RAP AND AVAILABILITY ANALYSIS OF MANUFACTURING SYSTEM: SMO AND PSO

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Abstract

In today's scenario manufacturing industries are highly complex and prone to failure. That's why redundancy allocation problem (RAP) and time dependent availability analysis plays a major role for the successful life cycle of a manufacturing industry. RAP is a Np-hard problem which is very difficult to solve by traditional methods. Therefore in this paper, RAP for the Manufacturing system is solved by Spider monkey optimization. SMO is recent meta-heuristic technique. Till now it is not used to solve RAP. Further results are compared with the Particle swarm optimization algorithm and comparison validates the better performance of SMO in this problem. As mentioned above, for avoiding the complete breakdown of the manufacturing system time- dependent availability is analyzed in this study. Firstly failure and repair data is collected from the manufacturing system then with the help of this information transition diagram is developed. Further equations are developed from transition diagram by using Markov birth death process then equations are solved with the use of Runge-Kutta method. This methodology is implemented in MATLAB.

Keywords: Availability, Reliability, RAP, Markov modelling, SMO, PSO, Manufacturing System.

1. Introduction

The demand for high-quality products and system reliability is increasing day by day in the current world business competitive market. It is observed that only those products will stand in the market, which is up to the desired market level and consumer's satisfaction level. Along with the increasing demand of quality products/systems in practical engineering the importance of reliability optimization is also increased. With the limitation of constraints (costs/ weight), important measurements can be used to increase system reliability. There are several measurements which can be used for increasing the system reliability but redundancy allocation is the important strategy for improving the reliability of the system with constraints. Redundancy allocation problem is a reliability optimization problem. It involves selection of components with appropriate levels of redundancy or reliability to maximize the system reliability under the defined constraints. The redundancy allocation problem was solved by heuristic algorithm(HA) and constraint optimization algorithm (COGA) [1].

In this study, RAP of the manufacturing system is solved by PSO and SMO techniques. A few years back, PSO technique which was a peculiarity has now become the zest of researchers in the world. PSO is a nature-inspired and population-based stochastic technique. It was first introduced in the year 1995 [2]. PSO was applied for solving RAP due to its robustness and its simplicity [3]. Hybrid PSO with local search algorithm was applied for solving RAP [4]. Comparative analysis is also done with Tabu search and Multi weighted objectives solutions. A hybrid PSO algorithm with local search was proposed for solving RAP in series-parallel system [5]. The reformulate of a crisp optimization problem from FMOOP has been done and then applied PSO for solving fuzzified MOOP under a number of constraints [6]. A hybrid particle swarm optimization with constraint optimization genetic algorithm was proposed for solving a RAP [7]. A bare bones PSO and sensitivity based clustering was proposed for solving multi-objective RAP [8]. Multi-objective PSO (MOPSO) was applied for solving RAP in an interval environment [9]. The effectiveness of the algorithm is demonstrated by two numerical examples in their study.

An improved PSO was applied for solving RAP [10]. Inertia and acceleration coefficients of the classical PSO are improved by considering normal distribution for the coefficients which improved the results. The formulation of RAP with global reliability (g-reliability) has been done and applied improved PSO algorithm with a specific particles under RAP [11]. The optimization of the reliability of the system was done with the allocation of the redundancy of the manufacturing systems using hybrid genetic and particle swarm algorithm [12]. The redundancy allocation problem was solved by using hybrid genetic simulating annealing algorithm and a comparative study is presented in this research [13]. The reliability of the pharmaceutical plant was optimized by using heuristic algorithm [14].

SMO algorithm is introduced by J.C. Bansal in the year 2014 [15]. SMO is stimulated by social behavior of a special kind of monkeys called as spider monkeys. Spider monkeys have been classified as animals with fission-fusion social structure. These monkeys follow fission-fusion social systems as they initially work in a large group and but as their needs change over time, they split into smaller forage groups, each led by an adult female. Consequently, the suggested approach can be roughly categorized as drawing inspiration from the intelligent foraging behavior of spider monkeys with fission-fusion social structures. The initialize phase, the global leader phase (GLP), the local leader phase (LLP), and the decision phase are the main four phases of the SMO algorithm.

SMO was used as an optimization technique for the community of electromagnetic [16]. SMO was enforced to figure out the optimal PIDA controller parameters to control the induction motor [17]. This was the initial strategy to attain such a goal using SMO. The outcomes were compared to the Dorf and PSO technique, and it was noticed that SMO outperformed both of other methods.

An effort was made to solve confined consistent optimization problem by employing the SMO algorithm for restricted optimization problems [18]. A new search feature was developed in SMO called Power Law-based Local Search (PLLS) [19]. The SMO technique was applied to classify diabetes and developed SMO that may be used to design the SM-Rule-Miner, an effective rule miner for diabetes diagnosis [20]. Comparing SM-Rule-Miner to other meta-heuristic based rule mining techniques, it was found that it had the second-best average classification performance rating and the highest accuracy sensitivity rating.

A survey was conducted on SMO, its applications, and variants, and compared the findings to other algorithms [21]. Recently, a modern Discrete Spider Monkey Optimization (DSMO) technique was applied to solve the problem of travelling salesmen [22]. SMO and deep neural networks were applied for the future forecasting of brands for marketing purposes by using Twitter data [23]. Further investigation showed that SMO was more reliable and computationally efficient than other techniques.

Most of the products are manufactured in manufacturing plants, which consist of several subsystems performing different operations. These subsystems are made up of mechanical parts that may fail due to wear and tear and also due to usage with the passage of time. The failure is a random aspect that is always related to the operative condition of any physical system. Its causes are either deterioration in the components of the system and human errors.

As a result, the primary priority is to maintain system performance measures such as reliability and availability and redundancy in order to achieve high-profit targets and productivity in terms of system failures. Reliability optimization and availability are closely related concepts. Reliability optimization involves improving the system's ability to operate without failure, while availability is a measure of the system's ability to be operational when it is required.

The behavior analysis of time-dependent availability of the manufacturing system is measured using the Runge-Kutta fourth-order method in MATLAB. The area synthesis procedure's availability was considered for the compost industry [24]. The reliability and quality attributes for two stochastic models of a framework were discussed which have two non-indistinguishable components, arranged in series, each unit having cold standby of same/equal capacity [25]. The time-dependent availability of repairable m-out of –n and cold standby systems were investigated using arbitrary distributions and repair facilities [26]. An instructional study on reasonable strategies for Markov modeling was considered [27]. The analysis of availability formulations of standby frameworks of parallel units was done [28].

The study of a two-unit warm reserve framework was discussed that expects a bivariate exponential thickness for the joint circulation of sub-units failure/repair rates [29]. The number of operational stages of a repairable Markov framework during interim finite time was studied [30]. Finite Markov processes were utilized to model a repairable framework with time-independent transition rates concerning individual conditions in reliability analysis. The complex system with the imperfect switching using various techniques such as the Markov-method and supplementary variable method was considered [31]. Failure/repair rates are considered as constant. Further, the N sub-unit framework was analyzed in which M sub-unit are warm standby and R sub units are used to repair the failed sub-units [32]. A closed equation is developed to discover reliability parameters under certain constraints and conclusion is made on the basis of this study that without a repairman, framework reliability diminishes. The shortest path study in stochastic systems; acquainted another methodology and getting the reliability capacity of time-subordinate frameworks with standby mode was discussed [33]. The application of pod propulsion that the number of vessel types has been increased consistently over the last two decades was highlighted [34]. A model was developed using Markov process [35]. Regression analysis was utilized in that study to gauge the different transition rates of the model. A cattle feed plant consisting of seven subsystems arrange in series was analyzed by using matrix method [36]. The mathematical model has been developed using the Markov birth-death process and made a transition diagram. The system's behavior was analyzed over an implanted Markov chain method [37]. The discrete-time and continuous-time measures were provided for each of the explicit Markov and two semi-Markov models for thermal availability plant using simulation modeling [38]. The performance of the steam-generating system was evaluated and analyzed for the availability of a thermal plant [39]. In their study, the system consists three subunits with a high-pressure heater, boiler drum, and economizer associated in series, parallel, and combination of these. Further, Markov model was used for analyzing the reliability of coal crushing unit of Badarpur thermal power plant [40]. Transition diagram and differential equations are developed and solved by a recursive approach. Markov modeling was used for the fertilizer plant and analyzed the reliability of the system [41]. Their study deals with Markov birth-death procedure, and the failure rates and repair rates of every system. The RPGT technique was used for the behavioral study of two units [42].

A stochastic model was analyzed that was to be considered two-unit redundant framework [43]. In this framework, the operational unit's software and hardware elements on failure are substituted by the cold standby unit, and replacement may be possible on fractional failure also. Markov model was used to analyze the reliability of the phased-mission system (PMS) [44]. Mathematical modeling is done by utilizing the state merging method. The analyze the reliability of the manufacturing system is done by Fault tree analysis [45].

2. Problem Description and Formulation

The following assumptions and notations are taken for solving RAP and to draw a transition diagram depicting the various possible working, reduced, and failed states, together with the transitional failure and repair rates of subsystems to analyze and discuss the behavior of time-dependent availability of the manufacturing system.

2.1. Assumptions

The assumptions are follows:

- Failure and repair rates are considered constant and statistically independent of each other. Not more than one unit can fail at a time.
- The repaired units work as if a new one.
- There is only one subsystem which has units in parallel; hence it can work in a reduced capacity, on the failure of all units of this subsystem, there is the complete failure of the system.
- All other subsystems (except one given above) have subunits in series, so if a single unit of these subsystems fail, then the whole of the system fails completely.
- No unit fails further when the system is reached in failed state.

2.2. Notations

The notations used in this research work are as follows:

Rs(n):	System reliability
g(.):	A function that yields the system reliability, based on unique subsystems, and which depends on the configuration of the subsystems
ni:	number of ith subsystems
h(n_i):	Cost of ith subsystem
n:	number of subsystems
Rs:	Rupees
y*:	(n1,n2, n3,…, n7) is optimal solution
A, B, C, D, E, F, G:	Indicate that the subsystems are working in full capacity.
$\bar{B}$:	Indicate the reduced state of the subsystem B.
λ_i (i=1, 2, 3, …, 7, 8):	Failure rates of the subsystems A, B, C, D, …, G, $\bar{B}$respectively.
μ_i(i=1, 2, 3, …, 7, 8):	Repair rates of the subsystems a, $\bar{B}$, c, d, …, g, brespectively.
a, b, c, d, e, f, g	Indicate the failure state of the subsystems A, B, C, D, E, F, G
$P_i(t)$ (i=0, 1, 2, 3, …, 14)	probability that system is in the ith state.
	Failed state
	Full working state
	Reduced state
S0	ABCDEFG
S2	A$\bar{B}$CDEFG
S1	aBCDEFG
S3	ABcDEFG
S_4	ABCdEFG
S_5	ABCDeFG
S_6	ABCDEfG
S_7	ABCDEFg
S_8	a$\bar{B}$CDEFG
S_9	AbCDEFG
S_{10}	A$\bar{B}$cDEFG

S_{11}	$A\bar{B}CdEFG$
S_{12}	$A\bar{B}CDeFG$
S_{13}	$A\bar{B}CDEfG$
S_{14}	$A\bar{B}CDEFg$

2.3. System Description

The system is described as:

- Data is collected from the manufacturing system.
- Data related to subsystems (machines) and the number of units connected in that subsystem, regarding subsystems, their configuring, and working.
- The system consists of seven subsystems: Overhead Crane, Roller, Blanking Machine, Stacker machine, Press machine, Molding, and Packing. These subsystems are connected in series for the proper functioning of the system at full capacity initially.
- Overhead Crane Subsystem (A): There is only one overhead crane having subunits in series.
- Roller Subsystem (B): The roller consists of one unit having subunits in parallel. It rolls the steel roll connected to the blanking machine.
- Blanking Machine (C): The blanking machine cuts the blanks having subunits in series.
- Stacker Subsystem (D): Blanks are stacked with the help of a stacker having subunits in series.
- Press Subsystem (E): Blanks are pressed for the desired shape by the Press subsystem having subunits in series.
- Molding Machine (F): The molding machine molds the pressed blanks for the desired shape having subunits in series.
- Packing Subsystem (G): Packing machine packs the final product having subunits in series.

Structural Representation of the system

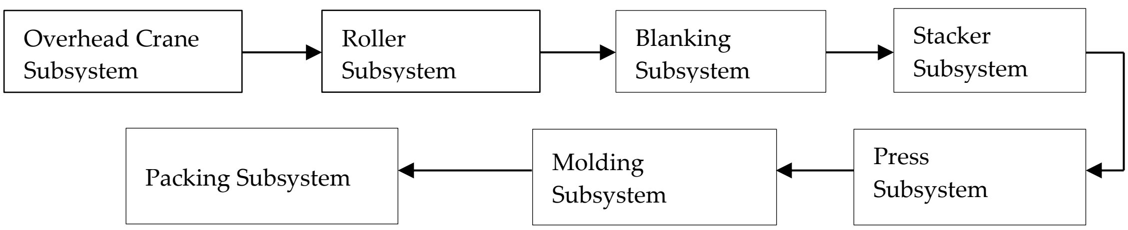

Figure 1: *System Structure*

Problem Statement

In this study, the data related to the subsystem's reliability and cost are presented in Table 1 of the manufacturing system. The given cost constraint is C= Rs 30490000. The objective function for the manufacturing system is to maximize the reliability and subject to cost constraint. The problem is represented by Equation (2), and the cost constraint presented by Equation (3).

The problem is to maximize :

$$R_s(n) = g\,(R_1(n_1),\ \ldots,\ R_n(n_n)) = \prod_{i=1}^{7} R_i\,(n) \tag{1}$$

$$R_i(n_i) = \prod_{i=1}^{7}[1 - [Q_i(n_i)]^{n_i}] \tag{2}$$

$$\sum_{i=1}^{7} h(n_i) * n_i \leq 30490000 \quad (3)$$

Table 1: *Reliability and Cost*

Subsystem	n_1	n_2	n_3	n_4	n_5	n_6	n_7
Reliability of subsystem $R_i(n_i)$	0.99	0.9762	0.9188	0.8155	0.8655	0.9287	0.9453
Cost of subsystem(Rs) $h(n_i)$	1280000	960000	2500000	1050000	10500000	950000	250000

Optimization using PSO and SMO Algorithms

Inspired by swarm intelligence in nature, PSO was developed by Kennedy and Eberhart in 1995 [2].

PSO is motivated by the social behavior of bird flocking and applies this behavior to guide the particles for searching the global optimal solutions. Mostly, in PSO, the particle population are randomly spread throughout the search space. The particles are considered to be flying in the search space. PSO searches for optima by updating generations after being initialized with a collection of random particles (solutions).

Each particle is modified by the following the two best values in every iteration. The first one is the best solution (fitness) it has obtained so far. This value is known as pbest. Another "best" value that is obtained by the particle swarm optimizer is the best value obtained so far by any particle in the population. This global best value is known as gbest. When a particle takes part of the population as its topological neighbors, the best value is a local best and is called lbest. The position and velocity updated with the help of two equations:

$$v_i = wv_i + c_1 r_1 (p_{best,i} - y_i) + c_2 r_2 (g_{best} - y_i) \quad (4)$$
$$y_i = y_i + v_i \quad (5)$$

Results of PSO

The results of the redundancy allocation solved by PSO are represented in tabular form. Table 2 shows different redundant units for various subsystems obtained by using PSO.

Table 2: *Results of PSO for the Manufacturing System*

Subsystems	n_1	n_2	n_3	n_4	n_5	n_6	n_7
Redundancy of the subsystems	2	1	2	3	1	3	3

SMO is stimulated by social behavior of a special kind of monkeys called as spider monkeys. Spider monkeys have been classified as animals with fission-fusion social structure. These monkeys follow fission-fusion social systems as they initially work in a large group and but as their needs change over time, they split into smaller forage groups, each led by an adult female. Consequently, the suggested approach can be roughly categorized as drawing inspiration from the intelligent foraging behavior of spider monkeys with fission-fusion social structures. The initialize phase, the global leader phase (GLP), the local leader phase (LLP), and the decision phase are the main four phases of the SMO algorithm.

Results of SMO

The results of RAP of the manufacturing system obtained by SMO are also represented in tabular form. Optimum redundant units of each subsystems redundant of each subsystem are represented in Table 3.

Table 3: *Results of SMO for the Manufacturing System*

Subsystems	n_1	n_2	n_3	n_4	n_5	n_6	n_7
Redundancy of the subsystems	3	2	3	3	1	2	5

Comparative analysis of the results of RAP by PSO and SMO

The comparative analysis of the results obtained by two algorithms PSO and SMO for the Manufacturing system in this research.

The comparative analysis of the results of RAP using PSO and SMO are represented in Table 3. Obtained results demonstrate the increase in the reliability of the manufacturing system.

Table 4: *Comparison of the best optimal solution by PSO and SMO*

Subsystems	n_1	n_2	n_3	n_4	n_5	n_6	n_7	Increase in the reliability
Redundancy								
PSO	2	3	2	5	1	3	5	
SMO	3	2	3	5	2	2	5	

The comparative analysis of the results obtained by these algorithms are described as follows:

The reliability value of the system before applying these two algorithms is 0.5236.
The values of the redundant units of each subsystem before using these algorithms are n*=(1,1,1,1,1,1,1).
The optimal solution of RAP using PSO is Rs(n*) = 0.8332 and the redundancy units n* = (2, 1, 2, 3, 1, 3, 3).
The increment in the value of reliability can be 51%.
The final solution of RAP using SMO is Rs(n*) = 0.8504 and redundant units of each subsystem n*= (3, 2, 3, 3, 1, 2, 4).
The reliability value of the system can be increased by 55% using SMO.
The reliability value of the system is increased by using both the algorithms.
The redundancy units of the subsystems n* are distinct for every subsystem by both the algorithms used in this research.
The larger increment in the reliability value of the system using SMO which is 55%.
The results shows that the batter results obtained by SMO and reliability is also improved by SMO than PSO.

Time dependent availability

The state transition diagram of the manufacturing system is drawn as follows:

2.4. State Transition Diagram

The first order Markov-process is used to develop the state transition diagram. A state transition diagram, together with transition rates, is drawn to describe the various states of the system, is given below in Figure 1.

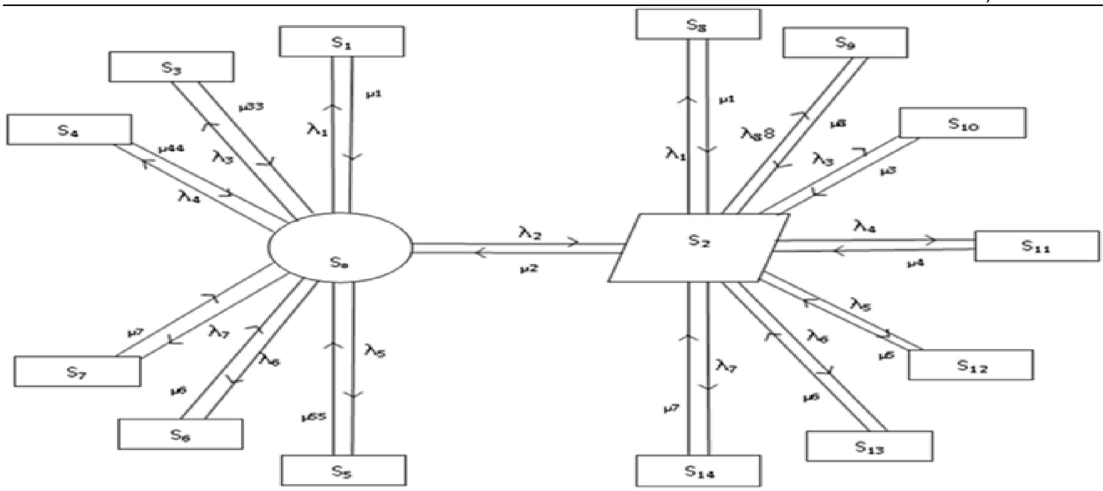

Figure 2: *State Transition Diagram of Manufacturing System*

2.5. Methodology- Runge-Kutta Fourth Order

Differential equations associated with the system are written using the Markov birth-death method, which is further solved using Runge-Kutta fourth-order method by ODE- 45 in MATLAB. Table and graph are drawn to represent the results of the time-dependent availability of the manufacturing system.

Mathematical Modelling:

The differential equations governing the system using the Markov birth-death process are as follows:

$$P_0'(t) + (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7)P_0(t) = \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_3(t) + \mu_4 P_4(t) + \mu_5 P_5(t) + \mu_6 P_6(t) + +\mu_7 P_7(t) \quad (6)$$

$$\mu_1 P_1(t) = \lambda_1 P_0(t) \quad (7)$$

$$P_2'(t) + (\lambda_1 + \mu_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8)P_2(t) = \lambda_2 P_0(t) + \mu_1 P_8(t) + \mu_8 P_9(t) + \mu_3 P_{10}(t) + \mu_4 P_{11}(t) + \mu_5 P_{12}(t) + \mu_6 P_{13}(t) + \mu_7 P_{14}(t) \quad (8)$$

$$\mu_3 P_3(t) = \lambda_3 P_0(t) \quad (9)$$

$$\mu_4 P_4(t) = \lambda_4 P_0(t) \quad (10)$$

$$\mu_5 P_5(t) = \lambda_5 P_0(t) \quad (11)$$

$$\mu_6 P_6(t) = \lambda_6 P_0(t) \quad (12)$$

$$\mu_7 P_7(t) = \lambda_7 P_0(t) \quad (13)$$

$$\mu_1 P_8(t) = \lambda_1 P_2(t) \quad (14)$$

$$\mu_8 P_9(t) = \lambda_8 P_2(t) \quad (15)$$

$$\mu_3 P_{10}(t) = \lambda_3 P_2(t) \quad (16)$$

$$\mu_4 P_{11}(t) = \lambda_4 P_2(t) \quad (17)$$

$$\mu_5 P_{12}(t) = \lambda_5 P_2(t) \quad (18)$$

$$\mu_6 P_{13}(t) = \lambda_6 P_2(t) \quad (19)$$

$$\mu_7 P_{14}(t) = \lambda_7 P_2(t) \tag{20}$$

3. Results

The results of time-dependent availability obtained using the Runge-Kutta fourth-order method by ODE 45 in MATLAB are represented below in Table 5 and Figure 2.

Table 5: *Time-dependent availability*

Time	Availability
0	1
20	0.827
40	0.8203
60	0.7932
80	0.7757
100	0.7644
120	0.7561
140	0.7515
160	0.7451
180	0.7328
200	0.7215

The availability of the system is also determined after the reliability of the system is improved by the technique SMO.

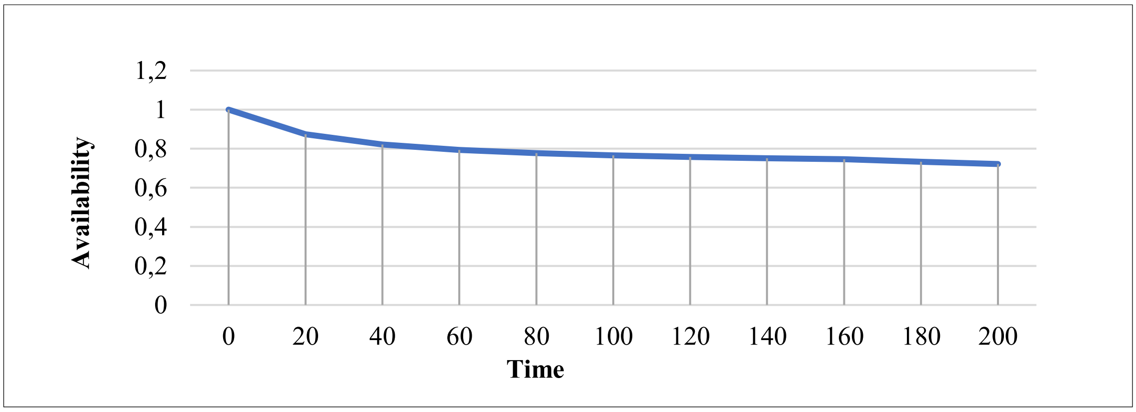

Figure 3: *Time-Dependent Availability*

4. Conclusion

In this study, redundancy is used as a key strategy for reliability optimization to improve system performance, minimize failures, and enhance the overall reliability and availability of a system or process. RAP is a mathematical optimization problem that involves determining the optimal allocation of redundancy to subsystems in order to improve the system reliability and availability. RAP is solved by SMO and results are compared with PSO.

RAP of the manufacturing system is solved by two optimization techniques PSO and SMO. The reliability of the manufacturing system is improved by both the techniques. But the increment of 55% in reliability of the manufacturing system by SMO which is greater than 51% by PSO.

The availability of the manufacturing system is also analyzed using Markov modelling. The calculations are done using Runge-Kutta method of forth order in MATLAB using the tool ode 45. It is concluded that system availability is a decreasing function of time. As time increases, the availability value of the system decreases.

5. Author Contribution Statement

In this manuscript all authors "contributed equally" to the study.

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