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Mathematical modeling and performance analysis of combed yarn production system: Based on few data

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ABSTRACT

The paper describes the availability of combed sliver production system, a part of yarn production plant. The units under study are specialized single purpose machines. Performance analysis of the system is carried out to identify the key factors. The optimum value of 'r', where 'r' represent the number of repairman to repair the twelve carding machines ($r \prec 12$), is calculated to maximizing the steady state availability of the system. The problem is formulated using probability consideration and supplementary variable technique. Probability considerations at various stages give differential-difference equations, which are solved using Lagrange method to obtain the state probabilities. The numerical analysis carried out helps in increasing the production rate by controlling the factors affecting the system i.e. availability optimization.

1. Introduction

Reliability, in general, can be defined as the probability of a system/device performing its anticipated purpose adequately for the intended period of time under the given operating conditions. Reliability is an important consideration in the planning, design and operation of the system. The process industries are the backbone of a country for its development. The process industries must provide continuous and long-term production to meet the ever-increasing demand at lower costs. The reliability and availability analysis of process industries can benefit in terms of higher production and lower maintenance. The need and application of reliability technology in the process industries is well understood by many researchers. Singh [1] analyzed the problem of system reliability with identical units having statically independent and dependent (common cause) failures. Singh [2] computed the state probabilities of a complex system with preemptive repeat priority repairs and failure of non-failed components. Subramanian and Anantharaman [3] carried out reliability analysis of a complex standby redundant system and estimated the comprehensive cost function. Dijkhuizen and Heijden [4] have given a series of mathematical models and optimization techniques, with which the optimal preventive maintenance intervals can be determined from an interval availability point of view. Kumar [5,6], Gupta et al. [7], Garg and Singh [8] and some other workers applied reliability technology to various industrial systems obtaining important results. Todinav [9] is proposed a new method for optimization of the topology of engineering systems based on reliability allocation by minimizing the total cost.

The present paper consists of a brief discussion of method of calculating some important reliability characteristic such as reliability function, failure frequency and renewal frequency. A yarn production plant situated in Himachal Pradesh (India) is chosen for study. Here, the production of combed sliver, a part of a yarn production system has been discussed in detail. The

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combed sliver production system further consists of four sub-systems blow room (B), carding machine (C), unilap machine (U) and comber machine (M), all working in series. Sub-system M is having multiple units working in parallel. The sub-system C is a 5-out-of-12: G system i.e. there are 12 carding machines working in parallel and the system works till there are at least 5 carding machines in good and operating state. Combed sliver production sliver fails either when there remain only four carding machines in working position, or sub-system B or U comes to failed state. When there remain only four carding machines are in working state, the system is under breakdown and the collective repair (including corrective and preventive maintenance) of all the carding machines is performed. In routine, normally eight or ten units remain in working states. The twelve carding machines are repaired with the help of 'r' repairmen where ($r < 12$). The optimum value for 'r' is calculated which maximizes the steady state availability of the system operating with ten or more carding machines. The production capacity of the plant is 34.56 tones combed yarn per day at optimum level. The target of the management to produce 29 tones combed yarn per day. This target can be achieved if at least ten carding machines remain in operative state. With this consideration, the performance of the system is examined. Numerical analysis is carried out making use of software package MATLAB.

2. The system

2.1. System description

There are four machines in the combed sliver production system. The first machine is the blow room. The raw cotton that arrives in the mill is in the form of hard pressed bales contains a lot of impurities. This cotton is fed manually into the blow room where opening, cleaning and removal of heavy particles, dust etc. of cotton is done. Cleaned fiber in sheet form, from the blow room is fed to the carding machines. Carding machine once again individualize and cleans the cotton fiber laps, remove neaps, short fiber ends and delivers compact carded sliver. Then unilap machine is used for processing the carded sliver transforming it into laps. This process helps in getting a good quality of comber material. Finally these laps are loaded on comber machine which further removes short fibers and remaining neaps, thus giving a fine combed sliver. Undergoing all these processes serially, we get a combed sliver. Fig. 1 gives the schematic flow chart of the combed sliver production process. The mathematical modeling is carried out for these machines that are prone to failure.

(1) *Blow room* (B):	consists of one unit which is subjected to major failure only
(2) *Carding machine* (C):	consists of twelve identical units(C_1, C_2, ..., C_{12}) which are working in parallel. This sub-system keeps the system operative if at least five carding machines remain in working states
(3) *Unilap machine* (U):	consists of one unit which is subjected to major failure only
(4) *Comber machine* (M):	consists of five identical units which are working in parallel and is subjected to minor failure only (assumed equivalent to no failure)

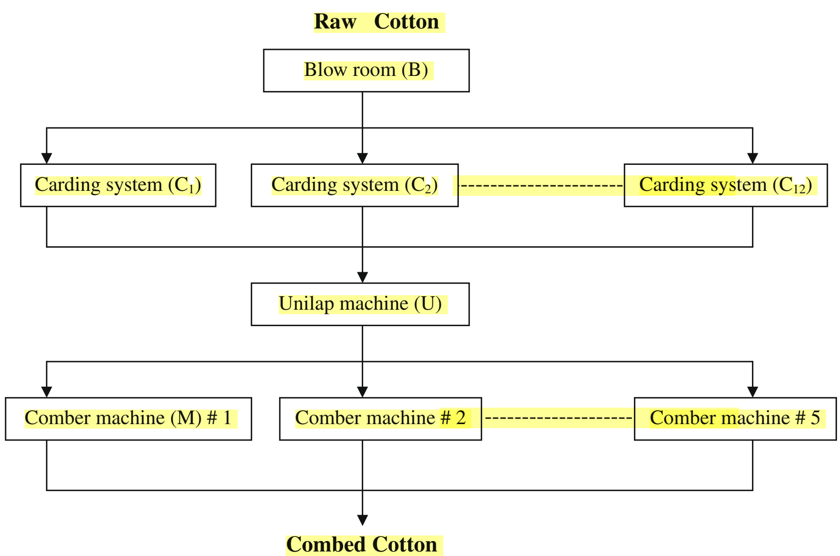

Fig. 1. Flow diagram of combed sliver production system.

2.2. Assumptions

The following assumptions are being associated with the system.

(1) All units are initially operating and are in good state.
(2) Each unit has two types of states viz., good and failed.
(3) A failed system is resorted to like new.
(4) All failure rates are constant where as the repair time of all the sub-systems are arbitrarily distributed, except repair rate of carding machines which are taken constant.
(5) All transition rates are statistically independent.
(6) The sub-system consists of 'r' repair facilities to handle maintenance activities of the sub-system C. For other sub-systems, independent repair facilities are available and their repair begins immediately whenever these sub-systems fail.
(7) When there remain four carding machine in working state then the system is taken under breakdown and the collective repair (including corrective and preventive maintenance) of all the twelve carding machines start immediately.
(8) There is no simultaneous failure among sub-systems.

2.3. Notations

In addition to the notations used for sub-systems, we have also used the following notations.

o	the sub-system/unit is running without any failure
g	unit is in good state but not operative
r	unit is under repair or repair continued
A^z	($A = B, U$) indicates the working state of blow room and unilap machine w.r.t. z, ($z = o, g, r$)
C_j^z	indicates the working states of the carding machine w.r.t. z, ($z = o, g, r$) where 'j' represents its remaining working carding machines. ($j = 5, 6, \ldots, 12$)
λ	constant failure rate of a carding machine
α	constant failure rate of sub-system blow room
ψ	constant failure rate of unilap machine
μ	constant repair rate of a carding machine
$\beta(x)$	repair rate of the sub-system blow room, having an elapsed repair time 'x'
$\upsilon(x)$	repair rate of the sub-system unilap machine, having an elapsed repair time 'x'
$\eta(x)$, $C(x)$	refer collective repair rate (including preventive and corrective repair) and pdf of repair time of all the 12 carding machines when only four carding machines are remained in working states
$P_{12}(t)$	probability that the system is working with full capacity at time t
$P_z(t)$	probability that the system is in 'z' state at time t ($z = 5, 6, \ldots, 11$)
$P_z(x, t)$	probability that the system is in 'z' state at time t and has an elapsed repair time 'x', ($z = 2, 3, 4$)

The *system state transition diagram* representing the probable transition cases of the system among states, using the above assumptions and notations is shown in Fig. 2.

3. Mathematical analysis of the system

Probability considerations give the following differential-difference equations associated with the transition diagram.

$$\left[\frac{d}{dt} + Q_{12}\right] P_{12}(t) = R_{12}(t), \tag{1}$$

$$\left[\frac{d}{dt} + Q_i\right] P_i(t) = (i+1)\lambda P_{i+1}(t) + \mu M_i P_{i-1}(t) \quad (i = 6, 7, \ldots, 11), \tag{2}$$

$$\left[\frac{d}{dt} + \alpha + \psi + 5\lambda + S\mu\right] P_5(t) = 6\lambda P_6(t), \tag{3}$$

$$\left[\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \eta(x)\right] P_4(x,t) = 5\lambda P_5(t), \tag{4}$$

$$\left[\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \upsilon(x)\right] P_3(x,t) = \psi \sum_{i=5}^{12} P_i(t), \tag{5}$$

$$\left[\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta(x)\right] P_2(x,t) = \alpha \sum_{i=5}^{12} P_i(t), \tag{6}$$

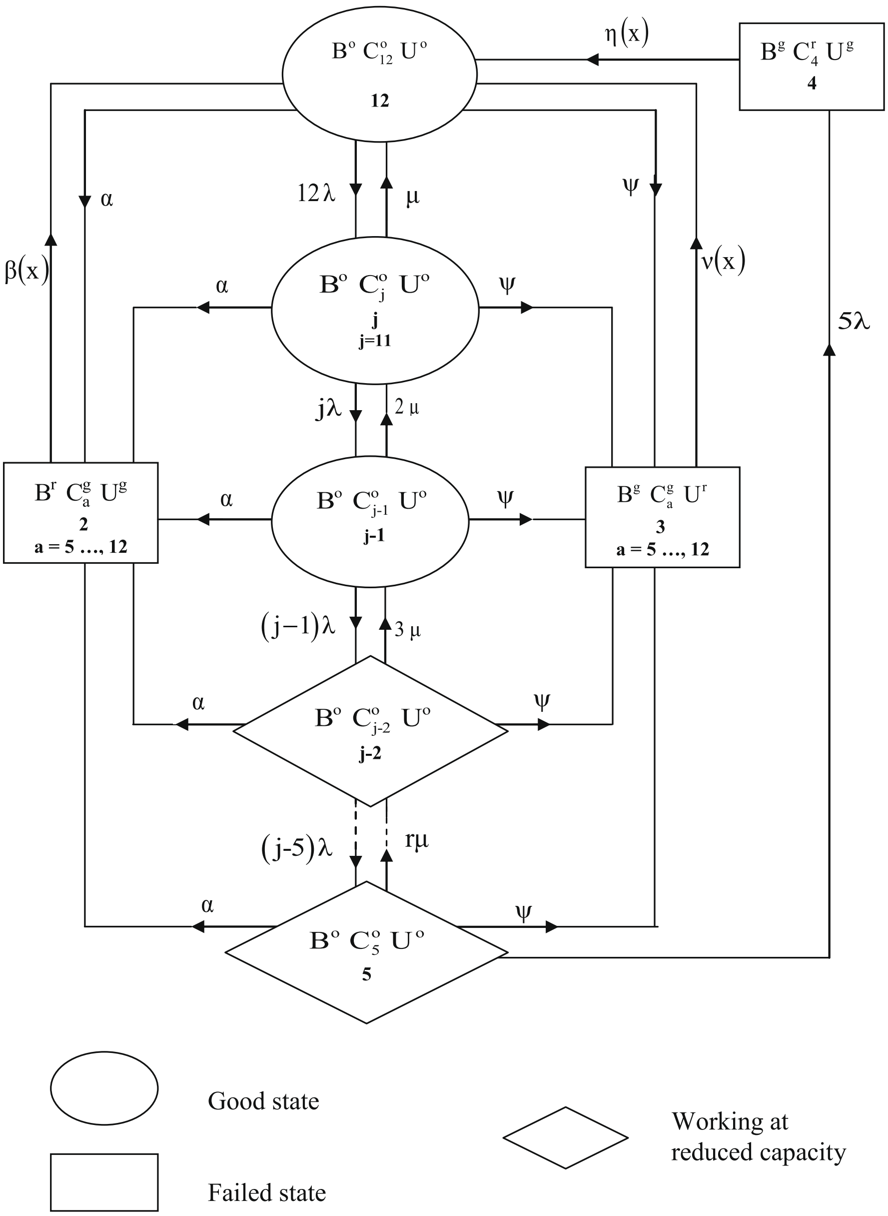

Fig. 2. Transition diagram.

where

$$Q_{12} = \alpha + \psi + 12\lambda,$$

$$Q_i = \alpha + \psi + i\lambda + \mu L_i, \quad i = 6, 7, \ldots, 11,$$

$$M_i = L_i + N,$$

$$L_i = \begin{Bmatrix} 12 - i \quad \text{and } N = 1 \quad \text{if } 1 \leqslant 12 - i \leqslant r - 1 \\ r \quad \text{and } N = 0 \quad \text{if } r \leqslant 12 - i \leqslant 7 \end{Bmatrix} \quad \text{for } i = 6, 7, \ldots, 11,$$

$$S = \begin{Bmatrix} 7 \quad \text{if } r = 7 \\ r \quad \text{if } r \leqslant 6 \end{Bmatrix},$$

$$R_{12}(t) = \mu P_{11}(t) + \int \eta(x) P_4(x,t)dx + \int \upsilon(x) P_3(x,t)dx + \int \beta(x) P_2(x,t)dx. \tag{7}$$

3.1. Initial and boundary conditions

$$\begin{aligned}
&P_{12}(0) = 1,\\
&P_z(0) = 0, \quad (z = 5, 6, \ldots, 11),\\
&P_z(x, 0) = 0, \quad (z = 2, 3, 4),\\
&P_4(0, t) = 5\lambda P_5(t),\\
&P_3(0, t) = \psi \sum_{i=5}^{12} P_i(t),\\
&P_2(0, t) = \alpha \sum_{i=5}^{12} P_i(t).
\end{aligned} \tag{8}$$

3.2. Solution of equations

Eqs. (1)–(3) are first order differential equations and Eqs. (4)–(6) are first order partial differential equations. Under the initial and boundary conditions (8), the Eqs. (1)–(6) are solved to give the solution represented by the relations as given below.

$$P_{12}(t) = e^{-Q_{12}t}\left(1 + \int R_{12}(t)e^{Q_{12}t}dt\right), \tag{9}$$

$$P_i(t) = e^{-Q_i t}\int \{(i+1)\lambda P_{i+1}(t) + \mu M_i P_{i-1}(t)\}e^{Q_1(t)}dt, \quad (i = 6, 7, \ldots, 11), \tag{10}$$

$$P_5(t) = e^{-(\alpha+\psi+5\lambda+S\mu)t}6\lambda \int P_6(t)e^{(\alpha+\psi+5\lambda+S\mu)t}dt, \quad S = r, \tag{11}$$

$$P_4(x, t) = e^{-\int \eta(x)dx}\left(5\lambda P_5(t-x) + 5\lambda \int P_5(t)e^{\int \eta(x)dx}dx\right), \tag{12}$$

$$P_3(x, t) = e^{-\int \upsilon(x)dx}\left(\psi \sum_{i=5}^{12} P_i(t-x) + \psi \int \sum_{i=5}^{12} P_i(t)e^{\int \upsilon(x)dx}dx\right), \tag{13}$$

$$P_2(x, t) = e^{-\int \beta(x)dx}\left(\alpha \sum_{i=5}^{12} P_i(t-x) + \alpha \int \sum_{i=5}^{12} P_i(t)e^{\int \beta(x)dx}dx\right), \tag{14}$$

In the above relations, $P_5(.)$ is in the term of $P_6(.)$, and on solving equations (10) and (11) recursively, $P_{11}(.)$ is obtained in terms of $P_{12}(.)$. After substituting the values of $P_{11}(.)$ in Eqs. (10)–(12), all the probabilities $P_i(.)$, (i = 4, 5, ... , 10) are obtained in terms of $P_{12}(.)$. Again on solving the Eqs. (13) and (14), all probabilities $P_i(.)$, (i = 2, 3, ... , 10)' are obtained in terms of $P_{12}(.)$, where $P_{12}(t)$ is as given in Eq. (1).

4. Reliability indices of the system

(i) Reliability function, $R_1(t)$ for the system if all the carding machines are in operative state (without failure) is given by

$$R_1(t) = P_{12}(t) = e^{-Q_{12}t}\left[1 + \int \left\{\int (\beta(x)P_2(x,t) + \upsilon(x)P_3(x,t) + \eta(x)P_4(x,t))dx + \mu P_{11}(t)\right\}e^{Q_{12}t}dt\right] \tag{15}$$

(ii) Reliability function, $R_{10}(t)$ for the system if 10 or more carding machines are in operative state is given by

$$\begin{aligned}
R_{10}(t) = \sum_{i=10}^{12} P_i(t) = \sum_{i=10}^{11} e^{-Q_i t}\left\{\int ((i+1)\lambda P_{i+1}(t) + \mu M_i P_{i-1}(t))e^{Q_i t}dt\right\}\\
+ \left[1 + \int \left\{\int (\beta(x)P_2(x,t) + \upsilon(x)P_3(x,t) + \eta(x)P_4(x,t))dx + \mu P_{11}(t)\right\}e^{Q_{12}t}dt\right]e^{-Q_{12}t},
\end{aligned} \tag{16}$$

(iii) The failure frequency function of the systemThe system transits to failed states on the failure of sub-systems B and U. For the system, the failure frequency function, $F(t)$ is given by

$$\begin{aligned}
F(t) = 5\lambda P_5(t) + (\alpha+\psi)P_{12}(t) = 30\lambda^2 e^{-(\alpha+\psi+5\lambda+S\mu)t}\int P_6(t)e^{(\alpha+\psi+5\lambda+S\mu)t}dt\\
+ (\alpha+\psi)e^{-Q_{12}t}\left[1 + \int \left\{\int (\beta(x)P_2(x,t) + \upsilon(x)P_3(x,t) + \eta(x)P_4(x,t))dx + \mu P_{11}(t)\right\}e^{Q_{12}t}dt\right]
\end{aligned} \tag{17}$$

(iv) The renewal frequency function of the system

The renewal frequency, $N_f(t)$ of the system is given by

$$\begin{aligned} N_f(t) &= \int_0^t \beta(x)P_2(x,t)dx + \int_0^t \upsilon(x)P_3(x,t)dx + \int_0^t \eta(x)P_4(x,t)dx \\ &= \int_0^t \beta(x)e^{-\int \beta(x)dx}\left\{\alpha\sum_{i=5}^{12}P_i(t-x) + \alpha\int\sum_{i=5}^{12}P_i(t)e^{\int\beta(x)dx}dx\right\}dx + \int_0^t \upsilon(x)e^{-\int\upsilon(x)dx}\left\{\psi\sum_{i=5}^{12}P_i(t-x)\right. \\ &\quad \left. +\psi\int\sum_{i=5}^{12}P_i(t)e^{\int\upsilon(x)dx}dx\right\}dx + \int_0^t \eta(x)e^{-\int\eta(x)dx}\left\{5\lambda P_5(t-x) + 5\lambda\int P_5(t)e^{\int\eta(x)dx}dx\right\}dx \end{aligned} \tag{18}$$

5. Special case

The steady state behavior of the system with constant transition rates can be analyzed by setting $t \to \infty$, $\frac{d}{dt} \to 0$ and $\frac{\partial}{\partial t} \to 0$, the limiting probabilities from Eqs. (1)–(6) are given below.

$$\begin{aligned} &Q_{12}P_{12}(t) = \mu P_{11} + \beta P_2 + \upsilon P_3 + \eta P_4, \\ &Q_iP_i = (i+1)\lambda P_{i+1} + \mu M_i P_{i-1}, \quad (i = 6,7,\ldots,11), \\ &(\alpha+\psi+5\lambda+S\mu)P_5 = 6\lambda P_6, \quad (S = r), \\ &\eta P_4 = 5\lambda P_5, \\ &\upsilon P_3 = \psi\sum_{i=5}^{12}P_i, \\ &\beta P_2 = \alpha\sum_{i=5}^{12}P_i. \end{aligned} \tag{19}$$

Solving the above system of equations recursively, we have.

$$\begin{aligned} &P_4 = K_7P_{12}, \\ &P_{j+4} = K_jP_{12}, \quad (j = 1,2,\ldots,6), \\ &P_{11} = Z_7P_{12}, \\ &P_3 = \frac{\psi}{\upsilon}\left(1 + Z_7 + \sum_{i=1}^{6}K_i\right)P_{12}, \\ &P_2 = \frac{\alpha}{\beta}\left(1 + Z_7 + \sum_{i=1}^{6}K_i\right)P_{12}, \end{aligned}$$

where

$$\begin{aligned} &Z_1 = \frac{6\lambda}{\alpha+\psi+5\lambda+S\mu}, \quad (S = r,7), \\ &Z_{i-4} = \frac{(i+1)\lambda}{\alpha+\psi+i\lambda+\mu L_i-\mu M_iZ_{i-5}}, \quad (i = 6,7,\ldots,11), \\ &K_6 = Z_6Z_7, \\ &K_j = Z_jK_{j+1}, \quad (j = 5,4,3,2,1), \\ &K_7 = \frac{5\lambda}{\eta}K_1. \end{aligned}$$

Arranging as in previous section, all the probabilities are obtained in terms of 'P_{12}', where 'P_{12}' is obtained by using the normalizing condition

$$\sum_{i=2}^{12}P_i = 1,$$

we get

$$P_{12} = \frac{1}{\left(1 + Z_7 + \sum_{i=1}^{6}K_i\right)\left(1 + \frac{\alpha}{\beta} + \frac{\psi}{\upsilon}\right) + K_7}. \tag{20}$$

Reliability indices of the system under steady state are obtained as

(i) The long run availability of the system 'A_1', if all the carding machines are in working states reduces to the form

$$A_1 = P_{12} = \frac{1}{\left(1 + Z_7 + \sum_{i=1}^{6} K_i\right)\left(1 + \frac{\alpha}{\beta} + \frac{\psi}{\upsilon}\right) + K_7}. \tag{21}$$

(ii) The long run availability of the system 'A_{10}', if 10 or more carding machines are in working states is obtained as

$$A_{10} = \sum_{i=10}^{12} P_i = \frac{1 + Z_7 + K_6}{\left(1 + Z_7 + \sum_{i=1}^{6} K_i\right)\left(1 + \frac{\alpha}{\beta} + \frac{\psi}{\upsilon}\right) + K_7}. \tag{22}$$

(iii) *The failure frequency* 'F' of the system takes the form

$$F = (\alpha + \psi)P_{12} + 5\lambda P_5 = \frac{\alpha + \psi + 5\lambda K_1}{\left(1 + Z_7 + \sum_{i=1}^{6} K_i\right)\left(1 + \frac{\alpha}{\beta} + \frac{\psi}{\upsilon}\right) + K_7}. \tag{23}$$

(iv) *The renewal frequency* 'N_f' is simplified to the form

$$N_f = \beta P_2 + \upsilon P_3 + \eta P_4 = \frac{(\alpha + \psi)(1 + Z_7 + \sum_{i=1}^{6} K_i) + 5\lambda K_1}{(1 + Z_7 + \sum_{i=1}^{6} K_i)(1 + \frac{\alpha}{\beta} + \frac{\psi}{\upsilon}) + K_7}. \tag{24}$$

6. Performance analysis

The performance analysis will help in pin pointing the factors that have an impact on the availability of the system. There are twelve carding machines and the production capacity of each carding machine is 27.9 kg compact sliver per hour. Two out of twelve machines in operation generally remain under preventive maintenance or repair due to the clogging of the moving parts which has to be cleaned. The management is interested to run at least ten carding machines to achieve the desired production rate i.e. 5.5 tons sliver per day. For this, the requisite number of 'r' repairmen for maintaining ten or more carding machines operative all the time, are kept ready. This ensures optimal steady state availability of the system by foreseeing the minimum repairmen requirement, thus reducing maintenance cost. Further the effect of failure and repair rates of different components on long run availability is also examined. The same have been studied in a way to possibly improve system availability.

6.1. Impact of repair facilities on the steady state availability

The number of repairmen needed for keeping 10 or more carding machines in operative state is obtained after analyzing the effect of number of maintainers that ensure the optimal steady state availability of the system. Impact of the number of maintainers (r) on steady state availability of the system 'A_{10}' is shown in Table 1.

Data taken for the system is as follows.

$$\alpha = \psi = .0015, \quad \lambda = .005, \quad \beta = \upsilon = .125, \quad \mu = .2, \quad \eta = .05.$$

From the Table 1, we see that the availability of the system 'A_{10}' improves significantly with increase in number of repairman. We also see that the system availability increases considerably till the number of repairmen 'r' is increased from one to three. After this there is no enhancement in the availability of the system. Thus three repairmen are sufficient to keep ten or more carding machines out of the total twelve carding machines in running states with probability .9739, which is the optimum value of 'r'.

6.2. Reliability indices of the system for the steady state

Reliability indices of the system using relations (21)–(24), taking above data and 'r = 3' is shown in Table 2.

Table 1
Steady state availability (A_{10}) vs. number of repairmen (r).

r	1	2	3	4	5	6	7
A_{10}	.9593	.9725	.9739	.9740	.9740	.9740	.9740

Table 2
The reliability indices of the system under steady state.

No	Reliability indices	Probability
1	Steady state availability of the system, 'A_1' if all the carding machines are in operative state	.7295
2	Steady state availability of the system, 'A_{10}' if 10 or more carding machines are in operative state	.9739
3	Failure frequency 'F'	.0022
4	Renewal frequency 'N_f'	.0029

Table 3
Effect of failure rates of sub-systems C and U on availability Taking α = .0015, $\beta = \upsilon$ = .125, μ = .2, η = .05, r = 3.

λ	ψ				
	.001	.0015	.002	.0025	.003
.003	.9798	.9759	.9721	.9684	.9646
.004	.9790	.9752	.9714	.9676	.9639
.005	.9777	.9739	.9702	.9664	.9627
.006	.9760	.9722	.9684	.9647	.9610
.007	.9737	.9699	.9662	.9625	.9588

Table 4
Effect of repair rates of sub-systems C and U on availability taking, $\alpha = \psi$ = .0015, λ = .005, β = .125, η = .05, r = 3.

μ	υ				
	. 1	.125	.15	.2	.25
.1	.9571	.9599	.9618	.9641	.9656
.15	.9680	.9708	.9727	.9751	.9765
.2	.9711	.9739	.9758	.9782	.9797
.25	.9723	.9752	.9771	.9795	.9809
.3	.9729	.9757	.9776	.9800	.9815

6.3. Effect of failure and repair rates of different units

After fixing the minimum number of repairmen for repair of carding machines corresponding to optimum availability of the system, the effect of failure and repair rates of different sub-systems on availability is studied. Tables 3 and 4 show this effect.

From the Tables 3 and 4, it is observed that the availability of the system decreases by approximately 0.6% and 1.5% with the increase in failure rate of carding machine (λ) from .003 (once in 333 h) to .007 (once in 142 h) and unilap machine (ψ) from .001 (once in 1000 h)to .003 (once in 333 h) respectively, and increases by 1.65% and 0.88% with an increase in repair rate (μ) of carding machine from .1 (once in 10 h) to .3 (once in 3.3 h) and unilap machine (υ) from .1 (once in 10 h) to .25 (once in 4 h) respectively.

7. Conclusion

The foremost outcome of the analysis is that it inferences the minimum number of repairmen needed for keeping ten or more carding machines out of twelve carding machines in working states with system availability .9739 is three. Once the minimum number of repairmen is fixed, the effect of failure and repair rates of the constituent components of the system is studied. It is found out that failure and repair rates of unilap machine and repair rates of carding machines highly affect the availability of the system. So the paper concludes that repair rates of carding machine and unilap machine must be improved which could be achieved with appropriate maintenance planning and thus the availability of the system could be improved. This information is vital for the management and helps in devising a comprehensive scheduling plan for utilizing suitable repair facility in order to achieve the optimum availability.

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