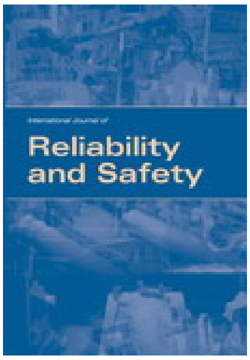

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Availability optimisation and selection of performance parameters of complex repairable system using PSO

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Availability optimisation and selection of performance parameters of complex repairable system using PSO

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Abstract: This research paper presents a numerical technique for the computation of availability and reliability metrics as well as the Mean Time Between Failures (MTBF), pertaining to a thread rolling machine. Seven repaired sub-systems are studied under this system, namely: motor, hopper feeder, fixed die block, movable die block, drive belt, coolant and lubricant unit, and control panel are arranged in order. The performance of system considered is analysed based on the Markov approach and assumes that the Failure and Repair Rate (FRR) of each sub-system follows a normal distribution. The decision support system is developed for achieving the maximum availability of system. The comparison between particle swarm optimisation and the Markov process is done to achieve optimum availability. The results are compared with other optimisation approaches and the optimised availability using PSO is calculated as 96.24% while it is 95.08% using the Markov method. The particle swarm optimisation algorithm sustains a wide range of different component performance indicators for optimising system availability goals as well as various performance parameters.

Keywords: availability; SSA; steady state analysis; particle swarm optimisation; reliability; TSA; transient state analysis; MTBF; mean time between failure; FRR; failure and repair rates.

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1 Introduction

Today automation has become the necessity of an industrial system which leads to the use of highly complex systems and it recognises the importance of maintaining a highly reliable system. These days, system reliability has played a crucial role in both manufacturing and industry, redundancy has become a very important technique used to improve system reliability. In the current industrial framework, due to fast developments in technology, it becomes vital to sustain the operating systems in a satisfactory working environment. Agushaka et al. (2023) discussed a novel population-based metaheuristic algorithm called the Gazelle Optimisation Algorithm (GOA) for optimisation problem. Mohamed et al. (2021) presented a paper based on the mixing of the Markov technique and the Universal Generation Function (UGF) technology which understands the most advanced and realistic models covering from perfect operation to total breakdowns in which system components may acquire different forms, and studied the performance distribution of complicated series and parallel to the repairable MSS depending on units. James (2021) presented RAM characteristics that are beneficial to various professionals seeking to update their understanding and discover detailed characteristics of RAM in the automobile industry for research, maintenance, academics, designs, etc., for future developments in automobiles. Saini et al. (2021) introduced a novel stochastic process for a redundant system of non-similar measures. The repeated relations for different reliability measures have been invented with the help of the semi-Markov method and regenerative point methods. Kumar and Kumar (2020) presented an approach to deal with the examination of several variables in perspective of reliability for a constructing plant, namely a rice producing unit, by considering climate conditions as well as availability for the Markov renewal process. The Laplace transformation is applied for the exact illustration of MTTF, availability and reliability. Afsharnia et al. (2020) by used the Markov chain process, which is a robust selective process in accordance with the actual scenarios of the sugarcane harvesting system in the agriculture industries, to determine the availability methods for the sugarcane harvester machine. Kumar et al. (2020) studied the various techniques used by analysts in several fields to scrutinise the conducting of the operating system. RAMD analysis, Particle Swarm Optimisation (PSO), Genetic Algorithm (GA), FMEA, supplementary variable technique, etc., where the techniques used. Tsarouhas (2019) computed RAM characteristics for the measurement and improvement of the conducting of an automatic production unit under a practical working environment. RAM characteristics are beneficial for determining maintenance time gaps and adequate maintenance plans for planning and organising. Kumar and Saini (2018) studied that the theory of the fuzzy method is used to analyse the availability of a sugar plant, and a assessed sub-systems' FRR and distribution factor influence on fuzzy system availability. The also used the Markov method to derive C–K differential equations. Barak and Barak (2018) investigated why the survey rate, repair rate and continuation rate all follow an anti-exponential distribution, and found that the FR and rate by which the system undergoes PM are static. The graphical representation for various reliability scales is obtained in static conditions using RPT and SMP for identification of the system. Compare et al. (2018) developed a decision support work plan based on Markov decision methods to get maximum profit from the Multi-State System (MSS) operations. The findings are indicated by a condition security system, which counts the health condition of the MSS components. Qiu et al. (2019) investigated the optimal maintenance policy and availability is inspected by the Markov method with downtime threshold. By activating the downtime threshold, the immediate and Steady State Availability (SSA) can be achieved. Bala and Yusuf (2017) addressed series-parallel unit modelling and performance assessment through Markov and probabilistic methods. Mathematical availability for every sub-system has been designed to assign different performance values for variable compositions of FRR of all subunits. Results obtained will further enhance the output of the system and be beneficial for well-timed execution of proper maintenance enhancement, determination, planning and optimisation. Fernández et al. (2016) studied a new approach based on the Markov process which presents very accurate results while estimating long-term processes for industrial scale. The model can be very easy to use in industries where the huge amount of pending data makes it hard to use other prediction approaches. Gupta et al. (2015) discovered the mathematical model based on a continuous-time Markov chain can be used to determine the performance of availability and reliability evaluations of a repairable system. Pittiglio et al. (2014) studied that in the manufacturing sector, more and more risk-based solutions are being used such as unit observations, maintenance and change management, to assist industrial government risk management. These solutions also provide reliable knowledge based on equipment failure rates and operating techniques. Ram et al. (2013) found that system reliability contains intervals to restore and the repairing of standby units is carried out according to general division while the restoration is because of human mistakes and uses the Gumbel-Hougaard family copula to carry out the operation. Laplace transformation and auxiliary variable analysis are used to examine the system. Bornatico et al. (2012) presented an approach to determining the optimum size of a system's primary units, using optimisation through observation and the result obtained from the PSO algorithm has been developed and compared to the results of the genetic algorithm solution. Bao and Cui (2012) analysed the dependability of a cold standby Markov repairable system with unnoticed failures and measures of reliability for the repairable systems are presented by mean downtime and availability indices. Peng and Dong (2011) presented an age structure Hidden Semi-Markov Model (HSMM) prognosis-based methodology to forecast system health. Exploitation hazard function and Conditioned-Based Maintenance (CBM) rely on the failure rate that may be a function of each system age and therefore the system conditions. El-Damcese and Temraz (2011) described the Markov technique's results for determining the availability and dependability of an MSS and this approach suggested representing regarding the homogeneous and non-homogeneous Markov technique of two stochastic computational methods. Çekyay and Özekici (2010) observed that the availability and MTTF of semi-Markov consist of a state with an unsystematic period. Markov process is described as the stochastic structure of the mission. MTTF and the system availability are based on maximum repair policy. Wu and Zhao (2010) presented a method that contains inspection, modelling of equipment depletion and preventive maintenance. With the help of Markov decision-making processes, they provide an optimal and cost-effective maintenance strategy that includes maintenance measures based on the condition determined during the inspection and the inspection intervals. El-Damcese (2009) demonstrated the evolution of a hot standby system's reliability and availability with respect to the time variable FRR when CCF was present. To ensure the system's availability and reliability, the Markov technique is used. Khatab et al. (2009) introduced that the system's availability of each sub-system is finding out by the use of the Markov model and the efficiency evaluation is developed by Monte Carlo simulation. Das Chagas Moura et al. (2008) studied that the semi-Markov approach has been developed to determine a maintenance policy in order to maximise each system's availability. To resolve the newly emerging optimisation issue, limited by the system performance cost and a new actual coding Genetic Algorithm (GA) is also introduced. Wang et al. (2007) studied the Binary Particle Swarm Optimisation (BPSO) to derive the system state that affects the generation system, including the expected energy not supplied and loss of load frequency and proposed a probabilistic method used for reliability estimation of power generating stations. Zheng et al. (2006) proposed a model for a single repairable system with the Markov approach in a comparatively shorter time and the system's availability was estimated for these new models as a measure of reliability. Chatterjee et al. (2005) developed a PSO based on Fuzzy-Neural Networks (FNNs) that is an occupied element in a robot system and managed by vocalised orders. The system has the following two practical applications that are: first, mobile robot navigation; and other, for controlling the movement of a redundant manipulator. Li et al. (2005) discussed an MSS formulation of multi-state units. There are two approaches to calculating the system's reliability by using the state transition probability matrix: in order to estimate a component's current state, they first use the state conversion probability indices of the supplied units, and then use the state conversion probability indices of the system that were obtained by simulating the states of the given units. Shi and Eberhart (1999) studied the performance of PSO (particle swarm optimiser) with four different functions in initial range settings elected. To enhance PSO's performance near the optima, a new approach such as using adaptive inertia weight is suggested. Arora and Kumar (1997) studied that system's availability analysis is taken constant repair and failure rate and the Markov process is used for the mathematical formulation. Demonstrations for MTBF and SSA are calculated. Sharma and Bazovsky (1993) described a reliability assessment of complex and large systems by using Markov models. These techniques are used for availability/reliability assessment of the system in defence and industry. Singh (1989) considered that a system with working units and hot standby units is with restore services and the problem is developed by using different techniques and solving the differential equation by using Lagrange's process. Cafaro et al. (1986) explained that the Markov approach is utilised to assess the system's availability and conversion rates of each sub-system in relation to the system's state. Planning conversion rates of single units into the system conversion rate matrix is possible due to the Markov model. Arora (1977) explained the standby redundant system of three models consisting of dissimilar units. Expression to derive the Laplace transforms of the steady-state availability and different probabilities and the used by the supplementary variable technique. Guild and Tourigny (1978) studied a system with reliability and availability concepts generated using a Markov approach. Increasing the number of systems components, the Markov method is required for the computer solution for the complex sets of differential equations. Gupta et al. (1982) described a redundant system with cold standby as subjected to a single repair service with repair time distribution and exponential failure. Analysed the system is determined by the reliability parameters that is SSA and MTSF and also the use of the semi-Markov method in a transient state. Chang (1983) presented a technique that is used in the optimisation of the production of a power generation unit with the help of an engineering approach and techniques covering the RAM analysis, availability goal and availability cost. Platz (1984) found that a continuous time Markov method covered several models of redundant systems which use off-described dependencies between the failures of components.

In this paper, we have set up an availability model existing of seven different sub-systems. The main aim is to take over the impact of FRR on every sub-system to find out the vital sub-system in the system. The system's description, assumptions, notations and data collecting are presented in Section 2. Section 3 includes the methodology, the mathematical formulation and the solution for the system under study, as well as the performance modelling of the system, while Section 4 provides an examination of the sub-system's performance. Section 5 of the paper's discussion of the numerical and graphical findings is followed by a Section 6 conclusion.

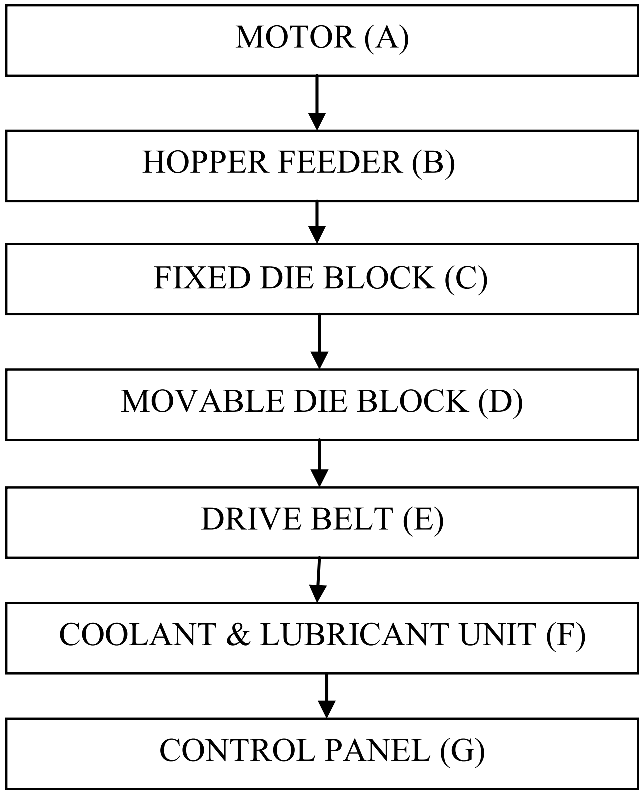
2 Description, assumption and notations of system: thread rolling machine of industrial system

The flat die thread rolling machine uses two dies: first fixed and second movable. The fixed die and moving die are positioned against each other. When the machine moves in the forward direction, at a time only one thread is rolled. The distance between the faces of the dies and the distance of the blank die together determines the length of thread that is manufactured after the machine's stroke. A flat die is used to create threads, tapping screws, knurling and machine and cap screws. The Thread Rolling Machine (TRM) consists of seven sub-systems namely the motor, hooper feeder, fixed die block, movable die block, drive belt, coolant and lubricant unit, and control panel. The following is a description of these sub-systems, which are set up in a series configuration:

1) *MOTOR (A)*: This component consists of a single unit; any malfunction within it directly results in a complete system failure.
2) *HOPPER FEEDER (B)*: Consisting of one unit, its failure is synonymous with a system failure.
3) *FIXED DIE BLOCK (C)*: Within this sub-system resides a solitary unit, the breakdown of which is synonymous with the failure of the entire system.
4) *MOVABLE DIE BLOCK (D)*: Comprising a singular unit, the collapse of this component equates to the system's overall failure.
5) *DRIVE BELT (E)*: It contains two belts. Failure of the unit is considered as when units of the first belt are failed goes to a reduced state and after that units of the second belt are failed then the system's failure.
6) *COOLANT AND LUBRICANT UNIT (F)*: Constituting a sole unit, its failure equates to a system failure.
7) *CONTROL PANEL (G)*: This sub-system includes one unit; its failure directly leads to a system failure.

The pictorial representation of all sub-systems of the thread rolling machine is shown in Figure 1 given below.

Figure 1 Schematic flow diagram of thread rolling machine



2.1 Assumptions

The assumptions given below are used in carrying out the mathematical modelling of the Thread Rolling Machine: The system contains seven sub-systems arranged in series. The Failure Rates and Repair Rates (FRRs) do not change over time, FRRs remain constant and independent, with no simultaneous failures between sub-systems. A single unit failure triggers system failure. The system cannot be in reduced capacity but can be in a working system or a faulty condition. No waiting time to start is required as adequate repair facilities are always provided. A repair system is in very good condition, i.e., as in a new system, functioning wise for the time duration that is taken into consideration. Standby units and active units are similar in nature and capacity.

2.2 Notations

The symbols used to analyse the behaviour and modelling of the Thread Rolling Machine, which are used to produce the transition/probability state diagram, are displayed in Table 1.

Table 1 Notations used in thread rolling machine

STATE	*Block diagram*	*Transition diagram*	*Full capacity (without standby)*	*Full capacity (with standby)*	*Reduced capacity*
NOTATIONS	Figure 1	Figure 2	ABCDEFG	----	E
STATE	Failure State	Failure Rates	Repair Rates	-----	-----
NOTATIONS	abcdefg	α_1 to α_7	β_1 to β_7	-----	-----

2.3 Data collection

Understanding the failure rate is crucial, also known as the hazard rate, of a population of products. The life bathtub curve is often used to represent this behaviour. The failure rates are often greater in the initial stages of operation. However, as the system operates normally, the failure rate drops to a stable figure which can be considered as the steady state. The failure rate of a group of items can be represented graphically by a life bathtub curve, according to research that was conducted through practical observations and conversations with maintenance engineers. This information is of utmost importance for the screw manufacturing plant to explore the various possibilities of selecting appropriate FRRs and related availability levels of its elements. By utilising the availability matrix, the plant can ensure optimal performance and minimise downtime, ultimately resulting in increased productivity and profitability. Towards the end of the system's life, the failure rate rises again due to wear and tear. Data was practically collected over a six-month period from process history records, daily operation reports, maintenance report sheets and conversations with maintenance engineers in order to calculate the FRRs and corresponding availability levels of the components of a screw manufacturing plant. Table 2 contains the values that were obtained. The plant can guarantee optimum performance and save downtime by using the availability matrix.

Table 2 Failure and repair rates of thread rolling machine of a screw manufacturing plant

Sub-system	*Ranges of failure rates*	*Ranges of repair rates*
Motor	0.000520–0.000920	0.053–0.093
Hopper Feeder	0.000347–0.000747	0.035–0.075
Fixed Die Block	0.000695–0.001095	0.068–0.108
Movable Die Block	0.000698–0.001098	0.069–0.109
Drive Belt	0.001215–0.005215	0.14–0.54
Coolant & Lubricant	0.00104–0.00504	0.12–0.52
Control Panel	0.000173–0.000573	0.018–0.058

3 Methodology

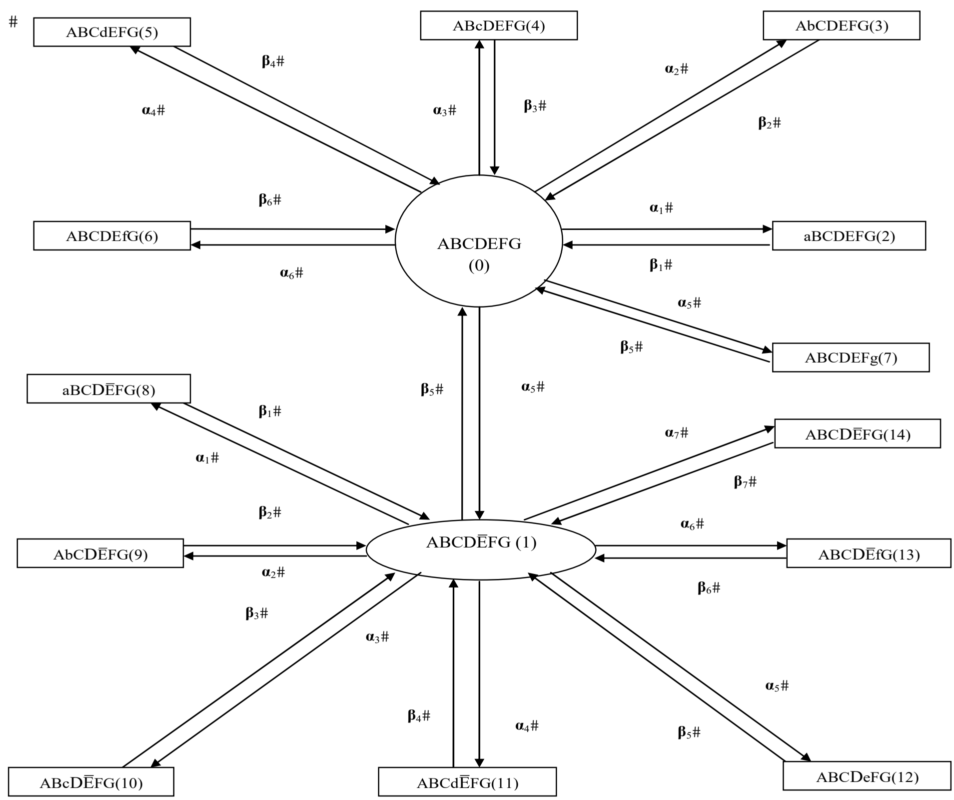
The methodology is concerned with availability analysis and execution of the modelling of the Thread Rolling Machine. Seven sub-systems have been studied in this sub-system. By taking the exponential distribution of FRR of sub-systems into consideration, several recommended methods make it challenging to estimate the availability of systems with items indicating related FRR. The scientific model of the assembly unit is created using

Markov models based on probabilistic methods. Finally, the model is used to improve and analyse the performance of the structure of each sub-system to select the most optimised sub-system and the PSO technique is useful to select the maximum system availability.

3.1 Performance modelling of the system

Markov modelling is a modelling method that is very useful for evaluating the reliability of intricate systems. This modelling technique is very useful in most situations. This model is very useful for simulating operating systems with failure and repair-related models. It is often used for responsible assessment of the availability and reliability of systems with a constant number of failures and repairs. Used in the conversion diagram to represent the probability of all possible conditions, such as full operating conditions, reduced operating conditions and fault conditions. The transition diagram of the Thread Rolling Machine (TRM) is shown in Figure 2. Below are all the details of the transition diagram of the thread-rolling machine.

Figure 2 Transition diagram of thread rolling machine



3.2 Formulation and solution of mathematical modelling

Figure 2 shows how to use the Markov process to generate the differential equations related to the transition diagram. The following system of differential equations is produced by several probability theories:

$$\left(\frac{D}{dt}+\sum_{i=1}^{7}\alpha_i\right)P_0(t)=\beta_1P_2(t)+\beta_2P_3(t)+\beta_3P_4(t)+\beta_4P_5(t)+\beta_5P_1(t)+\beta_6P_6(t)+\beta_7P_7(t) \tag{1}$$

$$\left(\frac{d}{dt}+\sum_{i=1}^{7}\alpha_i+\beta_5\right)P_1(t)=\beta_1P_8(t)+\beta_2P_9(t)+\beta_3P_{10}(t)+\beta_4P_{11}(t)+\beta_5P_{12}(t)+\beta_6P_{13}(t)+\beta_7P_{14}(t)+\alpha_5P_0(t) \tag{2}$$

$$\left(\frac{d}{dt}+\beta_1\right)P_2(t)=\alpha_1P_0(t) \tag{3}$$

$$\left(\frac{d}{dt}+\beta_2\right)P_3(t)=\alpha_2P_0(t) \tag{4}$$

$$\left(\frac{d}{dt}+\beta_3\right)P_4(t)=\alpha_3P_0(t) \tag{5}$$

$$\left(\frac{d}{dt}+\beta_4\right)P_5(t)=\alpha_4P_0(t) \tag{6}$$

$$\left(\frac{d}{dt}+\beta_6\right)P_6(t)=\alpha_6P_0(t) \tag{7}$$

$$\left(\frac{d}{dt}+\beta_7\right)P_7(t)=\alpha_7P_0(t) \tag{8}$$

$$\left(\frac{d}{dt}+\beta_1\right)P_8(t)=\alpha_1P_1(t) \tag{9}$$

$$\left(\frac{d}{dt}+\beta_2\right)P_9(t)=\alpha_2P_1(t) \tag{10}$$

$$\left(\frac{d}{dt}+\beta_3\right)P_{10}(t)=\alpha_3P_1(t) \tag{11}$$

$$\left(\frac{d}{dt}+\beta_4\right)P_{11}(t)=\alpha_4P_1(t) \tag{12}$$

$$\left(\frac{d}{dt}+\beta_5\right)P_{12}(t)=\alpha_5P_1(t) \tag{13}$$

$$\left(\frac{d}{dt}+\beta_6\right)P_{13}(t)=\alpha_6P_1(t) \tag{14}$$

$$\left(\frac{d}{dt}+\beta_7\right)P_{14}\left(t\right)=\alpha_7 P_1\left(t\right) \tag{15}$$

With initial condition at time t=0

$$P_i\left(t\right)=1 \text{ for } i=0$$

$$=0 \text{ for } i\neq 0$$

SSA of Thread Rolling Process

By putting $d/dt=0$ at $t\to\infty$ in equations (1) to (15) the steady-state probabilities are given as:

$$P_0=\frac{\beta_1 P_2+\beta_2 P_3+\beta_3 P_4+\beta_4 P_5+\beta_5 P_1+\beta_6 P_6+\beta_7 P_7}{\left(\frac{D}{dt}+\sum_{i=1}^{7}\alpha_i\right)} \tag{16}$$

$$P_1=\frac{\beta_1 P_8+\beta_2 P_9+\beta_3 P_{10}+\beta_4 P_{11}+\beta_5 P_{12}+\beta_6 P_{13}+\beta_7 P_{14}+\alpha_5 P_0}{\left(\frac{D}{dt}+\sum_{i=1}^{7}\alpha_i+\beta_5\right)} \tag{17}$$

$$P_2=\frac{\alpha_1}{\beta_1}P_0 \tag{18}$$

$$P_3=\frac{\alpha_2}{\beta_2}P_0 \tag{19}$$

$$P_4=\frac{\alpha_3}{\beta_3}P_0 \tag{20}$$

$$P_5=\frac{\alpha_4}{\beta_4}P_0 \tag{21}$$

$$P_6=\frac{\alpha_6}{\beta_6}P_0 \tag{22}$$

$$P_7=\frac{\alpha_7}{\beta_7}P_0 \tag{23}$$

$$P_8=\frac{\alpha_1}{\beta_1}P_1 \tag{24}$$

$$P_9=\frac{\alpha_2}{\beta_2}P_1 \tag{25}$$

$$P_{10}=\frac{\alpha_3}{\beta_3}P_1 \tag{26}$$

$$P_{11}=\frac{\alpha_4}{\beta_4}P_1 \tag{27}$$

$$P_{12} = \frac{\alpha_5}{\beta_5} P_1 \tag{28}$$

$$P_{13} = \frac{\alpha_6}{\beta_6} P_1 \tag{29}$$

$$P_{14} = \frac{\alpha_7}{\beta_7} P_1 \tag{30}$$

On putting the values of P_2, P_3, P_4, P_5, $P_{6,}$ P_7 in equation of (16) and we get the value of P_0

$$P_0 = \frac{\beta_1 P_2 + \beta_2 P_3 + \beta_3 P_4 + \beta_4 P_5 + \beta_5 P_1 + \beta_6 P_6 + \beta_7 P_7}{\left(\frac{D}{dt} + \sum_{i=1}^{7} \alpha_i\right)}$$

$$P_0 = \left(\alpha_1 P_0 + \alpha_2 P_0 + \alpha_3 P_0 + \alpha_4 P_0 + \alpha_6 P_0 + \alpha_7 P_0 + \beta_5 P_1\right) / A$$

$$AP_0 - \alpha_1 P_0 - \alpha_2 P_0 - \alpha_3 P_0 - \alpha_4 P_0 - \alpha_6 P_0 - \alpha_7 P_0 = \beta_5 P_1$$

$$P_0 \left(A - B\right) = \beta_5 P_1$$

$$P_0 = \frac{\beta_5 P_1}{\left(A - B\right)}$$

$$P_0 = CP_1 \tag{31}$$

On putting the values of P_8, P_9, P_{10}, P_{11}, $P_{12,}$ $P_{13,}$ $P_{14,}$ in equation of (17) and we get the value of P_1

$$P_1 = \frac{\beta_1 P_8 + \beta_2 P_9 + \beta_3 P_{10} + \beta_4 P_{11} + \beta_5 P_{12} + \beta_6 P_{13} + \beta_7 P_{14} + \alpha_5 P_0}{\left(\frac{D}{dt} + \sum_{i=1}^{7} \alpha_i + \beta_5\right)}$$

$$P_1 = \left(\alpha_1 P_1 + \alpha_2 P_1 + \alpha_3 P_1 + \alpha_4 P_1 + \alpha_5 P_1 + \alpha_6 P_1 + \alpha_7 P_1 + \alpha_5 P_0\right) / D$$

$$DP_1 - \alpha_1 P_1 - \alpha_2 P_1 - \alpha_3 P_1 - \alpha_4 P_1 - \alpha_5 P_1 - \alpha_6 P_1 - \alpha_7 P_1 = \alpha_5 P_0$$

$$P_1 \left(D - A\right) = \alpha_5 P_0$$

$$P_1 = \frac{\alpha_5 P_0}{\left(D - A\right)}$$

$$P_1 = EP_0 \tag{32}$$

Determine the probability of the fully operational state P_0 based on the normalised condition, i.e., the sum of the probabilities of all states of the system is equal to one.

$$\sum_{i=0}^{14} P_i = 1$$

$$P_0 = \frac{1}{N}$$

$$N = 1 + E + \frac{\alpha_1}{\beta_1} + \frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_6}{\beta_6} + \frac{\alpha_7}{\beta_7} + \frac{\alpha_1}{\beta_1}E + \frac{\alpha_2}{\beta_2}E + \frac{\alpha_3}{\beta_3}E + \frac{\alpha_4}{\beta_4}E + \frac{\alpha_5}{\beta_5}E + \frac{\alpha_6}{\beta_6}E + \frac{\alpha_7}{\beta_7}E$$

Availability for Thread Rolling Machine = Total of probability of operating state + reduced state

$$Availability(A_3) = \frac{1+E}{N} \tag{33}$$

where

$$A = \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \alpha_7$$

$$B = \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_6 + \alpha_7$$

$$C = \frac{\beta_5}{A - B}$$

$$D = \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \alpha_7 + \beta_5$$

$$C = \frac{\alpha_5}{D - A}$$

4 Performance analysis

Overall availability (A_{v1}) of the system availability as an operation of its FR (α_i) and RR (μ_i) provided from the equation (33) and which contains all possible operational states. All realistic values of (α_i, β_i) are taken into account in order to find out the highest system availability. The decision matrices for each component of a thread rolling machine in the manufacturing of screws are shown in Table 3.

Table 3 Decision matrices of the elements of a thread rolling machine

α_1 \ β_1	*0.053*	*0.063*	*0.073*	*0.083*	*0.093*	*Constant values*	
0.000520	0.9448	0.9462	0.9472	0.9479	0.9485	α_2=0.000347	β_2=0.035
0.000620	0.9431	0.9447	0.9459	0.9469	0.9476	α_3=0.000695	β_3=0.068
0.000720	0.9414	0.9433	0.9447	0.9458	0.9466	α_4=0.000698	β_4=0.069
						α_5=0.001215	β_5=0.14
0.000820	0.9397	0.9419	0.9435	0.9447	0.9456	α_6=0.00104	β_6=0.12
0.000920	0.9381	0.9405	0.9423	0.9436	0.9447	α_7=0.000173	β_7=0.018

Table 3 Decision matrices of the elements of a thread rolling machine (continued)

Hooper feeder

α_2 \ β_2	*0.035*	*0.045*	*0.055*	*0.065*	*0.075*	*Constant values*	
0.000347	0.9448	0.9467	0.9480	0.9489	0.9495	α_1=0.000520	β_1=0.053
0.000447	0.9422	0.9447	0.9464	0.9475	0.9483	α_3=0.000695	β_3=0.068
0.000547	0.9397	0.9428	0.9447	0.9461	0.9471	α_4=0.000698	β_4=0.069
						α_5=0.001215	β_5=0.14
0.000647	0.9372	0.9408	0.9431	0.9447	0.9459	α_6=0.00104	β_6=0.12
0.000747	0.9347	0.9388	0.9415	0.9434	0.9447	α_7=0.000173	β_7=0.018

Fix die block

α_3 \ β_3	*0.068*	*0.078*	*0.088*	*0.098*	*0.108*	*Constant values*	
0.000695	0.9448	0.9459	0.9468	0.9476	0.9482	α_1=0.000520	β_1=0.053
0.000795	0.9434	0.9448	0.9458	0.9466	0.9473	α_2=0.000347	β_2=0.035
0.000895	0.9421	0.9436	0.9448	0.9457	0.9465	α_4=0.000698	β_4=0.069
						α_5=0.001215	β_5=0.14
0.000995	0.9408	0.9425	0.9438	0.9448	0.9457	α_6=0.00104	β_6=0.12
0.001095	0.9395	0.9414	0.9428	0.9439	0.9448	α_7=0.000173	β_7=0.018

Movable die block

α_4 \ β_4	*0.069*	*0.079*	*0.089*	*0.099*	*0.109*	*Constant values*	
0.000698	0.9446	0.9458	0.9467	0.9474	0.9480	α_1=0.000520	β_1=0.053
0.000798	0.9433	0.9447	0.9457	0.9465	0.9472	α_2=0.000347	β_2=0.035
0.000898	0.9420	0.9435	0.9447	0.9456	0.9464	α_3=0.000695	β_3=0.068
						α_5=0.001215	β_5=0.14
0.000989	0.9407	0.9424	0.9437	0.9447	0.9455	α_6=0.00104	β_6=0.12
0.001098	0.9394	0.9412	0.9427	0.9438	0.9447	α_7=0.000173	β_7=0.018

Drive belt

α_5 \ β_5	*0.14*	*0.24*	*0.34*	*0.44*	*0.54*	*Constant values*	
0.001215	0.9448	0.9448	0.9449	0.9449	0.9449	α_1=0.000520	β_1=0.053
0.002215	0.9446	0.9448	0.9448	0.9448	0.9449	α_2=0.000347	β_2=0.035
0.003215	0.9444	0.9447	0.9447	0.9448	0.9448	α_3=0.000695	β_3=0.068
						α_4=0.000698	β_4=0.069
0.004215	0.9440	0.9446	0.9447	0.9447	0.9448	α_6=0.00104	β_6=0.12
0.005215	0.9436	0.9444	0.9446	0.9447	0.9447	α_7=0.000173	β_7=0.018

Coolant and lubricant unit

α_6 \ β_6	*0.12*	*0.22*	*0.32*	*0.42*	*0.52*	*Constant values*	
0.00104	0.9448	0.9483	0.9496	0.9503	0.9508	α_1=0.000520	β_1=0.053
0.00204	0.9374	0.9442	0.9468	0.9482	0.9490	α_2=0.000347	β_2=0.035
0.00304	0.9301	0.9402	0.9440	0.9460	0.9473	α_3=0.000695	β_3=0.068
						α_4=0.000698	β_4=0.069
0.00404	0.9230	0.9362	0.9412	0.9439	0.9456	α_5=0.001215	β_5=0.14
0.00504	0.9159	0.9322	0.9385	0.9418	0.9438	α_7=0.000173	β_7=0.018

Table 3 Decision matrices of the elements of a thread rolling machine (continued)

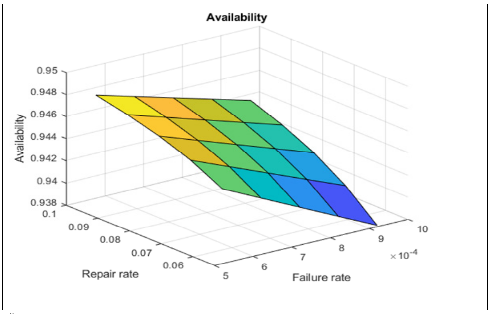
Control panel							
α_7 \ β_7	*0.018*	*0.028*	*0.038*	*0.048*	*0.058*	*Constant values*	
0.000173	0.9448	0.9478	0.9493	0.9502	0.9507	α_1=0.000520	β_1=0.053
0.000273	0.9398	0.9446	0.9469	0.9483	0.9492	α_2=0.000347	β_2=0.035
0.000373	0.9349	0.9415	0.9446	0.9464	0.9476	α_3=0.000695 α_4=0.000698	β_3=0.068 β_4=0.069
0.000473	0.9301	0.9383	0.9422	0.9445	0.9461	α_5=0.001215	β_5=0.14
0.000573	0.9253	0.9352	0.9399	0.9427	0.9445	α_6=0.00104	β_6=0.12

5 Numerical and graphical result of steady state analysis

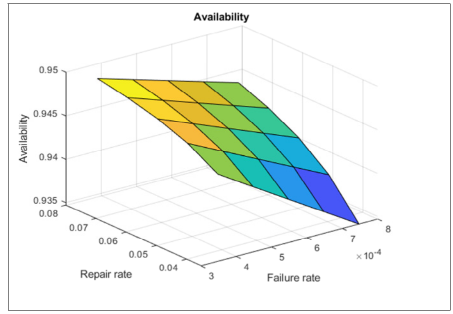
The decision matrices for steady-state analysis options are shown in Table 3 with the changes in the availability of the system. These matrices for steady-state analysis show the necessity of a particular system with the FRR of different components changing over an infinite period. These steady-state analysis matrices indicate the need for specific systems with changes. Table 3 shows the influence of the FRR of various components of the service priority decision support system on the SSA of the thread rolling machine. The observation mentioned below:

- The availability of the system is decreased by 0.67% due to the motor unit's Failure Rate (FR), which went from 0.000520 to 0.000920. A rise in the Repair Rate (RR), which climbed from 0.053 to 0.093, only marginally boosted the system's availability by 0.37%.
- The system availability for the Hopper feeder system reduces by 1.01% with an increase in the FR from 0.000347 to 0.000747, and barely increases by 0.47% with an increase in the RR from 0.035 to 0.075.
- The fixed die block's failure rate increased from 0.000695 to 0.001095, which resulted in a 0.53% drop in system availability. The RR increased from 0.068 to 0.108, which resulted in a 0.34% gain in availability.
- For movable die blocks, if the range of RR climbs (from 0.000698 to 0.001098), the system's availability decreases by 0.54%; nevertheless, as the RR rises (from 0.069 to 0.109), the system's availability marginally increases by 0.32%.
- According to the table below, it is possible to determine the system availability for the sub-system drive belt, and by increasing the FR from 0.001215 to 0.005215, the system availability is decreased by 0.12%. Similar to this, the availability of the system increases by 0.01% when RR increases from 0.14 to 0.54.

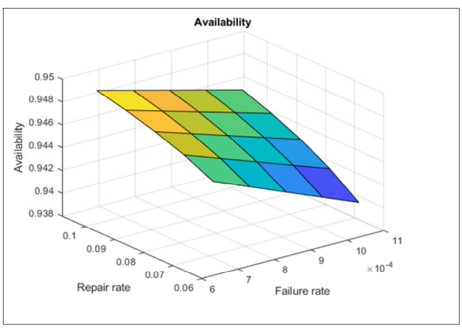
Figure 3 Shows how the availability of the thread rolling machine is affected by the FRRs of its components (see online version for colours)



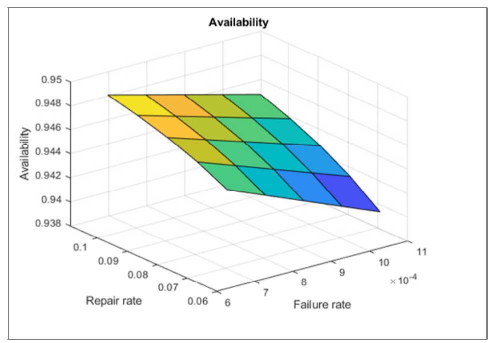
MOTOR



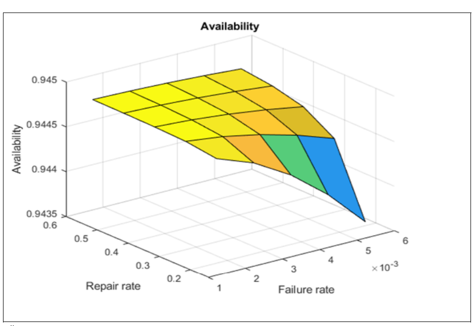
HOPPER FEEDER



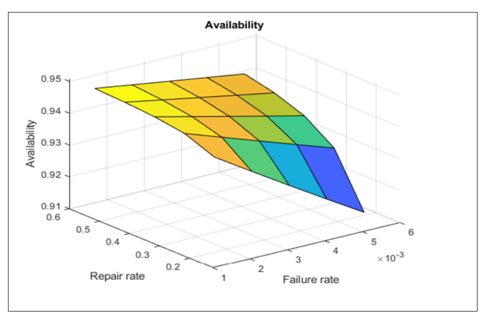
FIX DIE BLOCK



MOVABLE DIE BLOCK

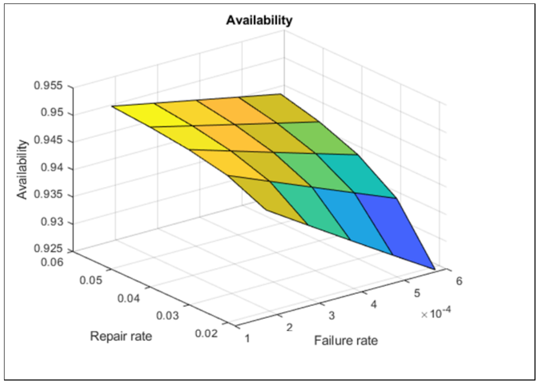


DRIVE BELT



COOLANT & LUBRICANT UNIT

Figure 3 Shows how the availability of the thread rolling machine is affected by the FRRs of its components (see online version for colours) (continued)



CONTROL PANEL

- From the Table 4, note that the availability of the system decreases by 2.89% when the FR increases from 0.00104 to 0.00504, and it increases by 0.60% when the RR increases from 0.12 to 0.52 for the coolant and lubricant unit.
- Last component of the system control panel increase of FR from 0.000173 to 0.000573 then the availability of the system is reduced by 1.95%, and when RR grows from 0.018 to 0.058 the availability of the system enhances by 0.59%.

Table 4 Decision support for thread rolling machine

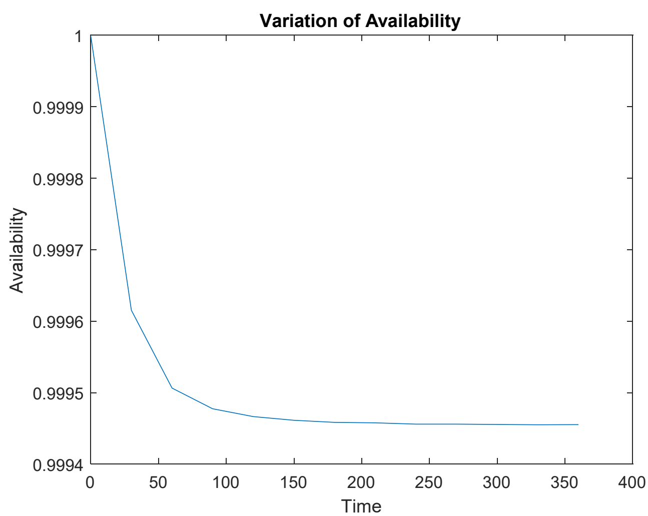
Sub-system	*Ranges of failure rates*	*Decrease in availability*	*Ranges of repair rates*	*Increase in availability*	*Rank/repair priority*
Motor	0.000520–0.000920	0.67%	0.053–0.093	0.37%	4
Hopper Feeder	0.000347–0.000747	1.01%	0.035–0.075	0.47%	3
Fixed Die Block	0.000695–0.001095	0.53%	0.068–0.108	0.34%	6
Movable Die Block	0.000698–0.001098	0.54%	0.069–0.109	0.32%	5
Drive Belt	0.001215–0.005215	0.12%	0.14–0.54	0.01%	7
Coolant & Lubricant	0.00104–0.00504	2.89%	0.12–0.52	0.60%	1
Control Panel	0.000173–0.000573	1.95%	0.018–0.058	0.59%	2

Using the Ranga Kutta method and the MATLAB R2018b tool, the Transient State Analysis (TSA) is carried out while taking a year's worth of time into consideration. The data of FRR of different sub-systems of TRM has been derived from previous maintenance data. The change in system availability over time becomes insignificant over time; it indicates that the system has reached SSA for TRM. Simpson 3/8 rule is used to evaluate MTBF in days, illustrating that the system will continue to exist for about 355 days in a year as shown in Figure 4 and Table 5. Therefore, the 05-day system downtime helps management strategically plan the maintenance of related systems.

Table 5 Variation in availability with time for thread rolling machine

Time (Days)	*Availability*	*Failure and repair rates*	
0	1		
30	0.9996		
60	0.9995		
90	0.9995		
120	0.9995	α_1=0.000520	β_1=0.053
150	0.9995	α_2=0.000347	β_2=0.035
180	0.9994	α_3=0.000695	β_3=0.068
210	0.9994	α_4=0.000698	β_4=0.069
240	0.9994	α_5=0.001215	β_5=0.14
270	0.9994	α_6=0.00104	β_6=0.12
300	0.9994	α_7=0.000173	β_7=0.018
330	0.9994		
360	0.9994		
MTBF=355.4			

Figure 4 Variation in availability with time for thread rolling machine (see online version for colours)



The availability function equation (33) is utilised as the goal function to determine the optimal FRR combination using the Particle Swarm Optimisation approach. The number of particles is considered between 16 and 21, and the number of iterations is considered between 50 and 2000 in intervals of 50. Table 6 presents the outcomes. As indicated in Table 6, the maximum availability was attained at 16 particles and 1500 iterations, resulting in a 96.24% availability rate. In Table 6, the appropriate FRRs are listed. Figure 5 depicts how the quantity of iterations and the particles affect the thread rolling machine's availability.

Table 6 Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=16

N	α_1	α_2	α_3	α_4	α_5	α_6	α_7	β_1	β_2	β_3	β_4	β_5	β_6	β_7	A_2
50	0.0005	0.0006	0.0010	0.0009	0.0050	0.0019	0.0003	0.0756	0.0735	0.0916	0.1083	0.3952	0.3464	0.0383	0.9522
100	0.0006	0.0004	0.0009	0.0009	0.0049	0.0029	0.0002	0.0845	0.0569	0.0962	0.0928	0.4247	0.2855	0.0474	0.9524
200	0.0009	0.0004	0.0010	0.0007	0.0014	0.0020	0.0002	0.0721	0.0563	0.1030	0.0926	0.1382	0.4536	0.0532	0.9532
500	0.0007	0.000	0.0010	0.0007	0.0035	0.0015	0.0002	0.0795	0.0690	0.0807	0.0951	0.1897	0.5030	0.0442	0.9560
1000	0.0006	0.0005	0.0007	0.0007	0.0045	0.0020	0.0002	0.0782	0.0467	0.0832	0.1068	0.4710	0.3635	0.0563	0.9571
1500	0.0006	0.0003	0.0008	0.0007	0.0013	0.0011	0.0003	0.0797	0.0592	0.0983	0.0994	0.2186	0.4338	0.0507	0.9624
2000	0.0005	0.0004	0.0007	0.0007	0.0020	0.0043	0.0002	0.0845	0.0534	0.0798	0.0818	0.2448	0.4288	0.0441	0.9540

Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=17

N	α_1	α_2	α_3	α_4	α_5	α_6	α_7	β_1	β_2	β_3	β_4	β_5	β_6	β_7	A_2
50	0.0006	0.0003	0.0008	0.0008	0.0049	0.0013	0.0002	0.0889	0.0517	0.0998	0.1062	0.4037	0.2176	0.0495	0.9583
100	0.0008	0.0005	0.0010	0.0007	0.0017	0.0016	0.0002	0.0845	0.0594	0.0946	0.0906	0.4623	0.3875	0.0420	0.9537
200	0.0006	0.0005	0.0008	0.0009	0.0044	0.0018	0.0003	0.0719	0.0671	0.0843	0.0955	0.3495	0.4377	0.0554	0.9547
500	0.0008	0.0005	0.0008	0.0007	0.0037	0.0010	0.0003	0.0708	0.0680	0.0971	0.0804	0.4279	0.3519	0.0551	0.9560
1000	0.0008	0.0004	0.0008	0.0009	0.0028	0.0018	0.0003	0.0831	0.0569	0.0931	0.0989	0.3460	0.3551	0.0480	0.9551
1500	0.0006	0.0004	0.0007	0.0010	0.0022	0.0019	0.0003	0.0602	0.0602	0.0737	0.1001	0.2505	0.2848	0.0525	0.9492
2000	0.0005	0.0004	0.0010	0.0010	0.0012	0.0013	0.0002	0.0928	0.0621	0.0859	0.0980	0.3023	0.5177	0.0536	0.9585

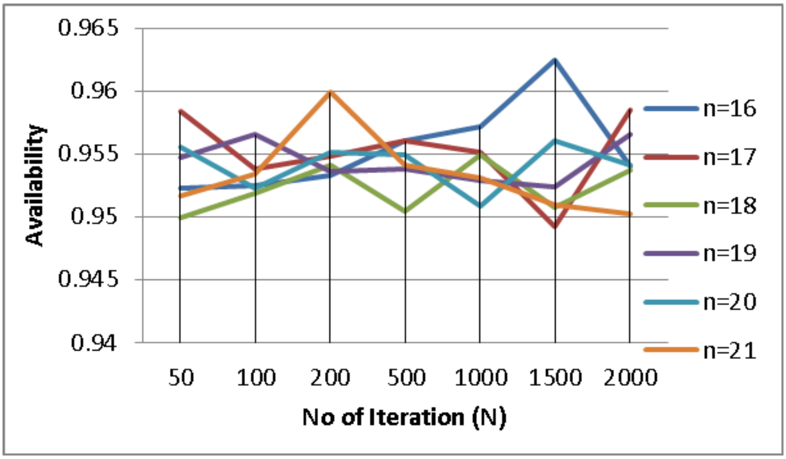
Table 6 Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=16 (continued)

N	α_1	α_2	α_3	α_4	α_5	α_6	α_7	β_1	β_2	β_3	β_4	β_5	β_6	β_7	A_2
Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=18															
50	0.0008	0.0005	0.0009	0.0009	0.0039	0.0015	0.0002	0.0615	0.0678	0.0910	0.1052	0.4607	0.2596	0.0487	0.9499
100	0.0006	0.0004	0.0008	0.0008	0.0044	0.0014	0.0004	0.0745	0.0517	0.0893	0.0974	0.3812	0.3727	0.0428	0.9518
200	0.0005	0.0005	0.0007	0.0010	0.0043	0.0026	0.0002	0.0650	0.0607	0.0925	0.0854	0.3640	0.4216	0.0507	0.9540
500	0.0006	0.0004	0.0007	0.0010	0.0051	0.0029	0.0003	0.0794	0.0581	0.0927	0.0696	0.4336	0.4289	0.0396	0.9504
1000	0.0006	0.0004	0.0009	0.0008	0.0022	0.0023	0.0001	0.0725	0.0614	0.0946	0.0878	0.4222	0.4071	0.0357	0.9549
1500	0.0007	0.0004	0.0007	0.0008	0.0043	0.0024	0.0004	0.0790	0.0580	0.0883	0.0867	0.3692	0.4225	0.0378	0.9507
2000	0.0005	0.0005	0.0007	0.0008	0.0015	0.0016	0.0004	0.0675	0.0529	0.0992	0.1010	0.2765	0.4092	0.0395	0.9537
Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=19															
N	α_1	α_2	α_3	α_4	α_5	α_6	α_7	β_1	β_2	β_3	β_4	β_5	β_6	β_7	A_2
50	0.0007	0.0004	0.0008	0.0008	0.0040	0.0029	0.0003	0.0754	0.0603	0.0840	0.1078	0.4767	0.4735	0.0512	0.9547
100	0.0006	0.0006	0.0007	0.0007	0.0020	0.0018	0.0003	0.0751	0.0695	0.1046	0.1001	0.1836	0.3362	0.0549	0.9565
200	0.0009	0.0005	0.0008	0.0008	0.0029	0.0050	0.0002	0.0866	0.0688	0.1016	0.0980	0.2771	0.4747	0.0587	0.9535
500	0.0006	0.0003	0.0010	0.0010	0.0036	0.0030	0.0002	0.0869	0.0442	0.1035	0.0979	0.1931	0.4328	0.0432	0.9538
1000	0.0005	0.0004	0.0008	0.0007	0.0020	0.0020	0.0003	0.0713	0.0472	0.1067	0.0902	0.2227	0.3540	0.0433	0.9528
1500	0.0006	0.0005	0.0009	0.0008	0.0031	0.0024	0.0002	0.0743	0.0575	0.0948	0.0966	0.4578	0.4270	0.0344	0.9523
2000	0.0006	0.0004	0.0008	0.0007	0.0022	0.0019	0.0002	0.0642	0.0499	0.0997	0.0813	0.3005	0.4573	0.0411	0.9565

Table 6 Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=16 (continued)

N	α_1	α_2	α_3	α_4	α_5	α_6	α_7	β_1	β_2	β_3	β_4	β_5	β_6	β_7	A_2
Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=20															
50	0.0008	0.0004	0.0008	0.0008	0.0016	0.0035	0.0003	0.0866	0.0719	0.0749	0.1078	0.2867	0.5136	0.0594	0.9555
100	0.0005	0.0004	0.0008	0.0008	0.0028	0.0033	0.0002	0.0650	0.0492	0.0898	0.0814	0.4404	0.5079	0.0458	0.9522
200	0.0006	0.0004	0.0008	0.0008	0.0013	0.0024	0.0003	0.0742	0.0739	0.0799	0.1040	0.4905	0.3038	0.0538	0.9551
500	0.0007	0.0006	0.0009	0.0008	0.0035	0.0011	0.0002	0.0807	0.0723	0.1040	0.0967	0.3943	0.2102	0.0433	0.9548
1000	0.0008	0.0003	0.0009	0.0009	0.0045	0.0044	0.0002	0.0804	0.0614	0.0964	0.0947	0.2396	0.4353	0.0460	0.9508
1500	0.0006	0.0005	0.0007	0.0008	0.0028	0.0013	0.0004	0.0718	0.0464	0.1087	0.0970	0.2372	0.4452	0.0576	0.9560
2000	0.0007	0.0004	0.0008	0.0008	0.0032	0.0012	0.0002	0.0701	0.0554	0.0712	0.1001	0.4173	0.3819	0.0385	0.9541
Effect of number of iteration (N) on the availability (A_2) of thread rolling machine at number of particles (n)=21															
N	α_1	α_2	α_3	α_4	α_5	α_6	α_7	β_1	β_2	β_3	β_4	β_5	β_6	β_7	A_2
50	0.0006	0.0004	0.0007	0.0010	0.0020	0.0016	0.0003	0.0789	0.0683	0.0877	0.0806	0.2123	0.2463	0.0514	0.9516
100	0.0005	0.0005	0.0009	0.0008	0.0016	0.0025	0.0002	0.0854	0.0650	0.0981	0.0824	0.1931	0.3267	0.0436	0.9533
200	0.0006	0.0004	0.0007	0.0007	0.0025	0.0029	0.0002	0.0821	0.0743	0.0939	0.0989	0.4395	0.4770	0.0358	0.9598
500	0.0007	0.0003	0.0007	0.0007	0.0015	0.0014	0.0003	0.0653	0.0699	0.0899	0.0746	0.4479	0.2677	0.0387	0.9541
1000	0.0007	0.0006	0.0007	0.0007	0.0044	0.0023	0.0002	0.0628	0.0670	0.0775	0.1060	0.4185	0.3952	0.0434	0.9530
1500	0.0006	0.0005	0.0009	0.0009	0.0029	0.0019	0.0003	0.0736	0.0614	0.0944	0.0779	0.2796	0.3628	0.0523	0.9509
2000	0.0006	0.0005	0.0009	0.0008	0.0018	0.0033	0.0002	0.0719	0.0692	0.0791	0.0956	0.2790	0.4118	0.0382	0.9501

Figure 5 Effect of number of iteration and particles on availability of thread rolling machine (see online version for colours)



The comparison between PSO optimisation and the Markov process is done to achieve optimum availability. The results shown in Table 6 represent that PSO optimisation gives enhanced steady state analysis while comparing with other optimisation approaches and the optimised availability using PSO is calculated as 96.24% while it is 95.08% using the Markov method.

6 Conclusion

A numerical method is proposed to determine the availability and reliability of MTBF and PSO applications to determine the best value for the availability of the thread rolling machine. The analysis carried out is by the Markov method and assumes that the FRR of every sub-system that is studied follows a numerical distribution. Considering the probabilities of various possible states, the Markov method is used to determine the repair priority of the considered case in the table. The transition state is solved using mathematical modelling and MATLAB 2018b tools. In addition, use the PSO method to optimise system performance, and check the impact of the number and generation of particles on system performance. The use of the PSO method to analyse the TRM's availability illustrates that the maximum availability of 96.24% is reached in various FRR combinations. The optimised result of TRM is by minimising maintenance costs for future research work. This method can be extended to general and multi-criteria optimisation problems to provide more beneficial and practical solutions for various types of industrial systems.

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