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Efficient computational stochastic framework for performance optimization of E-waste management plant

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ABSTRACT

Purpose: Reliability and maintainability are the key system effectiveness measures in process and manufacturing industries, and treatment plants, especially in E-waste management plants. The present work is proposed with a motto to develop a stochastic framework for the e-waste management plant to optimize its availability integrated with reliability, availability, maintainability, and dependability (RAMD) measures and Markovian analysis to estimate the steady-state availability of the E-waste management plant. In the analysis an effort is also made to identify the best performing algorithm for availability optimization of the e-waste plant.
Methodology: A stochastic model for a particular plant is developed and its availability is optimized using various metaheuristic approaches like a genetic algorithm (GA), particle swarm optimization (PSO), and differential evolutions (DE). The most sensitive component is identified using RAMD methodology while the effect of deviation in various failure and repair rates are observed by the proposed model. The failure and repair rates follow an exponential distribution. All time-dependent random variables are statistically independent.
Originality/Novelties: A novel stochastic model is presented for an e-waste management plant and optimum availability is obtained using metaheuristic approaches. The proposed methodology is not so far discussed in the reliability analysis of process industries.
Findings: The numerical results of the proposed model compared to identify the most efficient algorithm. It is observed that genetic algorithm provides the maximum value (0.92330969) of availability at a population size 2500 after 500 iterations. PSO algorithm attained the maximum value (0.99996744) of availability just after 50 iterations and 100 population size. So, its rate of convergence is faster than GA. The optimum value of availability is 0.99997 using differential evolution after 500 iterations and population size of more than 1000. These findings are very beneficial for system designers.
Practical Implications: The proposed methodology can be utilized to find the reliability measures of other process industries.

1. Introduction

In current age of science and technology management of wastage items becomes greatest challenge. Waste items come in many different forms such as bio waste, electronic waste, agricultural waste, industrial waste etc. Every kind of wastage have its own consequences and different handling methods. Today rapid growth of technology, up gradation of technical innovations in the electronic industry has led to one of the fastest growing waste streams in the world. The global market of electronic and electronic equipment (EEE) continues grow exponentially in many forms. E-waste is unwanted electronic items or not working equipment's those already completed their useful life, like electronic motor vehicles, mobile phones, computers, televisions, fax machines etc. It contains highly toxic substances that pose a danger to health and the environment. When the people have lack of

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knowledge about E-waste and E- waste is incinerated, the burning particles mix with soil or groundwater. Therefor it comes to the human body in the form of drinking water or food. Some of the E- waste components have mercury, lead, barium, chromium, arsenic, and cadmium. As er the Global E-waste generation is concerned, it is 59.5 million metric tons and projected to be 74.7 million metric tons in 2030 (Tiseo, 2019).

The hike in petrochemicals and government's determination to reduce greenhouse gases drives the consumers to use electric vehicles. In pandemic period use of computing devices increase in many folds. All these resulted as the increment in the E-waste. To handle this E-waste a sincere effort is required. Ikhlayel (2017) described the situation in which e-waste is mixed with solid waste. He is recommended that it needs special attention and integrative thinking can provide a solution of such issues. Kahhat et al. (2008) discussed the procedures adopted for e-waste collection, recycling, and reuse in U. S.A. Ghimire and Ariya (2020) described the recycling, composition, knowledge gap in production, and sustainability implications involved in e-waste. First regulation to manage e- waste in India was introduced in 2011 and it comes into effect in 2012. Kaya (2012) suggested a model for dismantling, shredding, separation, smelting and refining of waste electrical and electronic equipment's. After that the rules have been amended twice.

Various policies are recommended in this regulation for E-waste handling and establishment of E-waste management plant is prominent one. These plants are very complex having subsystems like central E-waste collection centre, object recognition unit, dismantling and destruction unit, disposal unit and crushing unit. The complex configuration of plants influences the working environment of it. And it becomes necessary to handle this plant with utmost care. For this reliability measures of the plant are the key performance assessment criteria. Several techniques like reliability, availability, maintainability, and dependability (RAMD), fault tree analysis, minimal cut-set approach, petri nets approach, semi-Markovian approach and Markovian approach exists in literature to evaluate the reliability characteristics of process plant. All these techniques evaluate the reliability as a local solution. Cheng et al. (2020) proposed an optimization model to improve the reliability of solid waste collection systems by reallocating the distribution of waste demand between facilities without decrease the waste generation or raise the waste management facilities capacity. Aggarwal et al. (2016) carried out RAMD analysis of skim milk powder production subsystem and identified the most critical component responsible for low performance of dairy plant. Zeng et al. (2015) developed a model to solve the e-waste problem in an integrated mobile recycling plant. Saini and Kumar (2019) studied an evaporation system with the objective to analyze the application of reliability, availability, maintainability, and dependability in identification of most sensitive subsystem in sugar plant. Chapman–Kolmogorov differential equations are derived using Markov birth–death process and all time dependent random variables associated with failure and repair rates are exponentially distributed.

Ni et al. (2021) conducted a systematic review of methodologies involved in e-waste management and identified new research agendas. Ahmadi and Amin (2019) developed an integrated chance-constrained stochastic model for a mobile phone closed-loop supply chain network with supplier selection. Kaya (2012) explored the outsourcing alternatives in waste management in a fuzzy environment. Wang et al. (2021) developed a stochastic model for reliability evaluation of warm standby embryonic cellular array. Deenadayalan and Vaishnavi (2021) invented deep learning based new techniques for reliability evaluation and forecasting using fault identification. Rahimifar et al. (2021) developed a random Markov model for energy consumption prediction in software defined wireless sensor networks. Jithish et al. (2021) suggested a decision-centric approach to develop secure and energy efficient cyber-physical systems and those results are not considered universally.

To achieve the global solution several soft computing techniques like genetic algorithm (Goldberg and Holland, 1988), particle swarm optimization (Kennedy and Eberhart, 1995) and differential evolution (Mullen et al., 2011; Storn and Price, 1997) have been employed in process industries. Kehar and Chopra (2021) used dynamic multi-objective differential evolution in visibility restoration of remote sensing images. Padmanabhan and Premalatha (2019) used different strategies of differential evolution for optimization of wind penetrated nonconvex dynamic power dispatch problem. Syu and Wu (2021) modified ORB trading policies using multi objective optimization techniques and particle swarm optimization. Sinwar et al. (2021) used nature-based algorithms GA and PSO in availability optimization of sewage treatment plant. From literature review, it is revealed that the reliability evaluation and performance optimization of E-waste management plants not explored so extensively so far. Salehi Amiri et al. (2020) determined the optimal sales level in a two-stage supply chain of perishable goods. Abdi et al. (2020) proposed innovative methodologies for designing the green supply chain network with pick-up and split delivery options.

Fasihi et al. (2021, 2021) suggested a bi-objective mathematical model for development of a fish closed-loop supply chain by using various multi-objective metaheuristic approaches. Hamdi-Asl et al. (2021) developed a model to achieve the sustainability in agricultural supply chain by taking case study of palm date. Zahedi et al. (Zahedi et al., 2021) designed a closed loop supply chain for multi-task sales agencies having multiple modes of transportation. Mousavi et al. (2021) used metaheuristic approaches in evaluation of the performance of the supply chain design of the blood decomposition employing the social factors. Akbarpour et al. (2021) developed an innovative e-waste management plant for smart cities using the vehicle routing problem under stochastic optimization. Amuthan and Arulmurugan (2021) developed a semi-Markov based hybrid trust prediction model for persisting lifetime using reliable cluster head selection in WSNs. Prajapati (2021) used particle swarm optimization algorithm for architecture recovery of large-scale many-objective software. Ghoushchi et al. (2021) proposed the methodology for the medical waste management by using Integrated SWARA-WASPAS framework operating on spherical fuzzy set.

Shahsavar (2022) suggested the procedure for bio-recovery of municipal plastic waste management working on the integrated decision-making structure. Salehi-Amiri et al. (2022) designed a sustainable waste management system accompanied with IoT facilities. Chouhan et al. (2022) developed a sustainable model for sugar mills based on decision-making techniques by considering the environmental effects. Kumar (2022) proposed an efficient stochastic model for the operational availability of steam turbine power plant components using population-based algorithms. Saini et al. (2022, xxxx) utilized metaheuristic approaches for the performance optimization of various process industries. Das et al. (2022) used genetic algorithm in the designing of designing multi-state computational grid by considering the ideas of cost and bandwidth.

By keeping all the above facts and figures in mind, it is observed that the reliability optimization of e-waste management plants is not explored so far. In addition, the usage of metaheuristic approaches to optimize the performance of e-waste management plant was not carried out. This motivates the authors to perform this study.

In short, the major contribution of this work is highlighted as follows:

- A novel stochastic framework is established to optimizing the steady state availability of e-waste management.
- The availability optimization is carried out using three well-established metaheuristic approaches viz. differential evolutions (DE), particle swarm optimization (PSO), and genetic algorithm (GA).
- The most sensitive component is identified using reliability, availability, maintainability, and dependability (RAMD) methodology.
- Exponential distribution is applied on failure and repair rates, and their impact of variation is observed using proposed model (i.e., Markovian approach).
- The numerical results of the proposed model are compared to identify the most efficient algorithm.

The whole manuscript is organized into six sections including the introductory section. Section 2, material and methods is designated for notations, system description, and description of various metaheuristic approaches. The RAMD analysis of the various subsystems is done in section 3 while steady state analysis of availability and its optimization is performed in section 4. Section 5 is devoted to discussion of results and conclusion is incorporated in section 6.

2. Material and methods

2.1. Notations

The following nomenclature is utilized for model development:

S. No.	Sub-system	Code		Failure rate/hr. τ_i	Repair rate/hr. μ_i
		Operative Mode	Failed Mode		
1	Collection unit	X	x	τ	μ
2	Classification unit	A	a	τ_1	μ_1
		B	b	τ_2	μ_2
3	Dismantling unit	C	c	τ_3	μ_3
		D	d	τ_4	μ_4
4	Crushing unit	E	e	τ_5	μ_5
5	Waste transfer	F	f	τ_6	μ_6
		G	g	τ_7	μ_7

$P'_0(t)$ = Derivative of the $P_0(t)$

$P_0(t)$,: At time t, the system at 0 state

○: Operative state

□: Failed state

2.2. System description

In present section, the configuration of the E-waste management plant is discussed. It is a very complex system having six units namely centralized E waste collection unit, classifiers, dismantling and destructing unit, crushing, disposal and transfer of hazardous treatment centre.

Initially, the E-waste is collected in smart E-waste collection boxes and after that waste is classified by object identification techniques. The classified material is segregated in various categories like small IT equipment, PCB, lamps, temperature exchange equipment's, etc. In next step dismantling and destruction of equipment started. The wastage having glass toxic contents either sent for disposal or transferred to the hazardous waste treatment center. The materials including plastic, copper, steel, aluminium is transferred for crushing and valuable material extracted or electronic cards exported for reuse. The flowchart of system description is given in Fig. 1. The failure and repair rates of all the units are drawn with the help of the plant personnel and reported in Table 1 along with the possible search space. All the random variables are statistically independent with each other and exponentially distributed. The system performed under the assumptions of availability of sufficient repair facilities, no simultaneous failures, and perfect repairs.

2.3. Optimization strategies

To optimize the steady state availability of e-waste management, three well-established metaheuristic algorithms viz. DE, GA and PSO are utilized. Based on literature review, it is observed that these algorithms are found to be suitable for availability optimizations of such systems. The brief description of these algorithms is mentioned in the subsequent subsections as follows.

2.3.1. Differential evolution

Differential Evolution (DE) (Storn and Price, 1997) is gaining interest in deriving optimized solutions to several engineering and scientific problems. However, DE is a heuristic approach, but it is not biologically inspired like other evolutionary algorithms (Georgioudakis and Plevris, 2020). Evolutionary algorithms make a few or no assumptions and start evolutions on the initial random solution. To derive an optimum solution from a search space of candidate solutions, DE stochastically performs the mutation, crossover, and selection. The Standard DE algorithm is simple in nature and requires adjusting only three control parameters. Sometimes the problem of predicting the right values of control parameters becomes hard and time-consuming for some problems. To cope with this, several variants of DE are also proposed by researchers and are termed as DE variants (Wang et al., 2011; Brest et al., 2006; Zhang and Sanderson, 2009). The standard DE algorithm is a direct search method that utilizes the population of individual solutions. The basic steps of standard DE are mentioned as follows:

1. Initialization: The initial population NP consists of whole parameter space of dimension D and is chosen randomly, or values supplied by user. Uniform probability distribution is assumed to be applicable for all random decisions. In case of availability of preliminary solution, the addition of normally distributed random deviations makes the initial population.

2. Mutation: The generation of new parameter vector is obtained by adding the difference of two population vectors. Three members of the population namely x_{r0}, x_{r1} and x_{r2} are chosen at random for creation of initial mutant vector v_i as given in (1) for each target vector $x_{i,G}, i = \{1, \cdots, NP\}$:

$$v_i = x_{r0} + F.(x_{r1} - x_{r2}) \quad (1)$$

Here, F indicates the differential weighting vector, and its values are generally between 0 and 1; and G indicates generation. The mutation continues until specified number of mutations takes place.

Crossover: Crossover obtains the trial vector u_i either from elements of donor vector v_i or from the elements of target vector x_i as given in (2):

$$u_{i,j} = \begin{cases} v_{i,j} & if \quad r_{i,j} \leq CR \ or \quad j = j_{rand} \\ x_{i,j} & otherwise \end{cases} \quad (2)$$

where $i = \{1, \cdots, NP\}$, $j = \{1, \cdots, D\}$, $r_{i,j}$ $U(0,1)$ is uniformly distributed random number generated for each j to ensure $u_i \neq x_i$ and CR is crossover probability.

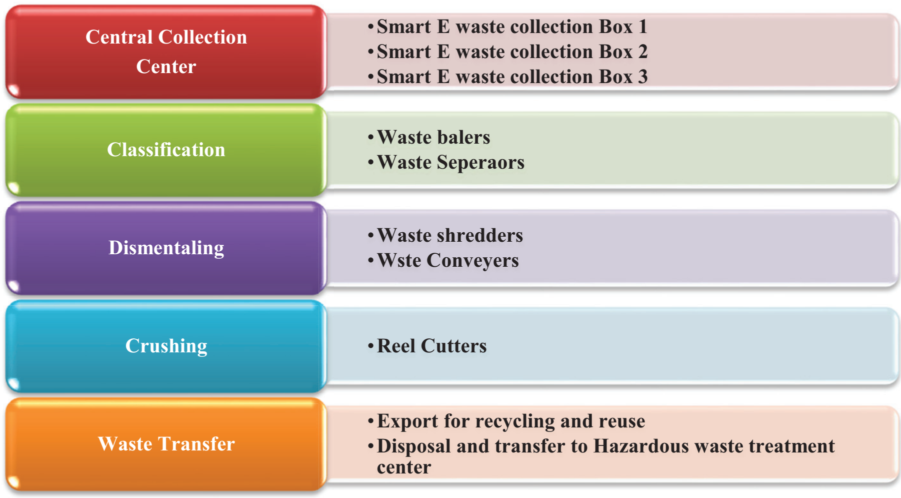

Fig. 1. Flow chart of E-waste management plant.

3 ***Selection***: To minimize, the trail vector is compared with target vector using greedy criterion. If $u_{i,G+1} < x_{i,G}$ then $x_{i,G+1} = u_{i,G+1}$ otherwise the old value of $x_{i,G}$ is retained.

2.3.2. Genetic algorithm

Genetic Algorithm (GA) (Goldberg and Holland, 1988) is a well-established population-based approach inspired from Darwinian theory of biological evolution process (survival of fittest). It is one of the prevalent evolutionary computation techniques that is characterized by fitness computations of individuals. Individuals with adequate fitness participate in next round of evolution. Initially random solution is termed as chromosome and parameters to be gene. The optimum solution can be obtained if the problem can be encoded using decision parameters. The variation in computation of genetic operators (selection, crossover, and mutation) creates new variants of the basic algorithm. The basic pseudocode of GA is mentioned in the algorithm 1 as follows:

Algorithm 1
Basic pseudocode of Genetic Algorithm (Goldberg and Holland, 1988).

```
START
Generation of initial population
Fitness computation
REPEAT
    Selection
    Crossover
    Mutation
    Fitness computation
UNTIL condition satisfied
STOP
```

In ***Selection***, the fitness value of individuals is compared with the threshold specified. Few implementations are based on random selection of individuals using roulette wheel mechanism. Two fittest individuals (parents) are selected for further reproduction of individuals. In ***Crossover***, new offspring are generated based on exchange of genes of selected parents until crossover point specified. The crossover point may be decided randomly or based on certain assumptions. Whereas, in ***Mutation*** the genes of an individual are shuffled or flipped according to the algorithm specified. Numerous mutation algorithms exist in research literature that provides autonomy to the researchers for their work.

2.3.3. Particle swarm optimization (PSO)

PSO (Kennedy and Eberhart, 1995) inspired by birds' social behavior is one of the efficient swarm intelligence-based meta-heuristic techniques. Here, particle refers to individuals of problem space that moves towards achieving common goal. The preliminary position of individuals is determined randomly based on constraints specified in lower bound and upper bound. Swarm on the other hand refers to the population of particles and the speed at which individuals move towards global optimization is referred to as velocity. On each movement of particles, the algorithm computes their fitness values known as personal best (or P_Best) and

Table 1
Failure and repair rates of subsystems.

Subsystems	RAMD and Markov Analysis Base values		Search Space	
	Failure Rates	Repair rates	Failure Rates	Repair rates
Collection unit	$\tau = 0.006$	$\mu = 0.285$	[0.00001–0.90]	[0.00001–2.00]
Classification	$\tau_1 = 0.007$	$\mu_1 = 0.281$	[0.00001–0.80]	[0.00001–2.10]
unit	$\tau_2 = 0.009$	$\mu_2 = 0.196$	[0.00001–0.95]	[0.00001–2.45]
Dismantling	$\tau_3 = 0.068$	$\mu_3 = 0.123$	[0.00001–0.97]	[0.00001–1.94]
Unit	$\tau_4 = 0.087$	$\mu_4 = 0.401$	[0.00001–0.96]	[0.00001–1.43]
Crushing unit	$\tau_5 = 0.041$	$\mu_5 = 0.318$	[0.00001–0.94]	[0.00001–3.20]
Waste transfer	$\tau_6 = 0.041$	$\mu_6 = 0.167$	[0.00001–0.87]	[0.00001–2.43]
	$\tau_7 = 0.041$	$\mu_7 = 0.167$	[0.00001–0.95]	[0.00001–2.08]

determines the next position by adding velocity values to the current position. The process of updating personal best based on global best is usually indicated as "learning from experiences". Algorithm converges upon reaching maximum iterations or satisfying stopping criteria. The basic equation of PSO is mentioned in Eq. (3). Here $x_i(t)$ denotes the position of a particle i in the search space at time t. Whereas, $v_i(t)$ indicates the velocity of particle i at time t. The updated position of a particle is achieved by adding the velocity to the current position, as stated in (3).

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (3)$$

The velocity $v_i(t+1)$ takes into account several other components viz. inertia coefficient, cognitive component, and the social component as mentioned in eq. (4).

$$v_i(t+1) = w.v_i(t) + c_1(p_i(t) - x_i(t)) + c_2(g(t) - x_i(t)) \quad (4)$$

Here, w indicates the inertia coefficient, $p_i(t)$ indicates personal best, $g(t)$ indicates the global best, $v_i(t)$ the initial velocity, and c_1 and c_2 are acceleration coefficients. The pseudocode of the standard PSO (Abbas and Abdulsaheb, 2016) is mentioned in the algorithm 2 as follows:

Algorithm 2
Basic pseudocode of Particle Swarm Optimization.

```
begin
          for each particle
          random initialization of position and velocity
     end for
    do
     for each particle
          evaluate fitness function
          if fitness > P_Best
               new P_Best = current fitness value
          end if
     end for
     choose G_Best from P_Best of all particles
     for each particle
          update velocity and position
     end for
    until stopping criteria satisfied
end begin
```

2.4. Simulation environment

For simulating the experimental evaluation, we have utilized RStudio (version 1.2.5042) on Windows10 64-bit with 8 GB of primary memory and Intel Core i7 7th generation CPU.

3. RAMD analysis of the E-waste plant

3.1. Collection unit

It is the primary unit of any e-waste management plant. Here, all the collected wastage stored in smart boxes. In proposed system it comprises three parallel smart boxes. The failure and repair rates of all boxes are same and exponentially distributed. The Markovian

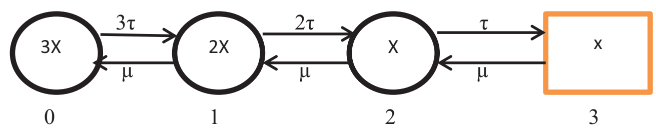

Fig. 2. State transition diagram of collection unit.

approach is used for reliability, availability, and maintainability analysis of collection unit. The state transition diagram of it is shown in Fig. 2.

The differential equations associated with the transition diagram of collection unit are as follows:

$$P_0'(t) = -3\tau P_0(t) + \mu P_1(t) \quad (5)$$

$$P_1'(t) = -(2\tau + \mu)P_1(t) + 3\tau P_0(t) + \mu P_2(t) \quad (6)$$

$$P_2'(t) = -(\tau + \mu)P_2(t) + 2\tau P_1(t) + \mu P_3(t) \quad (7)$$

$$P_3'(t) = \tau P_2(t) - \mu P_3(t) \quad (8)$$

Under steady state conditions, Eqs. (5)–(8) become

$$3\tau P_0(t) = \mu P_1(t) \quad (9)$$

$$(2\tau + \mu)P_1(t) = 3\tau P_0(t) + \mu P_2(t) \quad (10)$$

$$(\tau + \mu)P_2(t) = 2\tau P_1(t) + \mu P_3(t) \quad (11)$$

$$\tau P_2(t) = \mu P_3(t) \quad (12)$$

After solving Eqs. (9)–(12) and using normalization condition $\sum_{i=1}^{n} P_i = 1$, we get

$$P_1(t) = \frac{3\tau}{\mu}P_0(t);\ P_2(t) = \frac{6\tau^2}{\mu^2}P_0(t);\ P_3(t) = \frac{6\tau^3}{\mu^3}P_0(t) \quad (13)$$

Where.

$$P_0 = \left(1 + \frac{3\tau}{\mu} + \frac{6\tau^2}{\mu^2} + \frac{6\tau^3}{\mu^3}\right)^{-1} \quad (14)$$

3.2. Classification unit

It is a key unit of any e-waste management plant. Here, the collected wastage stored in smart boxes is classified by waste separators. It comprises two non-identical components having distinct failure and repair rates. The failure and repair rates are exponentially distributed. The Markovian approach is used for reliability, availability, and maintainability analysis of collection unit. The state transition diagram of it is shown in Fig. 3.

The Chapman-Kolmogorov differential equations associated with the transition diagram as shown in Fig. 3 for classification unit are:

$$P_0'(t) = -(\tau_1 + \tau_2)P_0(t) + \mu_1 P_1(t) + \mu_2 P_2(t) \quad (15)$$

$$P_1'(t) = -\mu_1 P_1(t) + \tau_1 P_0(t) \quad (16)$$

$$P_2'(t) = -\mu_2 P_2(t) + \tau_2 P_0(t) \quad (17)$$

Under steady state conditions, Eqs. (15)–(17) become,

$$(\tau_1 + \tau_2)P_0(t) = \mu_1 P_1(t) + \mu_2 P_2(t) \quad (18)$$

$$\mu_1 P_1(t) = \tau_1 P_0(t) \quad (19)$$

$$\mu_2 P_2(t) = \tau_2 P_0(t) \quad (20)$$

After solving Eqs. (18)–(20) and using normalization condition $\sum_{i=1}^{n} P_i = 1$, we get P_1 = 0.02418, P_2 = 0.00495 where

$$P_0\left(1 + \frac{\tau_1}{\mu_1} + \frac{\tau_2}{\mu_2}\right) = 1 \quad (21)$$

3.3. Dismantling unit

It is the prominent unit of any e-waste management plant. Here, destruction of the waste material is performed. In proposed system it consists of two components waste shredders and waste conveyors. The failure and repair rates of both components are different but exponentially distributed. The Markovian approach is used for reliability, availability, and maintainability analysis of dismantling unit. The state transition diagram of it is shown in Fig. 4.

The Chapman-Kolmogorov equations associated with the transition diagram as shown in Fig. 4 for dismantling unit are:

$$P_0'(t) = -(\tau_3 + \tau_4)P_0(t) + \mu_4 P_1(t) + \mu_3 P_2(t) \quad (22)$$

$$P_1'(t) = -\mu_4 P_1(t) + \tau_4 P_0(t) \quad (23)$$

$$P_2'(t) = -\mu_3 P_2(t) + \tau_3 P_0(t) \quad (24)$$

Under steady state conditions, Eqs. (22)–(24) become

$$(\tau_3 + \tau_4)P_0(t) = \mu_4 P_1(t) + \mu_3 P_2(t) \quad (25)$$

$$\mu_4 P_1(t) = \tau_4 P_0(t) \quad (26)$$

$$\mu_3 P_2(t) = \tau_3 P_0(t) \quad (27)$$

After solving Eqs. (25)–(27) and using normalization condition $\sum_{i=1}^{n} P_i = 1$, we get P_1 = 0.122588, P_2 = 0.312376 where

$$P_0\left(1 + \frac{\tau_4}{\mu_4} + \frac{\tau_3}{\mu_3}\right) = 1 \quad (28)$$

3.4. Crushing unit

It is the primary unit of any e-waste management plant. It performs the crushing of steel, plastic, and aluminium material. In proposed system it comprises a single component. The failure and repair rate of it follows exponentially distribution. The Markovian approach is used for reliability, availability, and maintainability analysis of collection unit. The state transition diagram of it is shown in Fig. 5.

The Chapman-Kolmogorov equations associated with the transition diagram as shown in Fig. 5 for crushing unit are:

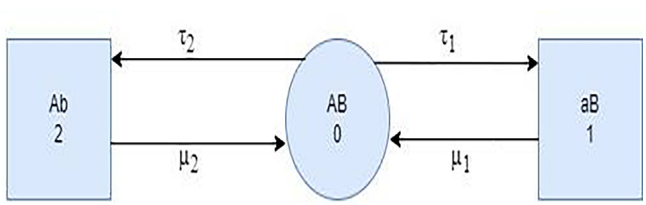

Fig. 3. State transition diagram of classification unit.

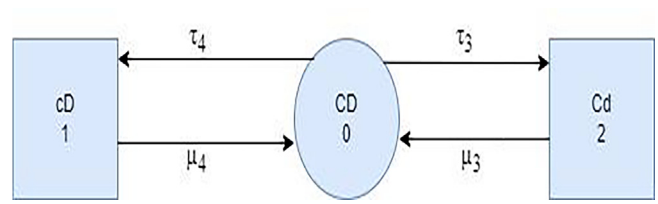

Fig. 4. State transition diagram of dismantling unit.

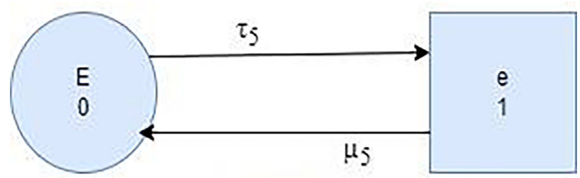

Fig. 5. State transition diagram of crushing unit.

$$P'_0(t) = \mu_5 P_1(t) - \tau_5 P_0(t) \tag{29}$$

$$P'_1(t) = -\mu_5 P_1(t) + \tau_5 P_0(t) \tag{30}$$

Under steady state conditions, Eqs. (29) and (30) become

$$\mu_5 P_1(t) = \tau_5 P_0(t) \tag{31}$$

After solving Eq. (31) and using normalization condition $\sum_{i=1}^{n} P_i = 1$, we get

$$P1 = 0.114206\, where P_0\left(1 + \frac{\tau_5}{\mu_5}\right) = 1 \tag{32}$$

3.5. Waste transfer unit

It is configured in last phase of e-waste management plant. From here useful material sent for recycling/reuse and material containing hazardous material transferred for advanced treatment or decomposition. In proposed system it comprises two non-identical components for this task. The failure and repair rates of both components are different and exponentially distributed. The Markovian approach is used for reliability, availability, and maintainability analysis of collection unit. The state transition diagram of it is shown in Fig. 6.

The Chapman-Kolmogorov equations associated with the transition diagram as shown in Fig. 6 for waste transfer unit are:

$$P'_1(t) = -(\tau_7 + \mu_6)P_1(t) + \tau_6 P_0(t) + \mu_7 P_2(t) \tag{33}$$

$$P'_0(t) = \mu_6 P_1(t) - \tau_6 P_0(t) \tag{34}$$

$$P'_2(t) = \mu_7 P_2(t) + \tau_7 P_1(t) \tag{35}$$

Under steady state conditions, Eqs. (33)–(35) become

$$(\tau_6 + \tau_7)P_1(t) = \tau_6 P_0(t) + \mu_7 P_2(t) \tag{36}$$

$$\mu_6 P_1(t) = \tau_6 P_0(t) \tag{37}$$

$$\mu_7 P_2(t) = \tau_7 P_1(t) \tag{38}$$

After solving Eqs. (36)–(38) and using normalization condition $\sum_{i=1}^{n} P_i = 1$, we get

$$P_1 = 0.188016,\ P_2 = 0.046155 \text{ where } \times P_0\left(1 + \frac{\tau_6}{\mu_6} + \left(\frac{\tau_7}{\mu_7}\right)\left(\frac{\tau_6}{\mu_6}\right)\right) = 1 \tag{39}$$

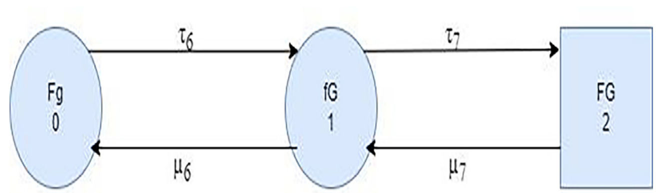

Fig. 6. State transition diagram of waste transfer unit.

From system structure, it is observed that all the components arranged in series configuration and failure of anyone causes complete system failure. So, RAM measures of the E waste system can be derived using expressions:

$$Reliability = \prod_{i=1}^{5} R_i(t) = e^{-0.1725t} \tag{40}$$

$$Availability = \prod_{i=1}^{5} A_i(t) = 0.9999230 \tag{41}$$

$$Maintainability = \prod_{i=1}^{5} M_i(t) = 1 - e^{-\mu_i t} \tag{42}$$

4. Steady state availability analysis of E-waste plant

The RAMD measures used to investigate the instantaneous performance as well as for identification of most critical component of the system. Among all measures availability is the most crucial measure that is highly influenced by its failure and repair rates as well as by time. So, it becomes necessary to investigate steady state availability of the system before reaching any decision about performance of the system. Thus, here a mathematical model for E-waste management plant is proposed using Markov birth–death process. Applying the notations and assumptions described in section 2 state transition diagram is prepared and shown in Fig. 7. The transition between states happened with some rate parameter. Using simple probabilistic arguments and changeover diagram, the mathematical model has been developed. The differential equations have been described as follows:

$$\begin{aligned} P_1(t+\delta t) = {} & (1 - 3\tau - \tau_1 - \tau_2 - \tau_3 - \tau_4 - \tau_5 - \tau_6 - \tau_7)P_1(t)\delta t \\ & + \mu P_2(t)\delta t + \mu_1 P_5(t)\delta t + \mu_2 P_6(t)\delta t + \mu_3 P_7(t)\delta t \\ & + \mu_4 P_8(t)\delta t + \mu_5 P_9(t)\delta t + \mu_6 P_{10}(t)\delta t + \mu_7 P_{11}(t)\delta t \end{aligned}$$

$$\frac{P_1(t+\delta t) - P_1(t)}{\delta t}$$

$= .(-3\tau - \tau_1 - \tau_2 - \tau_3 - \tau_4 - \tau_5 - \tau_6 - \tau_7)P_1(t) + \mu P_2(t)$
$+\mu_1 P_5(t) + \mu_2 P_6(t) + \mu_3 P_7(t) + \mu_4 P_8(t) + \mu_5 P_9(t)$
$+\mu_6 P_{10}(t) + \mu_7 P_{11}(t)$Taking limit $\delta t \rightarrow 0$, we get

$$\begin{aligned} & P'_1(t) + [3\tau + \tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5 + \tau_6 + \tau_7]P_1(t) \\ & = \mu P_2(t) + \mu_1 P_5(t) + \mu_2 P_6(t) + \mu_3 P_7(t) + \mu_4 P_8(t) \\ & \quad + \mu_5 P_9(t) + \mu_6 P_{10}(t) + \mu_7 P_{11}(t) \end{aligned} \tag{43}$$

Similarly,

$$\begin{aligned} & P'_2(t) + [2\tau + \mu + \tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5 + \tau_6 + \tau_7]P_2(t) \\ & = 3\tau P_1(t) + \mu P_3(t) + \mu_1 P_{12}(t) + \mu_2 P_{13}(t) + \mu_3 P_{14}(t) \\ & \quad + \mu_4 P_{15}(t) + \mu_5 P_{16}(t) + \mu_6 P_{17}(t) + \mu_7 P_{18}(t) \end{aligned} \tag{44}$$

$$\begin{aligned} & P'_3(t) + [\tau + \mu + \tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5 + \tau_6 + \tau_7]P_3(t) \\ & = 2\tau P_2(t) + \mu P_4(t) + \mu_1 P_{19}(t) + \mu_2 P_{20}(t) + \mu_3 P_{21}(t) \\ & \quad + \mu_4 P_{22}(t) + \mu_5 P_{23}(t) + \mu_6 P_{24}(t) + \mu_7 P_{25}(t) \end{aligned} \tag{45}$$

$$P'_4(t) + \mu P_4(t) = \tau P_3(t) \tag{46}$$

$$P'_{i+4}(t) + \mu_i P_5(t) = \tau_i P_1(t); i = 1,2,3,4,5,6,7 \tag{47}$$

$$P'_{j+11}(t) + \mu_j P_{12}(t) = \tau_j P_2(t); j = 1,2,3,4,5,6,7 \tag{48}$$

$$P'_{k+18}(t) + \mu_k P_{19}(t) = \tau_k P_3(t); k = 1,2,3,4,5,6,7 \tag{49}$$

Now taking limit $t \rightarrow \infty$ on Eqs. (43)–(49) and using normalization property $\sum_{i=1}^{25} P_i = 1$, we get

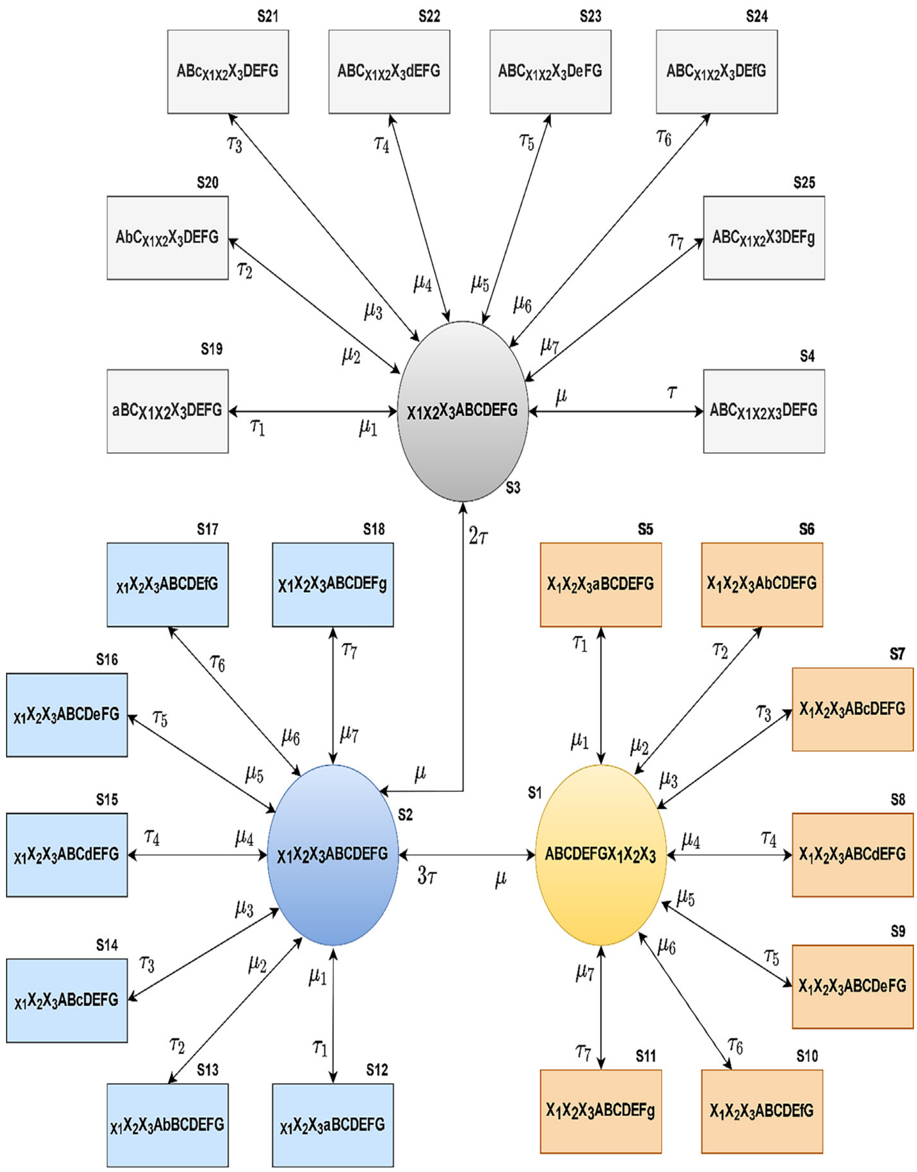

Fig. 7. State transition diagram of E-waste plant.

Table 2
Parameter values for metaheuristics.

Algorithm	Parameters
Genetic Algorithm	Population size = 100, 1000, 1500, 2000, 2500, 5000; Number of maximum iterations = 500; crossover rate = 0.7; mutation factor = 0.8
Particle Swarm Optimization	Population size = 100, 1000, 1500, 2000, 2500, 5000, number of maximum iterations = 500; inertia weight = 1; damping ratio = 0.9; global best = 2.8; personal best = 1.8
Differential Evolution	Population size = 100, 1000, 1500, 2000, 2500, 5000; Number of maximum iterations = 500; crossover rate = 0.7; mutation factor = 0.8

Table 3
Reliability indices of e-waste plant and its subsystems.

Indices	SS1	SS2	SS3	SS4	SS5
Availability	0.999998	0.99999	0.999998	0.99999	0.999955
Reliability	$e^{-0.018t}$	$e^{-0.016t}$	$e^{-0.0155t}$	$e^{-0.041t}$	$e^{-0.082t}$
Maintainability	$e^{-8999.994t}$	$e^{15999.9744t}$	$e^{-77499.5544t}$	$e^{-0.40999905t}$	$e^{-1822.14083t}$
Dependability	499999.001	999998.4	499997.125	9.999977	22221.2298
MTTR (hrs.)	0.000111112	0.0000625001	0.0000129033	2.43903	0.000548805
MTBF (hrs.)	55.556	62.5	6.4516129	24.3902439	12.195122

$$P_1 = \{1 + \frac{3\tau}{\mu} + 6\frac{\tau^2}{\mu^2} + 6\frac{\tau^3}{\mu^3} + \frac{\tau_1}{\mu_1} + \frac{\tau_2}{\mu_2} + \frac{\tau_3}{\mu_3} + \frac{\tau_4}{\mu_4} + \frac{\tau_5}{\mu_5} + \frac{\tau_6}{\mu_6} + \frac{\tau_7}{\mu_7} + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_1}{\mu_1}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_2}{\mu_2}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_3}{\mu_3}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_4}{\mu_4}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_5}{\mu_5}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_6}{\mu_6}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_7}{\mu_7}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_1}{\mu_1}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_2}{\mu_2}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_3}{\mu_3}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_4}{\mu_4}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_5}{\mu_5}\right) + 6(\frac{\tau^2}{\mu^2})(\frac{\tau_6}{\mu_6}) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_7}{\mu_7}\right)\}^{-1} \quad (50)$$

Similarly, probability at state are as follows:

$$P_2 = \frac{3\tau}{\mu}P_1, P_3 = 6\frac{\tau^2}{\mu^2}P_1, P_4 = 6\frac{\tau^3}{\mu^3}P_1, P_5 = \frac{\tau_1}{\mu_1}P_1, P_6 = \frac{\tau_2}{\mu_2}P_1, P_7 = \frac{\tau_3}{\mu_3}P_1, P_8 = \frac{\tau_4}{\mu_4}P_1, P_9 = \frac{\tau_5}{\mu_5}P_1, P_{10} = \frac{\tau_6}{\mu_6}P_1, P_{11} = \frac{\tau_7}{\mu_7}P_1, P_{12} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_1}{\mu_1}\right)P_1, P_{13} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_2}{\mu_2}\right)P_1, P_{14} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_3}{\mu_3}\right)P_1, P_{15} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_4}{\mu_4}\right)P_1, P_{16} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_5}{\mu_5}\right)P_1, P_{17} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_6}{\mu_6}\right)P_1, P_{18} = \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_7}{\mu_7}\right)P_1, P_{19} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_1}{\mu_1}\right)P_1, P_{20} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_2}{\mu_2}\right)P_1, P_{21} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_3}{\mu_3}\right)P_1, P_{22} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_4}{\mu_4}\right)P_1, P_{23} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_5}{\mu_5}\right)P_1, P_{24} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_6}{\mu_6}\right)P_1, P_{25} = 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_7}{\mu_7}\right)P_1 \quad (51)$$

The initial conditions associated with the Markov model of E-waste management plant are:

$$P_i(t=0) = \begin{cases} 1 & if\ \ i = 1 \\ 0 & if\ \ i \neq 1 \end{cases} \quad (52)$$

By using above differential difference equations and initial conditions an algebraic solution has been derived for a particular case using MATLAB R2019a. The steady state availability of E-waste management plant is:

$$\text{Availability} = P_1 + P_2 + P_3 = \left(1 + \frac{3\tau}{\mu} + 6\frac{\tau^2}{\mu^2}\right) \times \left\{1 + \frac{3\tau}{\mu} + 6\frac{\tau^2}{\mu^2} + 6\frac{\tau^3}{\mu^3} + \frac{\tau_1}{\mu_1} + \frac{\tau_2}{\mu_2} + \frac{\tau_3}{\mu_3} + \frac{\tau_4}{\mu_4} + \frac{\tau_5}{\mu_5} + \frac{\tau_6}{\mu_6} + \frac{\tau_7}{\mu_7} + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_1}{\mu_1}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_2}{\mu_2}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_3}{\mu_3}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_4}{\mu_4}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_5}{\mu_5}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_6}{\mu_6}\right) + \left(\frac{3\tau}{\mu}\right)\left(\frac{\tau_7}{\mu_7}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_1}{\mu_1}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_2}{\mu_2}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_3}{\mu_3}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_4}{\mu_4}\right) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_5}{\mu_5}\right) + 6(\frac{\tau^2}{\mu^2})(\frac{\tau_6}{\mu_6}) + 6\left(\frac{\tau^2}{\mu^2}\right)\left(\frac{\tau_7}{\mu_7}\right)\right\}^{-1} \quad (53)$$

It is observed that results derived from algebraic methods are local solution. To attain a global solution, here an effort has been made to optimize the availability of the system using genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution (DE). The search space for all the algorithms is given in Table 2.

Table 4
Impact of failure rates on e-waste plant's availability.

τ	Base values as Table 1	$\tau_{1+10\%\ of}\ \tau_1$	$\tau_{2+10\%\ of}\ \tau_2$	$\tau_{3+10\%\ of}\ \tau_3$	$\tau_{4+10\%\ of}\ \tau_4$	$\tau_{5+10\%\ of}\ \tau_5$	$\tau_{6+10\%\ of}\ \tau_6$	$\tau_{7+10\%\ of}\ \tau_7$
0.006	0.406399	0.405988	0.405642	0.397469	0.402847	0.404281	0.402385	0.402385
0.007	0.406394	0.405983	0.405637	0.397464	0.402843	0.404276	0.40238	0.40238
0.008	0.406388	0.405977	0.405631	0.397458	0.402836	0.40427	0.402373	0.402373
0.009	0.40638	0.405969	0.405623	0.39745	0.402828	0.404262	0.402365	0.402365
0.01	0.40637	0.405959	0.405613	0.397441	0.402818	0.404252	0.402355	0.402355
0.011	0.406357	0.405946	0.405601	0.397429	0.402806	0.404239	0.402343	0.402343
0.012	0.406343	0.405932	0.405586	0.397415	0.402792	0.404225	0.402329	0.402329
0.013	0.406326	0.405915	0.40557	0.397399	0.402776	0.404209	0.402313	0.402313
0.014	0.406307	0.405896	0.40555	0.397381	0.402757	0.40419	0.402294	0.402294
0.015	0.406285	0.405874	0.405528	0.39736	0.402735	0.404168	0.402273	0.402273

Table 5
Impact of repair rates on e-waste plant's availability with respect to repair rate μ.

μ	Base values as Table 1	$\mu_{1+10\%\ of}\ \mu_1$	$\mu_{2+10\%\ of}\ \mu_2$	$\mu_{3+10\%\ of}\ \mu_3$	$\mu_{4+10\%\ of}\ \mu_4$	$\mu_{5+10\%\ of}\ \mu_5$	$\mu_{6+10\%\ of}\ \mu_6$	$\mu_{7+10\%\ of}\ \mu_7$
0.285	0.406399	0.406774	0.40709	0.414873	0.409683	0.408344	0.410119	0.410119
0.286	0.406399	0.406774	0.40709	0.414873	0.409683	0.408345	0.410119	0.410119
0.287	0.4064	0.406774	0.40709	0.414873	0.409683	0.408345	0.410119	0.410119
0.288	0.4064	0.406774	0.40709	0.414873	0.409683	0.408345	0.41012	0.41012
0.289	0.4064	0.406774	0.40709	0.414874	0.409684	0.408345	0.41012	0.41012
0.29	0.4064	0.406774	0.40709	0.414874	0.409684	0.408345	0.41012	0.41012
0.291	0.4064	0.406774	0.40709	0.414874	0.409684	0.408345	0.41012	0.41012
0.292	0.4064	0.406774	0.407091	0.414874	0.409684	0.408345	0.41012	0.41012
0.293	0.4064	0.406774	0.407091	0.414874	0.409684	0.408345	0.41012	0.41012
0.294	0.4064	0.406774	0.407091	0.414874	0.409684	0.408345	0.41012	0.41012

Table 6
Availability of e-waste management plant corresponding to various population sizes after several number of iterations using DE, GA and PSO.

	Iteration\Pop.	100	1000	1500	2000	2500	5000
DE	10	0.57186	0.65088	0.67894	0.66324	0.64079	0.72968
	50	0.83808	0.88819	0.92715	0.93101	0.92166	0.93149
	100	0.97242	0.97508	0.98021	0.98161	0.98258	0.98718
	150	0.99088	0.99627	0.99588	0.99476	0.99574	0.99609
	200	0.99706	0.9984	0.99849	0.99886	0.9991	0.99911
	250	0.99875	0.99933	0.99962	0.99966	0.99951	0.99969
	500	0.99996	0.99997	0.99997	0.99997	0.99997	0.99997
GA	10	0.682163754	0.492237318	0.540949783	0.747069294	0.590373408	0.61942313
	50	0.788893712	0.899252001	0.805315996	0.741884876	0.777622629	0.661576147
	100	0.771045887	0.827706545	0.836137092	0.735580642	0.785460908	0.774586286
	150	0.891477728	0.77152548	0.856142927	0.792508543	0.904568546	0.84228081
	200	0.846061967	0.839109663	0.820325698	0.893291024	0.824479993	0.812661241
	250	0.886625412	0.796007602	0.899252001	0.841920101	0.869461721	0.853197045
	500	0.845926564	0.861549945	0.893794327	0.87633046	0.92330969	0.884338206
PSO	10	0.898239418	0.992268821	0.994314679	0.99972813	0.996432193	0.999838134
	50	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744
	100	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744
	150	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744
	200	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744
	250	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744
	500	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744	0.99996744

Table 7
Parameter estimation of various failure and repair rates of e-waste management plant after 10 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.0529	0.92284	0.03624	0.12722	0.08295	0.00456
	τ_2	0.15877	0.04971	0.06092	0.19568	0.20532	0.17171
10	τ_3	0.06665	0.09149	0.01819	0.11913	0.25295	0.03413
	τ_4	0.00313	0.34311	0.14934	0.32032	0.06145	0.06198
	τ_5	0.4034	0.08349	0.04827	0.01968	0.03633	0.02424
	τ_6	0.02124	0.00509	0.40671	0.03415	0.08065	0.01847
	τ_7	0.21382	0.00846	0.05119	0.02338	0.06172	0.28167
	τ	0.38242	0.18735	0.36506	0.40262	0.34349	0.59904
	μ_1	1.2472	0.87591	1.55099	1.68409	1.71711	1.16052
	μ_2	1.93771	0.69971	0.98216	1.52621	1.31209	1.79475
	μ_3	0.42959	1.57367	2.36789	2.04142	2.23198	1.5126
	μ_4	0.5028	1.72441	1.77371	1.8401	0.97955	1.02154
	μ_5	1.23894	1.15234	0.59584	0.98165	1.30841	1.34449
	μ_6	2.43742	2.42199	2.6806	1.97734	2.75863	2.70992
	μ_7	2.28645	0.98051	0.81938	1.88778	1.0616	1.88741
	μ	0.45831	0.89023	0.0401	0.32037	0.797	0.15482
GA	τ_1	0.062088398	0.024631284	0.124101766	0.000798516	0.281128146	0.15634331
	τ_2	1.477169575	0.11277188	0.344985661	0.226234824	0.135437411	0.001051267
	τ_3	0.039987682	0.002577529	0.035842737	0.025898667	0.13202867	0.038039374
	τ_4	0.02251269	0.035455529	0.004671065	0.141988286	0.144043099	0.023034206
	τ_5	0.005657059	0.001324544	0.002229503	0.011275149	0.000620237	0.000335157
	τ_6	0.09622308	0.002670865	0.05274112	0.001626294	0.007470696	0.005077256
	τ_7	0.282851894	0.102817063	0.206067881	0.188481239	0.125545206	0.308643643
	τ	0.055445781	0.374178938	0.729388402	0.12665264	0.826299752	0.270581548
	μ_1	0.647681475	0.153909262	0.35455813	0.661296639	0.232100617	0.143437651
	μ_2	3.969044075	0.464613159	0.790372418	1.016746503	0.508981683	0.773977148
	μ_3	1.664777646	0.004668892	2.225057601	0.367810618	5.134334095	0.572810645
	μ_4	1.031293665	0.171805014	0.556283734	1.603521516	1.701454059	3.708409592
	μ_5	0.392154782	0.714588879	0.327264713	1.087871263	0.491252164	1.292527745
	μ_6	1.767173972	1.492354247	0.446188395	1.05616157	0.333883398	0.338862692
	μ_7	1.14004701	0.27361917	0.480375382	1.751314908	0.65155174	0.287642444
	μ	1.403432413	0.302359521	0.843754672	1.241214288	2.095161866	5.445185148
PSO	τ_1	0.165205345	0.375369177	0.246261328	0.119520187	0.311501701	0.103190574
	τ_2	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_3	0.378082778	0.000001	0.000001	0.000001	1E-06	0.000001
	τ_4	0.009531185	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_5	0.020859416	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_6	0.092167019	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_7	0.00001	0.00001	0.006039983	0.00001	0.00001	0.00001
	τ	0.083709218	0.00001	0.00001	0.00001	0.00001	0.00001
	μ_1	1.444059853	1.369168067	1.199551548	1.546359321	1.52157281	1.704303954
	μ_2	0.551881469	1.098402739	1.826544541	1.270091104	1.581812507	1.604859634
	μ_3	2.45	1.572257702	1.58977744	1.942989573	2.259644907	1.556510145
	μ_4	1.682096469	1.131890095	0.700313569	1.746001	1.723494224	0.795326384
	μ_5	1.015105901	1.267547299	0.954322431	0.930041361	0.923379372	0.973263923
	μ_6	2.888924508	1.732159596	2.854079931	3.078448916	1.923062016	2.833431398
	μ_7	0.502163066	1.56997504	1.034630364	1.681446202	1.604311873	2.268436058
	μ	1.432112469	0.24312269	0.44486568	1.919669452	1.382975125	1.426826751

5. Results and discussion

In this section, RAMD and steady state availability results of e-waste management plant are illustrated. The impact of variation in various failure and repair rates on steady state availability is also investigated. Subsystem's failure and repair rates are varied by 10% and its effect is studied on availability. The results of steady state availability are appended in Tables 4–5. Table 3 shows the reliability, availability, maintainability, dependability, MTBF and MTTR results of all the subsystems. It is observed that SS3 has the minimum MTBF. E-waste plant reliability, maintainability and availability based on subsystems RAMD measures are shown in Eqs. (40)–(42) (Table 6).

Table 4appended the steady sate availability of e waste management plant derived through the model developed in Eq. (53). The base value of the availability is derived by using initial values of the parameters given in Table 1. After that +10% variation is made, and availability is evaluated. It is observed dismantling unit is highly sensitive as its failure rate τ_3 is very influential. It is revealed that availability of the system declines sharply with the increase of failure rate. The value of availability changes from 0.406399 to 0.331842.

Table 5 shows the steady sate availability of e-waste management plant derived through the model developed in Eq. (53). The base value of the availability is derived by using initial values of the parameters given in Table 1. After that +10% variation is made in repair rates, and availability is evaluated. It is observed that dismantling unit is highly sensitive as its repair rate (μ_3) shows highest increment in availability. It is revealed that availability of the system increases sharply with the increase of repair rate. The availability changes from 0.406399 to 0.457831.

In the last, an effort has been made to attain the optimum value of system availability. For this purpose, metaheuristic approached genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution (DE) applied on the availability function given in Eq. (53). The experiment is run at various population sizes between 100 and 5000 and different iterations from 10 to 500. The genetic algorithm provides the maximum value (0.92330969) of availability at population size 2500 after 500 iterations. PSO algorithm attained the maximum value (0.99996744) of availability just after 50 iterations and 100 population size. So, its rate of convergence is faster than GA. The optimum value of availability is 0.99997 using differential evolution after 500 iterations and population size more than 1000. The values of all the failure and repair rates is also estimated at various population sizes and number of iterations as shown in Table 7 and Appendix-I (Tables A1–A6).

6. Conclusion

The reliability characteristics namely reliability, availability, maintainability, and dependability play crucial role during the design phase as well as operation period of the e-waste management plants. In this situation the assessment of these measures at any instantaneous time points as well as long-time becomes necessary. The optimization of availability and parameter estimation becomes necessary to obtain a global solution. So, in this paper first RAMD analysis is performed and observed that availability of system and all subsystems is greater than 0.9999 at instant time point. But in long run the availability is sharply decreased, and it reached at 0.406399. The variation in availability is due to the variation in failure rates. And the variation of failure and repair rates also influences the availability of the plant. In this situation, it becomes necessary to assess such values of failure and repair rates in such a way that the system remains highly available. So, various metaheuristic approached GA, PSO and DE are applied on the availability model and optimum value 0.99997 of availability is achieved corresponding to the estimated parameter values. The results of RAM measures and estimated parameters can be used further to design the new e-waste management plants and to develop life cycle costing models. The present study is conducted on a single e-waste management plant. For more efficient results, it is recommended to perform the same on the data of several plants. Future works will be devoted to the estimation of parameters using some other nature inspired algorithms and to develop mathematical model to estimate the impact of simultaneous failures.

7. Compliance with Ethical Standards

Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Research involving human participants and/or animals: The authors declare that this work does not involve human participants and/or animals in any capacity.

Informed consent: The authors declare that this work does not involve any survey or participants in any capacity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix I

See

Table A1
Parameter estimation of various failure and repair rates of e-waste management plant after 50 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.08475	0.00247	0.01027	0.0075	0.00458	0.04594
	τ_2	0.02692	0.02795	0.02253	0.00343	0.03704	0.01653
	τ_3	0.09732	0.00652	0.00267	0.00015	0.01073	0.01682
	τ_4	0.01512	0.05963	0.00436	0.03487	0.00624	0.02589
	τ_5	0.03581	0.05079	0.02384	0.02276	0.02149	0.00531
	τ_6	0.02267	0.07325	0.04741	0.035	0.01055	0.00515
	τ_7	0.00558	0.01255	0.01243	0.01248	0.01104	0.01605

Table A1 (*continued*)

iter\NP		100	1000	1500	2000	2500	5000
	τ	0.61041	0.04466	0.173	0.01307	0.56288	0.1092
	μ_1	1.79198	1.70157	1.89479	1.90114	0.76242	1.83651
	μ_2	2.05971	2.02097	1.5185	1.11749	1.28977	2.06049
	μ_3	1.46896	1.45693	2.09163	1.95671	2.08887	2.24114
	μ_4	1.30248	1.70851	1.73708	1.46987	1.83297	1.78325
	μ_5	1.39701	1.36776	1.30725	1.37662	1.2687	1.38056
	μ_6	2.46502	2.57927	1.53286	1.63031	2.62098	2.53982
	μ_7	2.20441	2.2058	2.42463	2.36622	1.80039	1.89967
	μ	0.17604	0.0589	0.06824	0.86133	0.1731	0.79236
GA	τ_1	0.098327997	0.01738154	0.003515388	0.192275748	0.010373113	0.092431277
	τ_2	0.030409379	0.008744319	0.032787422	0.121067519	0.012298427	0.014053925
	τ_3	0.00182943	0.0125748	0.012367954	0.048070267	0.060326318	0.041246365
	τ_4	0.005613936	0.032024137	0.006530782	0.001045521	0.129367717	0.006353632
	τ_5	0.001222364	0.003764149	0.011417447	0.005679233	0.00075201	0.013488584
	τ_6	0.003657761	0.111388254	0.034681343	0.003549851	0.042892222	0.11355944
	τ_7	0.177076631	0.042301641	0.107953358	0.123440774	0.316848991	1.308051153
	τ	0.501120934	0.078218436	0.175652845	0.634945467	0.048171051	0.008672101
	μ_1	0.993182595	0.16094856	2.294633788	2.482122898	3.037155846	0.082416872
	μ_2	0.386625744	1.008208173	0.257178916	3.465070207	0.313120302	0.25808869
	μ_3	0.261749281	0.463045988	2.773815122	1.791882409	0.763480806	0.354424394
	μ_4	0.233102405	3.338438795	1.442271565	0.243985966	1.001274383	0.094912185
	μ_5	2.083199101	0.641292098	0.51911701	2.523363376	0.375943319	0.818691803
	μ_6	0.198377883	0.523102778	0.978526756	0.225834426	0.161910926	0.392587743
	μ_7	0.457235604	1.695710481	0.595720187	2.516927772	1.780389583	4.753323824
	μ	3.680074138	1.756110077	1.358768641	0.669707341	1.012579491	3.207952394
PSO	τ_1	0.00001404	0.00001001	0.00001001	0.00001000	0.00001000	0.00001000
	τ_2	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_3	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100
	τ_4	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_5	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_6	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_7	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	μ_1	1.54354775	1.88556932	1.92933335	1.93139298	1.96967002	1.88166433
	μ_2	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000
	μ_3	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000
	μ_4	1.93999995	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000
	μ_5	1.42999998	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000
	μ_6	3.19999996	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000
	μ_7	2.42999987	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000
	μ	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000

Table A2
Parameter estimation of various failure and repair rates of e-waste management plant after 100 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.00199	0.00726	0.01027	0.01134	0.0015	0.00081
	τ_2	0.02019	0.00461	0.01312	0.00451	0.00378	0.0045
	τ_3	0.00989	0.00956	0.00653	0.00145	0.00482	0.00193
	τ_4	0.0005	0.0131	0.00149	0.00045	0.00051	0.00013
	τ_5	0.00438	0.00008	0.00214	0.00126	0.00025	0.00069
	τ_6	0.0066	0.00376	0.00091	0.01188	0.01218	0.01616
	τ_7	0.01373	0.00866	0.00243	0.00895	0.00907	0.00298
	τ	0.47901	0.14148	0.09855	0.00126	0.05623	0.05587
	μ_1	1.7456	1.83461	1.7499	1.87643	1.28339	1.37645
	μ_2	2.06104	2.04219	1.9534	1.74077	1.75835	1.70275
	μ_3	1.91116	2.15991	2.17177	1.99063	2.38899	1.83707
	μ_4	1.91979	1.59276	1.64127	1.75656	1.71368	1.83513
	μ_5	1.35304	1.22552	1.40907	1.4039	1.27632	1.36365
	μ_6	2.97224	2.91507	2.17406	2.85071	1.65491	2.58969
	μ_7	2.10185	2.24017	1.71294	2.21234	2.21602	2.05197
	μ	0.00395	0.24666	0.16706	0.36423	0.54968	0.55292
GA	τ_1	0.018942685	0.098127856	0.173957729	0.052602187	0.092873994	0.099321941
	τ_2	0.036257837	0.023888896	0.019238457	0.110040438	0.257911489	0.129252606
	τ_3	0.030785089	0.011480337	0.001687625	0.001762628	0.007727482	0.08252085
	τ_4	0.01273129	0.032905235	0.013546923	0.03919958	0.028026597	0.016577261
	τ_5	0.008384474	0.003202844	0.007645753	0.006736844	0.007667393	0.000240709
	τ_6	0.15309501	0.043908133	0.062178979	0.058891505	0.010049556	0.016723778
	τ_7	0.206790843	0.236835525	0.177838744	0.017867212	0.011641792	0.360573717
	τ	0.534517907	0.025218872	0.043137292	0.30448676	0.212398297	0.005991856

(*continued on next page*)

Table A2 (*continued*)

iter\NP		100	1000	1500	2000	2500	5000
	μ_1	3.72432091	0.387803782	0.850568213	0.327427718	1.304834364	0.613345317
	μ_2	0.345583641	1.419956059	0.647855601	0.454891913	1.651801745	1.58109221
	μ_3	0.901383187	0.15700864	0.542729778	1.660394512	1.170979493	1.009832965
	μ_4	0.828525719	0.281580147	0.330751628	2.469297289	4.058497533	2.599622996
	μ_5	0.519599072	1.663364549	0.925277535	0.684749428	1.497681364	1.33493222
	μ_6	0.774699224	0.820876416	0.485520147	0.445686336	0.053605138	0.542847753
	μ_7	1.603741893	1.129009301	1.214112565	1.016305411	0.162716682	0.743649007
	μ	2.235205229	0.876187265	0.257951995	1.002070185	1.289538854	1.25462955
PSO	τ_1	0.00001003	0.00001033	0.00001000	0.00001003	0.00001085	0.00001004
	τ_2	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_3	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100
	τ_4	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_5	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_6	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_7	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	μ_1	1.97257913	1.91189597	1.92767814	1.88255134	1.99992728	1.92665879
	μ_2	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000
	μ_3	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000
	μ_4	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000
	μ_5	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000
	μ_6	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000
	μ_7	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000
	μ	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000

Table A3
Parameter estimation of various failure and repair rates of e-waste management plant after 150 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.00191	7.00E-05	0.00196	0.00039	0.00258	0.00058
	τ_2	0.00177	0.00285	2.00E-04	0.00332	0.00144	0.0006
	τ_3	0.00291	0.00019	0.0015	0.00072	6.00E-04	0.00065
	τ_4	0.00087	0.00448	6.00E-05	0.00053	0.00131	0.00305
	τ_5	0.00005	0.00269	0.00094	0.00216	0.00049	0.00111
	τ_6	0.00747	6.00E-05	0.00122	0.00025	0.00112	0.00048
	τ_7	0.00191	0.00025	0.00101	0.00243	0.00073	0.00053
	τ	0.38862	0.06792	0.02155	0.03028	0.06293	0.08855
	μ_1	1.7512	1.5066	1.23475	1.27364	1.8669	1.98854
	μ_2	2.03092	1.85866	2.09048	2.02668	1.77756	1.92042
	μ_3	2.2329	2.28743	1.74739	2.36682	2.33167	2.33751
	μ_4	1.92781	1.5929	1.60587	1.87191	1.70701	1.92731
	μ_5	1.37855	1.41864	1.39372	1.34131	1.38738	1.39784
	μ_6	3.16356	3.11195	2.9942	3.02876	2.87163	3.19006
	μ_7	2.33509	0.65497	2.34338	2.42699	2.29929	2.22258
	μ	0.09313	0.03999	0.74993	0.30045	0.00036	0.17423
GA	τ_1	0.061984879	0.001028614	0.062952778	0.045916654	0.000663558	0.07678634
	τ_2	0.036727337	0.361544766	0.012532802	0.266492622	0.080518589	0.034794864
	τ_3	0.013814557	0.085733529	0.036538108	0.211775166	0.023956679	0.001692315
	τ_4	0.024005561	0.004591531	0.018272291	0.009527564	0.024790136	0.05887881
	τ_5	0.007928857	0.007511107	0.002426165	0.008380384	0.00107309	0.006746754
	τ_6	0.041057755	0.0575407	0.026498829	0.026815894	0.00080602	0.103465509
	τ_7	0.040499743	0.418868505	0.288466465	0.18496036	0.016735919	0.139053821
	τ	0.000259929	0.085032838	0.035363601	0.112912364	0.144611428	0.141082039
	μ_1	0.595496518	0.505742114	0.351137923	1.021708445	0.628844795	1.84852738
	μ_2	1.03659918	2.762008766	1.156004484	2.90200593	1.107877535	0.678464054
	μ_3	0.821883161	1.239676646	0.171414856	1.676289106	1.732608624	0.716172076
	μ_4	0.847094462	0.284596668	0.891193935	0.989694961	0.853067636	1.437811628
	μ_5	0.493328334	0.628835792	0.184076092	1.399876787	2.170889039	0.694694133
	μ_6	0.530286731	0.603679495	0.717936599	0.297506512	0.396861885	0.497616306
	μ_7	0.397089181	1.547377015	3.060177996	0.861710986	0.938637581	1.574831195
	μ	1.645304076	1.570339004	1.065205421	1.531768971	2.687973728	1.851542454
PSO	τ_1	0.00001000	0.00001000	0.00001000	0.00001010	0.00001000	0.00001017
	τ_2	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_3	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100
	τ_4	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_5	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_6	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_7	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	μ_1	1.88758435	1.97021890	1.87961438	1.97800178	1.88469279	1.90218097

Table A3 (*continued*)

iter\NP		100	1000	1500	2000	2500	5000
	μ_2	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000
	μ_3	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000
	μ_4	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000
	μ_5	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000
	μ_6	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000
	μ_7	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000
	μ	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000

Table A4
Parameter estimation of various failure and repair rates of e-waste management plant after 200 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.00114	0.00031	0.00076	0.00017	0.00002	0.0001
	τ_2	0.00156	5.00E-04	2.00E-04	0.00009	0.00021	0.00011
	τ_3	0.00004	9.00E-04	0.00031	0.00033	0.00047	0.00027
	τ_4	0.00073	0.00022	0.00024	0.00109	0.00001	0.00027
	τ_5	0.00141	0.00013	0.00067	0.00007	0.00003	0.00038
	τ_6	0.00005	0.001	0.00026	0.00005	0.00073	0.00015
	τ_7	0.00035	0.00033	0.00032	0.00047	0.00067	0.00045
	τ	0.04774	0.03005	0.01225	0.0167	0.01219	0.02613
	μ_1	1.85131	1.96511	1.71458	1.9685	1.80575	1.79114
	μ_2	2.03588	1.65082	2.05889	1.93741	1.89672	1.96529
	μ_3	1.94578	2.42446	2.35938	2.41668	2.21722	2.34836
	μ_4	1.87947	1.9097	1.90861	1.90422	1.79596	1.937
	μ_5	1.4223	1.34004	1.39349	1.39596	1.36981	1.39379
	μ_6	2.98934	3.05686	2.99241	3.01579	2.93824	3.05262
	μ_7	2.33242	1.99625	2.27659	2.00904	2.34848	2.2956
	μ	0.00181	0.44807	0.80736	0.00178	0.05398	0.08714
GA	τ_1	0.006758744	0.083651709	0.09195037	0.048278547	0.027394809	0.019009945
	τ_2	0.069556761	0.056289837	0.186568394	0.039238147	0.1202491	0.081729199
	τ_3	0.003705374	0.03022232	0.037956359	0.068456073	0.007109911	0.035166173
	τ_4	0.130873297	0.014555226	0.051156863	0.013675671	0.046996482	0.003778835
	τ_5	0.01764361	0.014241921	0.000627769	0.00383984	0.004769226	0.002130655
	τ_6	0.004539613	0.009001206	0.007322473	0.060768878	0.011316122	0.004388266
	τ_7	0.077088332	0.346453605	0.027594259	0.013418323	0.194314582	0.038256579
	τ	0.247763283	0.049773856	0.290092504	0.056381591	0.929855712	0.006043907
	μ_1	0.437635966	0.208674318	1.084650799	0.65688313	0.672325512	0.106528693
	μ_2	2.706940391	1.152509256	2.862470313	0.987318943	1.642286663	0.833718604
	μ_3	0.166906587	1.741646312	0.872673339	1.778756221	2.034080997	0.266849051
	μ_4	1.781964328	1.918881077	0.286115661	1.874529901	1.63797774	0.584539929
	μ_5	0.586948685	1.11969803	0.23169425	0.14059163	1.057497377	0.018815746
	μ_6	1.195524326	0.677478059	0.767636743	0.687310745	0.783714217	0.653484433
	μ_7	1.221730925	1.399925223	2.154423639	2.019810478	1.119000804	1.487235224
	μ	1.041031025	0.821181332	1.819399331	0.842373614	4.063033952	0.833849805
PSO	τ_1	0.00001002	0.00001001	0.00001001	0.00001000	0.00001001	0.00001005
	τ_2	0.00001000	0.00001000	0.00001001	0.00001000	0.00001000	0.00001000
	τ_3	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100
	τ_4	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_5	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_6	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_7	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	μ_1	1.88465871	1.93255741	1.92562247	1.92289945	1.88046161	1.88781095
	μ_2	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000
	μ_3	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000
	μ_4	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000
	μ_5	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000
	μ_6	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000
	μ_7	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000
	μ	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000

Table A5
Parameter estimation of various failure and repair rates of e-waste management plant after 250 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.00022	0.00027	7.00E-05	0.00001	0.00016	0.00003
	τ_2	0.00069	6.00E-05	3.00E-05	0.00022	4.00E-05	0.00007
	τ_3	0.00023	0.00031	0.00017	0.00002	3.00E-05	0.00003
	τ_4	0.00011	0.00043	0.00021	0.00009	0.00027	0.00003
	τ_5	0.00063	4.00E-05	2.00E-05	0.00015	2.00E-04	0.00021
	τ_6	0.00003	0.00014	0.00033	0.00016	6.00E-05	0.00007
	τ_7	0.00044	0.00015	6.00E-05	0.00002	3.00E-05	0.00011
	τ	0.17619	0.00108	0.00328	0.01508	0.02523	0.00683
	μ_1	1.90451	1.99543	1.92547	1.93404	1.90997	1.98946
	μ_2	2.03282	2.01274	2.06174	2.09496	1.92667	2.07551
	μ_3	2.44214	2.33309	2.26989	2.28172	2.43602	2.33154
	μ_4	1.88858	1.88918	1.86126	1.84941	1.93068	1.93123
	μ_5	1.42404	1.39875	1.31907	1.35213	1.42834	1.40492
	μ_6	3.14647	2.95298	3.09376	3.12653	2.75931	2.98599
	μ_7	2.34278	1.9885	2.3938	2.25236	0.77436	2.10917
	μ	0.01164	0.30972	1.23309	0.17482	0.55061	0.00499
GA	τ_1	0.013858306	0.042034606	0.01738154	0.285028207	0.005739437	0.232853634
	τ_2	0.053625448	0.304531851	0.008744319	0.166707818	0.005595088	0.066622487
	τ_3	0.001216733	0.02018085	0.0125748	0.011054002	0.008587143	0.029742572
	τ_4	0.003969356	0.006524492	0.032024137	0.001854317	0.012226805	0.00410904
	τ_5	0.000715869	0.004545323	0.003764149	0.004544069	0.010498651	0.004752373
	τ_6	0.010568267	0.114608511	0.111388254	0.006755232	0.005947608	0.004903127
	τ_7	0.020977203	0.16684372	0.042301641	0.120837501	0.150384761	0.119483051
	τ	0.568519023	0.122138897	0.078218436	0.207651643	0.108633474	0.134734605
	μ_1	1.023176182	0.782495655	0.16094856	0.774352875	0.180236412	1.131036701
	μ_2	1.243801712	7.153833129	1.008208173	5.892877701	0.358899392	3.65472218
	μ_3	3.002018448	3.664567932	0.463045988	0.350509761	1.417374505	1.856237932
	μ_4	0.786858037	1.187021787	3.338438795	1.093945927	0.635113026	0.18890229
	μ_5	1.202614097	0.044202663	0.641292098	1.186047048	0.333203265	0.149453582
	μ_6	0.342255895	0.411372656	0.523102778	0.497830906	0.286455765	0.117301839
	μ_7	1.209224366	1.764665133	1.695710481	0.562735248	0.603059589	0.522328087
	μ	2.327188089	1.211315952	1.756110077	1.21951327	3.938239401	1.987590156
PSO	τ_1	0.00001040	0.00001012	0.00001006	0.00001014	0.00001001	0.00001012
	τ_2	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_3	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100
	τ_4	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_5	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_6	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_7	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	μ_1	1.97035254	1.89543123	1.97511433	1.99608431	1.97142867	1.89206276
	μ_2	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000
	μ_3	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000
	μ_4	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000
	μ_5	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000
	μ_6	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000
	μ_7	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000
	μ	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000

Table A6
Parameter estimation of various failure and repair rates of e-waste management plant after 500 iterations using DE, GA and PSO.

iter\NP		100	1000	1500	2000	2500	5000
DE	τ_1	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_2	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_3	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_4	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_5	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_6	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ_7	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	τ	0.00375	0.0009	0.00087	0.00057	0.00199	0.00076
	μ_1	1.99073	1.98158	1.97895	1.99572	1.9893	1.98901
	μ_2	2.08072	2.09936	2.07667	2.07853	2.09861	2.09133
	μ_3	2.43489	2.43724	2.4479	2.44872	2.42696	2.44244
	μ_4	1.92354	1.93565	1.92679	1.93519	1.92685	1.92996
	μ_5	1.42533	1.42558	1.42094	1.42427	1.42807	1.42869
	μ_6	3.18615	3.17014	3.19584	3.17974	3.19701	3.1831
	μ_7	2.39181	2.38537	2.40565	2.42144	2.42432	2.40701
	μ	0.06083	0.45402	0.15068	0.37328	0.2954	0.47076
GA	τ_1	0.250415176	0.013608071	0.244335011	0.014977493	0.082126135	0.016621164

Table A6 (*continued*)

iter\NP		100	1000	1500	2000	2500	5000
	τ_2	0.018518257	0.057539551	0.059458397	0.047129576	0.006118488	0.041893965
	τ_3	0.136978659	0.011272428	0.003869947	0.005449012	0.003805663	0.049295917
	τ_4	0.01457364	0.006701227	0.007351925	0.00844475	0.015009048	0.006790128
	τ_5	0.002512083	0.014092331	0.005256271	0.001736416	0.002255645	0.005792934
	τ_6	0.024581056	0.064619697	0.011398867	0.037741556	0.048294263	0.004198128
	τ_7	0.172434289	0.027984066	0.057100471	0.072488905	0.183308871	0.060289183
	τ	0.049741585	0.00270113	0.242244823	0.019881673	0.043490082	0.012449438
	μ_1	0.634460967	0.039635418	2.123045822	0.054758075	1.287456687	2.200988698
	μ_2	0.670022402	0.520371786	1.562756437	0.756527562	0.591910583	1.448795743
	μ_3	1.725428341	0.4109658	0.760776337	1.092352953	0.296834303	0.232009599
	μ_4	1.224108213	3.532653748	0.21564359	1.61283496	1.357555408	1.262330523
	μ_5	0.275686142	0.741320874	0.396810242	0.110426425	0.714578532	3.038349968
	μ_6	1.558575395	2.112667875	0.337719779	0.5402051	0.538478353	0.486405934
	μ_7	0.736033421	0.561555082	3.150501127	0.652287749	2.101035529	1.579590507
	μ	1.965034262	0.878857056	1.74867778	1.299768666	3.374213839	1.084156489
PSO	τ_1	0.00001030	0.00001020	0.00001000	0.00001077	0.00001001	0.00001000
	τ_2	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_3	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100	0.00000100
	τ_4	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_5	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_6	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ_7	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	τ	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000	0.00001000
	μ_1	1.95527309	1.99185185	1.88869575	1.99999751	1.88529923	1.97771036
	μ_2	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000	2.10000000
	μ_3	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000	2.45000000
	μ_4	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000	1.94000000
	μ_5	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000	1.43000000
	μ_6	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000	3.20000000
	μ_7	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000	2.43000000
	μ	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000	2.08000000

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