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Maintenance optimisation of a parallel-series system with stochastic and economic dependence under limited maintenance capacity

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ABSTRACT

Maintenance optimisation of a parallel-series system considering both stochastic and economic dependence among components as well as limited maintenance capacity is studied in this paper. The maintenance strategies of the components are jointly optimised, and the degradation process of the system is modelled to address the stochastic dependence and limited maintenance capacity issues. To overcome the "curse of dimensionality" problem where the state space of a parallel-series system increases rapidly with the increased number of components in the system, the factored Markov decision process (FMDP) is employed for maintenance optimisation in this work. An improved approximate linear programming (ALP) algorithm is then developed. The selection of the basis functions and the state relevance weights for ALP is also investigated to enhance the performance of the ALP algorithm. Results from the numerical study show that the current approach can handle the decision optimisation problem for multi-component systems of moderate size, and the error of maintenance decision-making induced by the improved ALP is negligible. The outcome from this research provides a useful reference to overcome the "curse of dimensionality" problem during the maintenance optimisation of multi-component systems.

1. Introduction

Parallel-series system configuration is a common feature for various industrial systems. A practical example of such a system is a pump station which contains several pump subsystems working in parallel, with each pump subsystem consisting of a pump and a motor connected in series. The defects of a pump can accelerate the degradation of its driving motor (i.e., the pump and the motor have stochastic dependence). If the pump and the motor in a pump subsystem are repaired simultaneously, the cost of setup and the loss of productivity can be reduced (i.e., the pump and the motor have economic dependence). Attributing to such dependence, a system-level maintenance strategy is normally considered rather than independent maintenance strategies for different components. Another practical issue for the maintenance of multi-component systems is the limitation of maintenance capacity, which also requires a system-level maintenance strategy to appropriately allocate limited maintenance resources to different components. However, when the system-level maintenance strategy is considered, the system state which is the combination of all component states is an essential input to the maintenance optimisation model. It then poses a challenge for maintenance optimisation of multi-component systems due to the cumbersome dimension of the system state space. To address this issue, this research uses the factored Markov decision process (FMDP) to deal with multi-state, inter-dependent components and limited maintenance capacity problems.

Components connected in series in a subsystem are assumed stochastically dependent in this paper. According to the definition by Nicolai and Dekker [1], the stochastic dependence, also termed as failure interaction, refers to the phenomena that the failure of a component can cause the failure (e.g., [2,3]) or the increase of the failure rate (e.g., [4–6]) of other components in the system. Most of the above-mentioned papers about failure interaction focused on systems with binary-state components. For systems with multi-state components, the failure interaction implies that the degradation processes of components relate to each other. The stochastic dependence among multi-state components have only been investigated in few papers. Zhang et al. [7] adopted the Markov decision process (MDP) to optimise the maintenance of a system with multi-state components by considering that the failure of a component can change the state transition probabilities of

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Nomenclature

ALP approximate linear programming
DBN dynamic Bayesian network
FMDP factored Markov decision process
LP linear programming
MDP Markov decision process
RMSE root mean square errors
N_s the number of subsystems
N_a the number of system-level maintenance actions
N_b the number of basis functions
$N_{b,n}$ the number of basis functions about subsystem n
N_t the number of maintenance teams
$S_{un}(S_{dn})$ the number of states of the upstream (downstream) component in subsystem n
$\mathbf{P_{un,i}}(\mathbf{P_{dn,i}})$ the transition matrix of the upstream (downstream) component in subsystem n, when the other component in subsystem n is in state i.
$P_{p,un}(P_{p,dn})$ the probability of successfully conducting the preventive maintenance for the upstream (downstream) component in subsystem n
$P_{c,un}(P_{c,dn})$ the probability of successfully conducting the corrective maintenance for the upstream (downstream) component in subsystem n
$c_{p,un}$ ($c_{p,dn}$) the cost rate of preventive maintenance to the upstream (downstream) component in subsystem n
$c_{c,un}$ ($c_{c,dn}$) the cost rate of corrective maintenance to the upstream (downstream) component in subsystem n
$c_{st,n}$ setup cost per unit time when subsystem n is under maintenance
$X_{un}(X_{dn})$ the state of the upstream (downstream) component in subsystem n
$\mathbf{X_s}$ the vector of the system state
$A_{un}(A_{dn})$ the maintenance action for the upstream (downstream) component of subsystem n
$\mathbf{A_s}$ the vector of the system-level maintenance action
$\boldsymbol{\gamma}_{\mathbf{un}}(\boldsymbol{\gamma}_{\mathbf{dn}})$ the vector of production rates of the upstream (downstream) component in subsystem n under different states
r_d the revenue brought about by one unit production rate of the system

The designations of the subscripts used in the terminologies described in the Nomenclature and in the subsequent text are also defined as follows:
n the indices of subsystems.
i the indices of component states.
i' the indices of subsystem states.
j the indices of basis functions.

other components. Bian and Gebraeel [8] modelled the degradation of a multi-component system by considering that the discrete-time degradation processes of the components are interdependent. They further extended their research in ref. [9] by using a continuous-time Markovian model to describe the interdependent degradation of components. Most recently, Liang and Parlikad [10] studied the condition-based maintenance problem of a system with load sharing interacted multistate components. Aggregation methods were used in their study to mitigate the state space explosion problem by combining similar system states.

The constraint of limited maintenance capacity considered in this paper has been investigated by several researchers. Marseguerra et al. [11] optimised the condition-based maintenance strategy of a complex system with multi-state components. In their work, the flexibility of the Monte Carlo approach was used to consider the limitation of maintenance technicians. Smidt-Destombes et al. [12] investigated the influence of spares, maintenance capacities, and maintenance strategies on the availability of a k-out-of-n system. Martorell et al. [13] treated the maintenance optimisation as a multi-objective optimisation problem. Both the availability and cost were used in the objective function, and human resource was regarded as a variable to be optimised. Pascual et al. [14] optimised both the mobile equipment fleet size and maintenance capacity using an improved closed network queueing model approach. While the above-mentioned studies focused on the problems incurred by the restricted maintenance capacity, some other studies investigated the allocation of maintenance capacity to different components. Do et al. [15] studied the influence of economic dependence, constraint of availability and the limited number of repairmen on the grouping maintenance strategy of a system. Fan et al. [16] optimised the maintenance of a repairable system with two dependent failure modes. The total maintenance capacity for the two failure modes were limited, and the effects of maintenance were related to the maintenance capacity spent. An important category of research about allocating the limited maintenance capacity is the selective maintenance proposed originally by Rice et al. [17]. The selective maintenance happens when the maintenance can only be performed between two consecutive missions with limited resources. These maintenance resources should be allocated to maximise the reliability during the next mission. Liu and Huang [18] studied the selective maintenance of a multi-state system with binary-state components. The imperfect maintenance of the system was modelled using the Kijima model. The study in Ref. [18] was extended by Pandey et al. [19] using a hybrid model to describe the effects of imperfect maintenance. Pandey et al. [20] further improved their own model [19] by assuming that the system contains multi-state components. Most recently, Dao et al. [21] introduced the economic dependence into the selective maintenance. The selective maintenance considered in these studies have successfully addressed the allocation of maintenance resources to different components. However, the horizon of optimisation considered in these works was limited to the period of next mission, which limits the capability for long-term maintenance planning. To address this issue, the infinite horizon is considered in this paper.

Most of the research work cited so far either assumed that components are binary-state and identical or the number of components is small. The reason of such assumptions is that the state space of a system with non-identical multi-state components can be extremely large, which is difficult to process using the commonly employed Markovian analysis approach. To overcome this difficulty, the FMDP is employed in this study for maintenance optimisation of a parallel-series system consisting of a moderate number of non-identical multi-state components. The FMDP, originally proposed by Boutilier et al. [22] in 1990s is an effective approach to representing an exponentially large MDP compactly according to the structural properties of the MDP. In this research, the structure of the MDP for the maintenance decision-making of a parallel-series system has two significant properties: (1) the state transition of a component only directly depends on the state of the other component in the same subsystem; (2) the system reward function of the MDP is the sum of rewards about different subsystems. In this paper, the two properties are termed as the transition independence and reward additivity, respectively. In