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Minimisation of Non-periodic Preventive Maintenance Cost in Series-parallel Systems

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ABSTRACT

A new method to optimise the non-periodic preventive maintenance model of a series-parallel system is proposed. A two-stage algorithm that incorporates the failure limit policy to determine maintenance components, maintenance times, and total maintenance cost is suggested. When the reliability of the system reaches a threshold value, preventive maintenance is performed. The first stage identifies the parallel sub-system required to be maintained, while the second stage determines the component required to be maintained in the parallel sub-system. A unit-cost life index (UCL) has been developed to evaluate the extent to which maintaining a component extends the life of a system for the parallel subsystem. Three simulated cases demonstrate the effectiveness and the practicality of the proposed method in optimising the non-periodic preventive maintenance model of a series-parallel system.

Keywords: Reliability, preventive maintenance, failure limit policy, importance measure.

1. INTRODUCTION

All equipment deteriorates with usage and progression in age. Preventive maintenance must be performed on a repairable series-parallel system to reduce failure rates and to improve reliability. The quality of maintenance is typically categorised into five classes: perfect maintenance, minimal maintenance, imperfect maintenance, worse maintenance, and worst maintenance according to degree of equipment restoration[1]. Furthermore, to satisfy practical requirements, various studies have constructed maintenance models and optimisation algorithms. However, most studies, such as those of Leou[2], Bris[3], *et al.*, and Samrout[4], *et al.*, concern periodic preventive maintenance models; non-periodic preventive maintenance policies for multi-component systems have been least studied. Since series-parallel systems with multiple components exhibit structural and economic dependencies, the failure of any component reduces the reliability of the system and affects the subsequent maintenance plan of the multi-component system. Accordingly, the optimisation of a maintenance model for a repairable series-parallel system must consider its intrinsic properties, including the structure of the reliability block diagrams, the maintenance priority of the sub-systems and their components, and the maintenance time points.

The importance measures of components are normally used for identifying design weaknesses, and evaluating the impact on proper functioning of a system in the case of the component failure. For example, Birnbaum's importance measure, criticality importance measure, Fussell-Vesely's importance measure, improvement potential and ratio-criterion are commonly used in practice[5,6]. These measures can also be employed in evaluating the extent to which maintaining a component can improve the system reliability. However, these measures[5,6] are based on a specific time, rather than on the entire lifetime of the system, and some limitations or drawbacks are responsible in evaluating the effect of components on system reliability in the parallel system. These disadvantages lead to inaccurately evaluate the contribution to the system in maintaining a component.

This study addresses primarily the non-periodic preventive maintenance model of a series-parallel system with perfect maintenance of each component, and proposes a novel optimisation algorithm. A unit-cost life (UCL) index, that takes into account the extent to which maintenance of a component extends the lifetime of parallel sub-systems, is developed to evaluate the importance of maintaining the components. The developed UCL index simultaneously considers the cost of maintenance and the reliability of parallel sub-systems using a continuous time horizon. Accordingly, a two-stage algorithm for optimising the non-periodic preventive maintenance model is proposed. The total maintenance cost is thus determined for the non-periodic maintenance model of a series-parallel system. Three simulated cases demonstrate the effectiveness and practicality of the proposed method in optimising the non-periodic preventive maintenance model.

2. LITERATURE

2.1 Optimisation of Maintenance Models

Maintenance is defined as the activities that retain or restore the operation status of a system. Normally, maintenance is classified as corrective or preventive[7]. Corrective

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maintenance includes minimal repairs and corrective replacement when a system fails. Preventive maintenance includes simple preventive maintenance and preventive replacement when a system is in operation. The maintenance policies of a repairable deteriorating system are: (i) age-dependent preventive maintenance policy, (ii) periodic preventive maintenance policy, (iii) failure limit policy, (iv) sequential preventive maintenance policy, (v) repair limit policy, and (vi) repair number counting and reference time policy[8]. Periodic preventive maintenance is widely used in practice simply because of its ease of implementation and management. This maintenance policy, applied in a series-parallel system with multiple components, received much attention. Tsai[9], *et al.* developed a periodic preventive maintenance schedule for a system with deteriorating electro-mechanical components and optimised it using a genetic algorithm (GA). Leou[2] proposed a novel algorithm for determining a maintenance schedule for a power plant. This algorithm combines the GA with simulated annealing to optimise maintenance periods and minimise maintenance and operational costs. Tsai[10], *et al.* also proposed a preventive maintenance policy for a multi-component system. Maintenance activities for components at each stage of preventive maintenance are determined by maximising the availability of the system for maintenance. Busacca[11], *et al.* focused on a high-pressure injection system at a nuclear power plant to establish a multi-objective optimisation model to obtain a maintenance strategy using GA. Bris[3], *et al.* proposed a periodic preventive maintenance model that minimises maintenance costs under the reliability constraint. The optimal maintenance period of each component after the first maintenance task for that component was determined using GA. Samrout[4], *et al.* optimised the Bris[3] case using the same procedure, but the ant colony algorithm was adopted to optimise the maintenance periods for all the components.

For a deteriorating system, non-periodic preventive maintenance policies more effectively improve the system status than does periodic preventive maintenance because the maintenance intervals of a deteriorating system are varied, rather than being fixed. Such a policy is more likely to yield superior solutions than the periodic preventive maintenance policy, despite its inconvenient implementation and management. However, the varied maintenance intervals increase the complexity in solving the non-periodic preventive maintenance model. Few studies on optimising the non-periodic preventive maintenance model of a series-parallel system have been published. Non-periodic preventive maintenance is performed when the failure rate or reliability indices of a unit reach a predetermined level for the failure policy.

Bergman[12] pioneered the failure limit policy in which replacement policies are governed by some state variables such as wear, accumulated stress or accumulated damage. When the variables reach their threshold values, preventive maintenance is performed. The proposed optimality criterion is the minimisation of the average long-run maintenance cost. Malik[13] proposed a policy in which preventive maintenance is performed when the reliability index reaches a threshold. The optimality criterion is the maximisation of the reliability value. Canfield[14] proposed a policy in which preventive maintenance is performed when the failure rate reaches a threshold. The optimality criterion is the minimisation of maintenance cost. Jayabalan and Chaudhuri[15] proposed a policy in which preventive maintenance is performed when the failure rate reaches a threshold. The optimality criterion is the minimisation of total maintenance cost. Jayabalan and Chaudhuri[16] proposed another policy in which preventive maintenance is performed when the age reaches a threshold. The optimality criterion is the minimisation of total maintenance cost. Deodatis[17], *et al.* proposed a Bayesian analysis methodology to determine non-periodic inspection intervals of fatigue-sensitive aircraft structures. The cited studies of non-periodic preventive maintenance policies either concentrate on single-unit systems or treat multiple components as a single-unit system, to determine an optimal maintenance policy. Few studies on non-periodic preventive maintenance have addressed series-parallel systems with multiple components. Castanier[18], *et al.* proposed a condition-based maintenance policy with non-periodic inspections of a two-unit series system. The maintenance decision–to inspect, to perform preventive replacement or to perform corrective replacement–is made separately for each component and opportunistic replacement is performed based on multi-threshold values, to minimise total maintenance cost. The settings of the multi-threshold values for each component increase the optimising complexity, particularly when the system contains a large number of components.

2.2 Importance Measures

The importance measures can be taken for identifying design weaknesses, and evaluating the impact on proper functioning of a system in the case of the component failure. In general, most of the importance measures are based on specific time to evaluate the impact on system reliability at which whether the component is functioning properly or not. The main importance measures include the Birnbaum's importance measure[5,6], Fussell-Vesely's importance measure[5,6], criticality importance measure[5,6], improvement potential[6] and ratio-criterion[3]. These measures hold some limitations or drawbacks in evaluating the effect of components on system reliability in the parallel system. The criticality importance measures and Fussell-Vesely's importance measures yield value of 1 for evaluating the effect of each component on the parallel system. Similarly, the values of improvement potential of components are the same for identifying the effect of each component on a parallel system. Therefore, these three measures are inappropriate to determine the components importance in a parallel system.

Although Birnbaum's importance measure can discriminate the importance of components in a parallel system, this measure is based on the viewpoint of reliability to determine the importance of component at a specific time, rather than on time period. The limitation leads to inappropriately evaluate the extent to which maintaining components benefit the series-parallel system. The ratio-criterion is resulted from Birnbaum's measure, and the maintenance cost is considered. Hence, its property is similar to Birnbaum's measure when the maintenance cost among the components does not vary to large extent. In summary, the already developed importance measures of components can be further improved to extend their utilities.

3. PROPOSED APPROACH

This study proposes a method for series-parallel system that efficiently optimises the non-periodic preventive maintenance model by applying a failure limit policy, in which preventive maintenance is performed when the reliability of the system reaches a threshold value (which is the allowable worst reliability value). The optimality criterion is the minimisation of total maintenance cost.

3.1 Construction of Non-periodic Preventive Maintenance Model

The maintenance cost model is based on the work of Bris[3], *et al.*, as follows:

$$\text{Minimise} \quad C_{PM} = \sum_{k=1}^{K}\sum_{i=1}^{E_K}\sum_{j=1}^{n_{e(i,k)}} C_j(e(i,k)) \tag{1}$$

$$\text{Subject to} \quad R_S(t) \geq R_0 \tag{2}$$

$$R_S(t) = \prod_{k=1}^{K}[1-\prod_{i=1}^{E_K}(1-R_i(t))] \tag{3}$$

where

C_{PM} is total maintenance cost;
$e(i,k)$ is the i^{th} component of the k^{th} parallel sub-system;
$n_{e(i,k)}$ is the total number of instances of maintenance of the i^{th} component of the k^{th} parallel sub-system;
$C_{j(e(i,k))}$ is the cost of the j^{th} instance of maintenance of the i^{th} component in the k^{th} parallel sub-system;
E_K is the number of components in the given k^{th} parallel sub-system;
K is the number of parallel sub-systems;
R_0 represents the allowable worst reliability value, and
$R_S(t)$ is the reliability of the system at time t.

3.2 Proposed Method

The proposed method is a two stage method.

Stage 1: Identify the parallel sub-system required to be maintained. This Stage consists of two steps:

Step 1: Determine maintenance time using Eqn (2) and (3), calculate the first time when the reliability of the system reaches the threshold value, given no maintenance and calculate the subsequent times when the reliability of the system reaches the threshold value, given maintenance of some components. These times are the times of maintenance of the system.

Step 2: Identify the maintained parallel sub-system. Given the time obtained in Step 1, calculate the unreliability values of all parallel sub-systems to identify the maintained sub-system. A larger unreliability value corresponds to a higher probability of failure of the sub-system, which causes the failure of the system. Therefore, the sub-system with the highest unreliability value is determined to be the maintained sub-system. The unreliability value is defined as follows.

$$F(t) = 1 - R(t) = \int_0^t f(u)du \tag{4}$$

where $F(t)$ is the cumulative distribution function; $R(t)$ is the reliability function, and $f(u)$ is the probability density function.

Stage 2: Identify component required to be maintained in parallel sub-system.

A UCL index is developed to evaluate the importance of components of parallel systems based on the entire lifetime of the system. This index quantifies the extent to which the maintenance of a component extends the life of a parallel sub-system per unit cost. The component with the highest UCL index value is identified as the component required to be maintained in a parallel sub-system. The developed UCL index is defined as follows:

$$UCL(i_{t_k}) = \int_{t_k}^{\infty} \frac{\left(\begin{array}{l} 1-\prod_{i=i_{t_1}}^{i_{t_k}}(1-r_i(t-t_k))\times \\ \prod_{j=1, j\neq i_{t_1}, i_{t_2}, \ldots, i_{t_k}}^{n}(1-r_j(t)) \end{array}\right)}{C_{i_{t_k}}} dt; \; 1 \leq i \leq n \tag{5}$$

where

t_k is the k^{th} maintenance time, $1 \leq k \leq m$, and t_m is less than the mission duration of the system;
i_{t_k} is the component maintained at t_k;
$C_{i_{t_k}}$ is the corresponding maintenance cost;
$UCL(i_{t_k})$ is the UCL index value of component i at time t_k;
$r_j(t-t_k)$ is the reliability function of component i at time t_k;
j are the components that are not maintained;
$r_j(t)$ is the reliability function of component j, and
n is the number of components in the system.

Repeating the above two stages for the duration of the mission yields the maintenance policy, including the maintained components and their maintenance times. The total maintenance cost is thus determined for the non-periodic maintenance model of a series-parallel system.

4. EFFICIENT VERIFICATION OF THE PROPOSED METHOD BY SIMULATED CASES

This work demonstrates the efficiency of the proposed method by simulating three series-parallel reliability systems comprising 15 components, compared with the periodic preventive maintenance model optimised by conventional GA. Each component was labeled with integers ranging from 1-15. Figures 1-3 present the simulated series-parallel structures. The first simulated structure consists of six parallel sub-systems; the second consists of four parallel sub-systems, and the third consists of 12 sub-systems. Obviously, the first two structures mainly characterise the parallel sub-systems where the numbers of components in each parallel sub-system in the second structure exceed those in the first structure. However, the third structure mainly characterises the series systems in which multiple-single components are serially connected. The parameters of each component in simulated cases were determined through random permutation of components which have Weibull distribution failure rates and maintenance costs. Table 1 lists the parameters of 15 components labeled alphabetically from A-O. This study first produced three permutations of components in a different alphabetical order. The obtained permutations were then matched with the components labeled by the integers in three simulated reliability structures to determine the parameters of all 15 components. Accordingly, three simulated cases were constructed. Table 2 lists the match results of the three simulated cases. Furthermore, the allowable worst system reliability was 0.9 and the mission duration was 50 months for both the first and the second simulated cases. Due to considering the series structure of the third simulated case, the system reliability was normally lower than that

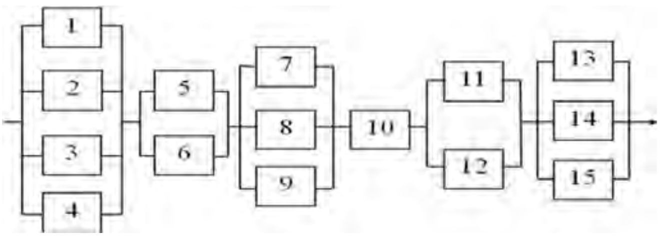

Figure 1. Reliability block diagram of the first simulated case.

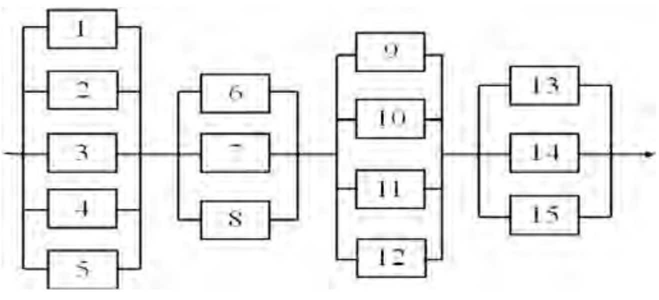

Figure 2. Reliability block diagram of the second simulated case.

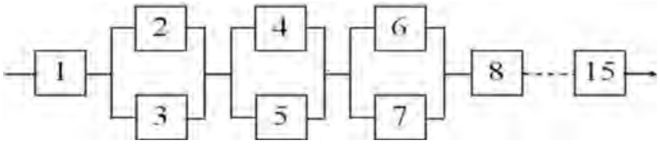

Figure 3. Reliability block diagram of the third simulated case.

of the parallel system, the allowable worst system reliability was set to 0.6 and the mission duration was 25 months.

Via the proposed method, the three simulated cases were optimised. To better understand the analytical procedure, this study presents the optimisation process of the first case in a stage-by-stage manner as follows.

First, Eqns (2) and (3) yield the first maintenance time, 9.1, that satisfies the constraint of allowable worst reliability, given no component maintenance. Secondly, Eqn. (4) yields the unreliability value of the six sub-systems at time 9.1. The calculated values for sub-systems 1, 2, 3, 4, 5 and 6 were 0.0000, 0.0002, 0.0010, 0.0718, 0.0283 and 0.0000, respectively. Since the fourth sub-system had the largest unreliability value, this sub-system was identified as the maintained sub-system. Furthermore, the fourth sub-system comprises only component 10, component 10 was therefore the maintained component. Subsequently, the second maintenance time was determined to be 13.85 when component 10 was maintained. The unreliability values for the six sub-systems 1, 2, 3, 4, 5 and 6 were 0.0001, 0.0010, 0.0061, 0.0201, 0.0744, and 0.0001, respectively, at that time, 13.85. As the fifth sub-system had the largest unreliability value, this sub-system was identified as the maintained sub-system. Equation (5) yields UCL index values of 7.7080 and 7.7936 for components 11 and 12 of the fifth sub-system. Since component 12 had the highest UCL index value, this component was identified as the maintained component. Repeating the above procedure, including determining the maintenance time, the maintained parallel sub-system, and the maintained component, throughout the 50 months of the mission, yields the maintenance policy of this case. Table 3 presents these calculations. The obtained maintenance policy involves 18 instances of maintenance during the mission duration of 50 months. The total maintenance cost was 110. Figure 4 shows the reliability curve. All reliability values exceed 0.9, satisfying the constraint of allowable worst reliability.

To demonstrate the proposed method that outperforms

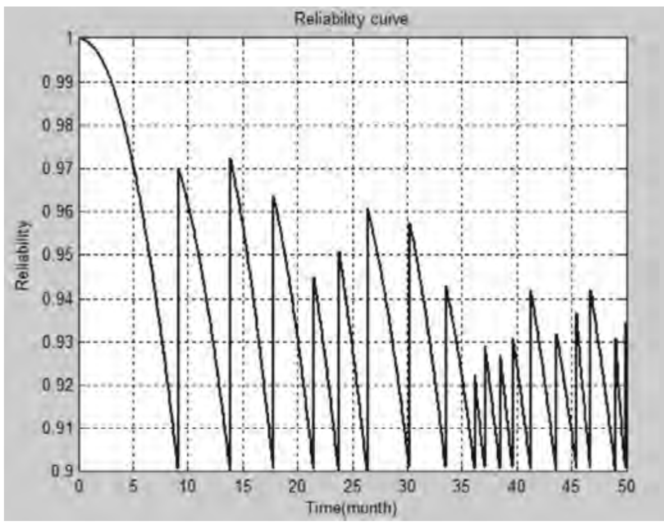

Figure 4. Reliability curve.

Table 1. Component parameters

Component	Probability Distribution	Parameter	MTTF (month)	Maintenance cost
A	Weibull	$\beta = 3,\ \eta=0.01$	89.3	15
B	Weibull	$\beta = 3,\ \eta=0.02$	44.65	10
C	Weibull	$\beta = 3,\ \eta=0.03$	29.77	5
D	Weibull	$\beta = 2,\ \eta=0.01$	88.62	15
E	Weibull	$\beta = 2,\ \eta=0.02$	44.31	10
F	Weibull	$\beta = 2,\ \eta=0.03$	29.54	5
G	Weibull	$\beta = 1.5,\ \eta=0.01$	90.27	15
H	Weibull	$\beta = 1.5,\ \eta=0.02$	45.14	10
I	Weibull	$\beta = 1.5,\ \eta=0.03$	30.09	5
J	Weibull	$\beta = 1.1,\ \eta=0.01$	96.49	15
K	Weibull	$\beta = 1.1,\ \eta=0.02$	48.25	10
L	Weibull	$\beta = 1.1,\ \eta=0.03$	32.16	5
M	Weibull	$\beta = 0.5,\ \eta=0.01$	200	15
N	Weibull	$\beta = 0.5,\ \eta=0.02$	100	10
O	Weibull	$\beta = 0.5,\ \eta=0.03$	66.67	5

Table 2. The component parameters of three simulated cases

Components	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
First case	H	O	B	J	G	D	C	K	N	F	L	I	E	M	A
Second case	O	I	E	K	N	J	G	M	L	C	D	F	A	B	H
Third case	I	F	J	L	O	K	N	G	A	D	M	H	E	C	B

Table 3. Maintenance time and maintained component of the first simulated case

Maintenance order	Maintenance time	Unreliability values of subsystems						Maintained subsystem	Highest UCL value	Maintained component
		1	2	3	4	5	6			
1	9.10	0.000	0.000	0.001	**0.072**	0.028	0.000	4		10
2	13.85	0.000	0.001	0.006	0.020	**0.074**	0.000	5	7.79	12
3	17.80	0.001	0.002	0.017	**0.066**	0.016	0.000	4		10
4	21.45	0.002	0.004	0.037	0.012	**0.047**	0.001	5	8.16	11
….	…..	….	…	….	…	….	…..	….	…	….
15	45.45	**0.043**	0.001	0.001	0.030	0.003	0.025	1	22.19	2
16	46.70	0.021	0.002	0.002	**0.044**	0.006	0.028	4		10
17	49.00	**0.039**	0.003	0.005	0.005	0.017	0.035	1	21.78	2
18	49.90	0.022	0.004	0.007	0.009	0.023	**0.037**	6	15.13	15
19	51.20									

Table 4. Maintenance periods of the first simulated case using conventional GA

Number of components	1	2	3	4	5	6	7	8	9	10	11	12	14
Maintenance periods	34	13	31	36	30	39	19	27	36	8	15	13	17

Table 5. Maintenance time and maintained components of the second simulated case

Maintenance order	Maintenance time	Unreliability values of sub-systems				Maintained sub-system	Highest UCL value	Maintained component
		1	2	3	4			
1	34.60	**0.044**	0.022	0.032	0.005	1	29.08	1
2	37.25	0.022	0.027	**0.047**	0.008	3	13.19	9
3	41.20	**0.044**	0.035	0.010	0.015	1	29.01	2
4	45.40	0.004	**0.044**	0.028	0.027	2	16.40	8
5	47.90	0.009	0.015	**0.042**	0.037	3	12.38	12
6	51.45							

Table 6. Maintenance periods of the second simulated case using conventional GA

Number of components	2	4	5	7	8	9	10	11	14
Maintenance periods	21	34	21	29	37	26	33	37	32

Table 7. Maintenance time and maintained component of the third simulated case

Maintenance order	Maintenance Time	Unreliability values of sub-systems									Maintained subsystem	The highest UCL value	Maintained component
		1	2	3	…	8	9	10	11	12			
1	6.30	0.08	0.00	0.05	…	**0.22**	0.04	0.02	0.01	0.00	8		11
2	8.00	0.11	0.00	0.07	…	**0.12**	0.06	0.03	0.01	0.00	8		11
3	8.65	**0.12**	0.00	0.08	…	0.08	0.07	0.03	0.02	0.01	1		1
4	9.85	0.01	0.01	0.10	…	**0.13**	0.08	0.04	0.03	0.01	8		11
5	10.55	0.01	0.01	**0.11**	…	0.08	0.09	0.04	0.03	0.01	3	15.90	4
…	…	…	…	…	…	…	…	…	…	…	…	…	…
22	21.90	0.06	0.06	**0.07**	…	0.06	0.00	0.02	0.01	0.08	3	16.45	4
23	22.45	0.07	0.06	0.00	…	**0.10**	0.01	0.02	0.01	0.08	8		11
24	22.85	0.08	0.07	0.01	…	0.06	0.01	0.03	0.01	**0.09**	12		15
25	23.60	0.09	0.07	0.01	…	**0.10**	0.01	0.03	0.01	0.00	8		11
26	24.05	**0.10**	0.08	0.02	…	0.07	0.02	0.03	0.02	0.00	1		1
27	25.00												

Table 8. Maintenance periods of the third simulated case using conventional GA

Number of components	1	2	3	4	5	6	7	10	11	12	13	14	15
Maintenance periods	7	9	13	10	19	16	15	9	4	2	7	8	9

the conventional GA which is widely used to optimise the periodic preventive maintenance model, the simulated cases were optimised by conventional GA. Appling the GA to solve the first simulated model can obtain the optimised maintenance periods of components and the corresponding total maintenance cost of 200. Table 4 lists the maintenance periods of components for the first simulated case. The other two simulated cases were thus optimised using the same optimisation procedure as in the first simulated case. For the second case, the optimal total maintenance cost in non-periodic preventive maintenance using the proposed method, and the optimal total maintenance cost in periodic preventive maintenance using conventional GA were 35, and 105, respectively. Table 5 lists these calculations for the proposed method. Table 6 lists the maintenance periods of components for conventional GA. For the third case, the optimal total maintenance costs using the proposed method and conventional GA were 295, and 380, respectively. Table 7 lists the calculations for proposed method. Table 8 lists the maintenance periods of components using conventional GA. Finally, Table 9 summarises the optimal total maintenance costs for the three cases using the proposed method and conventional GA. From the Table 9,

Table 9. Comparison of optimal total maintenance cost

Simulated cases	Proposed method	Conventional GA
The first case	110	200
The second case	35	105
The third case	295	380

the authors conclude the following:

1. The optimisation results of the proposed method outperform those of conventional GA.
2. Although the proposed method efficiently optimises three simulated cases of the non-periodic preventive maintenance model in comparison with conventional GA, the consistent results can also be extended to the simulated cases consisting of different types of series-parallel system configurations with various failure probability distributions of components.

5. CONCLUSIONS

The non-periodic preventive maintenance policy for the series-parallel systems has received less attention. This study addresses the non-periodic preventive maintenance model of the series-parallel systems, and proposes a new method to optimise it. The maintenance policy has thus been determined. A unit-cost life index has been developed to evaluate the extent to which maintaining a component extends the life of a parallel system. This index can more appropriately evaluate the effect of the components on the reliability of the parallel system than that of past importance measure of components. Although three simulated systems with different configurations comprising 15 components have demonstrated the efficacy of the proposed new method, the proposed method still has room for improvement in solving a large-scale model with complex series-parallel systems that comprise numerous sub-systems or components in future study.

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