsystem n
$\boldsymbol{\Theta}_{\mathbf{n}}$	the maintenance strategy space of subsystem n
$\boldsymbol{\Theta}_{\overline{\mathbf{n}}}$	the maintenance strategy space of the system excluding subsystem n
$(\boldsymbol{\lambda}_{\mathbf{n}})_{i,j}$	the transition rate of a component in subsystem n from state i to state j
$(\boldsymbol{\mu}_{\mathbf{n}})_{i,j}$	the repair rate of a maintenance activity that restores a component in subsystem n from state i to state j
$(\mathbf{c}_{\mathbf{n}})_{i,j}$	the cost of a maintenance activity that restores a component in subsystem n from state i to state j
$C_{ST,n}$	the setup cost before a series of maintenance activities for subsystem n
$\gamma_{n,i}$	the production rate of a component in subsystem n when the state of the component is i
r_p	reward per unit production rate of the series–parallel system
$\overline{R}$	the average revenue per unit time of the series–parallel system
$\overline{R}_P$	the average production revenue per unit time of the series–parallel system
$\overline{C}_{M,n}$	the average maintenance cost per unit time of subsystem n
$C_n(i, \boldsymbol{\theta}_{\mathbf{n}})$	the cost of the maintenance activity of a component in subsystem n when the state of the component is i and the strategy adopted is $\boldsymbol{\theta}_{\mathbf{n}}$
$(\boldsymbol{\lambda}_{\mathbf{n}}^{\mathbf{S}}(\boldsymbol{\theta}_{\mathbf{n}}))_{i',j'}$	the transition rate of subsystem n from state i' to state j' under maintenance strategy $\boldsymbol{\theta}_{\mathbf{n}}$
$(\boldsymbol{\pi}_{\mathbf{n}}(\boldsymbol{\theta}_{\mathbf{n}}))_{i'}$	the steady-state probability that subsystem n is in state i' under maintenance strategy $\boldsymbol{\theta}_{\mathbf{n}}$
$U_S(z)$	the UGF representing the production rate distribution of the series–parallel system
$u_n(z)$	the UGF representing the production rate distribution of subsystem n
g_v	level v of the production rate of the system
p_v	the probability that the system production rate is g_v
$g_{n,v}$	level v of the production rate of subsystem n
$p_{n,v}$	the probability that the production rate of subsystem n is $g_{n,v}$
$g_{\overline{n},v}$	level v of the production rate of the system excluding subsystem n
$p_{\overline{n},v}$	the probability that the production rate of the system excluding subsystem n is $g_{\overline{n},v}$
$p^*_{\overline{n},v}$	the optimal value of $p_{\overline{n},v}$, which maximises the average system revenue difference under two strategies of subsystem n
$p^{(\max)}_{n,v}$	the upper bound of the production rate distribution of subsystem n in stochastic ordering
$p^{(\min)}_{n,v}$	the lower bound of the production rate distribution of subsystem n in stochastic ordering
$p^{(\max)}_{\overline{n},v}$	the upper bound of the production rate distribution of the system excluding subsystem n in stochastic ordering
$p^{(\min)}_{\overline{n},v}$	the lower bound of the production rate distribution of the system excluding subsystem n in stochastic ordering
$UB_R(\boldsymbol{\theta}_{\mathbf{n}}, \boldsymbol{\theta}'_{\mathbf{n}})$	the upper bound of the average revenue difference when the maintenance strategy of subsystem n changes from $\boldsymbol{\theta}'_{\mathbf{n}}$ to $\boldsymbol{\theta}_{\mathbf{n}}$

The designations of the subscripts used in the terminologies described in the Nomenclature and in the subsequent text are also defined as follows:

i and j	the indices of a component state
i' and j'	the indices of a subsystem state
n and m	the indices of a subsystem
l	the index of a component
v and u	the indices of production rate levels

dependence. Doostparast et al. [15] used the simulated annealing algorithm to identify the optimal maintenance plan to minimise the total maintenance cost with respect to a desired level of system reliability. Rami et al. [16] obtained the optimal sequence of maintenance actions of a series–parallel system using the harmony search optimisation method. The heuristic algorithm has also been employed in several recent papers to deal with more complex maintenance optimisation problems. For example, several recent papers used the heuristic algorithm to optimise the system structure and the maintenance strategy of a multi-state system simultaneously [17–21]. Other works formulated the maintenance optimisation of a multistate system as a multi-objective optimisation problem [22,23]. Additional to the maintenance cost, other factors such as the average product number awaiting processing, system reliability and availability have also been included as objective functions in the above-mentioned papers.

In contrast, a number of recent publications focused on improving the accuracy and efficiency of the heuristic algorithm during maintenance optimisation. For example, Moghaddam and Usher [24] used both the genetic algorithm and the simulated annealing algorithm for maintenance optimisation of a multi-component system. The effectiveness and efficiency of the two algorithms were compared and discussed in their paper. Bris et al. [4] employed the genetic algorithm to optimise the periodic preventive maintenance plan of a series–parallel system. Samrout et al. [5] utilised the ant colony optimisation (ACO) algorithm to further improve the optimisation result obtained in Ref. [4]. Recently, Lin and Wang proposed a hybrid genetic algorithm [25] and an improved particle swarm optimisation [26] to tackle the optimisation problem