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ON THE USE OF CORRECTIVE MAINTENANCE DATA FOR PERFORMANCE ANALYSIS OF PREVENTIVELY MAINTAINED TEXTILE INDUSTRY

Manwinder Kaur[1], Arvind Kumar Lal[1], Satvinder Singh Bhatia[1] and Akepati Sivarami Reddy[2]
[1]School of Mathematics and Computer Applications,
Thapar University, Patiala PB-147004 (India)
[2]School of Energy and Environment, Thapar University, Patiala PB-147004(India)
Email:aklal@thapar.edu

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Abstract

In this paper, a method is proposed to improve the scheduled preventive maintenance of the system by assessing different kinds of availability and illustrated how the corrective maintenance data can be helpful to reschedule preventively maintained system. This method uses the concept of inherent availability to ensure to what extent maximum availability can be extended. The application of the proposed methodology has finally been demonstrated to six unit textile weaving industry situated in northern India. A mathematical formulation of Chapman – Kolmogorov differential difference equations, determining its availability, has been developed. A numerical study has been carried forward to quickly analyze the availability of the system on the actual corrective maintenance data taken from this industry.

Key Words: Availability, Chapman-Kolmogorov Equations, Maintenance Scheduling, Numerical Methods, Textile Weaving Process.

1. Introduction

In the era of competitions among the manufacturing companies, the demand of quality production within the stated time period increases for assuring the requirement of patrons. The availability of production systems play significant role for achieving this requirement. The production system's availability can be improved by maximizing the productivity of its sub-systems, which can be possible only through proper maintenance of the systems. Industries generally adopt two kinds of maintenance actions – preventive and corrective. While preventive maintenance is carried after a fixed interval of time to ensure the operational state of system through inspection of its units [1], corrective maintenance is provided to the system when it shows sudden breakdown and fails to respond.

Many mathematical models have been developed in literature for improving system performance and are also helpful for maintenance personnel in industry. Syamsundar and Naikan [15] constructed a segmented point process model to analyze the failure processes of maintained systems subject to a change in the process that can be identified as an off-line detection procedure. Subsequently, they [16] used it in a sequential manner for online detection to identify the change in the process. For making the system operational all the time, importance of preventive maintenance (PM) cannot be denied (Caputo *et al.* [1], Garg *et al.* [3]). However, timely given corrective maintenance helps system coming back in operation after sudden breakdown. If proper maintenance is not provided timely, the production process can drastically be affected in any industry. In order to schedule maintenance or to improve the operational levels of industry, a probabilistic parameter, availability, contributes major role. Several authors studied the availability for various industries and theirs systems.

Garg *et al.* [5] discussed preventive maintenance scheduling of pulping unit for paper plant industry through availability analysis. The availability analysis of different systems is also studied by by Goel and Singh [4] and Zhao [18]. Several authors such as Mahajan and Singh [12], Herder *et al.*[8], Trivedi *et al.* [17], Pandey *et al.* [13], Ram and Singh [14] etc. have discussed the reliability analysis of various systems. Gupta *et al.*[6,5] and Gupta *et al.* [7] have studied reliability and availability of the systems simultaneously. Kumar *et al.*[9] discussed the maintenance planning and resource allocation through birth and death process of urea fertilizer plant. Leou [11] have attempted to address these problems at different levels for unit maintenance with reliability and operation expenses. The mathematical models discussed in recent studies [2,**Error! Reference source not found.**] are helpful in improving the performance of the manufacturing process/systems. They considered the preventive maintenance data only. The aim of this research is to examine the effect of sudden breakdown of systems and their corrective maintenance repair times through stochastic model.

In this paper we have analyzed the unscheduled corrective maintenance actions to reschedule the preventively maintained systems by optimizing the sudden failure and repair rates. Though, there is always uncertainty to predict the exact sudden breakdowns of the manufacturing system. The corrective maintenance repair and failure times are converted into failure (failure in time) and repair (repair carried in time) rates of the system. Further, the time dependent availability and steady state availability analysis have been carried out to analyze the performance of production process. In order to optimize the failure and repair rate, the inherent availability is used while computing steady state availability. The approach thus developed has been applied to the textile weaving process for availability analysis on corrective maintenance data.

The paper is organized as follows: Section 1 is introductory in nature. A brief survey of literature available on this subject is also presented in this section. A complete description of the various subsystems of textile weaving process together with process flow chart has been discussed in Section 2. The notation of the subsystems and certain assumptions on which the present analysis is based, are also discussed in this section. Section 3 presents mathematical formulation of the problem determining the availability of the textile weaving process. In Section 4, analysis of time dependent availability and inherent availability have been carried out by varying transition rate of the subsystems to detect the sensitive subsystems. Certain conclusions drawn by comparing the values of inherent availability with long run availability to improve maintenance of the system are finally discussed in Section 5.

2. Production System: Textile Weaving Process

Textile weaving process is concerned with making cloth from yarn through interlacing. The production system for manufacturing textile weaving is divided into six subsystems for the present analysis and is shown in Figure 1. We discuss in brief the functioning of these subsystems.

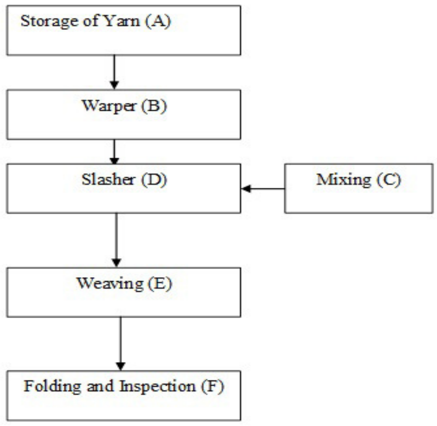

Figure 1: Process flow diagram

2.1. Weaving process

Storage of yarn: Production of fabric needs yarn as raw material of the process and its storage plays significant role to keep raw material damage free. Raw material storage system is represented by A. Under special environmental observation, this system is supposed to be never fails.

Warper: This system helps in preparation of base for a woven fabric. This system used to wind a definite number of thread ends in a precisely designed order (of given length) over a cylinder called beam by placing the spools (also known as thread reels) in a definite position on a frame, called creel. This consists of pneumatic subsystem, stop motion, scissors etc. Warper and associated facilities are prone to many major and minor failures. Warper is represented by B.

Mixing system: This system works parallel to warper and important part of the process. It is used to prepare a mixture of polyvinyl alcohol, starch, binder and organic softener. This mixture used to coat the warp beam to strengthen the thread. The mixture system consists of cooker, gasket, pressure gauge and motor. It should be taken care that nut-bolts should tie tightly while making mixture. This system is subject to major failures only. Mixing system is symbolized by C.

Slasher: Slasher, also known as sizing system is used to coat the warp beam with the mixture prepared in mixing system. Later warp is passed through dryer to retain the moisture. Each slasher system consists of dryers, motors, hydraulic, pneumatic system, press rolls beam, belts etc. This is subject to major and minor failures of the system. Subsystem slasher is represented by D.

Loom: Loom is a machine for weaving fabric by interlacing a series of vertical parallel threads of warp beam with horizontal parallel threads of other warp beam placed horizontally to the aforementioned one. That is, warp after sizing is transformed into fabric on a loom, through filling (interlacing of vertical warp thread with horizontal parallel threads). Thus woven fabric is then wound on a cloth beam. Loom is associated with major failures and represented by E.

Fabric inspection machine: Fabric inspecting system is used to check the quality of the textile before packaging. This is subject to major failures of the system Fabric inspecting system used to check the quality of the textile before packaging. This is subject to major failures of the system and denoted by the symbol F.

2.2. System notations

The following notations/symbols are used throughout the paper and are also used in transition diagram (Figure 2).

A, B, C, D, E, F	: Represent that systems are working in good states.
$\overline{B}, \overline{D}$	: Subsystems B and D are working with reduced capacity
λ_i (i=1,⋯,7)	: Failure rates of the subsystems $C, E, F, B, D, \overline{B}, \overline{D}$ respectively
μ_i (i=1,⋯, 7)	: Repair rates of subsystems $C, E, F, B, D, \overline{B}, \overline{D}$ respectively
$P_i(t)$ (i=1,⋯, 21)	: The probability that system is in the *ith* state at time *t*
$P_i'(t)(i=1,\cdots,21)$	: Rate of change of state with respect to time *t* at the i^{th} state of the system.
b, c, d, e, f	: The failed state of subsystems B, C, D, E, and F, respectively.

2.3. Assumptions

The following assumptions are considered in order to carry out the performance analysis for maintenance scheduling of textile weaving process through stochastic model:

(i) Repairs and failures are statistically independent with each other
(ii) Units of repair and failure rates are taken as per day
(iii) There is no simultaneous failure among the sub systems
(iv) Subsystems B and D can fail completely only through reduce states
(v) Repaired components are treated as new components
(vi) Repair of subsystems B and D is allowed in reduced state only up to a certain limit
(vii) Repair is carried out either in reduced or failed state of the system
(viii) Component based preventive maintenance for each subsystem is carried to avoid frequent failures.

3. Mathematical model for availability analysis of textile weaving process

In order to obtain probabilities of both transient and steady state of textile weaving process, Chapman - Kolmogorov differential difference equations as well as system of linear equations have been formulated considering transition diagram shown in Figure 2. The mathematical formulations, carried out in both the states, are discussed separately as follows:

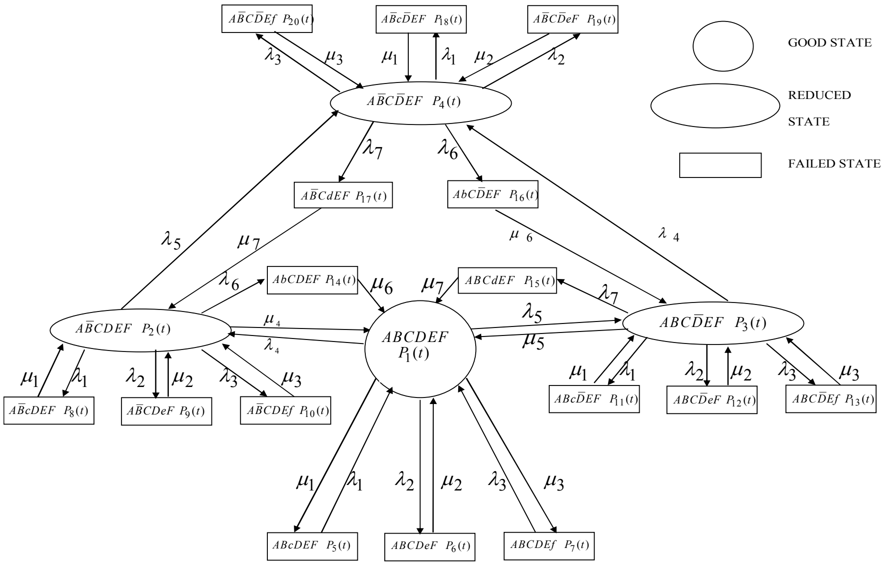

Figure 2: Transition diagram of textile weaving process

3.1. Transient state for time dependent availability analysis

The following system of linear differential equation is obtained at time $t+\Delta t$ using the mnemonic rule with probability consideration of various states shown in the transition diagram of the weaving process. The differential equation for the state one is obtained as:

$$P_1(t+\Delta t) = [1-(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5)]\Delta t\, P_1(t) + \mu_1\,\Delta t\, P_5(t) + \mu_2 \Delta t\, P_6(t) + \mu_3 \Delta t\, P_7(t) + \mu_4 \Delta t\, P_2(t) + \mu_5\, \Delta t\, P_3(t) + \mu_6 \Delta t\, P_{14}(t) + \mu_7\, \Delta t\, P_{15}(t) \quad (1)$$

Dividing (1) both sides by Δt and taking limit as $\Delta \text{t} \to 0$, we get

$$\frac{d\,P_1(t)}{dt} + \alpha_1 P_1(t) = \mu_1 P_5(t) + \mu_2 P_6(t) + \mu_3 P_7(t) + \mu_4 P_2(t) + \mu_5 P_3(t) + \mu_6 P_{14}(t) + \mu_7 P_{15}(t) \quad (2)$$

Similarly, system of differential equations for other states can be written as:

$$\frac{d\,P_2(t)}{dt} + \alpha_2 P_2(t) = \mu_1 P_8(t) + \mu_2 P_9(t) + \mu_3 P_{10}(t) + \lambda_4 P_1(t) + \mu_7 P_{17}(t) \quad (3)$$

$$\frac{d\,P_3(t)}{dt} + \alpha_3 P_3(t) = \mu_1 P_{11}(t) + \mu_2 P_{12}(t) + \mu_3 P_{13}(t) + \lambda_5 P_1(t) + \mu_6 P_{16}(t) \quad (4)$$

$$\frac{d\,P_4(t)}{dt} + \alpha_4 P_4(t) = \lambda_5 P_2(t) + \mu_3 P_{20}(t) + \mu_1 P_{18}(t) + \mu_2 P_{19}(t) + \lambda_4 P_3(t) \quad (5)$$

$$\frac{d\,P_{4+i}(t)}{dt} + \mu_i P_{4+i}(t) = \lambda_i P_1(t), \qquad i = 1,2,3 \quad (6)$$

$$\frac{d\,P_{7+i}\left(t\right)}{dt}+\mu_i P_{7+i}(t)=\lambda_i P_2(t), \quad i=1,2,3 \tag{7}$$

$$\frac{d\,P_{10+i}\left(t\right)}{dt}+\mu_i P_{10+i}(t)=\lambda_i P_3(t), \quad i=1,2,3 \tag{8}$$

$$\frac{d\,P_{14}\left(t\right)}{dt}+\mu_6 P_{14}(t)=\lambda_6 P_2(t) \tag{9}$$

$$\frac{d\,P_{15}\left(t\right)}{dt}+\mu_7 P_{15}(t)=\lambda_7 P_3(t) \tag{10}$$

$$\frac{d\,P_{16}\left(t\right)}{dt}+\mu_6 P_{16}(t)=\lambda_6 P_4(t) \tag{11}$$

$$\frac{d\,P_{17}\left(t\right)}{dt}+\mu_7 P_{17}(t)=\lambda_7 P_4(t) \tag{12}$$

$$\frac{d\,P_{17+i}\left(t\right)}{dt}+\mu_i P_{17+i}(t)=\lambda_i P_4(t), \quad i=1,2,3 \tag{13}$$

where,

$$\alpha_1=\sum_{i=1}^{5}\lambda_i;\quad \alpha_2=\sum_{\substack{i=1,\\ i\neq 4}}^{6}\lambda_i+\mu_4;\quad \alpha_3=\sum_{i=1,}^{4}\lambda_i+\mu_5+\lambda_7;\quad \alpha_4=\lambda_1+\lambda_2+\lambda_3+\lambda_7+\lambda_6$$

The initial conditions

$$P_i(0)=\begin{cases}1, & \text{if } i=1\\ 0, & \text{otherwise}\end{cases} \tag{14}$$

The system of differential equations (1-13) is called Chapman - Kolmogorov differential difference equations. Time dependent availability of the system $A\left(t\right)$ can be computed using the relation

$$A(t)=\sum_{i=1}^{4}P_i(t) \tag{15}$$

This further used to obtain mean time between system failures (MTSF), which is given by

$$MTSF=\int_0^t A\left(t\right)dt \tag{16}$$

For the given value of failure and repair rates of the subsystems, the mean time to repair (MTTR) can be computed by the following formula

$$MTTR=\frac{\sum_{i=1}^{7}\lambda_i\mu_i}{\sum_{i=1}^{7}\lambda_i} \tag{17}$$

The equations (16 -17) will finally be used to obtain the inherent availability A_i of the system and is given by

$$A_i=\frac{MTSF}{MTSF+MTTR} \tag{18}$$

3.2. Steady state for availability analysis

Steady state probability of the subsystems can be obtained by imposing the restriction $t \to \infty$ on the system of linear differential equations (1-13). So, the system of linear differential equations (1-13) reduces to following system of homogeneous linear equations:

$$\alpha_1 P_1 = \mu_1 P_5 + \mu_2 P_6 + \mu_3 P_7 + \mu_4 P_2 + \mu_5 P_3 + \mu_6 P_{14} + \mu_7 P_{15} \quad (19)$$

$$\alpha_2 P_2 = \mu_1 P_8 + \mu_2 P_9 + \mu_3 P_{10} + \lambda_4 P_1 + \mu_7 P_{17} \quad (20)$$

$$\alpha_3 P_3 = \mu_1 P_{11} + \mu_2 P_{12} + \mu_3 P_{13} + \lambda_5 P_1 + \mu_6 P_{16} \quad (21)$$

$$\alpha_4 P_4 = \lambda_5 P_2 + \mu_3 P_{20} + \mu_1 P_{18} + \mu_2 P_{19} + \lambda_4 P_3 \quad (22)$$

$$\mu_i P_{4+i} = \lambda_i P_1, \quad i = 1,2,3 \quad (23)$$

$$\mu_i P_{7+i} = \lambda_i P_2, \quad i = 1,2,3 \quad (24)$$

$$\mu_i P_{10+i} = \lambda_i P_3, \quad i = 1,2,3 \quad (25)$$

$$\mu_6 P_{14} = \lambda_6 P_2 \quad (26)$$

$$\mu_7 P_{15} = \lambda_7 P_3 \quad (27)$$

$$\mu_6 P_{16} = \lambda_6 P_4 \quad (28)$$

$$\mu_7 P_{17} = \lambda_7 P_4 \quad (29)$$

$$\mu_i P_{17+i} = \lambda_i P_4, \quad i = 1,2,3 \quad (30)$$

The solution of the systems of homogenous linear equations (19-30) are finally used to study the long run availability $A(\infty)$ for textile weaving process by computing the following relation

$$A(\infty) = \sum_{i=1}^{4} P_i \quad (31)$$

Following the approach earlier used by [6, 5, **Error! Reference source not found.**, 18], the system of linear differential difference equations (1-13) with initial conditions (14) have been solved numerically to calculate time dependent availability of the textile weaving process. The step size of iteration is assumed as, $h = 0.005$, as one hour. The numerical computations have been carried forward from $t = 0$ to $t = 360$ hour for various choices of failure and repair rates of the subsystems. The data of failure and repair rates, presented in Table 1, are the actual values of the various subsystems taken from the Nahar Fabrics Co. limited industry situated in Punjab, India. The values of probabilities thus computed are finally used in equation (15) to obtain the time dependent availability of the textile weaving process with the interval of 30 hours. The effects of failure and repair rates of the various subsystems on the time dependent availability have also been analyzed.

Table 1: Failure and repair rates data

C	λ_1	0.0014	μ_1	0.5
E	λ_2	0.0007	μ_2	0.33
F	λ_3	0.00028	μ_3	0.5
B	λ_4	0.0056	μ_4	0.5

D	λ_5	0.0014	μ_5	0.33
$\overline{B}$	λ_6	0.0019	μ_6	0.33
$\overline{D}$	λ_7	0.0056	μ_7	0.33

In order to compute steady state availability of textile weaving process, the system of homogeneous linear equations has been solved numerically using Gauss elimination method with partial pivoting to obtain steady state probabilities. As we require nontrivial solution of the system of homogeneous linear equations, one of the equations of the system (19-30) has been replaced by normalizing condition, that is,

$$\sum_{i=1}^{20} P_i = 1 \tag{32}$$

Once unknown $P_i(t), i = 1,...,20$ are computed, the long run availability or steady state availability $A(\infty)$ is obtained by using (31) for various combination of failure and repair rates of the subsystems. The MTSF of the system is next computed from (16) for one year using Simpson's one-third rule. In fact, the function $A(t)$ is integrated from 0 to 360 hour. Once MTSF and MTTR are known, inherent availability A_i is finally computed by using equation (18).

4. Time dependent availability analysis for detecting sensitive subsystems

In order to analyze the effect of corrective maintenance on system behavior of the process industry, we assume that each subsystem are preventively maintained so that the occurrence of failure could be avoided after every 300 operating hours during the off schedule time. Hence, preventive maintenance is taken as a part of system functioning state. Now, we shall first categorically examine the sensitivity of the particular subsystems on the basis of the availability analysis of the textile weaving process and then optimize the failure and repair rates of the weaving process.

By varying the failure rate λ_1 of subsystem C and keeping other parameters fixed (as shown in Table 1), we have computed time dependent availability for one year with the interval of 30 hours and results are shown in Figure 3*a*. Similarly, by varying the failure rate $\lambda_i, i = 2,...,7$ separately and taking other parameters, as given in Table 1, fixed, the time dependent availability of the manufacturing plants have also been computed and all the results are depicted in Figure 3. The computed values of MTSF and MTTR for each variation in $\lambda_i, i = 1,2,...,7$ are also obtained and their minimum and maximum values are presented in Table 2.

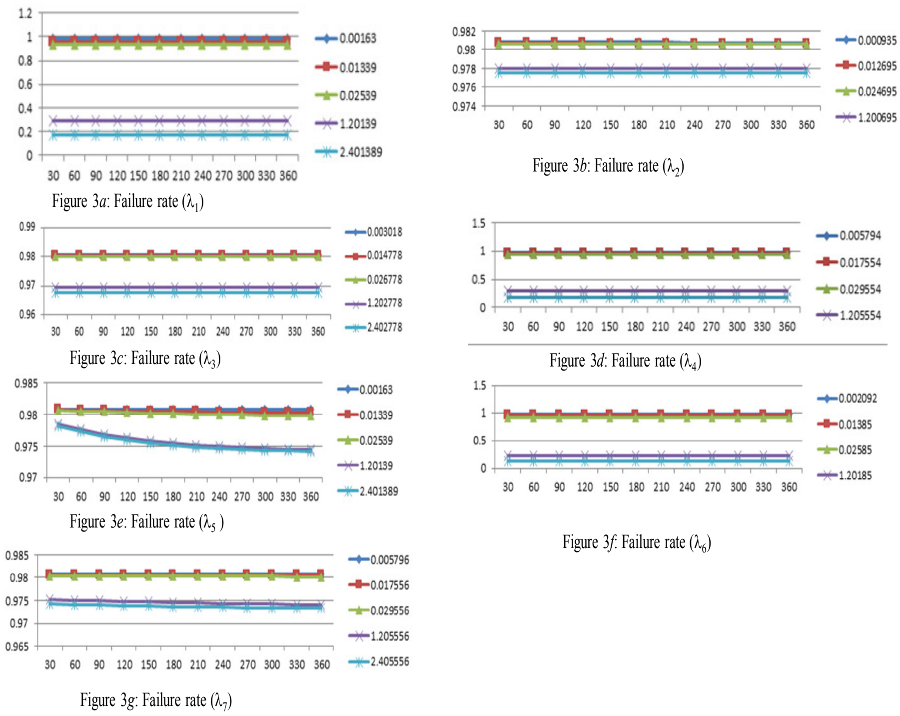

Figure 3*a*: Failure rate (λ_1)
Figure 3*b*: Failure rate (λ_2)
Figure 3*c*: Failure rate (λ_3)
Figure 3*d*: Failure rate (λ_4)
Figure 3*e*: Failure rate (λ_5)
Figure 3*f*: Failure rate (λ_6)
Figure 3*g*: Failure rate (λ_7)

Figure 3: Effect of failure rates on time dependent availability of weaving industry

The results exhibited in Figures (3*a*-3*g*) reveal that warping and mixing subsystem are affecting more to the system performance than the remaining subsystems in terms of time dependent availability. So, these are detected as the most sensitive subsystems of the weaving industry. Now, we shall carry out the behavior analysis of these sensitive subsystems only for long run availability in the subsequent section.

Table 2: Effect of failure rate of subsystems on the MTSF and MTTR

Variations in failure rate of subsystems	MTSF		MTTR	
	Maximum	Minimum	Maximum	Minimum
λ_1	313. 71	54. 98	0. 43	0. 49
λ_2	313. 85	312. 80	0.42	0. 33
λ_3	313. 85	309. 70	0.43	0.49
λ_4	313. 70	54. 98	0. 43	0. 49
λ_5	313. 85	312. 13	0. 43	0. 49
λ_6	313. 63	38. 93	0. 42	0. 33
λ_7	313. 85	311. 58	0.42	0. 33

4.1. Long-run availability analysis of sensitive sub-systems

On comparing the computed values of long run availability for various combinations of failure and repair rates of the sensitive subsystems only, it can be optimized for the maintenance planning of the system.

With the given choice of failure and repair rates, we have calculated inherent availability which is 0.99863. However, by giving variations to the failure rate of the subsystem, inherent availability changes by 0.0001% only. Hence, the inherent availability, obtained from the actual data, has been fixed to 0.99863 for further analysis.

As the subsystem B is one of the sensitive subsystems affecting the time dependent availability more, long run availability has been calculated for various pair of failure rate and repair rate (λ_4, μ_4) and results are presented in Table 3. In order to obtain the optimal value for maintenance scheduling, we have also obtained inherent availability of the system because it corresponds to the maximum availability of the system that it can achieve. Thus, the optimal choices of long run availability of the system are: [0.98960, 0.98960, 0.98960, and 0.98960] corresponding to the pair wise failure and repair rate [(0.005536, 1.69999), (0.005557, 2.9), (0.005794, 1.69999), (0.005794, 2.9)] for maintaining high inherent availability of the system.

Table 3: Systems availability results to detect optimized value of failure (λ_4) and repair rate (μ_4) of warping

λ_4 \ μ_4	0.5	0.50024	0.512	0.524	1.7	2.9
0.005557	0.98960	0.98960	0.98960	0.98960	0.98960	0.98960
0.005794	0.98959	0.98959	0.98959	0.98959	0.98960	0.98960
0.017554	0.98950	0.98950	0.98950	0.98950	0.98951	0.98951
0.029554	0.98941	0.98941	0.98941	0.98941	0.98942	0.98942
1.205554	0.98854	0.98854	0.98852	0.98851	0.98770	0.98738
2.405554	0.98885	0.98885	0.98883	0.98882	0.98793	0.98747
Underlined values represent optimal choices of long run availability corresponding to the pair wise failure and repair rates.						

Table 4: Systems availability results to detect optimized value of failure (λ_6) and repair rate (μ_6) of warping

μ_6 \ λ_6	0. 33	0. 334	0. 345	0. 357	1. 53	2. 73
0.00185	0.98960	0.98960	0.98960	0.98960	0.98962	0.98965
0.00209	0.98960	0.98960	0.98960	0.98961	0.98963	0.98967
0.01385	0.98986	0.98986	0.98986	0.98987	0.98993	0.99002
0.02585	0.99012	0.99012	0.99013	0.99014	0.99020	0.99031
1.20185	1.01758	1.01758	1.01758	1.01757	1.01752	1.01744
2.4019	1.04888	1.04888	1.04885	1.04883	1.04862	1.04828
Underlined values represent optimal choices of long run availability corresponding to the pair wise failure and repair rates.						

The result presented in Table 4 corresponds to the long run availability of the weaving process computed by various pair of failure and repair rate of subsystem B, that is, (λ_6, μ_6) and keeping other parameters unchanged. From the Table 4, it is noticed that for maintaining maximum availability of the system, the optimal choices for pair wise failure and repair are [(0.002092, 2.73), (0.00185, 2.73), (0.002092, 1.533) corresponding to the long run availability (0.00185, 1.53)] 0.989665, 0.989654, 0.989628, 0.989621.

Table 5: Systems availability results to detect optimized value of failure (λ_1) and repair rate (μ_1) of warping

λ_1 \ μ_1	0. 5	0.50024	0. 512	0. 524	1. 7	2. 9
0.00139	0.98960	0.98960	0.98966	0.98972	0.99152	0.99185
0.00163	0.98913	0.98913	0.98920	0.98927	0.99138	0.99177
0.01339	0.96664	0.96665	0.96723	0.96779	0.98463	0.98780
0.02539	0.94472	0.94474	0.94578	0.94680	0.97783	0.98378
1.20139	0.29321	0.29331	0.29813	0.30299	0.58328	0.70323
2.4019	0.17210	0.17217	0.17550	0.17887	0.41317	0.54472
Underlined values represent optimal choices of long run availability corresponding to the pair wise failure and repair rates.						

Similarly, maintaining subsystem C for achieving the maximum availability of the weaving process, long run availability analysis has been carried for the various pair-wise combination of failure and repair rates (λ_1, μ_1) and results are shown in Table 5. In this case, it is observed that the optimal choices for long run availability are 0.989596, 0.989597, 0.989660, and 0.989721 corresponding to the following pair-wise combination of failure and repair rate [(0.001329, 0.5), (0.00139, 0.50024), (0.00139, 0.512, 0.524)]. It is noted that whenever system availability approaches the inherent availability, system will show maximum performance and this trend will obviously be helpful to maintenance personnel of the industry.

5. Concluding observation

A comparative study of Tables (2-5) and Figures 3 (a - g) reveals that subsystems B and C (that is, warper and mixing system) affect more the performance of textile production system due to sudden breakdown. Therefore, it is recommended that industry management should pay more attention to these subsystems only so that performance of the system may improve. In order to help the management in smooth functioning of the plant, optimized values of failure and repair rates are to be provided using inherent availability instead of long run availability (see Table 2-4). In fact, management can set up periodic maintenance strategy with optimal combination of failure and repair rates to keep the system functioning at feasible echelon using the inherent availability. In this paper, we have also discussed how the corrective maintenance (CM) data can be helpful to reschedule the preventive maintenance of the machine systems by simulating results for constant failure and repair rates by solving the governing stochastic differential equation numerically. The problem becomes more complex for analyzing time dependent availability of the process industry when a mathematical model is developed assuming varying failure and repair rates of subsystems.

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