Reliability Engineering and System Safety 193 (2020) 106625

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A PSO approach for the integrated maintenance model

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ARTICLE INFO

Keyword:
Age reduction
Preventive maintenance
Corrective maintenance
Particle swarm optimization
Maintenance mode

ABSTRACT

To decrease the over-maintenance and under-maintenance phenomenon, this paper examined the relationship between facility reliability and lifespan so as to generate the optimal maintenance plan which includes the proper combination of maintenance time and maintenance modes. An age reduction maintenance model is built to describe the deterioration situation of the port facility, and a particle swarm optimization (PSO) based integrated approach is used to solve the model. The sensitivity analysis helps to determine the maintenance mode combination from which the total maintenance cost is minimized. The result shows that taking multiple maintenance modes into account would help optimize the total maintenance cost. In addition, the obvious difference between the reliability thresholds would assist in providing discrepant maintenance service. The results have indicated that when the thresholds of different maintenance mode are overlapped, the total maintenance cost is the highest.

1. Introduction

In recent years, the port economy gains a prosperous development, and the life cycle of port devices are designed to be longer, making facility management a critical part among the port management stream. The environmental and economic concerns become high, among which, the facility maintenance plays an important role. Most of the port facilities are exposed to a mixed environment of the windy, sunny, salty and high load operation. Any facility is a necessary link in the port operation chain, and the interruption of any link will cause a great damage to the port operation efficiency. Every year, about 11% of operating cost is used for maintenance, and this number has been increasing at an annual rate of 4% in recent years with the increase of port throughput [7]. Furthermore, according to the report on China port development [2], around twelve percent of the port machine OEM's revenue is coming from the maintenance activities, where the maintenance costs for crane are growing at double-digit rate annually [13]. To deal with these growing cost, an appropriate facility maintenance scheduling becomes essential both for port operators and port machine manufacturers.

Normal overcapacity often characterizes port operation due to the high facility cost. This causes port facilities are always operated either far beyond or below their full capacity subjected to the resilient loading plan. Such overcapacity or under-capacity usually results from various facility type and fluctuating workload. The variable facility type results in the wear and tear at varying degrees even when they are assigned the same workload. The workload fluctuation, either due to field dynamics or demand dynamics, leads to strong fluctuation in tear mix and deterioration extent.

Different types of facilities support smooth port operation, while outdoor environments intensifies serious wear and tear on the facility. A common practice is, therefore, to apply maintenance whenever possible to postpone or avoid excessive wear and tear [8]. Since maintenance recovers the reliability in some measures, their consideration has attracted increased attention with highlighted focus on reasonable maintenance mode. Various maintenance modes influence aging rates and thus impacts the next maintenance activities, such as maintenance interval, technique, and cost.

The nature of maintenance encourages highly discrepant maintenance modes to maintain production quality and facility reliability [37]. Preventive maintenance is therefore viewed as the main tool to minimize breakdowns, excessive depreciation and total cost [33]. Facility deterioration is distinguished, thus quick repair can restore specified malfunction to the acceptable tolerance while repair with replacement can improve the reliability into a higher level compared with quick repair at the expense of spare parts. However, an important assumption of repair with replacement is the available spare part inventory. Zahedihosseini et al. [36] pointed out that the cost-optimal maintenance policy is characterized by the frequencies of inspection and spare parts replenishment, thereby influencing the maintenance

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https://doi.org/10.1016/j.ress.2019.106625
Received 24 November 2018; Received in revised form 13 August 2019; Accepted 31 August 2019
Available online 06 September 2019
0951-8320/

intervention. These concerns heighten the need for efficiently planned maintenance activities, which including the interval and mode, so as to maintain the smooth operation at the economic cost.

Many maintenance processes in port are difficult to control and require continuous monitoring before reliability prediction. The implement of preventive activities varies with the time interval of monitoring, which is determined by a reliability criteria [35]. Multiple maintenance modes are therefore required to deal with the unexpected breakdown and the need for considering the spare part availability arises. Substitute maintenance decisions have to be made because the overall maintenance shall coordinate the maintenance resources such as key spare parts, highly skilled technicians, and operation interval. Their availabilities are scarce and must be economically scheduled.

As maintenance mode interacted with improved reliability, maintenance activities must consequently be made according to the field activities. The field constraints especially the operation workload complicated the scheduling of maintenance, therefore, multiple maintenance modes will provide a way to coordinate maintenance scheduling with the port service flow.

To simplify maintenance scheduling, most existing literature considers only one type of maintenance mode. Sometimes the maintenance is treated as a deformation of production, which is transferred as one of the regular production constraints. Moreover, the existing literature does not adequately reflect the characteristics of port facility maintenance. Port facilities subject to high load and deterioration require flexible schedule which implies multiple maintenance modes.

In this paper, we propose an improved PSO approach for maintenance scheduling that contributing to the research in several ways: First, we consider multiple types of maintenance activities, which including preventive maintenance and corrective maintenance. Second, we extend the maintenance type into maintenance modes which including maintenance with and without replacement. Third, we conduct sensitivity analysis by considering the reliability threshold for different maintenance mode. Finally, based on industry data, the numerical tests show the applicability of the improved PSO approach, and we applies an industry case study to validate both for small size problem and large size problem.

The reminder of the paper is organized as follows. Section 2 presents related studies on maintenance strategies and maintenance mode. Section 3 constructs an integrated maintenance model. In Section 4, an improved PSO approach is presented. Section 5 validates the proposed method with numerical experiments where both small-size problem and large-size problem are tested. In addition, sensitivity analysis is provided to find the optimal maintenance threshold for different maintenance modes. The conclusion is summarized in Section 6.

2. Literature review

2.1. Maintenance strategies

Gaining widespread attention recently with the focus of production efficiency, the study of maintenance led to the fairly fundamental reading of the operation process. Though maturing as an independent subject named as Total Productive Maintenance (TPM) in the 1960s with the rise of total quality management [4], the origins of maintenance can be traced to the breakdown/corrective maintenance where corrective action is applied on failure. With the inspection and prediction techniques such as electronic detecting, integration testing and computerized detection begin to influence the way maintenance was managed [20], propelled over a number of years by a series of innovations, TPM evolved into Condition based maintenance (CBM) [15]. CBM is capable of identifying fault based on actual condition obtained from in-situation, no-invasive tests operating and condition measurement. Therefore, CBM enjoys the benefits of efficiency, capital saving, and failure reduction. Recently, the concept of predictive is added to CBM and formed the proactive maintenance [11], which tries to identify, monitor and control failures through an emphasis on understanding and elimination of the cause of failure. The proactive maintenance activities include the development of design specifications, root cause failure analysis, and development of repair specifications [23]. Operating equipment asset management shall use concept and ideas from all types of maintenance and assemble them in a mix according to the practical requirements.

As a supplement of production, maintenance makes the production operation running efficiently [31]. Although influenced at its initial stage by mass-production, the evolution of maintenance is very much shaped by the economic concern, the market competition, constraints of the resource allocation, the feature of the facility, and the very specific skills of the workforce. Unlike mass production system which are designed to deal with batches of similar configurable products, maintenance system accesses to small number of facilities that are individually deteriorated and was therefore forced to provide a dedicated service to undertake the restoration of facilities [1], which would have impact on the production capacity of the system. This was in contrast to the mass manufacturing focus where access to an extensive market that required with large volumes of less differentiated products, which thus calls for the uniformity of the most economic production mode. In addition, the service nature of maintenance encouraged efficiency by offering multiple modes to differentiate the products while complexing the associated cost. Furthermore, the maintenance was conducted by well-trained workforce where not all workers were educated to undertake the same level of maintenance tasks. This results in the maintenance system to condition focused and enabled by the existence of multiple maintenance modes. Therefore, maintenance mode represents a new thinking when subjects to the limited maintenance resources on site. However, the research on maintenance mode remains scarcity.

2.2. Maintenance mode

Different types of maintenance will have different protection against failure. Differentiated by the implementation time, maintenance can be of two types: preventive maintenance (PM), i.e. before the failure, and corrective maintenance (CM), i.e. after the failure. As the purpose of PM is to maintain the facilities in a satisfying operating condition, a series of restoration is provided such as testing, measurement, adjustments, parts replacement, and cleaning. The scheduling of PM is usually related to production concern. One way of PM schedule is to treat maintenance tasks as a constraint of production and insert them into the pre-schedule production jobs [16]. The second approach is to separately arrange the production and maintenance ([3,5,17,25]; and [26]). Another way is to integrate production and maintenance and simultaneously optimize them ([18,21,24,27,28]; Mifadal et al., 2015; [6,9]). However, no matter which way is taken, PM cannot perfectly restore the machine to the brand new condition and machine keeps degrading [12]. In addition, too frequent preventive maintenance would inevitably lead to the increase of the failure frequency with the aging of equipment [38]. Therefore, CM is used as a means to increase productivity by restoring the breakdown facilities to an operational condition, and it has gained attention [22,29]. The implementation of CM is a step-by-step procedure: diagnosis, part elimination, part repair or replacement, the test of function, and continuation of use. The majority of the CM studies were undertaken to test different CM policies or strategies, few are dedicated to analyzing the relationship between PM and CM [32,34]. Therefore, both PM and CM possess multiple maintenance modes. However, few works have come to realize this point, and even analyze the impact of maintenance mode on maintenance schedule. So far, few work has taken multiple maintenance modes into account when conducting schedule. To bridge the gap, this research would involve multiple maintenance modes in both the PM and CM. There are other differences between our research and the aforementioned studies. First, the aforementioned studies did not consider all the generic maintenance modes, while we do. Second, unlike the aforementioned studies that focused on model building and simulation validation, we based our model validation on a real case study. Few empirical studies have been conducted concerning the maintenance management in the port operation. The interest of this paper is in exploring the combination of multiple maintenance modes that leading to effective port facility management performance.

3. An integrated maintenance model

This section introduces the proposed integrated age reduction model for maintenance problem with multiple maintenance modes consideration. As different maintenance types bring different protection against failure, the objective of the proposed model is to minimize the total maintenance cost, which includes two decisions: *when* will the maintenance been carried out and under *what* kind of maintenance mode. The former is used to know whether the maintenance happens before or after the failure, i.e. preventative maintenance or corrective maintenance, whereas the latter is to further determine the exact maintenance mode, i.e. maintenance with or without replacement.

Though the whole planning horizon is continuous, this model assumes it is finite and composed of multiple periods. Thus reliability of the subsequent facility is impacted by the precedent maintenance decisions. Under this condition, the facility management is confronted with a problem of maintenance time and maintenance mode. Though preventive maintenance can maintain the facility in a satisfactory operating condition, imperfect preventive maintenance action can only restore the facility into the previous condition and the accumulated deterioration may later cause a severe breakdown. Subjected to the parts availability and economical consideration, there are different corrective maintenance approaches to restore the facility to an in-service condition within tolerances or established limits.

To understand the impact of different maintenance mode on the facility reliability, we first examine the relationship between the maintenance and facility reliability. According to McCool [19], Weibull distribution is popularly applied to describe the facility reliability changes which fits the bathtub curve. Therefore, the probability density function (PDF), as f(t) is set as the fraction of time

$$f(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \times e^{-\left(\frac{t}{\eta}\right)^{m}} \quad (m, \eta > 0) \tag{1}$$

where m is the shape parameter and η is the scale parameter of the Weibull distribution. The cumulative density function (CDF), as F(t) is set as

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{m}} \quad (m, \eta > 0) \tag{2}$$

Then the reliability function is expressed as

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\eta}\right)^{m}} \quad (m, \eta > 0) \tag{3}$$

The failure rate function is deduced as

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \quad (m, \eta > 0) \tag{4}$$

Combining Eq. (3) and (4), the reliability function can also be depicted as

$$R(t) = e^{-\int_0^t \lambda(t)\mathrm{d}t} \tag{5}$$

Taking reference to the age reduction theory of Malik (2007), the outcome of the maintenance is the improved failure rate depends on the taken maintenance mode. After the i^{th} preventive maintenance, the failure rate is expressed as

$$\lambda_{i+1}(t) = \lambda_i(t + \theta T_i), \quad t \in (0, \ T_{i+1}) \tag{6}$$

where θ is the age reduction factor $(0 < \theta < 1)$, T_i is the i^{th} maintenance cycle, λ_i is the corresponding failure function while λ_{i+1} is that of the $(i+1)^{th}$ cycle. Assume there are two levels, i.e. PM_1 and PM_2, of preventive maintenance which can extend the facility reliability at different extent. Therefore, the age reduction factor for the two levels of preventive maintenance are indicated as $\theta_1$and θ_2, and δ_{ji} means the age reduction effect under a different level of preventive maintenance, which is the product of age reduction factor θ_i and facility working time ε_j, so

$$\delta_{ji} = \theta_i^* \ \varepsilon_j \tag{7}$$

where j is the maintenance cycle and $j = 1, 2, \ldots, n$.

Therefore, Eq. (6) can be updated as

$$\begin{aligned} &\lambda 1(t) = \lambda 0(t) \\ &\lambda 2(t) = \lambda 1(t + \varepsilon 1 - \varepsilon 1\theta i) = \lambda 0[(t + (1 - \theta i)\varepsilon 1] \\ &\lambda 3(t) = \lambda 2(t + \varepsilon 2 - \varepsilon 2\theta i) = \lambda 0[(t + (1 - \theta i)\varepsilon 1 + (1 - \theta i)\varepsilon 2] \\ &\cdots \\ &\lambda j(t) = \lambda 0[t + \textstyle\sum_0^{j-1}(1 - \theta i)\varepsilon j] \end{aligned} \tag{8}$$

Substituting Eq. (8) into Eq. (5) and the final reliability function is expressed as

$$Rj(t) = \exp\left(-\int_0^t \lambda j(t)\mathrm{d}t\right) = \exp\left(-\int_0^t \lambda 0\left[t + \sum_0^{j-1}(1 - \theta i)\varepsilon j\right]\mathrm{d}t\right) \tag{9}$$

Assumptions about the integrated maintenance problem are listed as follows:

- The facility works from brand-new and gradually tears out.
- The capacities of both preventive and corrective maintenance are limited and assumed to be fixed.
- All cost parameters and fixed costs are known in advance and assumed to be deterministic.
- The maintenance time shall be arranged between the operational intervals; otherwise, the tardiness would cause operation penalty.
- The age reduction rate is positively related to the preventive maintenance cost.
- The recovery effect of PM_2 is better than that of PM_1, thus $\theta_1 < \theta_2$.
- Preventive maintenance is carried out according to the monitored facility reliability. Compared with the reliability threshold, when the reliability change is less than 20%, the alarm would call and PM_2 is conducted; otherwise, PM_1 is taken.
- Maintenance with replacement is allowed and the inventory of the spare parts is not taken into consideration.

Notations

Symbol	Meaning
[0, L]	The facility finite working period
C_p	Total preventive maintenance cost
C_{pm_1}, C_{pm_2}	Unit cost of PM_1 and PM_2
C_c	Total corrective maintenance cost
C_{cm_1}, C_{cm_2}	Unit cost of CM_1 and CM_2
C_{fp}	Total penalty cost
C_{fpd}	Unit penalty cost for maintenance tardiness
$G(t)$	Time distribution function of CM_2
$g(t)$	The time Probability density function of CM_2
k, k_1, k_2	The number of time that CM, CM_1, CM_2 is carried out responsively
m, η	Shape parameter and scale parameter of the Weibull distribution
a,b	Parameters of fixed cost and variable cost for preventive maintenance
n, n_1, n_2	The number of time that PM, PM_1, PM_2 is carried out responsively
N	The number of maintenance task
$R(t)$	Reliability function of the facility
$R_j(t)$	Reliability function during the during the j^{th} PM interval
R_l	Lower bound of the facility reliability
t_j	Time to conduct the j^{th} PM
TC	Total maintenance cost
T_{cm_1}	Average time for CM_1
α	Time threshold for CM_1

δ_{ji}	Age reduction volume after the j^{th} PM, $j = 1, 2, \ldots$, n, and $i = 1$ or 2
ε_j	The time interval for PM, $j = 1, 2, \ldots$, n
θ_i	Age reduction factor for PM, $i = 1$ or 2
$\lambda_0(t)$	The initial failure rate function
$\lambda_j(t)$	Failure rate function during the j^{th} PM interval
μ_1, μ_2	Lower and upper threshold for preventive maintenance
υ	The threshold for corrective maintenance
ϕ	The coefficient of tardiness for CM_1, $\phi = 0$ or 1

Therefore, the objective of the maintenance problem is to minimize the total maintenance cost, i.e. Eq. (10), which is composed of the preventive maintenance cost, corrective maintenance cost, and the penalty cost for maintenance tardiness.

$$TC = C_p + C_c + C_{fp} \tag{10}$$

3.1. Preventive maintenance cost

As mentioned above, the age reduction volume δ_{ji} is positively related to the preventive maintenance cost, which can be expressed as the sum of fixed cost and variable cost. So

$$CPM_i = a_i + b_i\delta_{ji} = a_i + b_i\theta_i\varepsilon_j \tag{11}$$

where $i = 1$ or 2, $j = 1, 2, \ldots$, n, $a_i > 0, b_i > 0$, and $a_2 > a_1$.

The selection of PM mode is decided by the reliability change range of the facility. For example, when $R_j(t) \in (R_l, R_l + 20\%]$, PM_1 is selected; otherwise, when $R_j(t) \in (0, R_l]$, PM_2 is applied. The setting of 20% is based on the simulation results from practical data. The total preventive maintenance cost is revised as

$$Cp = \sum_0^{n_1} n_1 CPM_1 + \sum_0^{n_2} n_2 CPM_2 = \sum_0^{n1} n_1(a_1 + b_1\theta_1\varepsilon_j) + \sum_0^{n2} n_2(a_2 + b_2\theta_2\varepsilon_j) \tag{12}$$

3.2. Corrective maintenance cost

We use average corrective maintenance cost to simplify the model according to the historical CM record. So the total corrective maintenance cost is the sum of CM_1 and CM_2, and it is expressed as

$$Cc = CCM_1 \times k_1 + CCM_2 \times k_2 \tag{13}$$

where the number of corrective maintenance k is deduced by Eq. (8).

$$k = \sum_{j=1}^{n} \int_0^{\varepsilon j} \lambda j(t)\mathrm{d}t = \sum_{j=1}^{n} \int_0^{\varepsilon j} \lambda 0\left[t + \sum_0^{j-1}(1 - \theta i)\varepsilon j\right]\mathrm{d}t \tag{14}$$

where $\int_0^{\varepsilon j} \lambda j(t)\mathrm{d}t$ is the cumulative number of corrective maintenance during the j^{th} PM interval.

3.3. Tardiness penalty cost

As preventive maintenance is arranged during the operation interval and corrective maintenance with replacement (CM_2) is conducted by replacing the tear-out parts, only CM_1 may cause the extra operation interruption, thus tardiness penalty cost is influenced by the required time of CM_1 and it is depicted as

$$Cfp = Cfpd\left[\left(\int_\alpha^\infty \phi(t - \alpha)g(t)\mathrm{d}t\right)k_1\right] \tag{15}$$

Where ϕ equals to 1 when it is tardy; and 0 otherwise. The value of ϕ is decided by

$$\phi = \begin{cases} 1 & when\ t - a > 0 \\ 0 & when\ t - a \le 0 \end{cases} \tag{16}$$

According to the above explanation, the objective function is updated as minimizing the total maintenance cost:

$$\min TC = \min(Cp + Cc + Cfp) = \min\{[\textstyle\sum_0^{n1} n_1(a_1 + b_1\theta_1\varepsilon_j) + \sum_0^{n2} n_2(a_2 + b_2\theta_2\varepsilon_j)] + (CCM_1k_1 + CCM_2k_2) + Cfpd\,[(\int_\alpha^\infty \phi(t - \alpha)g_1(t)\mathrm{d}t)k_1]\} \tag{17}$$

s.t.

$$0 < \sum_1^n \varepsilon_j \le L \tag{18}$$

$$\lambda 0(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \tag{19}$$

$$m > 0, \eta > 0 \tag{20}$$

$$0 < \theta i \le 1 \tag{21}$$

$$0 < \mu 1 < \mu 2 < 1,\ \ 0 < \upsilon < 1 \tag{22}$$

$$R_j(t) \ge R_l \tag{23}$$

$$0 < CPM1 < CCM1 < CPM2 < CCM2 \tag{24}$$

Constraint (18) stipulates that all maintenance should happen in the determined time. Eq. (19) indicates the initial failure rate function. Constraints (20) define the Weibull parameters and Constraint (21) restrains the age reduction factor. Constraints (22) make sure the upper bound of PM threshold is larger than that of lower bound while constraint (23) restricts the threshold of CM. Constraint (24) sets the unit cost relationship among different modes of maintenance.

4. An improved PSO

Particle swarm optimization (PSO) is one of the newest methods in meta-heuristics that was suggested and developed by Kenndy and Eberhart [14]. This method is based on synchrony of bird flocking behavior where the optimal solution is rooted in an appropriate distance among neighbors. Similar to genetic algorithm, the PSO is a population-based algorithm [10], where the next generation is relied on two props: nearest neighbor velocity and its current position. Assume the solution space is D-dimension, and the solution cluster is composed of m particles. The position of the i[th] particle is represented as $x_i = (x_{i1}, x_{i2}, \ldots, x_{id})$ and its velocity is expressed as $p_i = (p_{i1}, p_{i2}, \ldots, p_{id})$. The current best position so far is recognized as $p_g = (p_{g1}, p_{g2}, \ldots, p_{gd})$. The propagation of the new generation is conducted according to the following equations:

$$v_{iD}^{k+1} = v_{iD}^k + c_1r_1(p_{iD}^k - x_{iD}^k) + c_2r_2\left(p_{gD}^k - x_{iD}^k\right) \tag{25}$$

$$x_{iD}^{k+1} = x_{iD}^k + v_{iD}^{k+1} \tag{26}$$

where k is the number of iteration; c_1 and c_2 are the learning factors and $c_1, c_2 \in [0, 4]$, which demonstrate the ability of self-learning and group-learning. r_1 and r_2 ($r_1, r_2 \in [0, 1]$) are the pseudo random numbers which are set to keep the variety of particles.

In order to improve the convergence of PSO, the inertia concept is added by Shi and Eberhart [30] to show the inherited velocity from the current particle. The value of the inertia factor can be adjusted to balance the search in the overall space or local space. Therefore, Eq. (25) is updated into

$$v_{iD}^{k+1} = \omega v_{iD}^{k} + c_1 r_1 (p_{iD}^{k} - x_{iD}^{k}) + c_2 r_2 \left(p_{gD}^{k} - x_{iD}^{k}\right) \tag{27}$$

In Eq. (27), the velocity of the next particle consists of inertia, self-learning and group learning. The steps of PSO are explained as follows:

Step 1 Initialize the particles, which include the velocity and position.
Step 2 Calculate the fitness value of each particle, and assess the current best position.
Step 3 Compare the current fitness value with the historical best value *pbest*$_i$, if better, replace the current best position; otherwise, move to the next step.
Step 4 Compare the current local best fitness value *pbest*$_i$with the overall best fitness value *gbest*, if better, update the overall best position.
Step 5 Iterate the loop a dupdate the velocity and position of each particle.
Step 6 If termination criteria are reached, stop the search; otherwise return to step two.

The real numbers are used to encode the maintenance tasks. Assume there are n maintenance tasks, and each particle position X is expressed as any sequence of these maintenance tasks. The velocity $v_i^{k=1}$ is explained as the chance of particle position movement which is restricted in the range [0, 1]. Thus the position of the particles is expressed as

$$X = [J_1, J_2, J_3 ..., J_N],\ \forall\ J_i \in [1, 2, 3, ..., N] \tag{28}$$

and

$$\begin{cases} Xi \neq Xj, & i \neq j \\ Xi = Xj, & i = j \end{cases} \tag{29}$$

The probability of the particle movement is formated as

$$Swap(v_{iD}^{k+1}) = \frac{|v_{iD}^{k+1}|}{n} \tag{30}$$

Take Fig. 1 as an example, 50 maintenance tasks are encoded. The i^{th} position has a velocity of 40 with 70 as the fitness value. When the random generated pseudocode is less than 0.8, this position will exchange with the one that has the best fitness value so far, which is 40 here. Therefore, the updated position is recognized as $X + V$. In addition, when any particle has the similar sequence with that of the local neighbors, the improved PSO will randomly exchange any two positions in the sequences.

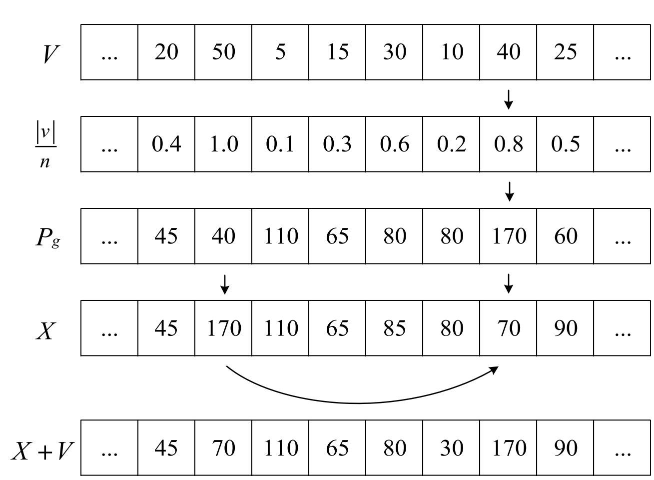


Fig. 1. The example of position update.

5. Computational experiments

To validate the proposed model, this section demonstrated a case company that carried out multiple maintenance modes to the port gantry crane. Two levels of preventive maintenance and corrective maintenance are conducted. PM_1 includes clearing, bolt fastening, mechanical lubrication, crack inspection, distortion recovery and etc. PM_2 includes cable replacement, engine refurbishment, rubber ring replacement, piston refurbishment, and spare parts replacement. Repairing dysfunctional spare parts is recognized as CM_1 while CM_2 applies replacement instead of repair.

The inputted parameters for the test are summarized in Table 1. The parameter setting of PSO is based on preliminary test where Appendix 2 shows the convergence situation when $n = 20$.

Two sets of experiments are conducted to prove the stability and efficiency of the proposed method. Experiment 1 shows the small size problem where the result of PSO is compared with that of the exact method. Experiment 2 refers to large size problems and the focus of the experiments is to analyze the effect of multiple maintenance modes.

5.1. Experiment 1

In experiment 1, Lingo is used to settle the same problem as the benchmark. Fig. 2 shows the optimal total maintenance cost when the maintenance tasks range from 5 to 12. However, when the maintenance task number is more than 10, the computational time of the exact method is more than 6 h, thus its result cannot have the fine timeliness. Generally, the comparison results show that both methods can find the optimal solutions, and the total maintenance cost as well as the number of maintenance increases with the increase of maintenance tasks. This trend is obvious with regard to all the number of maintenance modes except the mode of corrective maintenance with replacement, i.e. CM_2. This is because there is no much workload to tear out the facility for the small scale problems so that the expensive CM_2 can be reimbursed by frequent preventive maintenance. Furthermore, due to the replacement action, the recovery effect of PM_2 is better than that of PM_1, and the facility can be restored and continue to function at a higher reliability condition.

Table 2 demonstrates the detailed plan of the maintenance including the arrangement of maintenance time and mode. On one hand, the results show that the required maintenance time varied according to the assigned workload. The more workload, the more requirement of preventive maintenance. Especially the required number of PM_1 is positively related to the increase in maintenance tasks. As mentioned before, there is no such effect for the corrective maintenance with replacement. This is because that the expensive unit cost of CM_2will hinder its adoption. On the other hand, the time of the occurrence of PM_2 is around [1200, 1500] hours (see Fig. 3), for example, therefore, the inventory management can be implemented accordingly to control the preparation of the spare parts.

5.2. Experiment 2

To simulate the large scale problem as in Experiment 2, the number of maintenance tasks is increased at the scale step of 10 and stopped till 100 because the total maintenance time for 100 maintenance tasks is more than two years. As a result, Table 3 demonstrates the detailed maintenance plan of the near-optimal solutions.

In order to validate the performance of PSO, another population based metaheuristic, i.e. Genetic Algorithm (GA) is applied for the same question and the results comparison is summarized in Table 4. The parameter setting of GA is based on the preliminary test and listed as follows. The encoding approach for GA is integer encoding, and Goldberg's partial mapped crossover operator is applied with crossover rate 0.6. Meanwhile, mutation operator with mutation rate 0.2 is used. The stopping criteria for GA is 200 generations.

Table 1
Parameter input.

Parameter type	Parameter value	Parameter type	Parameter value
Weibull distribution	$m = 2$, $\eta = 1000$	Penalty cost for tardiness	$c_{fpd} = 10000$
Age reduction factor	$\theta_1 = 0.7$, $\theta_2 = 0.9$	Workload distribution	Discrete random distribution [100, 399]
Time threshold of CM_1	$\alpha = 4$	Learning factor	$c_1 = c_2 = 2$
Cost of corrective maintenance	$C_{CM1} = 3000$, $C_{CM2} = 10{,}000$	Inertia factor	$w = w_{\max} - (w_{\max} - w_{\min})*\frac{g}{T_{\max}}$
Stopping criteria for PSO	180	Inertia threshold	$w_{\max} = 0.9$, $w_{\min} = 0.4$
Threshold of maintenance	$\mu_1 = 0.6$, $\mu_2 = 0.8$ $v = 0.2$	Cost of preventive maintenance	$C_{PM1} = 1000+20\theta_1\varepsilon_j = 1000+14\varepsilon_j$, $C_{PM2} = 6000+20\theta_2\varepsilon_j = 6000+18\varepsilon_j$
Average CM_1 time	$T_{cm_1} = 2$	Maximal iteration number	$T_{\max} = 10{,}000$

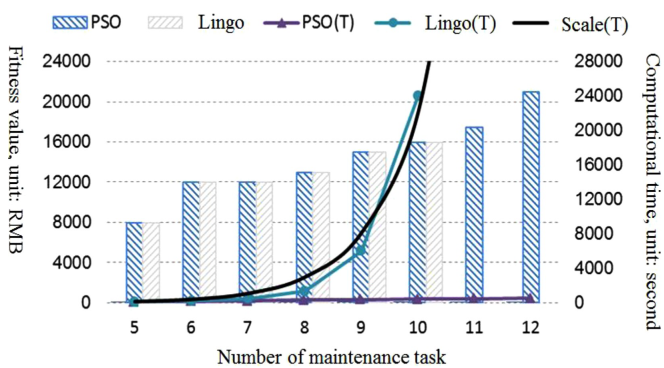


Fig. 2. Comparison between the exact method and the improved PSO.

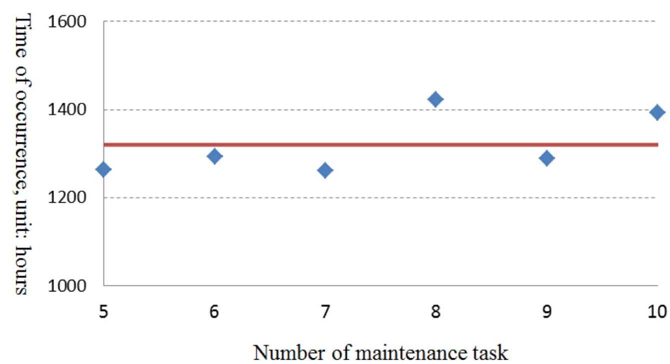


Fig. 3. Time of occurrence of PM_2.

From the results comparison, it is obvious to found that for mediate size problems, the solution differences between PSO and GA are still acceptable. When the problem size increases, PSO can obtain much better results than GA. With regard to the computational time, the tumbles of GA's computational efficiency weaken the reliability and competitiveness of such algorithm. The potential reason behind it may lies in the population generation rational of GA which is heavily relays on the previous quality of parent generation. Moreover, the maintenance mode impacts the reliability of subsequent tasks, which alters the actual number of scheduling tasks. When these two factors accumulated, the computational time increases sharply and the solution worsens.

Going through the results of large scale problems, it is found that the required number of maintenance increases with the expansion of problem size. The increased velocity of $PM_1$is faster than that of the other maintenance modes. This is due to the fact that with the facility age accumulated, the system calls for effective maintenance to delay the function failure. Moreover, the popularity of applying PM_1 can be explained as the cost setting of maintenance mode which can quickly restore the deterioration and not interrupt the regular operation

Table 2
Small scale problem results.

# of Task *N*	Maintenance mode *Mmin*/ time		Maintenance time of occurrence/h t_1/h	t_2/h	t_3/h	t_4/h	t_5/h	t_6/h	t_7/h	t_8/h	t_9/h	Workload assignment	Maintenance sequence
5	PM_1	2	669	866	–	–	–	–	–	–	–	197,370,398,325,299	2–5–1–3–4
	PM_2	1	–	–	1264	–	–	–	–	–	–		
	CM_1	0	–	–	–	–	–	–	–	–	–		
	CM_2	0	–	–	–	–	–	–	–	–	–		
6	PM_1	3	616	–	1094	–	1530	–	–	–	–	338,273,199,278,237,205	1–4–6–2–3–5
	PM_2	1	–	–	–	1293	–	–	–	–	–		
	CM_1	1	–	763	–	–	–	–	–	–	–		
	CM_2	0	–	–	–	–	–	–	–	–	–		
7	PM_1	3	617	871	–	–	1635	–	–	–	–	102,272,292,325,109,145,390	4–3–5–6–7–1–2
	PM_2	1	–	–	–	1261	–	–	–	–	–		
	CM_1	1	–	–	995	–	–	–	–	–	–		
	CM_2	0	–	–	–	–	–	–	–	–	–		
8	PM_1	4	369	745	1074	–	–	1998	–	–	–	110,347,211,266,329,348,229,158	8–3–1–4–5–6–2–7
	PM_2	1	–	–	–	–	1422	–	–	–	–		
	CM_1	1	–	–	–	1156	–	–	–	–	–		
	CM_2	0	–	–	–	–	–	–	–	–	–		
9	PM_1	6	650	903	–	–	1990	2301	2436	2561	–	382,253,135,318,125,311,371,279,387	8–7–2–9–4–1–6–3–5
	PM_2	1	–	–	–	1290	–	–	–	–	–		
	CM_1	1	–	–	982	–	–	–	–	–	–		
	CM_2	0	–	–	–	–	–	–	–	–	–		
10	PM_1	7	523	863	1008	–	–	1914	2300	2544	2695	227,243,386,151,386,244,340,347,176,145	8–9–7–10–3–2–1–5–6–4
	PM_2	1	–	–	–	–	1394	–	–	–	–		
	CM_1	1	–	–	–	1058	–	–	–	–	–		
	CM_2	0	–	–	–	–	–	–	–	–	–		

Table 3
Large scale problem results of PSO.

Number of task N	Total maintenance time/h	Minimized maintenance cost Zmin/RMB	Number of maintenance when cost is optimized/times				Total number of maintenance/time	Computational time/ second
			PM_1	PM_2	CM_1	CM_2		
10	2634	16,000	7	1	1	0	9	64.085
20	4775	35,000	11	3	2	0	16	126.452
30	7511	63,000	14	4	5	1	24	185.703
40	9479	77,000	22	5	5	1	33	231.738
50	11,250	93,000	28	5	5	2	40	280.488
60	15,337	137,000	34	6	9	4	53	358.426
70	17,879	163,000	38	7	11	5	61	461.321
80	20,947	195,000	44	10	17	4	75	536.379
90	22,131	204,000	52	10	14	5	81	590.644
100	24,137	226,000	56	11	18	5	90	671.94

Table 4
Results comparison for PSO and GA.

Task number	Near-optimal results		Computational time (seconds)	
	PSO	GA	PSO	GA
10	16,000	16,000	64.085	98.052
20	35,000	36,819	126.452	566.172
30	63,000	66,897	185.703	858.875
40	77,000	241,010	231.738	2001.167
50	93,000	468,450	280.488	3865.097
60	137,000	954,030	358.426	4592.026
70	163,000	164,390	461.321	5331.257
80	195,000	264,090	536.379	5769.567
90	204,000	436,560	590.644	6747.051
100	226,000	635,860	671.94	7604.423

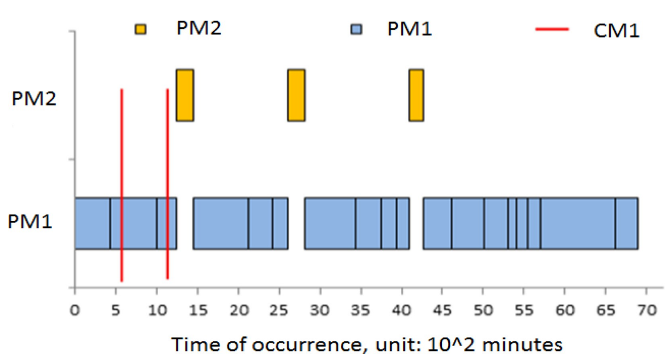


Fig. 4. The detailed maintenance plan when $n = 30$.

without much investment. Looking into a detailed maintenance plan ($n = 30$) that is shown in Fig. 4, it is found that the saving of cost lies in the arrangement of PM_1 at the maintenance cycle and during the off-hour.

In order to measure the effect of multiple maintenance modes, experiments are conducted to compare the necessity of two maintenance strategies. The aim of the comparison is to minimize the over-/under-maintenance. Thus Strategy A applies the four maintenance modes and strategy B contains only PM_1, CM_1 and CM_2. The results in Table 5 show that the total maintenance cost of Strategy A is generally better than that of Strategy B. We speculate that the reason for this result is the refined maintenance mode can save more cost with barely more times of maintenance. In addition, the total number of maintenance mode with replacement is almost the same for both strategies.

To further explore the reasons behind it, the detailed maintenance plan ($n = 20$) that is showed in Table 6. Overall, the arranged maintenance time of Strategy A is earlier than that of Strategy B, and the required number of maintenance is less. This result is linked to the segmented maintenance threshold of Strategy A that generates earlier inspection to figure out the deteriorating facility condition and take the necessary actions to prolong the facility life. Take the maintenance sequence 6 to 8 as an example (the bold letters), Strategy A firstly arranged maintenance task no. 2 to CM_1 at time 2060 in order to restore its failure, which would retain the facility reliability into the previous condition before failure. After that, PM_1 is allocated at time 2381 to improve the reliability. Thus maintenance task number 7 just needs one PM_2 at time 2595 to make sure the whole system works. On the contrary, in the same sequence, Strategy B required a costly CM_2 to achieve the same result which also interrupted the predetermined workload. Therefore, Strategy A enjoys a cheaper total maintenance cost due to the accurate maintenance mode as well as less workload interruption.

5.3. Sensitivity analysis

As the decision of the exact maintenance mode is made in accordance with facility reliability. The setting of the reliability threshold would be the key to determine the proper maintenance mode. Therefore this section will conduct the sensitivity analysis for three maintenance thresholds (i.e. μ_1, μ_2, and v). Based on the foregoing experiments, the tested ranges for μ_1 μ_2, and $v$are [0.3, 0.6), [0.7, 0.9], and [0.1, 0.3] respectively. The tested maintenance task number is 60. Experiment results are recorded in Appendix 1 where there are 36 combinations.

The results suggest that when $\mu_1 = 0.4$, $\mu_2 = 0.7$ and $v = 0.2$ (the bold letters), the total maintenance cost is minimum. When $v = 0.1$ any combination of the other parameters would cause stable and near-optimal results. Analyzing the parameter combination of the thresholds that generates the minimum or near-minimum cost, it is found that there is a clear threshold distinction between the parameters. To the opposite, when PM and CM share the same threshold like case #6, the total maintenance cost is the highest. The reason for this result is twofold. First, as the decision of maintenance mode is based on the facility reliability, the facility management is inclined to use effectively while costly maintenance action without much consideration of the cost and operation interruption penalty. Second, strict and low reliability threshold of corrective maintenance would restrain the adoption of expensive and sophisticated corrective maintenance because it is unnecessary to recover the facility to an as-good-as-new condition in most cases.

Looking into the individual thresholds, their relationship with the total maintenance cost is illustrated pairwisely in Fig. 5. Fig. 5a shows that when $\mu_1 > v$, with the increase of the lower PM threshold, the reliability of the facility has greatly been improved and the required corrective maintenance has been suppressed. In Fig. 5b, the total maintenance cost of $v = 0.3$ is more fluctuated compared with that of the other parameter values, and there is no much cost difference between the cases of $v = 0.1$ and $v = 0.2$. Similar results can be found in

Table 5
Cost analysis under two maintenance strategies.

Strategy	Number of task N	Total maintenance time/h	Minimized maintenance cost Zmin/ RMB	Number of maintenance when cost is optimized/times PM_1	PM_2	CM_1	CM_2	$PM_2 + CM_2$/times
A	10	2562	15,000	6	1	1	0	1
B	10	2562	16,000	6	–	0	1	1
A	20	5344	39,000	12	3	3	0	3
B	20	5344	44,000	11	–	1	3	3
A	30	6478	51,000	16	2	1	2	4
B	30	6478	54,000	21	–	1	3	3
A	40	9594	81,000	23	5	6	1	6
B	40	9594	88,000	26	–	4	5	5
A	50	12,506	110,000	27	6	9	2	8
B	50	12,506	117,000	32	–	5	7	7
A	60	15,414	134,000	34	6	8	4	10
B	60	15,414	152,000	34	–	6	10	10
A	70	17,435	159,000	41	4	8	7	11
B	70	17,435	174,000	43	–	7	11	11
A	80	21,145	198,000	46	6	12	8	14
B	80	21,145	220,000	51	–	13	13	13
A	90	23,623	222,000	51	10	17	6	16
B	90	23,623	245,000	53	–	14	15	15
A	100	25,787	242,000	52	11	18	7	18
B	100	25,787	267,000	65	–	14	16	16

Table 6
The detailed maintenance plan when $n = 20$.

#	$N = 20$ Strategy A Time of occurence	Maintenance mode	Maintenance task #	Strategy B Time of occurence	Maintenance mode	Maintenance task #
1	624	PM_1	15,14	675	PM_1	2,15
2	946	PM_1	1,5	993	PM_1	1,5
3	1011	CM_1	18	1341	CM_2	8
4	1284	PM_2	18	2033	PM_1	8,19,10
5	1988	PM_1	11,10	2177	PM_1	6
6	**2060**	$\mathbf{CM_1}$	**2**	**2268**	$\mathbf{CM_1}$	**9**
7	**2381**	$\mathbf{PM_1}$	**2**	**2536**	$\mathbf{PM_1}$	**9**
8	**2595**	$\mathbf{PM_2}$	**7**	**2808**	$\mathbf{CM_2}$	**17**
9	3219	PM_1	17,4	3500	PM_1	17,3,18
10	3548	PM_1	19	3716	PM_1	12
11	3764	PM_1	12	3853	PM_1	13
12	3903	PM_1	16	4067	PM_1	7
13	4014	PM_1	20	4408	CM_2	11
14	4158	PM_2	6	5094	PM_1	11,14,4
15	4829	PM_1	9,3	5344	PM_1	20,16
16	4944	CM_1	8			
17	5207	PM_1	8			
18	5344	PM_1	13			

Fig. 5c where when$\mu_1 = 0.3$the overall maintenance cost is the highest. Therefore, in the subsequent parameter test, the experiment of $v = 0.3$ and $\mu_1 = 0.3$ will be omitted. However, the setting of the upper PM threshold does not have much influence on the total maintenance cost as there are similar fluctuations in Fig. 5d. To sum up, it is better to set the lower PM threshold lower than 0.3, and the CM threshold larger than 0.3 to decrease the total maintenance cost.

6. Conclusions

This paper introduces an improved PSO approach from the lean maintenance perspective and develops the integrated age reduction maintenance model to deal with the comprehensive maintenance decision with multiple maintenance modes concern. The model was validated using practical examples and sensitivity analysis was conducted to figure out the best combination of reliability threshold for maintenance mode selection. The model and case analyses bring about the following conclusions.

First, introducing the multiple maintenance modes concern into the maintenance plan and optimizing total maintenance cost are feasible.

Second, total maintenance cost will decrease along with the concern of more maintenance modes under the limited maintenance resource constraints.

Third, parameter combinations about the reliability threshold will impact the maintenance mode distinction as well as the cost. When the reliability threshold of maintenance with or without replacement is not clear, the total maintenance cost will increase greatly. This is because the maintenance management is inclined to improve the system reliability as much as possible with the expense of fast and expensive spare part replacement. The switch of maintenance mode will lead to the

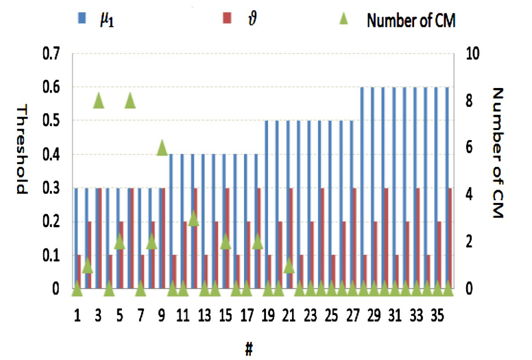


Figure 5a. The relationship between the maintenance threshold with the number of CM

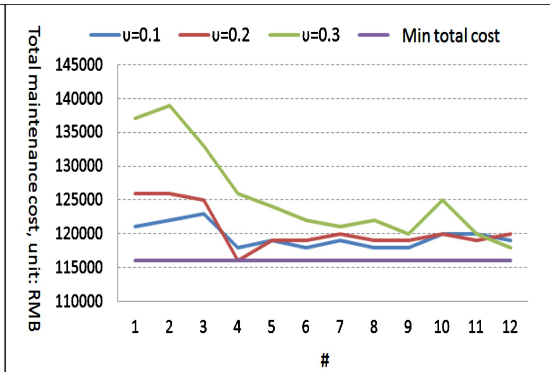


Figure 5b. The relationship between the CM threshold with the total maintenance cost

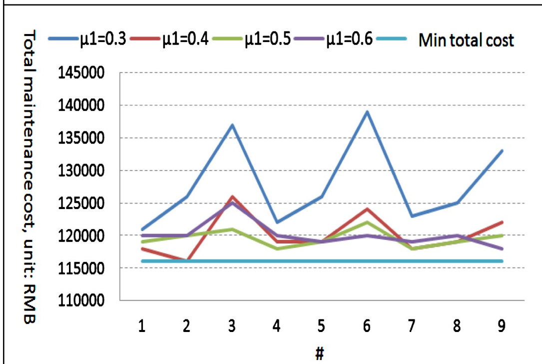


Figure 5c. The relationship between the PM lower threshold with the total maintenance cost

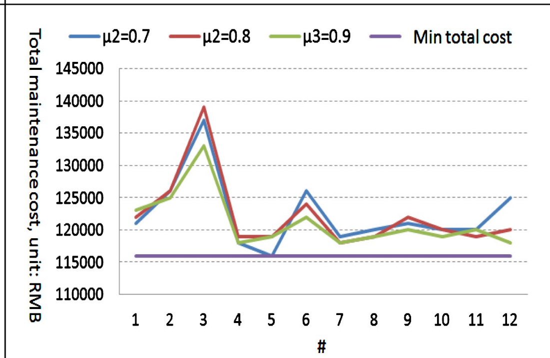


Figure 5d. The relationship between the PM upper threshold with the total maintenance cost

Fig. 5. The relationship between individual threshold with the total maintenance cost.

increasing cost. Besides, too frequent preventive maintenance cannot fully avoid the facility aging, and the growing deterioration will lead to a severe breakdown, which calls for the implementation of corrective maintenance.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (grant number 71701126) and the Shanghai Pujiang Program (grant number 15PJ1402800).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2019.106625.

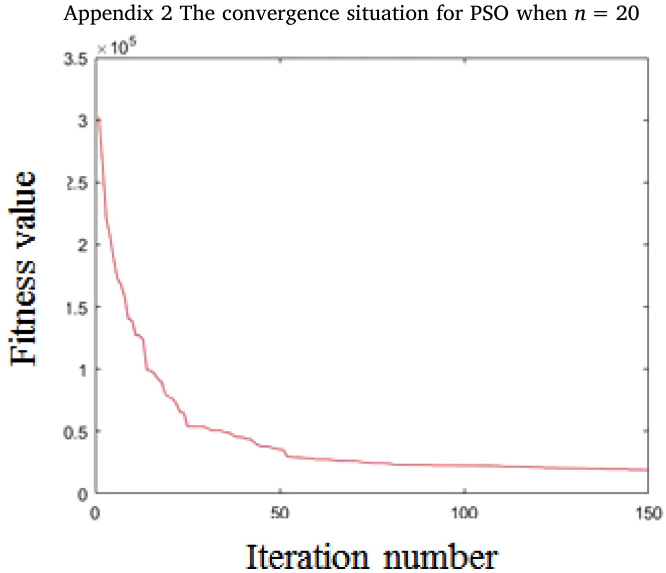
Appendix

Appendix 1 The relationship between the total maintenance cost and reliability thresholds when n = 60.

#	μ_1	μ_2	v	Number of maintenance when cost is optimized/times				Number of maintenance when cost is optimized/times
				PM_1	PM_1	PM_1	PM_1	
1	0.3	0.7	0.1	37	9	10	0	121,000
2	0.3	0.7	0.2	32	9	10	1	126,000
3	0.3	0.7	0.3	36	2	3	8	137,000
4	0.3	0.8	0.1	38	9	10	0	122,000
5	0.3	0.8	0.2	40	7	8	2	126,000
6	0.3	0.8	0.3	38	2	3	8	139,000
7	0.3	0.9	0.1	39	9	10	0	123,000
8	0.3	0.9	0.2	42	7	7	2	125,000
9	0.3	0.9	0.3	46	3	3	6	133,000
10	0.4	0.7	0.1	34	10	8	0	118,000
11	**0.4**	**0.7**	**0.2**	**35**	**10**	**7**	**0**	**116,000**
12	0.4	0.7	0.3	36	8	4	3	126,000

13	0.4	0.8	0.1	35	10	8	0	119,000
14	0.4	0.8	0.2	38	10	7	0	119,000
15	0.4	0.8	0.3	35	9	5	2	124,000
16	0.4	0.9	0.1	40	10	6	0	118,000
17	0.4	0.9	0.2	41	10	6	0	119,000
18	0.4	0.9	0.3	45	8	3	2	122,000
19	0.5	0.7	0.1	32	12	5	0	119,000
20	0.5	0.7	0.2	33	12	5	0	120,000
21	0.5	0.7	0.3	30	12	3	1	121,000
22	0.5	0.8	0.1	34	13	2	0	118,000
23	0.5	0.8	0.2	35	12	4	0	119,000
24	0.5	0.8	0.3	32	13	4	0	122,000
25	0.5	0.9	0.1	40	11	4	0	118,000
26	0.5	0.9	0.2	41	11	4	0	119,000
27	0.5	0.9	0.3	42	11	4	0	120,000
28	0.6	0.7	0.1	27	14	3	0	120,000
29	0.6	0.7	0.2	27	14	3	0	120,000
30	0.6	0.7	0.3	29	14	4	0	125,000
31	0.6	0.8	0.1	30	14	2	0	120,000
32	0.6	0.8	0.2	29	14	2	0	119,000
33	0.6	0.8	0.3	30	14	2	0	120,000
34	0.6	0.9	0.1	38	13	1	0	119,000
35	0.6	0.9	0.2	39	13	1	0	120,000
36	0.6	0.9	0.3	37	13	1	0	118,000

Appendix 2 The convergence situation for PSO when $n = 20$



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