OmniaScience

Journal of Industrial Engineering and Management
JIEM, 2018 – 11(4): 749-768 – Online ISSN: 2013-0953 – Print ISSN: 2013-8423
https://doi.org/10.3926/jiem.2649

A Condition-Based Opportunistic Maintenance Policy Integrated with Energy Efficiency for Two-Component Parallel Systems

Aiping Jiang, Yuanyuan Wang, Yide Cheng

Sydney Institute of Language and Commerce, Shanghai University (China)

ap724@shu.edu.cn, wangyuanyuan_0519@163.com, 13601765891@163.com

Received: May 2018
Accepted: September 2018

Abstract:

Purpose: This paper deals with the problem of traditional maintenance model ignoring energy consumption in two-component parallel systems. Thus, the aim of the article is to propose a new maintenance model with ecological consciousness for two-component parallel systems, which can improve the energy utilization and achieve sustainable development. The objective is to obtain the optimal maintenance policy by minimizing total cost.

Design/methodology/approach: This paper integrates energy efficiency into condition-based maintenance (CBM) decision-making for two-component parallel systems. Based on energy efficiency, the paper considers the economic dependence between the two components to take opportunistic maintenance. Specifically, the objective function consists of traditional maintenance cost and energy cost incurred by energy consumption of components. In order to assess the performance of the proposed new maintenance policy, the paper uses Monte-Carlo method to evaluate the total cost and find the optimal maintenance policy.

Findings: Simulation results indicate that the new maintenance policy is superior to the classical condition-based opportunistic maintenance policy in terms of total costs.

Originality/value: For two-component parallel systems, previous researches usually simply establish a condition-based opportunistic maintenance model based on real deterioration data, but ignore energy consumption, energy efficiency (EE) and their contributions of sustainable development. This paper creatively takes energy efficiency into condition-based maintenance (CBM) decision-making process, and proposes a new condition-based opportunistic maintenance policy by using energy efficiency indicator (EEI).

Keywords: energy efficiency, condition-based opportunistic maintenance, two-component parallel systems

To cite this article:

Jiang, A., Wang Y., & Cheng, Y. (2018). A condition-based opportunistic maintenance policy integrated with energy efficiency for two-component parallel systems. *Journal of Industrial Engineering and Management*, 11(4), 749-768. https://doi.org/10.3926/jiem.2649

1. Introduction

For fear of sudden failure, most companies are willing to repair/replace their components before breakdown. Garg, Rani, and Sharma (2013) simultaneously consider mechanical service, repair and replacement in periodic preventive maintenance. However, this maintenance policy only focuses on the fixed preventive maintenance interval, but ignore the real deterioration level of components. Nowadays, condition-based maintenance is used extensively in various industries, and companies always regard this method highly to ensure maintenance before breakdown. Although the corporations give high priority to the periodic preventive maintenance or condition-based maintenance, they ignore the fact that maintenance activities can strengthen or weaken the ecological burden exerted by system. Horenbeek, Kellens, Pintelon, and Duflou (2014) points out that energy, resources and environment all belong to the category of ecology. It came to be a common situation that companies take blind eyes to the machines in bad condition, since they will not maintain the components when they can still work, even if these components are gradually in poor state which will increase energy consumption. For instance, a ship company, when encounters motor boilers, blowers, belt conveyor belt relaxation and induced draft fan adjustment door open and closed out of work, will not conduct instant maintenance for the purpose of saving money, if these devices mentioned above incur small problems but they can still on operation. However, the negative point is that continuous uses without maintenance will seriously affect the key indicators alpha value of the combustion conditions (ie, air excess coefficient). In general, when the value is too large, the fan energy consumption increased sharply.

With the enhanced awareness of energy conservation, a new trend concerning about saving energy, protecting the environment, and achieving sustainable development is prevalent in modern society. In actual industrial production, a great amount of energy, such as electricity, etc. needs to be consumed to maintain machines' normal operation, and if the system cannot work in good condition, there would be much more energy loss in the manufacture process and thus pose a huge burden on the whole ecology. Thus, for most of the enterprises, it should be the long-term strategic focus how they can apply valid maintenance activities to the improvement of system's resource utilization and establishment of a green image. Traditional maintenance mainly focuses on controlling maintenance fee at a low level and keeping the reliability of the system at a high level, but ignores to avoid excessive energy consumption under operation. Therefore, it is imperative to consider the energy consumption of system under operation when developing a maintenance policy.

The rest of the paper is structured as follows: In section 2, several related research literatures are reviewed. Section 3 presents degradation model of individual component and introduces the energy efficiency indicator. Section 4 proposes the new condition-based opportunistic maintenance policy integrated with energy efficiency (EE). Section 5 conducts numerical experiments to testify the advantage of new proposed policy by comparing new proposed and classical maintenance policy. Finally, conclusions and future work are stated in Section 6.

2. Literature Review

The reliability and maintainability are the critical factors for maintenance activities, because their purpose is to estimate the probability of failure. Therefore, some scholars are interested in studying the reliability and failure function. For example, Garg and Sharma (2012) propose a two-phase approach to get more precise distribution parameters of reliability, failure rate and repair rate. Maintenance plays a significant role in an industrial system to ensure normal operation. However, most industrial systems are rather complicated and they have some subsystems with components. In order to save money, time and manpower, managers are suggested using three indicators simultaneously, including reliability, availability and maintainability, to find the critical components that affects the performance of the entire system mostly (Garg, 2014a,b). With the development of the sensor technology, condition-based maintenance (CBM) has been considered a more efficient strategy (Ahmad, 2012; Jardine, Lin, & Banjevic, 2006), as CBM is based on the actual conditions of a component monitored through sensors. Over the past few years, the research on the CBM decision-making of multi-component systems has developed vastly. In the study of multi-component systems maintenance, components may depend on each other in three different ways including stochastic dependence, economic dependence and structural dependence (Dao & Zuo, 2017).

The economic dependence provides opportunities to maintain several components jointly, and thus reducing high fixed set-up costs (such as sending a maintenance team to the site, which incurred once maintenance action is performed on one component). Several literatures have pointed out that group maintenance actions can reduce the total costs of the system (Bouvard, Artus, Bérenguer, & Cocquempot, 2011; Qian & Wu, 2014; Tian, Jin, Wu, & Ding, 2011; Tian & Liao, 2011; Zhang, Zhou, Sun, & Ma, 2012). When considering economic dependence, it is sensible to take group or opportunistic maintenance policies into account. Opportunistic maintenance can be recognized as dynamic group maintenance, because workers will not maintain non-failed components unless they are in opportunistic zone (Cavalcante & Lopes, 2014). Compared with group maintenance, opportunistic maintenance can reduce the waste of maintenance resources.

Several papers have proposed opportunistic maintenance policy in CBM in terms of economic dependence. Wijnmalen and Hontelez (1997) is the first one to propose a condition-based opportunistic maintenance policy based on deterioration level of components. It points out that if one component is going to repair, group maintenance actions only occur when the deterioration level of another component is over its opportunistic threshold. Barbera, Schneider, and Watson (1999) proposes a condition-based opportunistic maintenance policy based on exponential failures for a two-component series system. And finally, the long-term average cost is minimized by dynamic programming. When comes to a two-component series system, Castanier, Grall, and Berenguer (2005) also formulates a condition-based opportunistic maintenance policy, in which the deterioration level can be obtained by non-periodic inspections. It points out that the degradation process of the system after maintenance has the semi-regenerative properties and this policy finally establishes a minimum cost rate model based on the semi-renewal theory. For a two-component parallel system, Li, Deloux and Dieulle (2016) studies a condition-based maintenance policy considering both stochastic and economic dependence among components. It presents a new decision rule which permits the maintenance grouping in advance or postponed maintenance. Zhu, Peng, and Houtum (2015) presents an optimal CBM policy that minimizes the long-term mean maintenance cost per unit time for a multi-component system with continuous deterioration. They point out that it is more economical to preventively maintain several components simultaneously. Finally, the advantage of the presented policy is analyzed by a three-component series system of wind turbine. In recent years, some scholars intend to optimally plan maintenance activities for multi-component systems based on prognostic information and presents a dynamic predictive maintenance policy for multi-component systems (Bian & Gebraeel, 2014; Nguyen, Do, & Grall, 2014; Shi & Zeng, 2016). Furthermore, Jiang, Duan, Tian, and Wei (2015) and Keizer, Teunter and Veldman (2016) propose a condition-based opportunistic maintenance policy for redundancy systems separately. Jiang et al. (2015) establishes a reliability analysis model of the system with the basis of the remaining useful life (RUL) of components. This real-time sampling can reduce unnecessary preventive maintenance costs and high fixed maintenance costs of components, thereby increasing the efficiency of the whole redundant system. Finally, three numerical examples are used to verify the feasibility and flexibility of the model. Keizer et al. (2016) points out that in redundancy systems, the maintenance of some failed components can be postponed, under the condition that the reliability of the whole system is not reduced. Finally, the optimal maintenance policy can be obtained by dynamic programming. Despite the single-objective model above, some scholars are inclined to multi-objective optimization. Garg (2016) presents a method for obtaining the optimum maintenance interval by considering maximum availability and minimum maintenance cost. For a series system, Garg and Sharma (2013) consider the maximum reliability of system and minimum design cost as the two objectives. Then, they solve the reliability allocation problem of subsystems by fuzzy nonlinear programming. Based on the two objectives, Garg, Rani, Sharma, and Vishwakarma (2014a) allocate the reliability for a series-parallel system. As well known, reliability and cost parameters are under uncertainties normally in design phases. Therefore, under the condition that parameters are imprecise, Garg, Rani, Sharma, and Vishwakarma (2014b) utilize intuitionistic fuzzy programming techniques to solve a multi-objective reliability optimization problem.

In summary, traditional condition-based maintenance strategies merely focuses on reducing maintenance costs. Although these strategies ensure the safety and reliability of the system, they ignore the ecological impacts. Additionally, the fact that the maintenance activities can increase or reduce the ecological impacts resulted from system's normal operation is ignored. Generally, reasonable maintenance activities can reduce the ecological impact caused by the system itself, otherwise the maintenance activities can increase the ecological burden. However, with the increasingly serious problems of energy and environment, several literatures of CBM with ecological awareness have been proposed over the past decade. Hoang, Do, and Iung (2016a, 2017) point out that maintenance activities (such as maintenance time, preventive or corrective maintenance, etc) can be influenced when considering some ecological aspects. Mora, Vera, Rocamora, and Abadia (2013) and Xu and Cao (2014) conclude that different maintenance actions on deteriorated components can lead to different effect on ecology. Horenbeek et al. (2014) is the first one to integrate ecological factors in a maintenance optimization model. This model can be considered as an ecological analysis tool which covers many maintenance strategies (such as failure-based, block-based and use-based maintenance). Then, the presented model, which concerns an integrated economy and ecology, can determine the optimum maintenance interval. Chouikhi, Dellagi, and Rezg (2012) propose a CBM model from the respect of probability and statistics and combine environmental problems with maintenance activities. Preventive maintenance takes place when the amount of released refrigerant gas exceeds the alarm threshold and this action helps enterprises avoid a large penalty cost caused by excessive refrigerant gas release. Tlili, Radhoui, and Chelbi (2015) has made a further improvement in 2015. It proposes a preventive maintenance threshold value below the alarm threshold, which can avoid a huge economic penalty more effectively. In addition to the environmental problems (the release of refrigerant gas, etc.), some scholars also consider energy consumption in CBM decision-making. Hoang et al. (2016b) proposes a CBM model for a single-component system considering the energy consumption, in which maintenance activities can be performed based on the energy efficiency (EE) of the components. This model aims to minimize the total cost including maintenance cost and energy consumption cost. Nevertheless, literatures, in which CBM model stresses energy consumption during components' normal operation for multi-component systems are absent till now. In view of this situation, we propose a new condition-based opportunistic maintenance model integrated with energy efficiency for a two-component parallel system in this paper.

3. Degradation Model and Energy Efficiency Indicator

Throughout this paper, we consider a two-component parallel system. The energy consumption of the system is the sum of energy consumption of individual component. The two components have their own different energy consumption process incurred by different degradation process of them.

3.1. Notations

Some notations used in this paper are summarized as follows:

ΔT_i: Fixed inspection interval of component i, $i = 1,2$

$E_i(t)$: The energy consumption during one-time unit of component i (from t to $t + 1$), $i = 1,2$

$EEI_i(t)$: The energy efficiency indicator during one-time unit of component i, $i = 1,2$

$EEIL_i$: Corrective maintenance threshold for component i in new proposed maintenance policy, $i = 1,2$

$EEIM_i$: Preventive maintenance threshold for component i in new proposed maintenance policy, $i = 1,2$. $EEIM_i < EEIL_i$

$X_i(t)$: Degradation level during one-time unit of component i, $i = 1,2$

L_i: Corrective maintenance threshold for component i in classical maintenance policy, $i = 1,2$

M_i: Preventive maintenance threshold for component i in classical maintenance policy, $i = 1,2$. $M_i < L_i$

α_i:, β_i: Scale and shape parameters of the deterioration process of component i

S_i: Running speed of component i, $i = 1,2$

O_i: The useful output during one-time unit of component i, $i = 1,2$

$\phi(t)$: The cumulative useful output of the whole system during the period $(0, t]$

C_t: Cumulative total cost during the period $(0, t]$

IC_t: Cumulative inspection cost of the whole system during the period (0, t]

MC_t: Cumulative maintenance cost of the whole system during the period (0, t]

EC_t: Cumulative energy cost of the whole system during the period (0, t]

CO: Long-run expected cost of system per useful output unit

c_{nsp}^{Di}: Each deterioration inspection cost of component i, $i = 1,2$

c_{nsp}^{Ei}: Each energy consumption inspection cost of component i

c_p^i: A preventive maintenance cost for component i, $i = 1,2$

c_c^i: A corrective maintenance cost for component i, $i = 1,2$

c_s: A fixed set-up cost

E_p: The energy price

N_p^i: The number of preventive maintenance for component i, $i = 1,2$

N_c^i: The number of corrective maintenance for component i

N_{nsp}^i: The number of inspection for component i

N_{GM}: The number of grouping maintenance

$\int_0^t E_i(x)dx$: The amount of energy consumption for component i during the period (0, t]

Pp_2: The probability that the energy efficiency indicator of component 2 exceeds its preventive maintenance threshold at current inspection time

Pc_1: The probability that the energy efficiency indicator of component 1 exceeds its legislation at the next inspection time.

PP: The opportunity maintenance threshold in new proposed maintenance policy and it is the threshold of Pp_2

PC: The postponed maintenance threshold in new proposed maintenance policy and it is the threshold of Pc_1

PP': The opportunity maintenance threshold in classical maintenance policy

PC': The postponed maintenance threshold in classical maintenance policy

CS: The cost saving, it is the difference between CO^* of *Policy* 0 and that of *Policy* 1

3.2. Degradation Model

The Gamma process has been successfully selected to describe the gradual degradation process of individual component in different industrial systems (Dieulle, Bérenguer, Grall, & Roussignol, 2003; Noortwijk, 2009). The Gamma process has several characteristics as follows:

- $X_i(0) = 0$, $i = 1,2$.
- $X_i(t)$ has independent increments,
- For $t > \tau > 0$, the increment of deterioration level for component i $X_i(t) - X_i(\tau)$ follows a Gamma probability density function with the shape parameter $\alpha_i(t - \tau)$ and the scale parameter β_i:

$$f_{\alpha_i(t-\tau),\ \beta_i}(x) = \frac{\beta_i}{\Gamma(\alpha_i(t-\tau))}(\beta_i x)^{\alpha_i(t-\tau)-1} e^{-\beta_i x} \tag{1}$$

Given $\alpha_1 = 1$, $\beta_1 = 1$ and $\alpha_2 = 1$, $\beta_2 = 2$, then the degradation process of two components are illustrated in Figure 1.

Figure 1 reveals clearly that the deterioration level of each component increases gradually as the time flies. However, the degradation rate of component 1 is lower than that of component 2, because the scale parameter $\alpha_i\beta_i$ represents the degradation speed of component i and $\alpha_1\beta_1 < \alpha_2\beta_2$. Generally, different couples of parameters(α and β) can generate different deterioration behaviors.

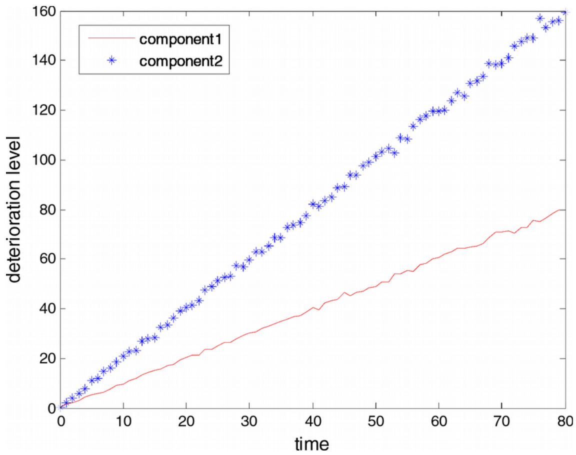

Figure 1. Degradation process of two components

3.3. Energy Efficiency Indicator

Hoang et al. (2016b) has pointed out that energy consumption of component i varies over time and it depends on the degradation level and the running speed. In order to ensure the stable operation of the whole system, we need to control the running speed of different components (constants in this paper). Therefore, the energy consumption during one-time unit depends only on the deterioration level $X(t)$:

$$E(t) = f(t, X(t)) \tag{2}$$

Suppose that $S_1 = S_2 = 200$, the energy consumption process of the two components are illustrated in Figure 2.

Similar to Figure 1, Figure 2 shows that the energy consumption rate of component 1 is lower than that of component 2. However, the energy consumption rate of each component is growing over time. This means that there would be much more energy consumption in the manufacture process if the components are in bad condition, even if they can still run. Therefore, we propose a new maintenance policy integrated with energy efficiency for a two-component parallel system.

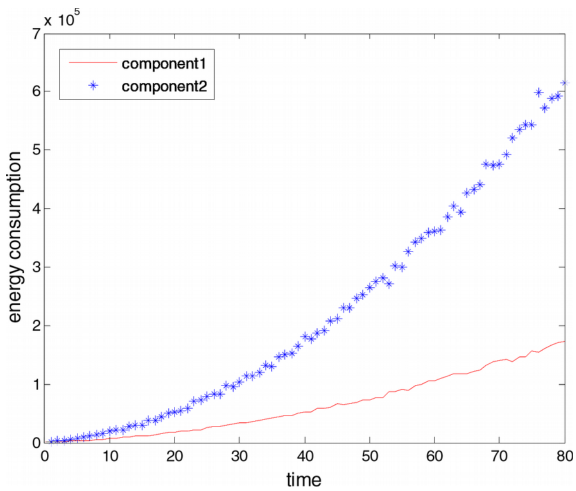

Figure 2. Energy consumption process of components

The useful output during one-time unit of each component depends on its running speed as follow:

$$O = f(t, S) \tag{3}$$

Therefore, the useful output during one-time unit of each component is constant.

Energy efficiency indicator (EEI) has been introduced in maintenance decision-making. EEI represents the amount of energy consumption needed to produce one useful output. Its mathematical expression is as follow:

$$EEI(t) = \frac{E(t)}{O} \tag{4}$$

Hence, energy efficiency indicator also depends on the deterioration level of components:

$$EEI(t) = f(t, X(t)) \tag{5}$$

4. Maintenance Policy

In this section, we intend to propose a new condition-based opportunistic maintenance policy integrated with energy efficiency for a two-component parallel system. The policy is based on the following assumptions:

1. A component is not affected by the degradation of another and only the economic dependence between them is considered in this paper.
2. Inspection tasks for each component are only performed with its own fixed interval and their duration can be negligible.
3. An inspection cost of energy consumption is not higher than a deterioration inspection cost ($c_{nsp}^{Ei} \leq c_{nsp}^{Di}$).
4. A preventive maintenance action takes place for each component when the energy efficiency indicator exceeds its preventive maintenance threshold. The action has a specific maintenance cost c_p^i for the component and a set-up cost c_s.
5. If the energy efficiency indicator exceeds a legislation for component i, a corrective maintenance action is then performed. This action has a specific maintenance cost c_c^i for the component and a set-up cost c_s.
6. Both preventive and corrective maintenance are assumed to be perfect and the maintenance time can be ignored.

In general, both the energy consumption and deterioration level of each component can be monitored. However, Hoang et al. (2016b) point out that measuring the current deterioration level of a component is more complicated than inspecting the current energy consumption, therefore, we also assume ($c_{nsp}^{Ei} \leq c_{nsp}^{Di}$) in condition-based opportunistic maintenance policy as Hoang et al. (2016b). But we also make the additional sensitivity analysis with various c_{nsp}^{Ei} and c_{nsp}^{Di} in 5.2.1 section.

In case an inspection indicates that the energy efficiency indicator of an component exceeds its legislation, the component would be considered in a rather serious state and will generate large energy consumption which would lead to a penalty, and then a corrective maintenance is performed. In order to reduce the chances of being in such serious situation, a preventive maintenance threshold lower than a legislation is considered. It should be noted that both preventive and corrective maintenance are instantaneous as Li et al. (2016). In order to comparatively analyze the minimum long-run expected cost of system per useful output unit for new proposed maintenance policy in this paper and for traditional maintenance policy as in Li et al. (2016), we also assume that the maintenance time can be negligible in this paper.

4.1. Long-Run Expected Cost of System Per Useful Output Unit

In order to assess the effectiveness of new proposed maintenance policy, we use the long-run expected cost of system per useful output unit as the objective function:

$$\min \quad CO = \lim_{t \to +\infty} \frac{C_t}{\phi(t)} \tag{6}$$

The cumulative useful output of the whole system during period (0, t] is calculated as:

$$\phi(t) = (O_1 + O_2)t \tag{7}$$

Where O_1 and O_2 is the useful output during one time unit of component 1 and component 2 respectively.

During the period (0, t], cumulative cost of the whole system includes cumulative inspection cost, maintenance cost and energy cost:

$$C_t = IC_t + MC_t + EC_t \tag{8}$$

Where:

An inspection cost of energy consumption is trigged by each inspection operation and thus IC_t depends on the number of inspection. The cumulative inspection cost of the whole system includes the inspection costs of both two components:

$$IC_t = \sum_{i=1}^{2} c_{nsp}^{Ei} N_{nsp}^{i} \tag{9}$$

Similarly, MC_t is related to the number of both preventive and corrective maintenance of each component. A set-up cost and an individual maintenance cost are both generated once each maintenance (preventive or corrective) is performed. Thus, the cumulative maintenance cost of the whole system is written as:

$$MC_t = \sum_{i=1}^{2} ((c_p^i + c_s)N_p^i + (c_c^i + c_s)N_c^i) \tag{10}$$

EC_t is the product of energy price and the total amount of energy consumed by the whole system:

$$EC_t = Ep \cdot \sum_{i=1}^{2} \int_0^t E_i(x)dx \tag{11}$$

Therefore, the cumulative cost of the whole system is the sum of Equations (9), (10) and (11), so it can finally be expressed as:

$$C_t = \sum_{i=1}^{2} (c_{nsp}^{Ei} N_{nsp}^{i} + c_p^i N_p^i + c_c^i N_c^i + c_s(N_p^i + N_c^i) + Ep \int_0^t E_i(x)dx) \tag{12}$$

In industry, taking maintenance actions of two components jointly is more economical than repairing them separately. When a component is repaired, the cost of maintenance (both preventive and corrective) includes two parts: a fixed set-up cost c_s shared by two components and individual maintenance cost of each component (c_p^i or c_c^i). Set-up cost refers to the cost resulted from the same maintenance preparation, such as maintenance devices, technology, workers and so on. Therefore, two individual preventive or corrective maintenance incur two set-up costs c_s while grouping maintenance of two components only incurs single c_s. Thus, a set-up cost can be saved when two components are maintained simultaneously, which can ultimately reduce total maintenance cost and improve the economic benefit for a company. In order to make the best use of economic dependence, it is necessary to find an opportunity to postpone the preventive maintenance of one component or repair the other in advance. Hence, the cumulative cost of the whole system can be reduced by a set-up cost multiplied by the number of grouping maintenance (N_{GM}) as follows:

$$C_t = \sum_{i=1}^{2} (c_{nsp}^{Ei} N_{nsp}^{i} + c_p^i N_p^i + c_c^i N_c^i + c_s(N_p^i + N_c^i) + Ep \int_0^t E_i(x)dx) - c_s N_{GM} \tag{13}$$

4.2. A New Opportunistic Maintenance Policy Integrated with Energy Efficiency (*Policy* 0)

Traditional condition-based opportunistic maintenance policies do not consider energy consumption during the operation of components. In response to the enhanced awareness of energy conservation over the whole world, this paper proposes a new condition-based opportunistic maintenance decision rule by using energy efficiency indicator (EEI).

Since the actual energy consumption of components can be achieved by inspection (then EEI is calculated), we can consider the inspection time as the decision moment. Suppose that the current time is $n\Delta T_1$ (the moment of nth inspection for component 1). If the energy efficiency indicator of component 1 $EEI_1(n\Delta T_1)$ exceeds its preventive maintenance threshold, a maintenance action (preventive or corrective) can be performed for component 1 according to CBM decision rule. On the one hand, once the energy efficiency indicator of component 2 $EEI_2(n\Delta T_1)$ also reaches its preventive maintenance threshold at the same time, then we can take the preventive maintenance for component 2 in advance. On the other hand, the time of next inspection $(m + 1)\Delta T_2$ (the moment of $(m + 1)$th inspection for component 2) is very close to $n\Delta T_1$ (see Figure 3).

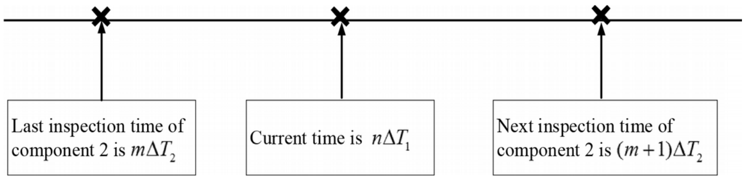

Figure 3. Sketch of inspection time

In such a situation, it is possible to postpone preventive maintenance for component 1. Although both the status of component 2 at current time and the status of component 1 at the next inspection time are unknown, we can determine the opportunistic maintenance activities by calculating two probability values in Figure 4 which details the maintenance decision process.

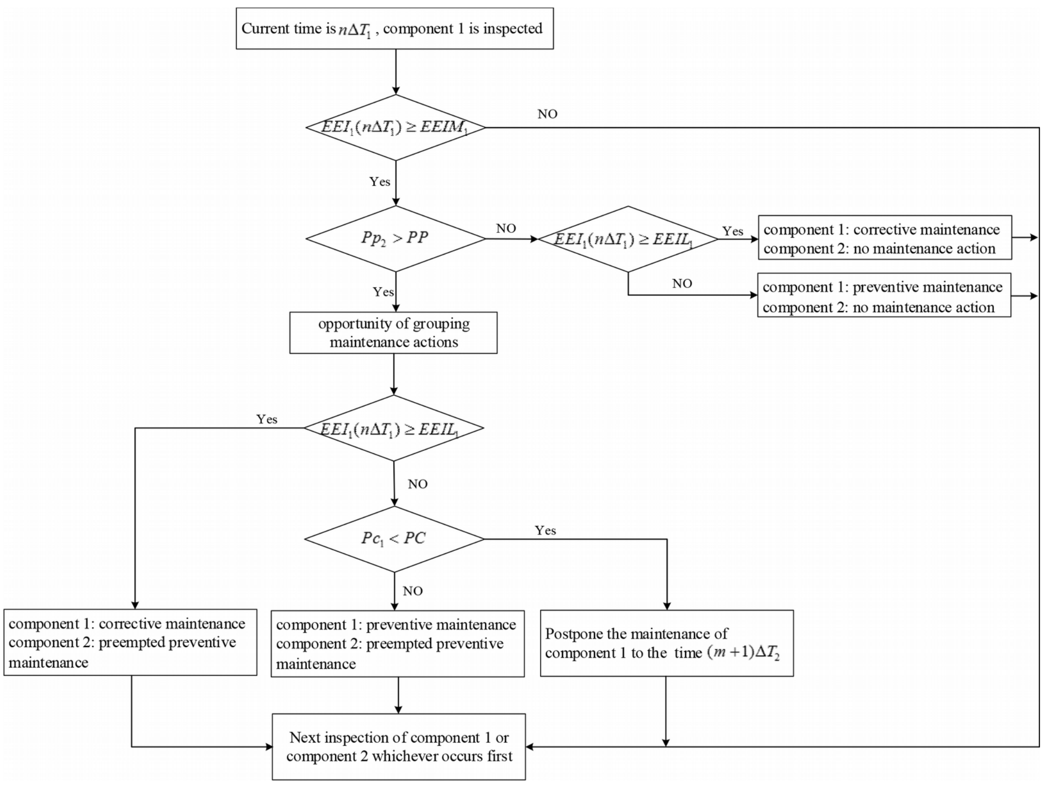

Figure 4. Decision rule of maintenance when component 1 is inspected at time $n\Delta T_1$

$Pp_2 = P(EEI_2(n\Delta T_1) \geq EEIM_2 \mid EEI_2(m\Delta T_2) = a)$ represents the probability that the energy efficiency indicator of component 2 reaches its preventive threshold at current time $n\Delta T_1$, under the condition that the energy efficiency indicator of component 2 does not reach its preventive maintenance threshold at its last inspection time $m\Delta T_2$ ($a < EEIM_2$. According to Equation (5), the value of Pp_2 can be obtained by firstly transforming energy efficiency indicator of component 2 into the corresponding deterioration level, as $X_2(t) = f^{-1}(t(EEI_2(t))$. Pp_2 is related to the last energy efficiency indicator of component 2 and it is calculated as follows:

$$\begin{aligned} Pp_2 &= P(EEI_2(n\Delta T_1) \geq EEIM_2 \mid EEI_2(m\Delta T_2) = a) \\ &= P(f^{-1}(t, EEI_2(n\Delta T_1)) \geq f^{-1}(t, EEIM_2) \mid f^{-1}(t,a)) \\ &= P(X_2^{EEI_2(n\Delta T_1)} \geq X_2^{EEIM_2} \mid X_2^a) \\ &= P(X_2^{EEI_2(n\Delta T_1)} - X_2^a \geq X_2^{EEIM_2} - X_2^a) \end{aligned} \tag{14}$$

Where $X_2^{EEI2(n\Delta T1)} - X_2^a$ follows Gamma distribution with parameter $(n\Delta T_1 - m\Delta T_2)\alpha_2$ and β_2. Then according to Equation (1), Pp_2 can be calculated as follows:

$$\begin{aligned} Pp_2 &= P(X_2^{EEI_2(n\Delta T_1)} - X_2^a \geq X_2^{EEIM_2} - X_2^a) \\ &= \int_{X_2^{EEIM_2} - X_2^a}^{+\infty} f_{\alpha_2(n\Delta T_1 - m\Delta T_2),\beta_2}(x)dx \\ &= 1 - \int_0^{X_2^{EEIM_2} - X_2^a} f_{\alpha_2(n\Delta T_1 - m\Delta T_2),\beta_2}(x)dx \end{aligned} \tag{15}$$

$Pc_1 = P(EEI_1((m + 1)\Delta T_2) \geq EEIL_1 \mid EEI_1(n\Delta T_1) = b)$ is the probability that the energy efficiency indicator of component 1 will exceed its legislation at the next inspection time $(m + 1)\Delta T_2$ and the current EEI of component 1 is denoted by b. Similar to Pp_2, the value of Pc_1 is computed as follows:

$$\begin{aligned} Pc_1 &= P(EEI_1((m+1)\Delta T_2) \geq EEIL_1 \mid EEI_1(n\Delta T_1) = b) \\ &= P(f^{-1}(t, EEI_1((m+1)\Delta T_2)) \geq f^{-1}(t, EEIL_1) \mid f^{-1}(t,b)) \\ &= P(X_1^{EEI_1((m+1)\Delta T_2)} \geq X_1^{EEIL_1} \mid X_1^b) \\ &= P(X_1^{EEI_1((m+1)\Delta T_2)} - X_1^b \geq X_1^{EEIL_1} - X_1^b) \\ &= \int_{X_1^{EEIL_1} - X_1^b}^{+\infty} f_{\alpha_1((m+1)\Delta T_2 - n\Delta T_1),\beta_1}(x)dx \\ &= 1 - \int_0^{X_1^{EEIL_1} - X_1^b} f_{\alpha_1((m+1)\Delta T_2 - n\Delta T_1),\beta_1}(x)dx \end{aligned} \tag{16}$$

Li et al. (2016) points out that *PP* and *PC*, the threshold of Pp_2 and Pc_1, are difficult to compute. Therefore, *PP* and *PC* will be set in advance and they are optimized through simulation.

From Figure 4, we conclude the following six maintenance activities:

- No opportunity of grouping maintenance:
  1. If $EEI_1(n\Delta T_1) < EEIM_1$, no maintenance activity will be carried out and we need to wait for the next inspection. This means that component 1 still operates well and does not cause a great amount of energy consumption.
  2. If $EEIM_1 \leq EEI_1(n\Delta T_1) < EEIL_1$ and $Pp_2 \leq PP$, only a preventive maintenance of component 1 takes place.
  3. If $EEI_1(n\Delta T_1) \geq EEIL_1$ and $Pp_2 \leq PP$, only a corrective maintenance action of component 1 is performed.

  Pp_2 represents the probability that component 2 needs a preventive maintenance at current time. Obviously, taking a maintenance action of component 2 too early will increase maintenance cost (Pp_2 is too small). Therefore, no maintenance action will take place when $Pp_2 \leq PP$. It's worthy to take group maintenance only when Pp_2 is large enough ($Pp_2 > PP$). If $Pp_2 \rightarrow 1$, component 2 will be repaired immediately at the next inspection time $(m + 1)\Delta T_2$. In this case, a preventive maintenance for component 2 is carried out in advance, in order to save one set-up cost c_s and avoid the energy efficiency indicator of component 2 beyond its legislation before next inspection time.

- Opportunity of grouping maintenance is identified:

4. If $EEI_1(n\Delta T_1) \geq EEIL_1$ and $Pp_2 > PP$, a corrective maintenance is performed for component 1 and the preventive maintenance is preempted for component 2.

   It's inadvisable to postpone maintenance for component 1 when the energy efficiency indicator of component 1 exceeds its legislation. This indicates that the current energy consumption of component 1 is too large, thus component 1 must be maintained immediately. Therefore, we need to take a corrective maintenance for component 1 and preempt the preventive maintenance for component 2 at current time.

5. If $EEIM_1 \leq EEI_1(n\Delta T_1) < EEIL_1$, $Pp_2 > PP$ and $Pc_1 \geq PC$, a preventive maintenance is performed for component 1 and the preventive maintenance is preempted for component 2.

6. If $EEIM_1 \leq EEI_1(n\Delta T_1) < EEIL_1$, $Pp_2 > PP$, and $Pc_1 < PC$, the preventive maintenance of component 1 is postponed to the next inspection time $(m + 1)\Delta T_2$.

   Pc_1 is the probability that the energy efficiency indicator of component 1 will exceed its legislation at the next inspection time $(m + 1)\Delta T_2$. An unreasonable postponed maintenance (when Pc_1 is large) maybe take a risk that the energy efficiency indicator of component 1 reaches its legislation before repaired at the next inspection time. If $Pc_1 \rightarrow 0$, then the energy efficiency indicator of component 1 will almost be lower than its legislation before the next inspection time. Therefore, the maintenance of component 1 can be postponed only when Pc_1 is small enough ($Pc_1 < PC$).

   Specifically, if Pp_2 is small enough, it is useless to postpone maintenance for component 1, because component 2 would hardly be repaired at the next inspection time $(m + 1)\Delta T_2$. In such case, grouping maintenance will rarely take place at the next inspection time even if the maintenance of component 1 is postponed. Therefore, we should check the condition $Pp_2 > PP$ at first.

5. Numerical Experiments

This section will compare the proposed *Policy* 0 with the classical maintenance policy (*Policy* 1) in order to testify the superiority of *Policy* 0. We use Monte-Carlo method to imitate the operation process and obtain the optimum decision variables. According to Li et al. (2016), the maintenance decision rule of *Policy* 1 is similar to that of *Policy* 0. But the nature of *Policy* 1 is that all maintenance activities in this policy are determined by deterioration level of components, whereas *Policy* 0 is based on energy efficiency. Finally, the long-run expected cost of system per useful output unit of *Policy* 0 and that of *Policy* 1 are both estimated by Equation (6). However, it is significant to notice that the inspection cost of *Policy* 1 depends on deterioration inspection operation (c_{nsp}^{Di}), instead of energy consumption inspection cost (c_{nsp}^{Ei}) in Equation (13). Detailed description of *Policy* 1 is shown in Appendix A.

5.1. Simulation Analysis

All maintenance activities in *Policy 0* are determined by the energy efficiency of components. According to Equation (4), the energy efficiency indicator of component i is a function of the energy consumption and the useful output during one time unit. The energy consumption can be estimated by the non-linear fitting of some historical data from different operating status and it is expressed as (Hoang et al., 2016b):

$$\begin{aligned} E_i(t) = {} & \frac{7856}{S_i} + 44.91 + \frac{19.54}{X_i(t)} + 0.168 * S_i - 1.19 * 10^{-5} * (S_i)^2 * X_i(t) \\ & - 4.36 * 10^{-5} * (S_i)^2 + 0.011 * (S_i)^2 * X_i(t) + 0.104 * S_i * X_i(t)^2 \\ & + 1.8 * 10^{-5} * (S_i)^2 * X_i(t)^2 \end{aligned} \quad (17)$$

Without loss of generality, we define S_i as a constant in the range of 400 to 1200.

Meanwhile, the useful output during one time unit of component i is provided as (Hoang et al., 2016b):

$$O_i = \frac{S_i * 6}{250} \tag{18}$$

Then the energy efficiency indicator of component i can be obtained based on Equations (4), (17) and (18).

In *Policy* 0, the decision variables are ΔT_1, ΔT_2, $EEIM_1$, $EEIM_2$, PP, PC. In *Policy* 1, the decision variables are ΔT_1, ΔT_2, M_1, M_2, PP', PC'. Total time should be large enough to ensure the number of inspection and acquire more reliable results. The parameters of two policies are shown in Table 1.

Table 2 shows costs of inspection and maintenance activities, all the costs are unit cost.

For the record of computing long-run expected cost of system per useful output unit, large amount of simulation is preceded. Different combinations of decision variables can lead to different results. The optimal long-run expected cost of system per useful output unit (CO^*) and decision variables of two policies are found and specifically shown in Table 3.

Table 3 shows that the optimal long-run expected cost of system per useful output unit of *Policy* 0 is 8.8046($/*product*). And it also presents that the optimal long-run expected cost of system per useful output unit of *Policy* 1 is 9.4622($/*product*), which is higher than that of *Policy* 0. Therefore, *Policy* 0 is superior to *Policy* 1 in terms of the long-run expected cost of system per useful output unit. Additional, the optimal decision variables of *Policy* 0 are $\Delta T_1^* = 9$, $\Delta T_2^* = 8.5$, $PP^* = 0.9$, $PC^* = 0.05$, $EEIM_1^* = 2800$(Wh/*product*), $EEIM_2^* = 2750$(Wh/*product*). The optimal decision variables of *Policy* 1 are $\Delta T_1^* = 10.5$, $\Delta T_2^* = 9.5$, $PP'^* = 0.88$, $PC'^* = 0.06$, $M_1^* = 10.5$, $M_2^* = 9$. Table 3 shows that PP^* and PP'^* are both close to 1. It also reveals that PC^* and PC'^* are both close to 0. In general, the value of PP^*, PP'^* should be large enough and the ideal value of them are 1. But the value of PC^*, PC'^* ought to be small enough and the ideal value of them are 0. Thus these results are consistent with actual situation.

Policy	Component	α	β	S	Corrective maintenance threshold	
					$EEIL$	L
Policy 0	component 1	5/7	1/7	500	15000	–
	component 2	9/5	1/5	600		
Policy 1	component 1	5/7	1/7	500	–	40
	component 2	9/5	1/5	600		

Table 1. Parameters for two policies

Policy	Component	c_p	c_c	c_s	Ep	c_{nsp}^E	c_{nsp}^D
Policy 0	component 1	80	150	100	0.025	5	–
	component 2	100	200			10	–
Policy 1	component 1	80	150	100	0.025	–	10
	component 2	100	200			–	15

Table 2. Data of various cost parameters

Policy	CO^*	ΔT_1^*	ΔT_2^*	$EEIM_1^*$	$EEIM_2^*$	M_1^*	M_2^*	PP^*	PC^*	PP'^*	PC'^*
Policy 0	8.8046	9	8.5	2800	2750	–	–	0.9	0.05	–	–
Policy 1	9.4622	10.5	9.5	–	–	10.5	9	–	–	0.88	0.06

Table 3. CO^* and optimal decision variables for two policies

5.2. Sensitivity Analysis

In order to discuss the performance of our new proposed condition-based opportunistic maintenance policy integrated with energy efficiency (*Policy* 0), various sensitivity analyses are carried out in the following.

5.2.1. Sensitivity Analysis to Inspection Costs

It is significant to conduct a sensitivity analysis with various c_{nsp}^{Ei} and c_{nsp}^{Di} (i = 1,2). All simulation results for two policies are given in Table 4.

$c_{nsp}^{E}(c_{nsp}^{D})$ 1	$c_{nsp}^{E}(c_{nsp}^{D})$ 2	Policy	CO^*	ΔT_1^*	ΔT_2^*	$EEIM_1^*$	$EEIM_2^*$	M_1^*	M_2^*	PP^* (PP'^*)	PC^* (PC'^*)
2	5	*Policy* 0	8.4977	8	7.5	2850	2850	–	–	0.88	0.04
		Policy 1	8.6245	8.5	8	–	–	12.5	11	0.88	0.06
5	10	*Policy* 0	8.8046	9	8.5	2800	2750	–	–	0.9	0.05
		Policy 1	8.9229	10	9.5	–	–	11.5	10	0.85	0.05
10	15	*Policy* 0	9.0180	10	9.5	2750	2700	–	–	0.92	0.05
		Policy 1	9.4622	10.5	9.5	–	–	10.5	9	0.88	0.06
20	25	*Policy* 0	9.6227	12	11	2650	2600	–	–	0.9	0.04
		Policy 1	9.9122	12.5	12	–	–	8.5	8	0.85	0.06

Table 4. CO^* and optimal decision variables of two policies with different inspection costs

5.2.2. Sensitivity Analysis to Running Speed

Concerning the simulation analysis and the sensitivity analysis on inspection costs above, we have concluded that *Policy* 0 performs better than *Policy* 1 in terms of the long-run expected cost of system per useful output unit. Since both the energy consumption and useful output are associated with the running speed, this section makes a sensitivity analysis of the running speeds for two policies. All the optimal long-run expected costs of system per useful output unit of two policies are given in Table 5.

As shown in Table 5, when S_i changes, CO^* of *Policy* 0 fluctuates between about 6.5 and 10.5 with $c_{nsp}^{E1}=5, c_{nsp}^{E2}=10$, while corresponding CO^* varies between about 7.0 and 11 with $c_{nsp}^{E1}=10, c_{nsp}^{E2}=15$. However, CO^* of *Policy* 1 fluctuates in the range of about 7.5 and 14.5 as S_i changes. Thus it can be concluded that CO^* of *Policy* 0 is relatively more stable because CO^* of *Policy* 0 varies less than that of *Policy* 1. Therefore, we can conclude that the maintenance decision making by using EEI can lead to a better performance.

In addition, it is very clear that CO^* of *Policy* 0 with $c_{nsp}^{E1}=10, c_{nsp}^{E2}=15$ is higher than that of *Policy* 0 with $c_{nsp}^{E1}=5, c_{nsp}^{E2}=10$ regardless of the values of running speed.

It is significant to notice that CO^* of *Policy* 0 is always lower than that of *Policy* 1 when $c_{nsp}^{Ei} < c_{nsp}^{Di} (i = 1,2)$. It's also true even if $c_{nsp}^{Ei} = c_{nsp}^{Di}$. In summary, *Policy* 0 is superior to *Policy* 1 because *Policy* 0 leads to the lower long-run expected cost of system per useful output unit.

S_i		$CO^*(\$/product)$		
1	2	*Policy* 0		*Policy* 1
		$c_{nsp}^{E1} = 5, c_{nsp}^{E2} = 10$	$c_{nsp}^{E1} = 10, c_{nsp}^{E2} = 15$	$c_{nsp}^{D1} = 10, c_{nsp}^{D2} = 15$
400	600	7.6455	7.80347	8.7666
	700	8.4831	8.6119	8.8434
	750	9.9434	10.1951	10.8663
	850	8.4831	9.0272	14.5072
	1000	9.6817	10.6111	14.1614
500	600	8.8046	9.0180	9.4622
	700	8.9654	10.2676	10.8366
	750	9.3619	9.9996	12.7055
	850	8.6354	9.1769	12.0303
	1000	10.5624	11.0623	13.4347
600	600	8.3897	8.7403	11.0577
	700	8.6236	9.0866	11.1952
	750	8.6893	9.2766	10.5845
	850	9.7666	10.0733	10.8548
	1000	9.6294	10.0372	12.6944
800	600	7.0237	7.1502	7.6482
	700	7.1761	7.9921	9.5943
	750	7.2944	7.4440	8.0494
	850	7.8564	8.2915	12.0556
	1000	8.7939	9.3156	12.8961
1000	600	7.1006	7.4524	8.3809
	700	6.4407	7.2414	9.2648
	750	6.6694	7.3222	10.734
	850	7.9341	8.5943	11.4848
	1000	7.1504	7.4644	13.4993

Table 5. CO^* of two policies with different S_1 and S_2

5.2.3. Sensitivity Analysis to Deterioration Parameter

In the above sections, *Policy* 0 has been justified to perform better than *Policy* 1 in terms of the long-run expected cost of system per useful output unit. This section studies the impact of variation of degradation process denoted by β_i on CO^* in two policies. Table 6 provides all the simulation results.

According to Table 6, as $\beta_i(i = 1,2)$ rise, CO^* of *Policy* 0 increases with various $c_{nsp}^{Ei}(i = 1,2)$, as well as CO^* of *Policy* 1. When $c_{nsp}^{E1} = 5 < c_{nsp}^{D1}$, $c_{nsp}^{E2} = 10 < c_{nsp}^{D2}$, we find that *Policy* 0 always provides lower CO^* than *Policy* 1 with varying $\beta_i(i = 1,2)$. It is significant to notice that the superiority of *Policy* 0 still exists even if $c_{nsp}^{E1} = c_{nsp}^{D1} = 10$ and $c_{nsp}^{E2} = c_{nsp}^{D2} = 15$.

In addition, an interesting outcome about the cost saving between *Policy* 0 and *Policy* 1 has been found. It is shown in the following Figure 5 and Figure 6.

β_i		$CO^*(\$/product)$		
		***Policy* 0**		***Policy* 1**
		$c_{nsp}^{E1}=5, c_{nsp}^{E2}=10$	$c_{nsp}^{E1}=10, c_{nsp}^{E2}=15$	$c_{nsp}^{D1}=10, c_{nsp}^{D2}=15$
1/7	1/5	8.8046	9.0180	9.4622
	4/5	14.2354	15.4097	18.229
	6/5	26.7061	28.9565	39.5396
	8/5	50.4158	55.45636	71.2063
4/7	1/5	10.7715	11.5343	13.3257
	4/5	22.1597	23.1124	26.4622
	6/5	32.0184	33.9808	45.3559
	8/5	57.3448	61.4623	78.736
6/7	1/5	13.3712	13.8403	16.5624
	4/5	24.8793	26.6877	30.6793
	6/5	35.1783	38.3766	51.64895
	8/5	59.5298	64.4372	82.9243
10/7	1/5	18.1974	18.5574	21.7594
	4/5	27.1303	28.3755	33.4511
	6/5	38.4867	41.7915	57.865
	8/5	63.6751	67.7577	89.7444

Table 6. CO^* of two policies with different β_1 and β_2

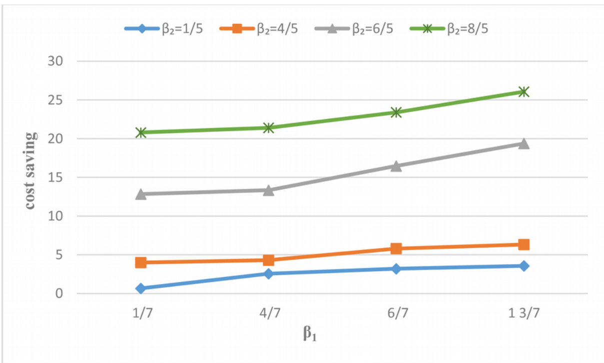

Figure 5. The cost saving with various β_i when $c_{nsp}^{E1}=5$, $c_{nsp}^{E2}=10$

Figure 5 shows that when β_2 is fixed, the cost saving increases as β_1 increases. Similarly, when β_1 is fixed, the larger β_2 the more cost saving is. Moreover, the finding is also suitable for the cost saving when $c_{nsp}^{E1}=c_{nsp}^{D1}=10$ and $c_{nsp}^{E2}=c_{nsp}^{D2}=15$, seeing Figure 6.

Figure 6 reveals clearly that when β_2 is fixed, the cost saving increases gradually as β_1 rises. And it also presents that when β_1 is fixed, the cost saving also increases as β_2 rises.

Above all, larger variation of degradation process (high value of β_i) leads to a higher cost saving even if each energy consumption inspection cost equals to each deterioration inspection cost. To sum up, *Policy* 0 is superior to *Policy* 1 and the superiority of *Policy* 0 rises as β_i increases.

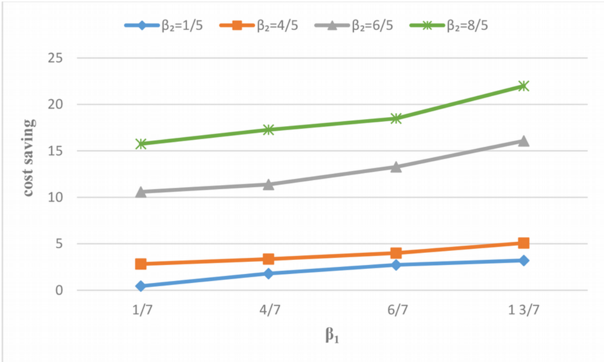

Figure 6. The cost saving with various β_i when $c_{nsp}^{E1} = 10$, $c_{nsp}^{E2} = 15$

6. Conclusion

In the past, some companies would not maintain the components when they could still work, even if these components were gradually in poor state which would increase energy consumption. With the enhanced awareness of energy conservation, it will be an inevitable trend to consider energy consumption in maintenance decision-making. Compared with classical maintenance policy (*Policy* 1), the new proposed maintenance policy (*Policy* 0) in this paper can save total cost including energy cost. The simulation results and sensitivity analyses show that *Policy* 0 always results a lower long-run expected cost of system per useful output unit than *Policy* 1, even if each energy consumption inspection cost equals to each deterioration inspection cost. In addition, *Policy* 0 always performs better than *Policy* 1 regardless of the value of the running speeds. Furthermore, larger variation of deterioration process leads to a higher cost saving of the whole system provided by *Policy* 0 compared to *Policy* 1.

In summary, the new proposed maintenance policy in this paper performs better than the existing maintenance policy, because the new policy can save total cost including both economic and ecological costs. The new proposed policy integrated with energy efficiency in this paper helps enterprises achieve sustainable development. Therefore, in order to establish green images for companies, managers need to consider both economic cost and energy consumption when they make maintenance plans. In addition, they can integrate energy efficiency into maintenance decision-making if possible.

Although the new proposed maintenance policy performs well, there still exists some limitations. With regard to two-component parallel system, this paper only considers the economic dependence. However, stochastic dependence exists in two-component parallel systems. Furthermore, only energy consumption is considered in this paper, which is one of the ecological impacts.

On the basis of this paper, both stochastic and economic dependence will be studied in the future. Our research will also focus on applying the proposed maintenance policy into a more complex system, such as series-parallel system. Other ecological impacts, such as carbon dioxide emissions, will be studied in the future. In addition, indicators that energy efficiency and any other ecological impacts will be taken into maintenance decision-making. This would be a rather interesting research field in the future.

Declaration of Conflicting Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding

The research described in this paper has been funded by the National Natural Science Foundation of China (Grant No. 71302053).

References

Ahmad, R. (2012). A review of condition-based maintenance decision-making. *European J of Industrial Engineering*, 6(5), 519-541. https://doi.org/10.1504/EJIE.2012.048854

Barbera, F., Schneider, H., & Watson, E. (1999). A condition based maintenance model for a two-unit series system. *European Journal of Operational Research,* 116(2), 281-290. https://doi.org/10.1016/S0377-2217(98)00189-1

Bian, L., & Gebraeel, N. (2014). Stochastic modeling and real-time prognostics for multi-component systems with degradation rate interactions. *Iie Transactions,* 46(5), 470-482. https://doi.org/10.1080/0740817X.2013.812269

Bouvard, K., Artus, S., Bérenguer, C., & Cocquempot, V. (2011). Condition-based dynamic maintenance operations planning & grouping. Application to commercial heavy vehicles. *Reliability Engineering & System Safety,* 96(6), 601-610. https://doi.org/10.1016/j.ress.2010.11.009

Castanier, B., Grall, A., & Berenguer, C. (2005). A condition-based maintenance policy with non-periodic inspections for a two-unit series system. *Reliability Engineering & System Safety,* 87(1), 109-120. https://doi.org/10.1016/j.ress.2004.04.013

Cavalcante, C.A.V., & Lopes, R.S. (2014). Opportunistic Maintenance Policy for a System with Hidden Failures: A Multicriteria Approach Applied to an Emergency Diesel Generator. *Mathematical Problems in Engineering.,* 2014(3), 1-11. https://doi.org/10.1155/2014/157282

Chouikhi, H., Dellagi, S., & Rezg, N. (2012). Development and optimisation of a maintenance policy under environmental constraints. *International Journal of Production Research,* 50(13), 3612-3620. https://doi.org/10.1080/00207543.2012.670929

Dao, C.D., & Zuo, M.J. (2017). Selective maintenance of multi-state systems with structural dependence. *Reliability Engineering & System Safety,* 159, 184-195. https://doi.org/10.1016/j.ress.2016.11.013

Dieulle, L., Bérenguer, C., Grall, A., & Roussignol, M. (2003). Sequential condition-based maintenance scheduling for a deteriorating system. *European Journal of Operational Research,* 150(2), 451-461. https://doi.org/10.1016/S0377-2217(02)00593-3

Garg, H. (2014a). A hybrid GA-GSA algorithm for optimizing the performance of an industrial system by utilizing uncertain data *in Handbook of Research on Artificial Intelligence Techniques and Algorithms* (625-659). USA: IGI Global.

Garg, H. (2014b). Reliability, Availability and Maintainability Analysis of Industrial Systems Using PSO and Fuzzy Methodology. *Mapan,* 29(2), 115-129. https://doi.org/10.1007/s12647-013-0081-x

Garg, H. (2016). Bi-criteria optimization for finding the optimal replacement interval for maintaining the performance of the process industries *in Modern Optimization Algorithms and Applications in Engineering and Economics* (643-675). USA.

Garg, H., Rani, M., & Sharma, S.P. (2013). Preventive maintenance scheduling of the pulping unit in a paper plant. *Japan Journal of Industrial & Applied Mathematics,* 30(2), 397-414. https://doi.org/10.1007/s13160-012-0099-4

Garg, H., Rani, M., Sharma, S.P., & Vishwakarma, Y. (2014a). Bi-objective optimization of the reliability-redundancy allocation problem for series-parallel system. *Journal of Manufacturing Systems,* 33(2), 353-367. https://doi.org/10.1016/j.jmsy.2014.02.008

Garg, H., Rani, M., Sharma, S.P., & Vishwakarma, Y. (2014b). Intuitionistic fuzzy optimization technique for solving multi-objective reliability optimization problems in interval environment. *Expert Systems with Applications,* 41(7), 3157-3167. https://doi.org/10.1016/j.eswa.2013.11.014

Garg, H., & Sharma, S.P. (2012). A two-phase approach for reliability and maintainability analysis of an industrial system. *International Journal of Reliability Quality & Safety Engineering,* 19(03), 155-445. https://doi.org/10.1142/S0218539312500131

Garg, H., & Sharma, S.P. (2013). Multi-objective reliability-redundancy allocation problem using particle swarm optimization. *Computers & Industrial Engineering,* 64(1), 247-255. https://doi.org/10.1016/j.cie.2012.09.015

Hoang, A., Do, P., & Iung, B. (2016a). *Prognostics on energy efficiency performance for maintenance decision-making: Application to industrial platform TELMA.* Paper presented at the Prognostics and System Health Management Conference-Beijing.

Hoang, A., Do, P., & Iung, B. (2016b). Investigation on the use of energy efficiency for condition-based maintenance decision-making. *IFAC-PapersOnLine,* 49(28), 73-78. https://doi.org/10.1016/j.ifacol.2016.11.013

Hoang, A., Do, P., & Iung, B. (2017). Energy efficiency performance-based prognostics for aided maintenance decision-making: Application to a manufacturing platform. *Journal of Cleaner Production,* 142, 2838-2857. https://doi.org/10.1016/j.jclepro.2016.10.185

Horenbeek, A.V., Kellens, K., Pintelon, L., & Duflou, J.R. (2014). Economic and Environmental Aware Maintenance Optimization. *Procedia Cirp,* 15, 343-348. https://doi.org/10.1016/j.procir.2014.06.048

Jardine, A.K.S., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems & Signal Processing,* 20(7), 1483-1510. https://doi.org/10.1016/j.ymssp.2005.09.012

Jiang, X., Duan, F., Tian, H., & Wei, X. (2015). Optimization of reliability centered predictive maintenance scheme for inertial navigation system. *Reliability Engineering & System Safety,* 140, 208-217. https://doi.org/10.1016/j.ress.2015.04.003

Keizer, M.C.A.O., Teunter, R.H., & Veldman, J. (2016). Clustering condition-based maintenance for systems with redundancy and economic dependencies. *European Journal of Operational Research,* 251(2), 531-540. https://doi.org/10.1016/j.ejor.2015.11.008

Li, H., Deloux, E., & Dieulle, L. (2016). A condition-based maintenance policy for multi-component systems with Lévy copulas dependence. *Reliability Engineering & System Safety,* 149, 44-55. https://doi.org/10.1016/j.ress.2015.12.011

Mora, M., Vera, J., Rocamora, C., & Abadia, R. (2013). Energy Efficiency and Maintenance Costs of Pumping Systems for Groundwater Extraction. *Water Resources Management,* 27(12), 4395-4408. https://doi.org/10.1007/s11269-013-0423-z

Nguyen, K.A., Do, P., & Grall, A. (2014). Condition-based maintenance for multi-component systems using importance measure and predictive information. *International Journal of Systems Science Operations & Logistics,* 1(4), 228-245. https://doi.org/10.1080/23302674.2014.983582

Noortwijk, J.M.V. (2009). A survey of the application of gamma processes in maintenance. *Reliability Engineering & System Safety,* 94(1), 2-21. https://doi.org/10.1016/j.ress.2007.03.019

Qian, X., & Wu, Y. (2014). Dynamic Control-limit Policy of Condition based Maintenance for the Hydroelectricity Generating Unit. *International Journal of Security & Its Applications,* 8(2), 95-106. https://doi.org/10.14257/ijsia.2014.8.2.10

Shi, H., & Zeng, J. (2016). Real-time prediction of remaining useful life and preventive opportunistic maintenance strategy for multi-component systems considering stochastic dependence. *Computers & Industrial Engineering,* 93, 192-204. https://doi.org/10.1016/j.cie.2015.12.016

Tian, Z., Jin, T., Wu, B., & Ding, F. (2011). Condition based maintenance optimization for wind power generation systems under continuous monitoring. *Renewable Energy,* 36(5), 1502-1509. https://doi.org/10.1016/j.renene.2010.10.028

Tian, Z., & Liao, H. (2011). Condition based maintenance optimization for multi-component systems using proportional hazards model. *Reliability Engineering & System Safety,* 96(5), 581-589. https://doi.org/10.1016/j.ress.2010.12.023

Tlili, L., Radhoui, M., & Chelbi, A. (2015). Condition-Based Maintenance Strategy for Production Systems Generating Environmental Damage. *Mathematical Problems in Engineering,* 2015, 1-12. https://doi.org/10.1155/2015/494162

Wijnmalen, D.J.D., & Hontelez, J.A.M. (1997). Coordinated condition-based repair strategies for components of a multi-component maintenance system with discounts. *European Journal of Operational Research,* 98(1), 52-63. https://doi.org/10.1016/0377-2217(95)00312-6

Xu, W., & Cao, L. (2014). Energy efficiency analysis of machine tools with periodic maintenance. *International Journal of Production Research,* 52(18), 5273-5285. https://doi.org/10.1080/00207543.2014.893067

Zhang, Z., Zhou, Y., Sun, Y., & Ma, L. (2012). Condition-based maintenance optimisation without a predetermined strategy structure for a two-component series system. *Eksploatacja i Niezawodnosc - Maintenance and Reliability,* 14(2), 120-129.

Zhu, Q., Peng, H., & Houtum, G.J.V. (2015). A condition-based maintenance policy for multi-component systems with a high maintenance setup cost. *Or Spectrum,* 37(4), 1007-1035. https://doi.org/10.1007/s00291-015-0405-z

Appendix A

***Policy* 1**

An existed classic condition-based opportunistic maintenance policy is extended by considering the energy consumption during the operation of the whole system. We named the extended classic maintenance policy as *Policy* 1. The maintenance decision rule of *Policy* 1 is similar to that of *Policy* 0. But the nature of *Policy* 1 is that all maintenance activities in this policy are determined by deterioration level of components.

Suppose that the current time is $n\Delta T_1$ as in Figure 3 above (the moment of nth inspection for component 1). Six kinds of maintenance activity in *Policy* 1 are concluded in the following:

- No opportunity of grouping maintenance:

  1. If $X_1(n\Delta T_1) < M_1$ no maintenance activity will be carried out and we need to wait for the next inspection. This means that component 1 still operates well.
  2. If $M_1 \le X_1(n\Delta T_1) < L_1$ and $Pp_2 \le PP'$, only a preventive maintenance of component 1 takes place.
  3. If $X_1(n\Delta T_1) \ge L_1$ and $Pp_2 \le PP'$, only a corrective maintenance action of component 1 is performed. In this situation, we can consider that the component 1 fails.

     Pp_2 represents the probability that a preventive maintenance of component 2 takes place at current time. In this policy, it refers the probability that degradation level of component 2 reaches its preventive maintenance threshold at current time. Obviously, taking a maintenance action of component 2 too early will increase maintenance cost (Pp_2 is too small). Therefore, no maintenance action will take place when $Pp_2 \le PP'$. It's worthy to take group maintenance only when Pp_2 is large enough ($Pp_2 > PP'$).

- Opportunity of grouping maintenance is identified:

  4. If $X_1(n\Delta T_1) < L_1$ and $Pp_2 > PP'$, a corrective maintenance is performed for component 1 and the preventive maintenance is preempted for component 2.
  5. If $M_1 \le X_1(n\Delta T_1) < L_1$, $Pp_2 > PP'$, and $Pc_1 \ge PC'$, a preventive maintenance is performed for component 1 and the preventive maintenance is preempted for component 2.
  6. If $M_1 \le X_1(n\Delta T_1) < L_1$, $Pp_2 > PP'$, and $Pc_1 < PC'$, the preventive maintenance of component 1 is postponed to the next inspection time $(m + 1)\Delta T_2$.

     In this policy, Pc_1 is the probability that component 1 will fail at the next inspection time $(m + 1)\Delta T_2$. An unreasonable postponed maintenance (when Pc_1 is large) maybe take a risk that component may fail before repaired at the next inspection time. If $Pc_1 \rightarrow 1$, then component 1 will hardly fail before the next inspection time. Therefore, the maintenance of component 1 can be postponed only when Pc_1 is small enough ($Pc_1 < PC'$).

     In this policy, the long-run expected cost of system per useful output unit is also Equation (6) above:

$$\min \quad CO = \lim_{t \to +\infty} \frac{C_t}{\phi(t)} \tag{6}$$

Where:

The cumulative useful output of the whole system is Equation (7) above:

$$\phi(t) = (O_1 + O_2)t \tag{7}$$

Cumulative cost of the whole system includes cumulative inspection cost, maintenance cost and energy cost. It depends on the number of deterioration inspection, preventive maintenance and corrective maintenance, as well as total amount of energy consumption. Its mathematic expression is as the following:

$$C_t = \sum_{i=1}^{2} (c_{nsp}^{Di} N_{nsp}^{i} + c_p^i N_p^i + c_c^i N_c^i + c_s (N_p^i + N_c^i) + Ep\int_0^t E_i(t)dx) - c_s N_{GM} \tag{19}$$

It should be noted that the inspection cost of *Policy 1* depends on deterioration inspection operation (c_{nsp}^{Di} in Equation(19)), instead of energy consumption inspection cost(c_{nsp}^{Ei}) in Equation (13).