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Optimal design of a multi-state system with uncertainty in supplier selection

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ABSTRACT

This paper formulates a bi-objective two-stage stochastic programming model simultaneously for two conditions including a joint modular redundancy allocation, and an imperfect opportunistic maintenance optimization of a multi-state weighted k-out-of-n system. Although categorizing system elements based on cost and reliability characteristics is addressed by literature, this paper categorizes system elements considering the uncertain behavior of suppliers. Further more in this paper a condition based maintenance method is developed considering economic dependence and fixed inspection intervals. The objective is to determine jointly (1) an optimal system structure, (2) an imperfect opportunistic maintenance strategy, and (3) inspection intervals. This proposed approach not only is capable of minimizing the system life cycle cost, but also it addresses maximizing system availability. A three-phase simulation procedure is used to evaluate the performance terms of the studied system for several scenarios. To illustrate the proposed approach an optimal design of a wind farm is also provided. Sensitivity analysis is also investigated in this paper. To obtain Pareto optimal solutions, a multi-objective version of ant colony optimization is used.

1. Introduction

Optimizing the structural redundancy is a key step for the performance of a repairable system. The common form of redundancy which has been addressed by literature is weighted k-out-of-n system. In general, literature of k-out-of-n system structure may be classified into three main branches: (1) redundancy optimization, (2) maintenance optimization, and (3) Joint redundancy and maintenance optimization.

Most of the existing papers on the redundancy optimization problem of repairable k-out-of-n systems such as Amari and Pham (2007), Boddu and Xing (2013), Kulturel-Konak, Smith, and Coit (2003), and Xie et al. (2014) used the traditional binary-state assumption. However, in many practical cases, a k-out-of-n system may include of elements which have more than two levels of performance. So that the level varies from perfect functioning to complete failure.

Some authors such as Khatab, Nahas, and Nourelfath (2009), Moghaddass, Zuo, and Wang (2011), Ruiz-Castro and Li (2011), and Yuan (2012) focused on a k-out-of-n system performance with a limited number of repair persons. Although component selection problem is an important issue in an optimal design, few researchers including Boddu and Xing (2013), Atashgar and Abdollahzadeh (2016), and Kulturel-Konak et al. (2003) have contributed to the optimal component selection problem for k-out-of-n systems. In these studies, the components are categorized based on known reliability and cost characteristics. On the other hand, Qi, Zhang, Zuo, and Yang (2014) and Ushakumari and Krishnamoorthy (2004) proposed maintenance policies based on the number of failed components and fixed time intervals. These studies assumed that there are perfect maintenance actions. In practice, however, a repair effort allows usually a component departure to an intermediate condition. The new condition of the component is worse than a new one but it is better than just before the failure (Huang & Wang, 2014; Liu, Xu, Xie, & Kuo, 2014). To overcome the weakness Pham and Wang (2000), Ding and Tian (2011), Ding and Tian (2012), and Abdollahzadeh, Atashgar, and Abbasi (2016) introduced opportunistic maintenance policies considering imperfect maintenance actions.

All resources mentioned above have not considered health condition monitoring data. Liu, Huang, Wang, Li, and Yang (2013), Nourelfath, Châtelet, and Nahas (2012), and Tian, Jin, Wu, and Ding (2011) introduced condition based maintenance policies considering components health state thresholds and continuous monitoring of a system component. Furthermore literature addresses that some researchers such as Chen, Ye, and Xie

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(2013), de Smidt-Destombes et al. (2004, 2006, 2009), Atashgar and Abdollahzadeh (2016), Levitin and Lisnianski (1999), Liu et al. (2013), Moghaddass, Zuo, and Pandey (2012), Nourelfath et al. (2012), and Xiao and Peng (2014) have provided their researches based on joint redundancy and maintenance optimization. Table 1 shows the summarized information of our literature review and addresses along with the opportunities that are provided in this research.

In this paper, the trade-off between multi-state weighted k-out-of-n system redundancy and maintenance strategy is analyzed simultaneously using a multi-objective stochastic optimization model. In this proposed model, each subsystem is categorized based on initial cost, component failure/repair characteristics, performance rate, and also uncertain behavior of supplier. To the best of our knowledge, this is the first time that the uncertain behavior of component suppliers is addressed. The two objective function of the proposed model are maximization of the multi-state weighted k-out-of-n system expected availability, and minimization of the expected system life cycle cost. Furthermore, an imperfect opportunistic maintenance approach with periodic inspection of the components health state is developed considering the limited number of maintenance teams. To find the optimal solution of the proposed optimization model, a multi-objective version of ant colony optimization algorithm is also approached.

This paper is organized as follows: Section 2 describes the features of the considered multi-state weighted k-out-of-n system. The maintenance strategy and the proposed performance evaluation method are introduced in Sections 3 and 4, respectively. Section 5 presents our developed multi-objective stochastic optimization model. In Section 6, an ant colony optimization algorithm is developed. An application of the model for an optimal design of a wind farm is analyzed in Section 7. A sensitivity analysis is also reported in this section. Finally, Section 8 is allocated to our conclusion and remarks.

2. System description

In this study, a weighted k-out-of-n system is considered which constitute from several different types of subsystems. Different from existing approaches that consider binary or multi-state elements, our approach considers multi-state subsystems composed of several multi-state components. Fig. 1 shows the general structure of the considered multi-state k-out-of-n system. This figure indicates that for each subsystem type i ($i = 1, 2, \ldots, k$), there exist x_i subsystems connected in parallel; furthermore this figures addresses that each subsystem contains N main components connected in series.

It is assumed that the j^{th} ($j = 1, 2, \ldots, N$) component of each subsystem type has m_j different health states, where state 1 represents the perfect functioning state and state m_j reflects the completely failure state. Fig. 2 shows the degradation process of a component. In this figure, $g_{j,d}$ denotes the efficiency level of the j^{th} component of each subsystem type working at state D ($D = 1, 2, \ldots, m_j$). It is set from the best efficiency rate i.e. $g_{j,1} = 1$ to the last acceptable one i.e. g_{j,m_j-1} ($g_{j,1} \geqslant g_{j,2} \geqslant \ldots \geqslant g_{j,m_j-1}$). The component efficiency rate is zero when its state is addressed by m_j (i.e. $g_{j,m_j} = 0$).

A subsystem may be also considered as a multi-state based on its component state. Several different structure functions are used in literature to show the production rate of a system composed of multi-state components. In this paper, the production rate of a subsystem ($GSB(t)$) at any time ($t \geqslant 0$) is defined as a function of the minimum efficiency level of its components and subsystem nominal production rate:

$$GSB_i(t) = NPR_i * \underset{j \in \{1,2,\ldots,N\}}{arcmin} (G_j(t)) \tag{1}$$

where NPR_i and $G_j(t)$ indicate the nominal production rate of the i^{th} subsystem type and the efficiency rate of the j^{th} component, respectively. To satisfy the minimum required demand, the overall

Table 1
Classification of the k-out-of-n system optimization literature.

Source	Component state		Repair capacity			Repair type			System inspection	
	Binary	Multi	One	Limited	Infinite	Minimal	Imperfect	Perfect	Continuous	Intermittent
Kulturel-Konak et al. (2003)	●				●			●	–	–
Amari and Pham (2007)	●				●			●	–	–
Boddu and Xing (2013)	●				●			●	–	–
Xie, Liao, and Jin (2014)	●				●			●	–	–
Khatab et al. (2009)	●			●				●	–	–
Yuan (2012)	●			●				●	–	–
Moghaddass et al. (2011)	●		●					●	–	–
Ruiz-Castro and Li (2011)		●		●				●	–	–
Pham and Wang (2000)	●		●			●		●	–	–
Ushakumari and Krishnamoorthy (2004)	●		●					●	–	–
Qi et al. (2014)	●				●			●	–	–
Ding and Tian (2011), Ding and Tian (2012)	●				●	●	●	●	–	–
Abdollahzadeh et al. (2016)	●			●		●	●	●	–	–
Tian et al. (2011)	●				●			●	●	–
Levitin and Lisnianski (1999)	●				●			●	–	–
de Smidt-Destombes, van der Heijden, and van Harten (2004)		●		●				●	–	–
de Smidt-Destombes, van der Heijden, and Van Harten (2006)		●		●				●	–	–
de Smidt-Destombes, van der Heijden, and van Harten (2009)	●			●				●	–	–
Moghaddass et al. (2012)	●			●				●	–	–
Nourelfath et al. (2012)		●			●	●	●	●	●	–
Liu et al. (2013)		●			●	●	●	●	●	–
Chen et al. (2013)	●				●			●	–	–
Xiao and Peng (2014)		●			●	●		●	–	–
Atashgar and Abdollahzadeh (2016)	●		●	●		●	●	●	–	–
Present study		●	●	●		●	●	●		●