2022

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Original Publication Citation

Javadnejad, F., Sharifi, M. R., Basiri, M. H., & Ostadi, B. (2022). Optimization model for maintenance planning of loading equipment in open pit mines. *European Journal of Engineering and Technology Research*, *7*(5), 94-101. https://doi.org/10.24018/ejeng.2022.7.5.2907

European Journal of Engineering and Technology Research
ISSN: 2736-576X

Optimization Model for Maintenance Planning of Loading Equipment in Open Pit Mines

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***Abstract* — Maintenance plays a significant role in operating costs in the mining industry. Improving this matter controls maintenance costs and enhances productivity and production effectively. Shovels are one of the most widely used loading machines in non-continuous activities. Thus, evaluating and optimizing their availability is one of the essential solutions to achieving high productivity and cost reduction. This paper presents a mathematical programming model to maximize availability and minimize the total expected costs. We programmed the proposed nonlinear planning model using the Symbiotic Organisms Search (SOS) meta-heuristic algorithm in Matlab software. It determines the optimal maintenance intervals for different parts of the shovel. The maintenance-benefit analysis approach selects various maintenance activities in optimal maintenance intervals. The model is implemented in a practical case study, Chadormalu Iron Mine, to evaluate its performance. The failure distribution matches the Weibull distribution function. The computational results show the efficiency of the presented approach.**

***Keywords* — Multi-Objective Model, Symbiotic Organisms Search (SOS), Meta-Heuristic Algorithm, Weibull Distribution, and Maintenance-Benefit Analysis.**

I. INTRODUCTION

The world's population is rapidly becoming urbanized [1]. This development requires optimal production of minerals. All mining projects are associated with uncertainties in the future profitability related to operation cost and income [2]. one of the most critical operational costs in mining is maintenance costs. With the growing size and complexity of equipment and failure consequences and their stoppage in the production line, maintenance has become one of the main tools of planned optimization. It helps to achieve more accessibility of equipment with the lowest maintenance cost. Most maintenance researchers have considered optimum preventive maintenance intervals for different goals, such as minimizing maintenance and life cycle costs and maximizing profit, availability, and reliability in different mono-objective or multi-objective problems. The decrease in preventive maintenance intervals leads to the frequency of stopping the production line, and the increase in preventative maintenance intervals leads to increased equipment failure probability, causing significant maintenance costs.

Optimizing the maintenance intervals is a significant step toward reducing the maintenance costs of equipment and machines. Optimizing these intervals has been studied by many researchers. There has been much focus, particularly in academic spheres, on various articles investigating maintenance optimization.

Kay [3] looked at the optimal preventive maintenance times in terms of three criteria of accessibility, average cost, and maintenance income for a single-parameter Weibull distribution function. Many researchers have noticed and welcomed the criteria and relationships presented by Kay.

Chareonsuk *et al.* [4] evaluated a multicriteria decision-making problem to determine the optimal maintenance intervals. The criteria in their research were total expected cost and reliability. Their study considers a system with Weibull distribution and four-time intervals as alternatives. The cost and reliability chart determined the best time interval by the interval-PROMETHEE method. Furthermore, they carried out sensitivity analysis on the weight of different criteria.

Mullor *et al.* [5] Consider a class of candidate models for each component to formalize the uncertainty on the occurrence of failures and the effect of maintenance activities using a real data example. The best model, which might be different components, is then selected via maximum likelihood. The selected models are used to derive the cost per time unit and the average reliability of the equipment, the objective functions of a multi-objective Optimization Problem with maintenance intervals of every single component as a decision variable.

Tsai *et al.* [6] proposed a genetic algorithm for a periodic maintenance problem in a system to maximize the unit lifetime cost of the system with reliability constraints. Their research included two kinds of activities (repair and replacement). They first considered a time interval and then obtained the optimal maintenance activities for the subsystems. Repeated this procedure at different times, they chose the time with the most per-unit-time cost as the optimal maintenance interval. Tsai *et al.* [7] have studied the optimal maintenance interval based on maximizing availability. They considered three maintenance activities: inspection, repair, and replacement. While they regarded the subsystem's time with the minor optimal interval as the periodic interval maintenance time for all subsystems, They recognized The appropriate activity for the subsystems based on maintenance-benefit analysis [7].

Chitra [8] is considered an optimal maintenance interval based on minimizing life cycle costs. Bris *et al.* [9] proposed a model with cost and availability objectives. They developed a genetic algorithm to find the best maintenance time for a series-parallel system with 11 subsystems having exponentially distributed failures (only for inspection

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Submitted on October 01, 2022.
Published on October 26, 2022.
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DOI: http://dx.doi.org/10.24018/ejeng.2022.7.5.2907

activity). They also claimed that this approach could be applied to complicated series-parallel structures and non-exponential failure rates [9].

Nguyen *et al.* [10] proposed an artificial intelligence-based maintenance approach that first constructs a predictor based on an artificial neural network (ANN) for estimating maintenance costs at the system level. Learning, generalization, function approximation ability, and parallel structure are the essential properties of artificial neural networks [11], [12]. They employed a customized multi-agent deep reinforcement learning algorithm to optimize maintenance decisions that can be applied to large-scale systems [10].

Danyain *et al.* [13] used the Artificial Intelligence (AI) technique for the maintenance operation of the wheel-bearing component of a railcar. Data from a secondary source was pre-processed and iteratively trained using a specialized training algorithm in a machine learning environment under supervised training until it produced a model capable of making predictions. The result indicates the feasibility of the developed AI model for predicting the remaining useful life of a wheel-bearing component [13].

Meng *et al.* [14] consider preventive maintenance (PM) scenarios in the assembly line balancing problem to simultaneously improve production efficiency and smoothness. For this multi-objective problem, a heuristic rule relying on tacit knowledge is dug up via gene expression programming to obtain an acceptable solution quickly [14].

Samrout *et al.* [15] improved the research results of Bris *et al.* [9] using the model and information of series-parallel presented by Bris in 2003 and the ant colony approach [15]. Duarte *et al.* [16] determined the optimal maintenance intervals for series systems with fixed repair rates and linear increasing failure rates by presenting an optimization model. The objective function of the proposed model was to minimize corrective and preventive maintenance costs subject to availability constraints [16].

Sachdeva *et al.* [17] presented a bi-objective programming model maximizing availability and minimizing the ratio of preventive maintenance to corrective maintenance to find the optimal maintenance interval. They implemented their model using a genetic algorithm and Simulink in a paper mill manufacturing system [17]. Mariappan *et al.* [18] stated three optimal maintenance intervals (Fig. 3) based on Availability, average cost, and maintenance income per unit time criteria, and the equation $\propto \geq 1-\mathrm{KR}(\mathrm{t})$ for each criterion. These three maintenance intervals are the intersection time of curve $\propto$ and curve$1-\mathrm{KR}(\mathrm{t})$, the time with the most distance between curve $\propto$ and curve $1-\mathrm{KR}(\mathrm{t})$, and the optimal time for each criterion. Then, an optimal maintenance time was selected from these three times using a collaborative and repetitive system.

Following previous research, Mariappan *et al.* [18] calculated the optimal maintenance time among three criteria, availability, cost, and income using goal programming in 2011. Their research consists of three stages. They obtained the optimal maintenance time in the first stage using a collaborative system for each criterion. In the second stage, criteria are determined using the inter-criteria correlation method, and optimal maintenance times are calculated through three goal programming models in the third stage [18].

Garg *et al.* [19] proposed a nonlinear optimization model minimizing the ratio of preventive maintenance cost to corrective maintenance cost per time unit. The model's constraints were corrective maintenance, preventive, and life cycle costs. They implemented the model for a paper mill manufacturing system using a bee algorithm to solve the problem and calculate the optimal times of subsystems [19]. Afterward, they applied an optimal maintenance-benefit analysis presented by Tsai *et al.* [6] [7] to implement one of the inspections, repair, and replacement activities for each subsystem in an optimal time [19]. Garg [20] developed the former model to maximize availability and minimize the ratio of preventive maintenance cost to corrective maintenance cost. The model's constraints were availability, remedial maintenance, preventive, and life cycle costs. He implemented his model for a paper mill manufacturing system using a geo-biological algorithm. Like his previous study, he used the Tsai benefit indicator to apply maintenance activities [20].

Li *et al.* [21] addressed two performance-based measures, performance availability and probabilistic resilience. They used these measures to quantify the system's behavior for continuous multistate systems (MSSs). Li *et al.* [21] implemented a Monte Carlo-based method to analyze the performance change process of the system. Finally, they proposed an optimization framework to find the optimal preventive maintenance (PM) interval considering per-unit-time cost, system breakdown rate, performance availability, and probabilistic resilience [21].

Adhikary *et al.* [22] presented a multi-objective model (maximizing availability and minimizing the ratio of preventive maintenance cost to corrective maintenance cost) to optimize a continuous-series system and solved it using a multi-objective genetic algorithm. They also implemented their model on coal boiler tubes in thermal power plants with the distribution function of Weibull [22].

Basiri *et al.* [23] investigated the reliability of the electric cable shovel of the Chadormalu Iron Ore Mine in Iran. The failure distribution function of the subsystems whose failure information is available as provided by statistical analysis using EasyFit 5.5, Minitab 18, and the subsystems with low or unavailable failure information generated by experts using normal distribution function. The criticality of subsystems was determined using Birnbaum and Fussell–Vesely importance measures reliability. Results showed that cable shovel reliability had reached zero after 40 hours and subsystems of crowd gearbox, swing gearbox, lubrication, and bucket door are the most critical subsystems [23].

This paper presents a bi-objective model, maximizing availability and minimizing the ratio of the total expected cost to the preventive maintenance cost. In the following, the proposed model is coded using a symbiotic organism search algorithm in MATLAB 18. A maintenance-benefit analysis is applied to choose maintenance activities (repair or replacement) in optimal maintenance intervals. We used this approach to plan for the Chador Malu Iron Ore Mine, which manufactures 2100 tons of iron per hour.

II. MATHEMATICAL MODEL

In this section, we described the proposed model by defining the evaluated criteria in maintenance.

Where:

f(t) = failure function
F(t) = failure density function
h(t) = failure rate
R(t) = reliability function
M = mean time between failures
T = maintenance period
Mc = the mean corrective maintenance time
Mp = the mean preventive maintenance time
$\bar{T}$ = mean time between replacement
A_c = availability in corrective maintenance
A_c = availability in preventive maintenance
c_c = cost per time unit in corrective maintenance
c_p = cost per time unit in preventative maintenance
C_c = average cost in corrective maintenance
C_p = average cost in preventive maintenance

A. Decision-Making criteria

Availability, profit rate, life cycle cost, and reliability are the decision criteria of the proposed model. The notations for the proposed model are as follows.

B. Availability

Availability under the corrective and preventive maintenance are formulated as (1) and (2).

$$A_c = \frac{M}{M+m_c} \tag{1}$$

$$A_p = \frac{\bar{T}}{\bar{T}+m_c R(T)+m_p[1-R(T)]} \tag{2}$$

To carry out preventive maintenance, the availability of preventative maintenance must be greater than corrective maintenance. Thus, we have (3) and (4) as follows:

$$A_p \geq A_c \tag{3}$$

$$\frac{\bar{T}}{\bar{T}+m_c R(T)+m_p[1-R(T)]} \geq \frac{M}{M+m_c} \tag{4}$$

1) Average maintenance cost

The average maintenance costs under corrective and preventive maintenance are formulated as follows:

$$C_c = \frac{c_c . m_c}{M+m_c} \tag{5}$$

$$C_p = \frac{[1-R(T)]m_c c_c + R(T) m_p c_p}{\bar{T}+R(T)m_p+[1-R(T)]m_c} \tag{6}$$

The preventive maintenance cost must be lower than the corrective maintenance cost to carry out the preventative maintenance. Thus, we have (7) and (8) as follows:

$$C_p \leq C_c \tag{7}$$

$$\frac{[1-R(T)]m_c c_c + R(T) m_p c_p}{\bar{T}+R(T)m_p+[1-R(T)]m_c} \leq \frac{c_c m_c}{M+m_c} \tag{8}$$

Assuming: $\alpha = \frac{\bar{T}}{M}, \mu = \frac{\mathrm{mc}}{M},\ \gamma = \frac{\mathrm{mp}}{mc},\ \delta = \frac{\mathrm{cp}}{cc}, \omega = \frac{cc}{p},\ k_1 = 1-\gamma, and\ \ k_2 = 1-\delta\gamma$, (4) and (8) come into the following equations:

$$\alpha \geq 1 - k_1 R(t) \tag{9}$$

$$\alpha \geq 1 - k_2 R(t) \tag{10}$$

In some papers, (11) has been used as a constraint in the optimization model, given that t=∞ the equation $\int_0^\infty R(t)dt = M$ is satisfied. Thus, the α value is always within the interval 0 to 1. As a result, the constraint $0 \leq \alpha \leq 1$ is an extra constraint.

$$0 \leq \alpha = \frac{\bar{T}}{M} = \frac{1}{M} R(t)\mathrm{dt} \leq 1 \tag{11}$$

2) Life cycle cost

Life cycle cost is another constraint that many researchers have used. (11) demonstrates this cost:

$$LCC = c_p \frac{R(T).T_0}{\int_0^T R(t)dt} + c_c \tag{11}$$

By deriving from (9), the minimum life cycle cost is obtained as follows:

$$\frac{d}{d(T)}(\mathrm{LCC}) = 0 \dashrightarrow$$

$$\frac{T_0\left[\int_0^T R(t)dtR(T)(c_p-c_c) - R^2(\acute{T})(c_p-c_c) - R(T)c_c\right]}{\left[\int_0^T R(t)dt\right]^2} = 0 \dashrightarrow$$

$$R(T) + h(T)\int_0^T R(t)dt = \frac{c_c}{c_c-c_p} \tag{12}$$

Based on [17], [19], [20], (12) have been changed into (13) to use in maintenance planning.

$$R(T) + h(T)\int_0^T R(t)dt \leq \frac{c_c}{c_c-c_p} \tag{13}$$

Consider a machine with a Weibull distribution (α=600, β=2.0), cost information (Cc=5000, Cp=500), and 5000 hours of maintenance duration. If (13) is changed to lower than or equal to zero and f1 denotes the right side of the equation, and f2 represents the ratio of life cycle cost to the average preventive maintenance cost during maintenance (LCC/c_p), the values of f1 and f2 are graphically depicted in Fig. 1.

According to Fig. 1, the minimum life cycle cost occurs at time 202. (15) is the lower part of the time axis of function f1. Applying this equation does not seem appropriate, noting life cycle cost within the interval 0 to 202. This indicator is used in the model according to (14):

$$R(T) + h(T)\int_0^T R(t)dt \geq \frac{c_c}{c_c-c_p} \tag{14}$$

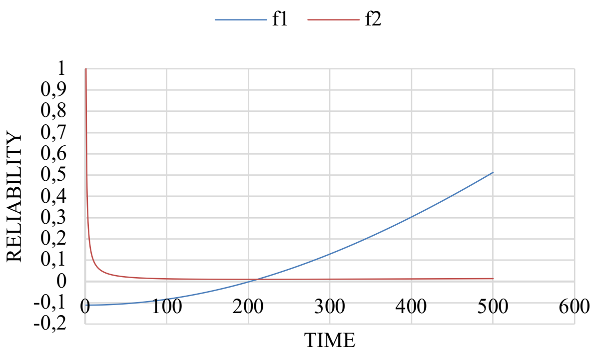

Fig. 1. Derivation of function LCC (f1) and ratio (f2).

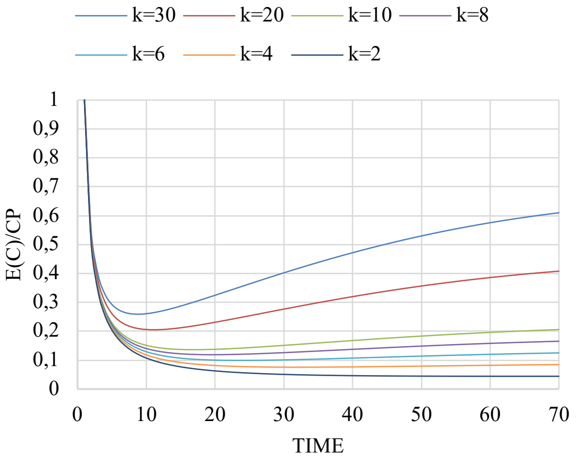

Fig. 2. Total expected cost per unit curve.

3) *Total expected cost*

Chareonsuk *et al.* [4] considered two criteria (reliability and total expected cost) to reach the optimal maintenance time interval. The total expected cost per time unit is formulated as follows:

$$E(C(t)) = \frac{C_p R(T) + C_c F(t)}{tR(t) + \int_0^T tF(t)dt} \tag{15}$$

If (15) is formulated like (16), the total expected cost of corrective maintenance cost will be within (0, 1).

$$E(C) = \frac{E(C(t))}{C_p} = \frac{R(T) + kF(t)}{tR(t) + \int_0^T tF(t)dt}, \quad k = \frac{C_c}{C_p} \tag{16}$$

Also, the curve of total expected cost per unit time in different ratios of corrective maintenance cost to preventive maintenance cost for a machine with failures having Weibull distribution (α=50, β=1.8) is shown in Fig. 2.

C. *Optimization Model*

According to the described criteria in the previous section, the maintenance optimization model is as follows:

$$Max\ \frac{A_p}{E(C)}$$

$$A_p = \frac{\bar{T}}{\bar{T} + m_c R(T) + m_p[1 - R(T)]}$$

$$E(C) = \frac{E(C(t))}{c_p} = \frac{R(T) + kF(t)}{tR(t) + \int_0^T tF(t)dt}, \qquad k = \frac{c_c}{c_p}$$

S.t:

$$C_p \le C_c \dashrightarrow \frac{[1 - R(T)].m_c.c_c + R(T).m_p.c_p}{\bar{T} + R(T).m_p + [1 - R(T)].m_c} \le \frac{c_c.m_c}{M + m_c}$$

$$A_p \ge A_c \dashrightarrow \frac{\bar{T}}{\bar{T} + m_c R(T) + m_p[1 - R(T)]} \ge \frac{M}{M + m_c} \dashrightarrow$$

$$R(T) + h(T)\int_0^T R(t)dt \ge \frac{c_c}{c_c - c_p} \tag{17}$$

III. RELIABILITY UNDER MAINTENANCE MODEL

The maintenance activities identification before maintenance planning is crucial to improve the system's performance and reliability. The reliability of each system is a function of its life span, and each maintenance activity reduces the lifetime and improves it. The system's reliability in stage j of maintenance is calculated under mechanical inspection (lubrication, grease, rinsing, etc.), repair, and replacement according to (18) to (20) [6], [7], and [20].

$$Reliability\ in\ inspection\ mode\ = reliability\ at\ the\ end\ of\ the\ previous\ stage \times R\left(\frac{1}{m1}(t - (j-1)tp)\right) \tag{18}$$

$$Reliability\ in\ repair\ mode = (reliability\ at\ the\ end\ of\ previous\ section \times m2\ (the\ difference\ between\ reliabilities\ at\ the\ start\ and\ end\ of\ the\ last\ stage)) \times R\left(\frac{1}{m1}(t - (j-1)tp)\right) \tag{19}$$

$$Reliability\ in\ replacement\ mode = R(t - (j-1)tp) \tag{20}$$

The improvement factor of mechanical inspection activity, repair, and periodic interval for preventive maintenance are denoted by m1, m2, and tp, respectively. The improvement factor is a value within the interval 0 to 1 that can be defined as a ratio of the remaining system's lifetime after maintenance activity to the new life of the system. Assume a system with a failure following Weibull distribution (α=4000, β=2.0), optimal time (t_p=2000), and improvement factors (m1=0.8, m2=0.5). Changes in reliability over optimal intervals under different maintenance activities will be shown in Fig. 3.

If subsystems of a system are replaced according to their optimal time, the system's availability is severely reduced due to many stops. The minimum maintenance optimal time is considered the periodic interval to avoid this problem. In each period, if the reliability of a subsystem is less than the minimum reliability for that subsystem, the replacement politic is executed on the subsystem. Otherwise, the evaluating criterion to manage the maintenance politic is the reliability value of the subsystem with the current conditions in the next stage. If the reliability value for the next step is more significant than R_{min}, the subsystem needs no maintenance activity. Otherwise, the maintenance-benefit analysis presented by Tsai in 2003 (21) is applied to select maintenance activities.

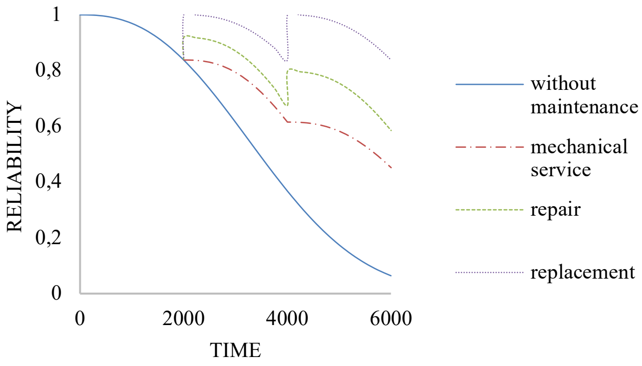

Fig. 3. Changes in reliability under different maintenance activities.

$$B_{i,k} = \frac{\int_{tj}^{\infty} R_{i,j-1}(t)dt - \int_{tj}^{\infty} R_{i,j}(t)dt}{C_{i,k}} \tag{21}$$

The index K indicates the type of maintenance activity. The index $C_{i,k}$ denotes each of the maintenance activities on subsystem i. The action that leads to the most maintenance profit ($B_i^* = Max(B_{i,k})$) is selected to apply activity for subsystem i.

IV. SOLUTION METHOD

This paper applies a Symbiotic Organisms Search (SOS) algorithm. This population-based algorithm is a powerful and modern meta-heuristic algorithm that Cheng and Prayogo presented to optimize the mathematical models in a continuous environment [24]. The symbiotic relationship of organisms This algorithm is inspired by the symbiotic relationships of living things. The SOS algorithm uses three symbiotic relationships: Mutualism, Commensalism, and Parasitism, to find the optimal point. Mutualism or mutual symbiosis is a relationship between two species that benefit mutually from that relationship, like aphids and ants. Commensalism is a mutual symbiosis between two species in which one benefits and the other is unaffected or neutral, such as sharks and remora fish. Finally, parasitism is a compulsory mutual symbiosis between two species in which one benefits and the other is harmed, such as Human and Ascaris functions. The steps of the SOS algorithm are organized as follows:

Step 1: Like other population-based algorithms, the SOS generates the initial population (ecosystem) in the feasible search space. The organisms (feasible solutions) must be generated randomly.

Step 2: The best feasible solutions among the population (Xbest) or the best current organisms are selected.

Step 3 (Mutualism phase): For each organism, a different organism is selected randomly, and new organisms are generated according to (22) and (23). If the new organisms (new solutions) improve the objective function, they are replaced by the former organisms. In the former equations, BF_1 and BF_2 are random numbers. They take 1 or 2 values.

$$X_{inew} = X_i + rand(0,1) * (X_{best} - \left(\frac{X_i + X_j}{2}\right) * BF_1 \tag{22}$$

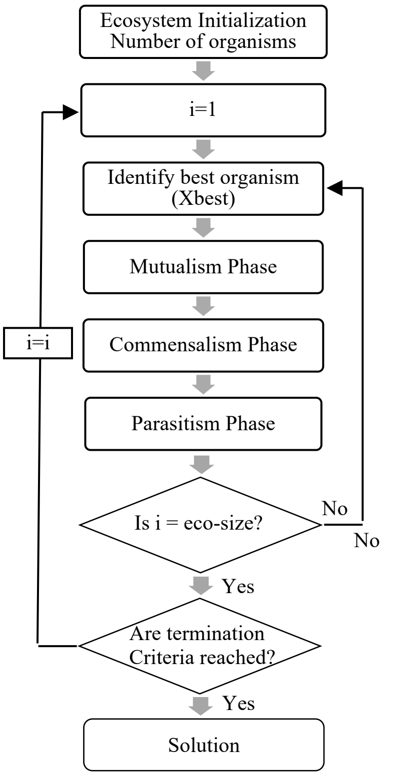

Fig. 4. The symbiotic organisms search (SOS) [25].

$$X_{jnew} = X_j + rand(0,1) * (X_{best} - \left(\frac{X_i + X_j}{2}\right) * BF_2 \tag{23}$$

Step 4 (Commensalism phase): For each organism, a different organism is selected randomly, and a new organism is generated randomly according to Eq. 24. If the new organism (new solution) improves the objective function, it is replaced by the former organism.

$$X_{inew} = X_i + rand(-1,1) * (X_{best} - X_j) \tag{24}$$

Step 5 (Parasitism phase): A different organism is selected randomly for each organism. The first and the second organisms are assumed to be parasites and guests, respectively. In the parasite organism, one of the problem variables is replaced by a random number within its range. If the parasite organism is better than the guest organism based on its objective functions, the parasite organism takes the guest organism's place.

Step 6: steps 3-5 are repeated for all organisms.

Step 7: Is the termination condition been met? If the termination condition is fulfilled, steps 2-6 are repeated. Otherwise, the optimal solution for the proposed problem is the best feasible organism in the ecosystem. Fig. 4 demonstrates the SOS process.

V. CASE STUDY

The presented model in section 2 is implemented to plan for the P&H 2100 BL cable shovel of Chadormalu Iron Mine in Iran, producing 2100 tons of iron per hour.

By examining the way to separate the subsystems of similar road construction and mining machinery in other studies [26]-[29] and also by using the opinion of experts and the Chadormello mining maintenance group, cable shovel subsystems were identified as follows:

1- Cable system: It is made of three different cables (suspension, trip, and lift). The suspension cable connects the boom to the gantry. The trip cable opens the shovel bucket, and the lift cable links the shovel's bucket to the hoist drum.
2- Bucket system: The bucket consists of a trunk, door latch, arc, and clutch—the lift cable links to the bucket by its arc to lift it. The clutch links the entrance to the bottom of the bucket.
3- Stick system: Stick links the bucket from one side and boom to the other side. Some pegs at the bottom of the stick allow the origination of movements such as forwarding and backward movements. The stick can also move upwards and downwards around the connecting axis, Changing the lift cable length.
4- Undercarriage system and fixed chassis: Chains or shafts (sand), rollers, idler, tumbler, and revised chassis are closed on the chassis of the wheel.
5- Engine system and power transmission: This system consists of the crowd, propel, trip, swing, primary motor, magnet torque, and chain case. The main engine is the most crucial part of a shovel. It moves the magnet torque (magnetic induction) and rotates it so that the hoist gearbox moves and the bucket lifts. Also, it drives the chain case gearbox and makes the swing generator and crowd/propel generator swing to supply the power for swing, crowd, and propel engines. Crowd, propel, and trip engines are located outside the mobile chassis and in free space.
6- Pneumatic system: In the cable shovel, lubrication, brake, and horn are carried out by wind forces. Thus, this system contains the subsystems of lubrication, brake, horn, and wind transfer system.
7- Electrical system: This system includes sections such as the electric current transfer path from the fixed chassis to the mobile chassis, an alternating current of medium pressure, an alternating current of the weak force, and direct current circuits. These seven systems are considered series systems since failure in each system causes the machines to stop.

A. Data Gathering for Failure and Repair

Data about failure and repair has been collected from the maintenance unit of Chadormalu mine reports over 15 months. Weibull and exponential distribution were used for failure and repair times of the cable shovel's central systems, respectively. Table I shows the scale parameters (α), shape parameters (β), failure Weibull distribution, time and cost of repair and replacement, and improvement factor.

B. Analysis of Result

The optimal maintenance intervals for each system are obtained according to the parameters of each system in Table I and by solving the presented nonlinear programming model in section II using the SOS algorithm.

The minimum maintenance interval for the systems of cable shovels relates to the electrical system with 39 hours. Thus, this time is considered the optimal maintenance interval to execute the maintenance planning of systems.

TABLE I: FAILURE INFORMATION, TIME, COST, AND IMPROVEMENT FACTOR FOR THE MAINTENANCE ACTIVITIES

Systems	Failure data (Weibull distribution)		Time (hour)		Cost ($ per hour)		Improvement Factor
	α	β	repair	Replacement	repair	Replacement	
cable	366.07	2.044	0	3.2	658.76	0	-
bucket	67.88	0.921	0	8.15	6729.24	0	-
stick	517.2	1.671	40.1	86.4	130.93	0.80	22.04
undercarriage	429.3	1.643	0	120.24	53.61	0	-
engine & gearbox	112.47	1.458	3.22	3.79	633.83	0.90	199.46
pneumatic	135.52	1.417	4.26	12.30	219.07	0.93	21.55
electric	84.48	1.680	37.72	118.29	66.02	0.50	16.66

TABLE II: OPTIMAL MAINTENANCE INTERVALS FOR CABLE SHOVEL SYSTEM

Systems	Decision parameters (α, β)		MTBF (h)	Optimal interval
cable	α=366.07	β=2.044	324.3	363.5
bucket	α=67.88	β=0.921	70.5	189.1
stick	α=517.2	β=1.671	462.1	284.3
undercarriage	α=6429.3	β=1.643	384.1	206.6
engine and gearbox	α=112.47	β=1.458	101.9	220.2
pneumatic	α=135.52	β=1.417	123.3	121.1
electric	α=84.48	β=1.680	75.4	38.8

TABLE III: SCHEDULING OF MAINTENANCE ACTIVITIES FOR CABLE SHOVEL SYSTEM (WITHOUT MAINTENANCE=0, REPAIR=2, REPLACEMENT=3)

stage	cable	bucket	undercarriage	engine & gearbox	pneumatic	electric	stick
j=1	0	3	0	0	0	2	0
j=2	0	3	0	3	2	3	0
j=3	0	3	0	0	0	2	0
j=4	0	3	0	3	2	3	2
j=5	0	3	2	0	0	2	0
j=6	3	3	0	3	2	3	0
j=7	0	3	2	0	0	2	2
j=8	0	3	0	3	2	3	0
j=9	0	3	2	0	0	2	2
j=10	0	3	0	3	2	3	0

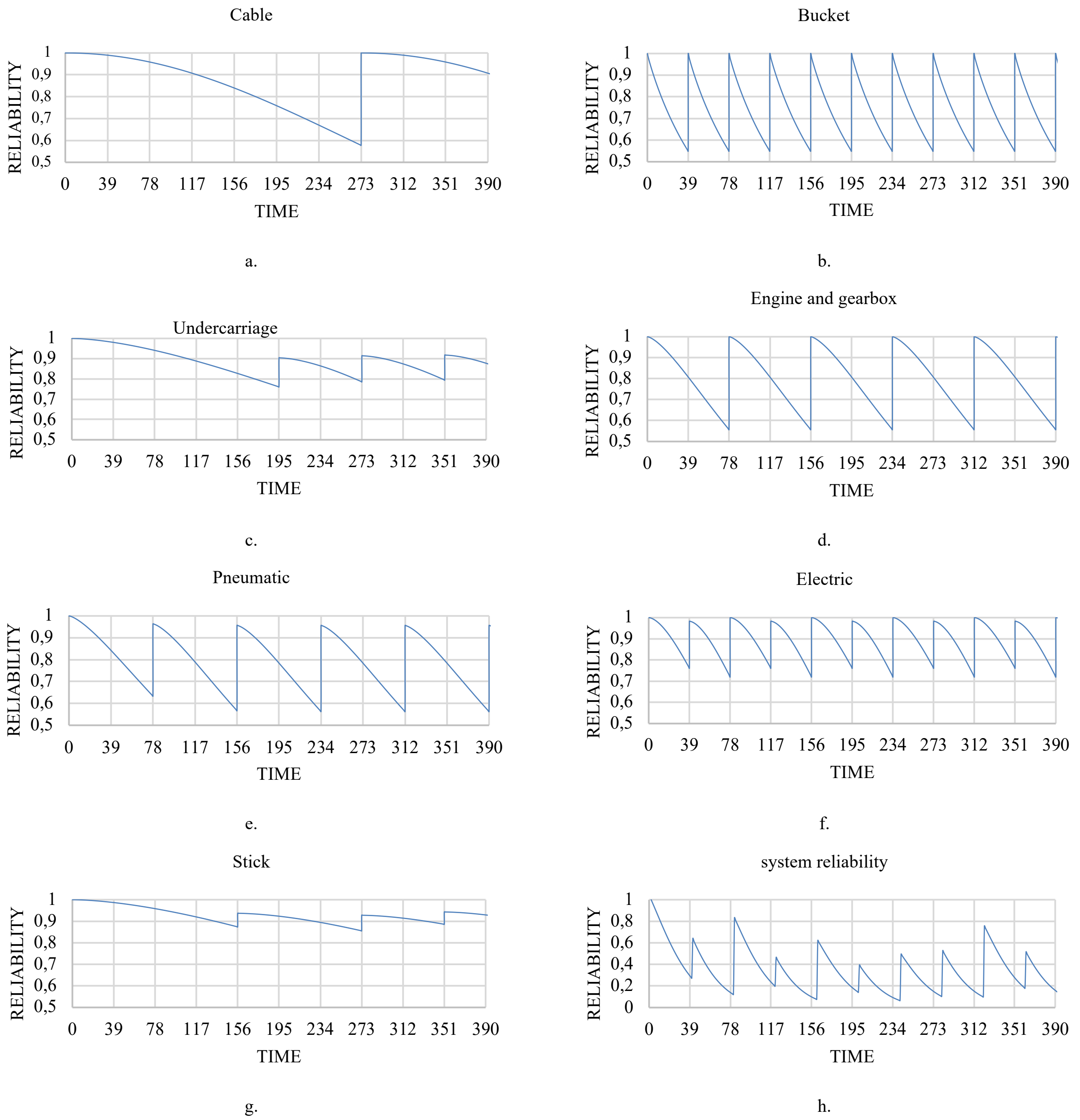

Fig. 5. Reliability of different systems of cable shovel (subsystem's optimal intervals for repair or replacement): (a) the cable subsystem; (b) the bucket subsystem; (c) the undercarriage subsystem; (d) the engine and gearbox subsystem; (e) the pneumatic subsystem; (f) the electric subsystem; (g) the stick subsystem; (h) the system reliability.

Noting the expert's opinion, the minimum reliability of systems to execute the maintenance activities in periodic time is for cable systems such as a bucket, stick, chained wheel, engines, and electrical and pneumatic gearbox, taking the values of 0.5, 0.5, 0.7, 0.5, 0.5, 0.75 and 0.85 [28]. The maintenance-benefit analysis is used to carry out the optimal maintenance scheduling for each system in optimal maintenance intervals (Table III).

Fig. 5 demonstrates the reliability of systems considering the maintenance scheduling (repair or replacement) in optimal intervals.

VI. Discussion And Conclusions

By increasing the equipment's size and complexity, the consequences of failures and their stops in the production line become more intense. So, maintenance and repair are considered the main tools for planned optimization to achieve more equipment availability in line with the maintenance cost.

Optimizing the maintenance intervals is a significant step in reducing maintenance costs and increasing the availability of equipment and machines. This paper presents a new model to optimize the maintenance intervals with two objectives: maximizing availability and minimizing the ratio of the total expected cost to the preventive maintenance cost. The model was carried out by using the SOS algorithm coding in MATLAB. This approach is implemented to plan for the maintenance of cable shovels of the Chadormalu ore iron mine in Iran, producing 2100 iron ore per hour.

The cable shovel is divided into seven subsystems (cable, bucket, stick, undercarriage, engine, gearbox, pneumatic and electric). The failure is distributed according to the Weibull function. The optimal maintenance times for subsystems are

364, 189, 284, 207-, 220-, 121-, and 39 hours using SOS to solve the multi-objective model. Thus, these times are considered the optimal maintenance intervals to carry out the maintenance schedule.

The Maintenance-benefit analysis is applied to select the maintenance activities (repair or replacement). The cable system, bucket, engines, and power transmission need replacement every 273, 39, and 78 hours, respectively. The pneumatic system needs to repair every 78 hours. The undercarriage system needs to repair every 78 hours after 195 hours of work. The electric system gets repaired and replaced alternately every 39 hours. Finally, the stick system gets repaired every 117 and 78 hours after 156 hours of working.

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