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Grouping-Maintenance of Multi-Components Production System Under Ecological Background

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Abstract:

Purpose: The purpose of this paper is to propose an opportunistic group maintenance model for a multi-component series system considering reducing CO_2 emission and increasing system efficiency, which establishes a maintenance policy to minimize the cost rate of the system life cycle.

Design/methodology/approach: Structural dependence and economic dependence between the components in a multi-component series system are analyzed to make a condition-based maintenance policy. To minimize the cost rate of the system life cycle, clustering theory and two decision variables, which include the preventive maintenance cycle multiplier and basic preventive maintenance interval of each component, is utilized to make an opportunistic policy for system optimal maintenance under the background of increasing energy efficiency and reducing CO_2 emissions.

Findings: It can be concluded that the government imposes fines on excessive CO_2 emissions and energy consumption indicators, which can influence the maintenance decisions of enterprises, promote enterprises to shorten the cycle of preventive maintenance, and avoid excessive CO_2 emissions of various components and exceed the indicators as much as possible, so as to enable enterprises to actively save energy, reduce emissions and control carbon emissions. Furthermore, when the single preparation cost of repair maintenance increases, enterprises need to shorten the maintenance period to avoid frequent component failures. As the cost of a single prep for preventive maintenance rises, organizations need to extend maintenance cycles and avoid frequent parts downtime - minimizing their own repair costs.

Practical implications: Considering the high maintenance cost and low energy efficiency of multi-component systems, this model assists production managers to have better maintenance of these systems.

Originality/value: 1.Model innovation: comprehensive consideration of two variables in the selection of decision variables for preventive maintenance or opportunistic maintenance; The selection and synthesis of ecological factors when making ecologically conscious maintenance decisions for multi-component systems make up for the gaps of single variables and one-sided indicators in previous studies and models. 2. Methodological innovation: In the identification of opportunity maintenance, the idea of clustering is first combined; In the simulation analysis, genetic algorithm is used to obtain the optimal parameters quickly and accurately. A blend of management, statistics, biology and computer science.

Keywords: multi-component system, opportunistic maintenance, carbon dioxide emission, energy efficient index, intelligence

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1. Introduction

Generally, the breakdown of components in a series system could cause enormous costs such as system failure, some of which even bring about high potential danger. For example, a sudden failure of an aircraft could endanger the safety of working staff and has a negative impact on the surrounding environment (Hamdan, Tavangar & Asadi, 2021). In order to avoid or delay the potential failure or breakdown, the research about condition-based maintenance (CBM) has gained increasing attention in the past years. CBM refers to a maintenance strategy that checks the real-time condition of equipment to support maintenance decisions to take action on maintenance and repair (Al-Najjar, 2007). Compared with planned maintenance, CBM may prevent inadequate and unnecessary maintenance. Currently, most complex multi-component systems are equipped with monitors to collect real-time data about electric flow, voltage sensors, tachometers, etc. (Lee, Wu, Zhao, Ghaffari, Liao & Siegel, 2014). Despite the structural variety of multi-component systems in practice, the dependence between components exists, which could have an impact on the utility and efficiency of the whole system. Therefore, increasing research on CBM focuses on complex system structure and the dependence between the components in the system. A number of studies have identified three types of dependence between components in a complex system: economic dependence, structural dependence, and stochastic dependence (Dekker, Wildeman & Schouten, 1997; Nicolai & Dekker, 2006; Thomas, 1986). We mainly examine structural dependence and economic dependence.

The development of modern industrialization and the rapid increase in population deteriorates energy consumption and CO_2 emissions. However, most previous studies on the maintenance policy of a series system focus on the cost optimization of maintenance practice but ignore the negative impact of a system on the environment due to maintenance delay. Excessive maintenance, lack of maintenance, or unexpected breakdowns can all contribute to increases in the carbon footprint. Excessive maintenance can add up to a large carbon output due to the energy and resource-intensive processes involved in manufacturing replacement parts (Ziegler, Winther, Hognes, Emanuelsson, Sund & Ellingsen, 2013). On the other hand, both breakdowns caused by lack of maintenance and unexpected breakdowns have the potential to lead to emergency transportation of parts, further increasing carbon emissions (Ferreira, Silva, de Brito, Dias & Flores-Colen, 2021). In recent years, traditional maintenance policies have failed to meet the global high-standard requirements on ecological protection. Instead, there is a growing importance of new maintenance policies considering increasing energy efficiency and reducing the emissions of waste gas, wastewater, and other waste material (Chouikhi, Dellagi & Rezg, 2012; Tlili, Radhoui & Chelbi, 2015). Specifically, an increasing number of researchers develop new maintenance policies which could improve energy efficiency in production, reduce the environmental pollution of production, enhancing the competitiveness of enterprises subjected to environmental regulations. For example, Anh, Phuc and Iung (2015) and Mora, Vera, Rocamora and Abadia (2013) point out that environmental factors could influence the CBM adopted by managers. Vassiliadis and Pistikopoulos (2000) propose an optimal maintenance framework to quantify the balance between production revenue, repair costs, and environmental risk.

The purpose of this paper is to propose a maintenance framework for a multi-component series system with two variables of preventive maintenance cycle multiplier and basic preventive maintenance interval of each component, which is applied to develop a maintenance policy for this system considering the impact of energy efficiency and emission reduction. This policy is based on the instantaneous failure rate of components and energy efficiency indicators. Clustering theory is utilized to make opportunistic maintenance for component groups. National and industrial regulations for CO_2 emissions and energy efficiency indicators are considered to integrate environmental protection and maintenance practices. In the next section we review the relevant literature, especially the previous research on multi-component series systems. Section 3 illustrates the cost calculation and the maintenance models in several cases. Section 4 provides an example of industrial application, which proves the effectiveness of the proposed maintenance policy.

2. Literature Review

Traditional multi-component maintenance policies include preventive maintenance (PM) which occurs when the system is still working, and maintenance after system breakdown or failure detection (Patton, 2004; Thomas, Levrat, Iung & Cocheteux, 2009). For maintenance after fault diagnose, Breakdown maintenance is the repair of faulty items as quickly as possible by replacing parts without in-depth analysis of the root cause (Sellitto, 2022). Compared to preventive maintenance with many unnecessary interventions, BM to some extent can save the cost. There are two kinds of preventive maintenance strategies: planned maintenance and CBM (Baraldi, Compare & Zio, 2013; British Standards Institution, 2017). Planned maintenance is scheduled routinely to maintain the system regularly. The most frequent one is the maintenance of aging machines (Liu, Dong & Chen, 2018). However, its weakness is the lack of adaption to the specific working environment of the equipment. For example, maintenance staff might take insufficient maintenance to the potential failure of equipment, which could lead to some serious consequences such as system failure or downtime, or they might perform excess maintenance to equipment. CBM mainly includes real-time condition monitoring of the system, online alarm system, and periodic inspection (Alaswad & Xiang, 2017). CBM could plan and perform inspection and maintenance activities at a certain time interval to adapt to the specific condition of equipment (Ingemarsdotter, Kambanou, Jamsin, Sakao & Balkenende, 2021). Proportional-hazards models, Wiener process, Gamma process, inverse Gaussian process, and other stochastic processes (Lawless & Crowder, 2004; Peng, 2015; Wei, Zhao, He & He, 2019; Zheng, Chen & Gu, 2020) are usually applied in CBM to simulate the degree of system degradation or system inefficiency. Update cycle theory and Markov chains are commonly applied in CBM models to determine the continuous state and discrete state of components; commonly used decision variables include fixed inspection interval, unfixed inspection interval, maintenance threshold, etc (Jiang, 2010, 2013; Liang, Liu, Xie & Parlikad, 2020). Compared to planned maintenance, CBM could largely solve insufficient maintenance and excess maintenance (de Jonge, Teunter & Tinga, 2017). In addition, Tlili et al. (2015) discuss the impact of two different inspection methods, fixed inspection interval, and unfixed inspection interval, on CBM. The discussion shows that unfixed interval can more effectively alleviate maintenance costs and environmental pollution.

Generally, structural dependence of a multi-component series system is static. In a series system, each component is indispensable to the system's performance. Early studies mainly discussed the concept that the failure of one component leads to the replacement of other components because of structural dependence (Van Horenbeek & Pintelon, 2013). Camci (2009) also discusses the failure of some components causes the breakdown of other components. Recent studies tend to assume some systems are more dependent on their physical structure. In such systems, some components in normal condition are unable to work because of the failure of other components (Nguyen, Phuc & Grall, 2015). System structure has a significant impact on the design of CBM policy. Specifically, it has a duel effect on developing optimal maintenance strategies. One effect is the failure of a single component results in high system breakdown costs, which could be avoided by preventive maintenance activity. The other effect is the structural dependence of a series system requires the whole system to stop working when one component is being maintained. This also provides opportunistic maintenance for other components. Xia, Xi, Zhou and Lee (2013) state that opportunistic maintenance could allow a maintenance portfolio for all components in a certain period once one component is in need of maintenance.

The structural dependence between components should be analyzed to decide appropriate maintenance policy. Economic dependence influences maintenance cost, which means that a combined maintenance portfolio for multiple components could be more expensive or have a lower cost compared with the maintenance of a single component. When the combined maintenance portfolio of multiple components causes a higher cost than the independent maintenance of each component, the system is subjected to negative economic dependence. For example, additional maintenance staff or equipment is needed to maintain multiple components simultaneously in a company. Another example of negative economic dependence is some maintenance staff operate maintenance in a limited space, which could lead to congestion and increase maintenance errors. However, few studies discuss negative economic dependence on CBM. Positive economic dependence usually occurs in the following industries with high maintenance costs such as an offshore windmill which requires maintenance staff to maintain the component on site, or oil refineries whose systems need to be closed when the components are being maintained or repaired. This dependence is modeled as set-up costs, which are paid for every maintenance, irrelevant to the number of components (Laggoune, Chateauneuf & Aissani, 2009). However, when a system is composed of multiple subsystems or components, it includes system set-up costs, subsystem set-up costs, and component set-up costs (Tian & Liao, 2011; Wijnmalen & Hontelez, 1997).

As improving energy efficiency is becoming a major concern in the world, many researchers have explored extensively the relationship between production efficiency and environmental issues. Suppen, Onosato and Iwata (1999) analyze the model of system reliability to propose a maintenance policy to meet ISO14000 requirement, which aims to protect staff safety and health, and alleviate the detrimental impact on the production process. Chouikhi et al. (2012) point out that governments around the world are making stricter regulations to encourage green energies and environmental protection due to global environmental degradation. For example, high-carbon emitting manufacturers possibly face financial penalties and limited access to the market. However, most traditional maintenance policies tend to ignore it. Thus, it is very possible that the system has achieved the penalty threshold ahead of the planned schedule. To avoid such high penalty costs, they propose a CBM policy based on mathematical probability theory. This maintenance policy considers environmental issues comprehensively, and assumes a system undergoes two moments: from a perfect state to the state that the amount of CO_2 emissions is above the preventive maintenance threshold, then to the system breakdown. These two-time variables conform to a joint probability density function, which could distinguish the system states. Based on the system states, maintenance staff acquires the probability of PM, BM, and the inspection in a system, thereby getting the cost rate of the system replacement cycle. Based on the research of Chouikhi et al. (2012), Tlili et al. (2015) discuss the penalty costs when CO_2 emissions exceed the target set by governments. They set the emissions limitation requirement as a system preventive threshold, which could assist factories to avoid the penalty caused by excess carbon emissions. Meanwhile, Tlili et al. (2015) suggest that this kind of penalty cost should be taken as a cost function in the system replacement cycle, thereby acquiring a more realistic total cost.

This paper develops a maintenance decision model based on multi-grouping optimization, which may provide assistance to maintenance managers to make preventive maintenance for a series system. This model considers PM, BM and OM strategies simultaneously and could address a series system with a great quantity of components. It defines the cost objective function for maintenance tasks (PM, BM and OM) in the whole system. The structural and economic dependence of components in a system are considered in modeling the maintenance policy. Based on defining the optimal maintenance groups, the particle swamp algorithm searches for the minimal PM cycle multiplier and basic preventive maintenance interval of each component under the background of increasing energy efficiency and reducing carbon emissions.

3. Formulation of the Maintenance Models

3.1. Model Assumption

For the maintenance models, it is assumed as following:

1. Instantaneous failure rate of components in a system of long-term operation of industrial machinery complies to independent two-parameter Weibull distribution; all components are in the wear stage (shape factor >1).
2. Energy consumption amount of each component complies to Wiener process; energy consumption level is independent from instantaneous failure rate.
3. Let τ be the basic preventive maintenance interval. The preventive maintenance cycle for each component is an integer multiple of τ. Accordingly, the maintenance cycle for th component is $\tau_i = k_i\tau$, $k_i \in N^*$, $i = 1, 2, \ldots, q$, let k_i be the preventive maintenance cycle multiple for the i th component.

4. All maintenance tasks make the system to the “as good as new” state; the maintenance time is negligible.
5. Breakdown maintenance is only used for failed components.
6. All costs relevant to maintenance are set as average costs, which are assumed to be a constant. Let $K\tau$ be the system life cycle, where $K = lcm\{k_1, k_2, \ldots, k_q\}$.
7. The penalty-related cost of excess CO_2 emissions is based on legal regulation on emission limitation.
8. The penalties for excess energy consumption will be decided after the completion of system life cycle, which is based on energy consumption of the whole cycle.

3.2. Model Formulation

Laggoune et al. (2009) assume that instantaneous failure rate of each component in the system complies to independent Weibull distribution. Probability density function of instantaneous failure rate of each component is given by the following Equation (1):

$$f_i\left(t;\eta_i,\beta_i\right)=\frac{\beta_i}{\eta_i}\left(\frac{t}{\eta_i}\right)^{\beta_i-1}e^{-\left(t/\eta_i\right)^{\beta_i}},t>0,,i=1,2,\ldots,q \quad (1)$$

Where, t is the time, and for each component i, β_i is the shape parameter defining the failure rate over time, and η_i is the scale parameter defining the time scale.

Accordingly, with the same variables in Equation (1), the cumulative distribution function of each component $F_i(t)$ is given by the following Equation (2):

$$F_i\left(t\right)=1-e^{-\left(t/\eta_i\right)^{\beta_i}},t>0,i=1,2,\ldots,q \quad (2)$$

The cumulative distribution function of the whole system instantaneous failure rate F_{sys} is given by the following Equation (3):

$$F_{sys}\left(t\right)=1-e^{-\left(t/\eta\right)^{\beta}},t>0 \quad (3)$$

where, n is the total number of components in the system.

Assuming energy consumption amount of each component complies to Wiener process, it is given by the following Equation (4):

$$E_i\left(t\right)=\lambda_i t+\sigma_i W\left(t\right),t>0,i=1,2,\ldots,q \quad (4)$$

where, for each component i, $E_i(t)$ is the energy consumption at time t, λ_i is the drift rate of the process and σ_i is the volatility of the process in the standard Brownian motion $W(t)$.

It is worth noticed that, the assumption that all devices are in the wear phase (shape factor > 1) is based on the actual use of the devices in our research dataset. The equipment we analyzed is mainly long-run industrial machinery that has typically experienced sufficient operating time to enter the wear phase of its life. At this stage, the failure rate of the equipment increases due to the continuous wear and aging of the parts, which is consistent with the two-parameter Weibull distribution used in our model, which well describes the growth of the failure rate over time. If the device is in the infant death phase (form factor > 1), our model will need to be adjusted to reflect this different failure rate characteristic. During the infant death phase, the failure rate of the equipment decreases over time, usually due to manufacturing defects or initial operational adjustments. If such devices need to be included in the analysis, three-parameter Weibull model is more suitable which needs to be discussed for the further researches.

3.2.1. System Description

We discuss a multi-component series system. The whole system breakdown occurs with high set-up cost if any component fails. When breakdown maintenance is taken for the failed component, opportunistic maintenance gives staff opportunities to y maintain preventively other components. According to the assumption 4, the amount of CO_2 emissions is proportionate to energy consumption, which is given by the following Equation (5):

$$Q_{CO_2} = \mu Q_E\left(K\tau\right) = \mu\sum_{i=1}^{q} E_i\left(K\tau\right) \tag{5}$$

Where μ is the coefficient of CO_2 emissions and energy consumption, $Q_E(K\tau)$ is the energy consumption quantity of the whole system until the time τ.

3.2.2. Maintenance Policy Description

Initially, maintenance schedule is created for each component in the whole system (see Figure 1). Preventive maintenance tasks are performed based on a planned date for all components. Meanwhile, only when a failed component leads to the system breakdown, breakdown maintenance tasks are performed and opportunistic maintenance applies. Based on the OM principle, some components are selected for preventive maintenance,

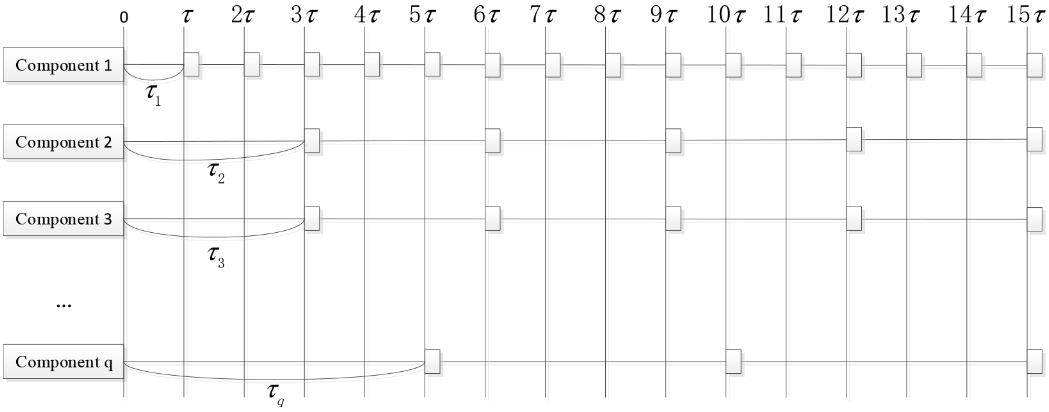

Figure 1. Scheduled preventive maintenance cycle.

From Figure 1, we can see that the life cycle of this system is 15 τ. Specifically, the PM cycle of component 1 is 1 τ; the PM cycles for both of component 2 and 3 are 3 τ; PM cycle for component q is 5 τ. It means that if none of components is subjected to failure, 15 PMs are performed for component 1 during the whole life cycle, 5 PMs tasks for component 2 and 3, 3 PMs for component q.

3.2.3. Costs Structure

The system life cycle costs can be divided into two parts: maintenance costs and penalty costs.

3.2.3.1. Maintenance costs

The first part in maintenance costs, which is constant, is relevant to common system maintenance costs, including allocating maintenance staff, safety facilities, disassembling machine, transportation, equipment and the time costs in these maintenance and repair tasks.

The common system maintenance cost could be defined as "set-up-cost", which includes BM set-up-cost (noted C_0^B) and PM set-up-cost (noted C_0^P). It is considered hat C_0^B costs more than C_0^P because of two reasons. On the one hand, the emergency character of the corrective intervention is emergent, for which optimal tools and procedures are not available, so the maintenance staff is limited to use available tools and the procedures are quick but expensive. On the other hand, PM can be prepared ahead of time, and it could be performed when production loss penalty is decreased.

The second part in maintenance costs, which is variable, is relevant to the specific features of the maintained component, including replacement part costs, specific equipment, labor costs and maintenance procedures. In addition, it is relevant to production loss when the component is selected and repaired.

It is noted C_i^B for the BM costs of the i_{th} component and C_i^P for the PM costs of the i_{th} component. It is considered that C_i^B cost more than C_i^P, because the PM costs include only the replacement part and the labor costs.

When a maintenance task is carried out, the total system maintenance cost consists of the two parts described above. The system maintenance cost of planned PM is given by the following Equation (6):

$$C_{sys}^P = \sum_{k=1}^{K}\left[\left(C_0^P + \sum_{i\in G_{P,k}} C_i^P\right)\left(1 - F_{sys}\left(k\tau\right)\right)\right] \tag{6}$$

Where, $G_{P,k}$ is group of components to be preventively replaced at the kth scheduled time instant: $i\,|\,k/k_i = Integer$, $i = 1, q$; $k = 1,k$.

Breakdown maintenance is performed when the failure of the jth component leads to the breakdown of the system, and the failed component is replaced; meanwhile, predefined opportunistic maintenance policy is applied to select and maintain other components preventively, which will be illustrated later. In such a situation, BM cost of the whole system life cycle is noted $C_{sys}{}^B$, which is given by the following Equation (7):

$$C_{sys}^B = \sum_{k=1}^{K}\sum_{j=1}^{q} F_j(k\tau)\left(C_0^B + C_j^B + \left(\sum_{i\in G_{h,k}, i\neq j} C_i^P\right)\right)\left(\prod_{i\in G_{h,k}, i\neq j}\left(1 - F_i(k\tau)\right)\right) \tag{7}$$

Where $G_{h,k}$ refers to the group of components selected and maintained preventively according to opportunistic maintenance policy when jth component fails before $k\tau$.

3.2.3.2. Penalty Costs

Penalty costs include two parts: penalty costs due to excess CO_2 emissions (which is noted C_{CO_2}) and penalty costs due to excess energy consumption (which is noted C_E). The calculation of these two costs requires the quantity of energy consumption, which is estimated by the following Equation (8):

$$Q_E\left(t\right) = \sum_{i=1}^{q} E_i\left(\left\lceil \frac{t}{k_i\tau} \right\rceil \tau\right) \tag{8}$$

In China, energy indicator is defined as the quantity of energy consumption per unit production, which is given by the following Equation (9):

$$EI\left(t\right) = \frac{Q_E\left(t\right)}{lt} \tag{9}$$

Where l is defined as the production efficiency of the whole system.

Carbon dioxide penalty costs are calculated on the basis of the number of excess emissions, which is given by the following Equation (10):

$$C_{CO_2} = f_{CO_2}\left(Q_{CO_2} - Q_{GOV}\right)^+ \tag{10}$$

Where f_{CO_2} is the penalty cost of excess carbon dioxide emissions per unit, Q_{GOV} is the carbon dioxide emission allowance set by governments. The penalty shall be charged in excess of the emissions allowance.

Penalty costs due to excess energy consumption occur at the end of system life cycle. Penalty is charged based on the average energy consumption of the whole cycle, which is given by the following Equation (11):

$$C_E = I_E C_E^0, I_E = \begin{cases} 1, EI(K\tau) \geq EI_{GOV} \\ 0, EI(K\tau) < EI_{GOV} \end{cases} \tag{11}$$

Where EI_{GOV} is the energy consumption indicator set by governments, and I_E is an indicator function to decide whether the energy consumption of the system exceeds energy consumption limit set by governments at the end of whole system life cycle. A factory is subjected to a heavy penalty if the energy consumption limit is exceeded.

To conclude, the cost rate of the whole system life cycle is given by the following Equation (12):

$$E[C(\tau, k_1, k_2, \ldots, k_q)] = \frac{C_{sys}^B + C_{sys}^P + C_{co_2} + C_E}{K_\tau} \tag{12}$$

3.2.4. Opportunistic Multi-Grouping Decision

Because of the multi-component series structure, an opportunistic maintenance (OM) is applied to preventively maintain other non-failed components when the failure of one component leads to breakdown of a system. Maintenance staff take the opportunity to maintain preventively some components scheduled to undergo PM during next basic preventive maintenance interval, or replace preventively some components which are in need of replacement in the immediate future. Integrated with replacing the failed component when some certain value is reached, OM drives production efficiency, reduces the downtime frequency of the system, and saves the average set-up cost per one single BM. Hence, the maintenance cost of the whole system is decreased. Figure 2 illustrates an OM example.

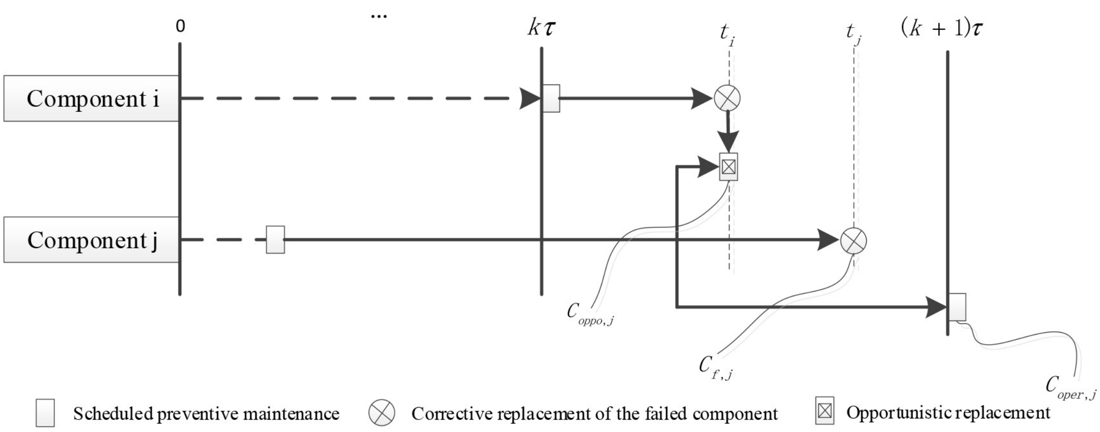

Figure 2. Opportunistic maintenance example

Figure 2 shows that when component *i* fails at the time t_i, component *j* is scheduled to undergo PM during the next basic preventive maintenance interval. Two options of maintenance policy are to be selected: one option is to preventively maintain component *j* when the failed component *i* is repaired. BM is on component *i*, and PM is on component *j*. The maintenance cost of component *j* is given by the following Equation (13):

$$C_{oppo,j} = C_j^P \left(1\text{-}F_j(t_i)\right) \tag{13}$$

The other option is that BM performs only on failed component *i*. Meanwhile, no maintenance activity performs on component *j*, which is scheduled to reach its next maintenance cycle in the immediate future, leading to two possibilities. The first possibility: component *j* works normally before the next scheduled maintenance cycle, whose cost during this period is given by the following Equation (14):

$$C_{oper,j} = \left(1 - F_j\left(\left\lceil \frac{t_i}{k_j \tau} \right\rceil \tau\right)\right)\left[\left(C_0^P + C_j^P + \mu f_{CO_2}\left(E_j\left(t_j\right) - E_j\left(t_i\right)\right)\right)\right] \tag{14}$$

The second possibility: component *j* fails before the next scheduled maintenance cycle, causing system breakdown. Assuming component *j* fails at the time t_j, its cost during this period is given by the following Equation (15):

$$C_{f,j} = F_j(t_j)\left\{C_0^B + C_j^B + \mu f_{co_2}\left(E_j(t_j) - E_j(t_i)\right)\right\} \tag{15}$$

The choice between the two options depends on the economic dependence under three conditions: when $C_{oppo,j} \leq C_{oper,j} + C_{f,j}$, opportunity is taken to maintain preventively component *j* when BM performs on component *i*. Otherwise, no maintenance activity performs for component *j*.

Opportunistic multi-grouping decision goes through three following steps:

Step 1: when the failure of component i at the time t_i leads to the system breakdown, the group of components scheduled to undergo PM during the next basic preventive maintenance interval is located, which is given by the following Equation (16):

$$G_{P,ti} = \left\{ j \,|kj\,| \left\lceil \frac{t_i}{\tau} \right\rceil, t_i > 0, \tau \in N^* \right\} \tag{16}$$

The reason is that PM is scheduled on this group of components in the immediate future. Based on economic dependence, earlier PM could effectively avoid the system breakdown and save the set-up cost of the whole system due to BM.

Step 2: Instantaneous failure rate and energy consumption indicator of other components are inspected, normalized, and categorized into different groups. The group of components with the largest average instantaneous failure rate and the group of components with the worst energy consumption indicator are acquired. The union of these two groups and G_{P,t_i} in step 1 are the potential opportunist multi-component group $G'_{h,k} = G_{P,t_i} \cup G_{EI,t_i} \cup G_{F,t_i}$.

Step 3: Based on economic dependence, opportunistic multi-component group $G_{h,k}$ is obtained finally.

3.2.5. Maintenance Policy Process

To conclude, Figure 3 shows the intelligent opportunistic multi-component group maintenance model for a series system considering reducing carbon emission and increasing energy efficiency.

Figure 3 shows the 6 steps in this process:

Step 1: Initialize the life of each component and input maintenance policy;

Step 2: Follow the guideline for maintenance cycle set by equipment manufacturers to develop an initial PM schedule;

Step 3: Determine the state of the component before scheduled PM time;

Step 4: Perform BM on the failed component if its failure leads to the system breakdown, and inspect other components to determine opportunistic maintenance which performs if necessary;

Step 5: Perform initial PM schedule performs if failure is not observed;

Step 6: Determine the completion of the system life cycle. If it is not completed, repeat step 3-5 until its completion; if it is completed, repeat step 1-5 until the minimal cost rate of the life cycle is obtained.

This is the detailed description of the cost rate of the system life cycle. Next section the simulation will be applied to acquire optimal scheduled PM maintenance cycle of each component and provide optimal condition-based maintenance policy. Meanwhile, sensitive analysis will examine the penalties for excess CO_2 dioxide emissions, the penalties for excess energy consumption, the setup cost of each time PM, and the setup cost of each time BM.

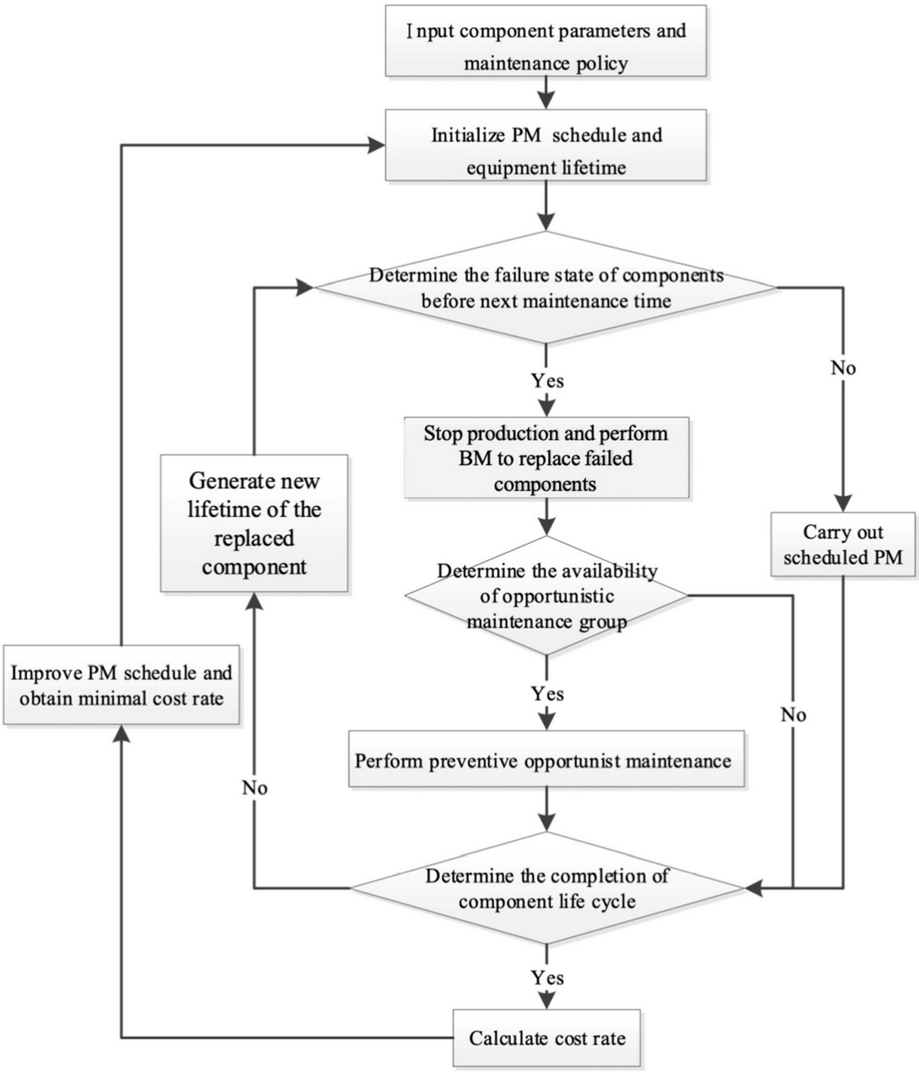

Figure 3. Map for maintenance policy process

4. Simulation And Sensitivity Analysis

4.1. Case Study

In this research, we apply the proposed maintenance model to the centrifugal compressor in the catalytic reforming unit of Skikda refinery. This factory is located in Algeria as the most important oil refinery in this country, and the first units, with the production capacity of 15 million tons per year, began to work in 1980. Basically, the multiple staging compressor consists of the stator and the rotor. This case study is based on early research (Laggoune et al., 2009), which publicly disclosed its data and set the parameters for our research.

Table 1 and 2 (Laggoune et al., 2009) shows the eight essential components in a refinery, which are examined by a simulation analysis. The parameters for these eight components are given by:

Component	Code	Shape parameter (β)	Scale parameter (η)	MTBF days
Sheathing	C286	1.73	486	483
Sheathing	C285	1.88	507	475
Tightness	C275	2.43	286	240
Stub bearing	C230	2.53	898	787
Tightness ring	C460	2.14	905	844
Carrying bearing	C419	3.55	736	636
Stub bearing	C401	2.68	1094	888
Labyrinth support	C780	2.09	1388	1047

Table 1. Failure data and Weibull parameters of the system components

Component	Code	Corrective cost (€)	Preventive cost (€)	Cost ratio corrective/preventive
Common costs		36,000	1,200	30
Sheathing	C286	14,868	3,639	4.1
Sheathing	C285	39,204	5,438	7.2
Tightness	C275	44,880	7,398	6.1
Stub bearing	C230	57,876	8,277	7.0
Tightness ring	C460	73,860	13,554	5.4
Carrying bearing	C419	46,752	14,130	3.3
Stub bearing	C401	48,568	21,356	2.3
Labyrinth support	C780	74,232	24,348	3.1

Table 2. Common costs and maintenance costs

The system production efficiency is fixed at 3000 kg crude oil per day. The penalty charged for excess CO_2 emissions is fixed at 2 euros per kilogram, and the penalty for excess energy consumption is 1fixed at 50000 euros per cycle.

4.2. Numerical Analysis

Optimal maintenance policy for the multi-component series system is obtained based on genetic algorithm, which could minimize the system cost rate of its life cycle, optimize the basic preventive maintenance interval and the multiplier of scheduled PM cycle for each component. Table 3 shows the optimal results of maintenance policy.

$k_1/k_2/k_3/k_4/k_5/k_6/k_7/k_8$	$K\tau$ (days)	τ (days)	$\tau_1/\tau_2/\tau_3/\tau_4/\tau_5/\tau_6/\tau_7/\tau_8$ (days)	Minimum cost rate (€/day)
3/5/6/10/4/2/3/6	5700	95	285/475/570/950/380/190/285/570	1127

Table 3. Optimal results of maintenance policy

Table 3 and Figure 4 shows the multiplier of maintenance cycle for each component is 3/5/6/10/4/2/3/6. Consequently, PM activities are scheduled for component 1 and component 7 simultaneously, and for component 3 and component 8 simultaneously. The life cycle of the whole system is 5700 days, and basic preventive maintenance interval is 95 days. The corresponding optimal maintenance cycles from component 1 to component 8 are 285 days, 475 days, 570 days, 950 days, 380 days, 190 days, 285days and 570 days. The minimal cost rate of the system life cycle is 1127 euros per day.

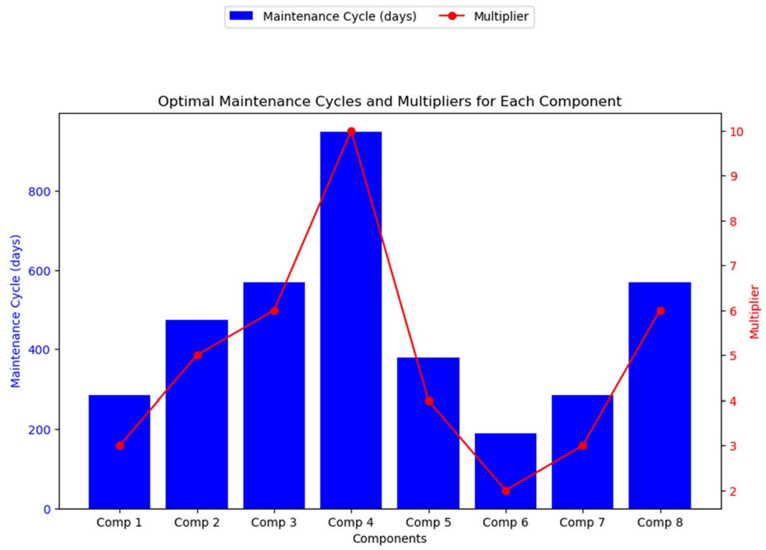

Figure 4. Optimal Maintenance Cycles and Multipliers for Each Component

4.3. Sensitivity Analysis

The section will vary the values of four parameters: the penalties for excess CO_2 emissions, the penalties for excess energy consumption, the set-up cost of each time PM, and the set-up cost of each time BM. We investigate the influence of these four parameters on the optimal cost rate.

4.3.1. Penalties for excess CO_2 emissions f_{CO_2}

It is noted f_{CO_2} for the penalties for excess CO_2 emissions. The optimal cost rates under different conditions are obtained by varying f_{CO_2}, which are illustrated in Table 4.

f_{CO_2}	$k_1/k_2/k_3/k_4/k_5/k_6/k_7/k_8$	$K\tau$ (days)	τ (days)	$\tau_1/\tau_2/\tau_3/\tau_4/\tau_5/\tau_6/\tau_7/\tau_8$ (days)	Minimum cost rate (€/day)
4	3/5/6/10/4/2/3/6	5700	95	285/475/570/950/380/190/285/570	1127
8	3/5/6/10/4/2/2/6	4080	68	204/340/408/680/272/136/136/408	1491
12	3/3/5/10/4/3/3/5	3540	59	177/177/295/590/236/177/177/295	1654

Table 4. Sensitivity analysis results

As shown in Table 4, when f_{CO_2} is increased, PM schedule is changed to avoid heavy penalties for excess CO_2 emissions. Specifically, the refinery shortens basic preventive maintenance interval, to avoid excess CO_2 emitted by each component to the utmost. Besides, the maintenance cycle multiplier of each component decreases. Consequently, the PM cycle for each component and the whole system life cycle are shortened. However, when f_{CO_2} is increased, the upward trend of cost rate is irreversible even if the finery shortens the life cycle to decrease the quantity of CO_2 emissions to the utmost.

4.3.2. Penalties for Excess Energy Consumption C_0^E

The penalties for excess energy consumption are noted C_0^E. The optimal cost rates under different conditions are obtained by varying C_0^E, which are illustrated in Table 5:

As shown in Table 5, when C_0^E is increased, PM schedule is changed to avoid heavy penalties for excess energy consumption. Specifically, the refinery shortens basic preventive maintenance interval, to avoid excess energy consumed by each component to the utmost. Besides, the maintenance cycle multiplier of each component decreases, and thereby shortens the PM cycle for each component. However, the whole system life cycle is not necessarily shortened. On the other hand, it shows that when C_0^E is increased, the upward trend of cost rate is irreversible even if the finery shortens the life cycle to avoid excess energy consumption to the utmost.

C_0^E	$k_1/k_2/k_3/k_4/k_5/k_6/k_7/k_8$	$K\tau$ (days)	τ (days)	$\tau_1/\tau_2/\tau_3/\tau_4/\tau_5/\tau_6/\tau_7/\tau_8$ (days)	Minimum cost rate (€/day)
150000	3/5/6/10/4/2/3/6	5700	95	285/475/570/950/380/190/285/570	1127
200000	2/6/6/9/5/3/3/5	6210	69	138/414/414/621/345/207/207/345	1839
250000	2/6/9/9/5/6/3/6	3540	49	177/177/295/590/236/177/177/295	2607

Table 5. Sensitivity analysis results of C_0^E

4.3.3. Set-up cost of each time BM C_0^B

The set-up cost of each time BM is noted C_0^B. The optimal cost rates under different conditions are obtained by varying the value of C_0^B, which are illustrated in Table 6:

C_0^B	$k_1/k_2/k_3/k_4/k_5/k_6/k_7/k_8$	$K\tau$ (days)	τ (days)	$\tau_1/\tau_2/\tau_3/\tau_4/\tau_5/\tau_6/\tau_7/\tau_8$ (days)	Minimum cost rate (€/day)
36000	3/5/6/10/4/2/3/6	5700	95	285/475/570/950/380/190/285/570	1127
54000	2/7/6/9/6/3/3/6	9072	72	144/504/432/648/432/216/216/432	1860
72000	3/8/10/12/6/7/5/8	39480	47	141/376/470/564/282/329/235/376	2740

Table 6. Sensitivity analysis results of C_0^B

As shown in Table 6, when C_0^B is increased, PM schedule is changed to avoid heavy penalties for excess energy consumption. Specifically, the refinery shortens basic preventive maintenance interval, to avoid to the utmost the frequent system breakdown due to component failure. However, the maintenance cycle multiplier for each component is not necessarily decreased. On the other hand, it shows that when C_0^B is increased, the upward trend of cost rate is irreversible even if the finery shortens the basic preventive maintenance interval and the PM cycle for each component to avoid the frequency system breakdown due to internal failure.

4.3.4. Set-up cost of each time PM C_0^P

The set-up cost of each time PM is noted C_0^P. The optimal cost rates under different conditions are obtained by varying C_0^P, which are illustrated in Table 7:

C_0^P	$k_1/k_2/k_3/k_4/k_5/k_6/k_7/k_8$	$K\tau$ (days)	τ (days)	$\tau_1/\tau_2/\tau_3/\tau_4/\tau_5/\tau_6/\tau_7/\tau_8$ (days)	Minimum cost rate (€/day)
1200	3/5/6/10/4/2/3/6	5700	95	285/475/570/950/380/190/285/570	1127
1800	3/4/5/8/4/3/3/6	13560	113	339/452/565/904/452/339/339/678	1713
2400	3/4/6/9/4/2/4/7	34776	138	414/552/828/1242/552/276/552/966	2607

Table 7. Sensitivity analysis results of C_0^P

As shown in Table 7, when C_0^P is increased, the refinery changes PM schedule to avoid the high cost caused by frequent PM. Specifically, the refinery lengthens basic preventive maintenance interval, to avoid to the utmost the frequent PM activities for each component. Meanwhile, the maintenance cycle multiplier for each component is generally increased. However, it shows that when C_0^P is increased, the upward trend of cost rate is irreversible even if the finery lengthens the basic preventive maintenance interval and the PM cycle for each component to avoid frequent PM, as the system breakdown due to component failure increases.

Finally, we have combined the changes in the minimum cost rate (in viridis color) and maintenance cycle (in autumn color) when every two input parameters vary, as shown in Figure 5 below.

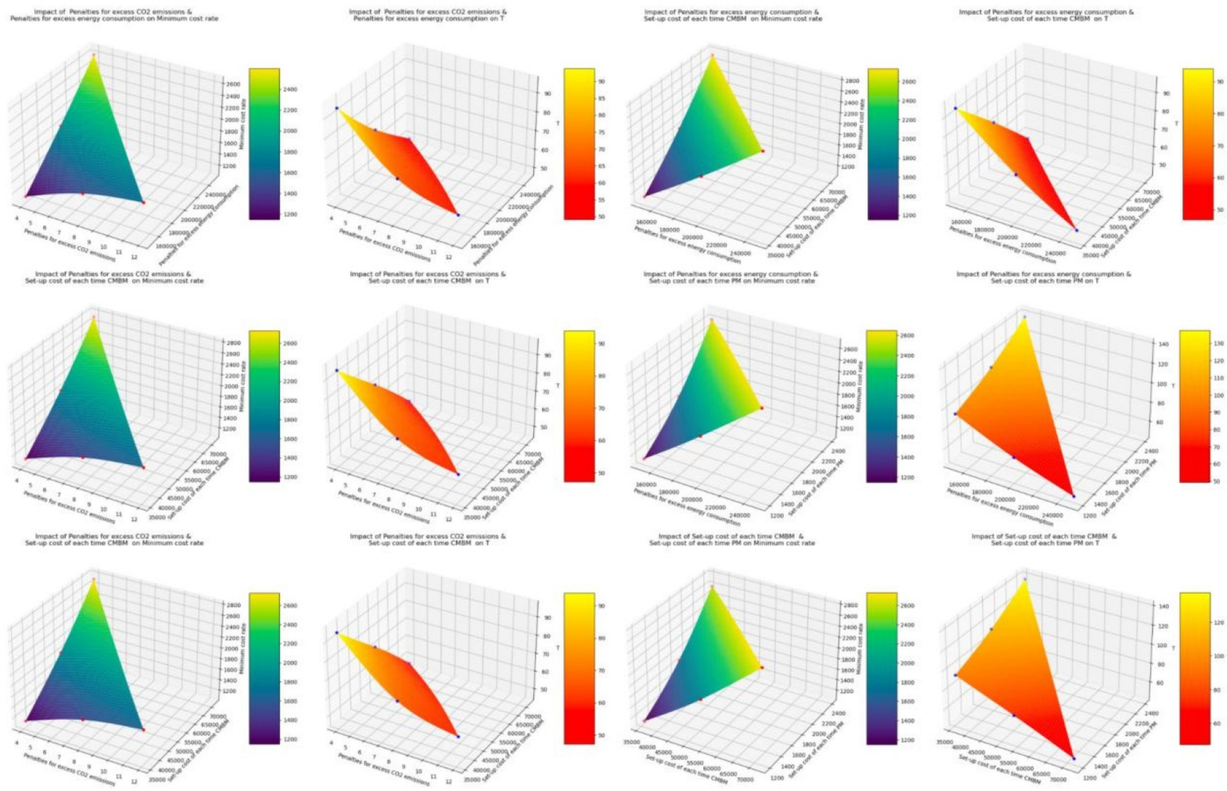

Figure 5. output variables change under small variations in input parameters

Based on the sensitivity analysis of the penalties for excess CO_2 emissions and excess energy consumption, set-up cost of each time BM, and set-up cost of each time PM, the variation of these four parameters influences the basic PM cycle and each component PM cycle, which can be summarized as the following:

1. When the two penalties are increased, the refinery shortens the maintenance cycle to avoid the heavy penalties for excess CO_2 emissions and energy consumption. However, the cost rate of the whole system life cycle remains an upward trend.
2. When the set-up cost of each time system BM is increased, the refinery shortens the maintenance cycle to avoid frequent system breakdown due to component failure. However, the cost rate of the whole system life cycle remains an upward trend is increased.
3. When the set-up cost of each time system PM is increased, maintenance cycle is lengthened, to avoid frequent PM. However, inadequate PM could lead to frequent component failures, and thereby cause system breakdown. Consequently, the total cost of BM increases greatly, leading to the increase of cost rate of the whole system life cycle.

5. Conclusion

In this paper, the intelligent opportunist group maintenance model for multi-component series systems is proposed based on clustering theory and two decision variables of preventive maintenance cycle multiplier of each component and basic preventive maintenance interval. This model aims to minimize the system's life-cycle cost rate in the context of improving energy efficiency and reducing CO_2 emissions. Structural dependence and economic dependence between the components are analyzed to develop the condition-based maintenance policy. For the maintenance model, it is assumed that instantaneous failure rate of components in a system complies to independent Weibull distribution; energy consumption amount of each component complies to Wiener process; energy consumption level is independent from instantaneous failure rate; the quantity of CO_2 emissions and energy consumption level is directly proportional. Based on clustering theory and economic dependence, the intelligent opportunistic group maintenance policy decides the component group subjected to opportunistic maintenance and obtain the system's life-cycle cost rate. Genetic algorithm is exploited to obtain the optimal PM multiplier of each component and the basic preventive maintenance interval.

Finally, the sensitivity analysis of the penalties for excess CO_2 emissions and excess energy consumption, the set-up cost of each time BM, and the set-up cost of each time PM shows that the variation of these four parameters influences the PM cycle schedule and the system's life-cycle cost rate.

Further research can be carried out related to the study in this paper. For example, due to the high downtime cost in some industries such as oil refineries, the production systems in these industries tend to be regarded as redundant. Future

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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