Performance Modeling and Availability Analysis of Yarn Dyeing System of a Textile Industry

P. C. Tewari, Rajiv Kumar, Dinesh Khanduja

Abstract—This paper discusses the performance modeling and availability analysis of Yarn Dyeing System of a Textile Industry. The Textile Industry is a complex and repairable engineering system. Yarn Dyeing System of Textile Industry consists of five subsystems arranged in series configuration. For performance modeling and analysis of availability, a performance evaluating model has been developed with the help of mathematical formulation based on Markov-Birth-Death Process. The differential equations have been developed on the basis of Probabilistic Approach using a Transition Diagram. These equations have further been solved using normalizing condition in order to develop the steady state availability, a performance measure of the system concerned. The system performance has been further analyzed with the help of decision matrices. These matrices provide various availability levels for different combinations of failure and repair rates for various subsystems. The findings of this paper are therefore, considered to be useful for the analysis of availability and determination of the best possible maintenance strategies which can be implemented in future to enhance the system performance.

Keywords—Availability Analysis, Markov Process, Performance Modeling, Steady State Availability.

I. INTRODUCTION

RELIABILITY Analysis is one of the main tools to ensure agreed delivery deadlines, which in turn maintain certain intangible factors such as customer goodwill and company reputation. Downtime often leads to both tangible and intangible losses. These losses may be due to some unreliable subsystems/components; so an effective strategy needs to be framed for the maintenance, replacement and design changes related to those subsystems and components. The Textile Industry comprises of large complex engineering systems arranged in series, parallel or a combination of both the configurations. Some of these systems are yarn manufacturing, yarn and fiber dyeing, fabric weaving, fabric processing, sewing thread. The important process of a Textile Industry, upon which the quality of products depends, is the Dyeing Process. In the process of Yarn Dyeing, yarns in cheese form from storage are fed into a Pre Winding Machine to convert the cones into soft packages by winding the yarn on polypropylene cheeses. These polypropylene cheeses contain the perforations from which the dye liquor circulates through the yarn with an inside to outside flow. The packages are loaded into the carrier situated into the Dyeing Machine where into-out flow is used to dye the package. Passing the hot air through the packages dries the wet packages on the Rapid Dryer and then conditioning is done by passing the cool air to keep constant moisture content of the yarn. Then, the Post Winding Machine is used to convert the dyed packages into the cone. The industrial systems have attracted the attention of several researchers in the area of reliability engineering. M. R. R. Khan et al. [1] described a simulation modeling technique for assessing the availability of an ammonia plant. Coit et al. [2] proposed a multiple objective formulation for maximizing the system availability. Dai et al. [3] developed an optimization model for the grid service allocation using Genetic Algorithm. Sharma et al. [4] presented the application of Reliability, Availability and Maintainability (RAM) analysis in a process industry. Kumar et al. [5] discussed the performance evaluation and availability analysis of ammonia synthesis unit of a fertilizer plant. Garg et al. [6] developed the mathematical model of a Cattle Feed Plant using a Markov Birth-Death Process. The differential equations have been solved for the steady-state. The system performance has also been studied.

Garg et al. [7] developed a reliability model of a block-board manufacturing system of a plywood industry using time dependent and steady state availability under idealized and faulty Preventive Maintenance. Sachdeva et al. [8] described a new multi criteria optimization framework for deriving optimal maintenance schedules for preventive maintenance which considers availability, maintenance cost and life cycle costs as the criteria for optimization using Petri Net. Kumar and Tewari [9] discussed the mathematical modeling and performance optimization of CO_2 Cooling System of a Fertilizer Plant using Genetic Algorithm. The differential equations have been derived based on Markov Birth-Death Process using Probabilistic Approach. Khanduja et al. [10] developed a performance model for stock preparation unit of a paper plant using Markov approach and optimize the performance using Genetic Algorithm. Zequn Wang et al. [11] presented a new approach, referred to as Nested Extreme Response Surface [NERS] that can efficiently tackle time dependency issue in time-variant reliability analysis and enable to solve such problem by easily integrating with advanced time-independent tools.

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II. SYSTEM DESCRIPTION

The process flow diagram of Yarn Dyeing System of a Textile Industry is shown in Fig. 1. It consists of five sub-systems as described below:

A. Pre Winding Machine (A)

This machine is used to convert the cones into soft packages by winding the yarn on polypropylene cheeses. These polypropylene cheeses contain the perforations from which the dye liquor circulates through the yarn with an inside to outside flow. This machine consists of drum, motor and cradles. This machine is subjected to minor failure only.

B. Dyeing Machine (B)

Dyeing Machine is used to dye the grey yarn in package form. The packages are loaded into the carrier situated into the machine where into-out flow is used to dye the package. It consists of a dyeing tank, a suction pump (centrifuge pump), water inlet and outlet valves, steam inlet and outlet valves, air pressure valves. Failure of anyone component causes failure of this subsystem. This machine is subjected to major failure.

C. Rapid Dryer (C)

Passing the hot air through the packages dries the wet packages on the Rapid Dryer .During drying operation, hot air is passed in in-out motion. The hot air from the spindle perforation comes in contact with package material. The hot air vaporizes the water. It consists of tank, motor, main vessel, heater, blower, cooler, mist separator, lip sealing ring. Failure of anyone component causes failure of this subsystem. This machine is subjected to major failure.

D. Post Winding Machine (D)

This machine is used to convert the dyed packages into the cone form. The same machines are used in post winding as that in pre winding with some differences. Spindles are used in place of cradle. Wax roller applies wax. Taper angle is provided to cones. Drum diameter is reduced. This machine is subjected to minor failure only.
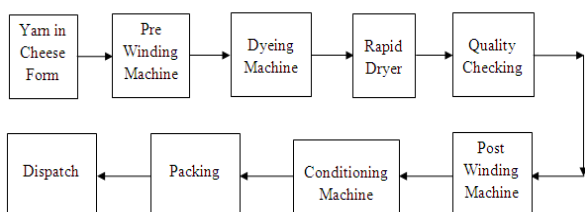

Fig. 1 Schematic Flow Diagram of Yarn Dyeing System of a Textile Industry

E. Conditioning Machine (E)

Uniformity of moisture in yarn may suffer due to dyeing and drying treatments. To achieve this uniformity conditioning is done. It is a microprocessor controlled automatic machine exclusively for processing of different types of yarns. It is based on principle of condensation of steam. This machine consists of automatic door, vacuum pump, control valves, water inlet pump. Failure of anyone component causes failure

of this subsystem. This is subjected to minor as well as major failure.

All the above mentioned subsystems, except subsystems A and D, can shut down due to major failures while subsystems A and D may work in reduced capacity states also.

III. ASSUMPTIONS

i. Failure and repair rates for each subsystem are constant and statistically independent.
ii. Not more than one failure occurs at a time.
iii. Performance wise a repaired unit is as good as new.
iv. The standby units are of the same nature and capacity as the active units.
v. All the units are initially operating and are in working state.

IV. NOTATIONS

The notions associated with the Transition Diagram (Fig. 2) are as follows:

|	
A, B, C, D, E	: Subsystems in good operating state.
$\bar{A}$, $\overline{D}$	: indicate that A and D are working in reduced capacity.
a, b, c, d, e	: indicate the failed states of A, B, C, D, E.
λ_i	: Mean constant failure rates from A, B, C, D, E, $\bar{A}$, $\overline{D}$ to the states $\bar{A}$, b, c, $\overline{D}$, e, a, d.
μ_i	: Mean constant repair rates from states a, b, c, d, e to the states A, B, C, D, E.
$P_i(t)$	: Probability that at time 't' all units are good and the system is in i^{th} state.
(')	: Derivatives w.r.t. 't'.
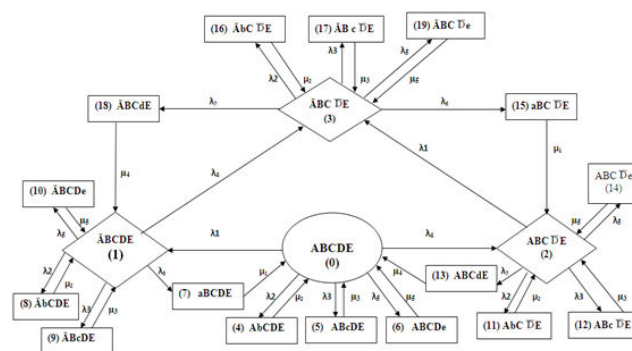
Fig. 2 Transition Diagram of Yarn Dyeing System of a Textile Industry

V. PERFORMANCE MODELING OF THE SYSTEM

The differential equations associated with the transition diagram shown in Fig. 2, are developed on the basis of Markov-Birth-Death Process. Various probability considerations generate the following sets of differential equations:

$$P_0^{'}(t) + K_0 P_0(t) = \mu_1 P_7(t) + \mu_2 P_4(t) + \mu_3 P_5(t) + \mu_4 P_{13}(t) + \mu_5 P_6(t) \ (1)$$

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$$P_1^{'}(t) + K_1P_1(t) = \lambda_1P_0(t) + \mu_2P_8(t) + \mu_3P_9(t) + \mu_4P_{18}(t) + \mu_5P_{10}(t) \quad (2)$$

$$P_2^{'}(t) + K_2P_2(t) = \mu_1P_{15}(t) + \mu_2P_{11}(t) + \mu_3P_{12}(t) + \lambda_4P_0(t) + \mu_5P_{14}(t) \quad (3)$$

$$P_3^{'}(t) + K_3P_3(t) = \lambda_1P_2(t) + \mu_2P_{16}(t) + \mu_3P_{17}(t) + \lambda_4P_1(t) + \mu_5P_{19}(t) \quad (4)$$

$$P_4^{'}(t) + \mu_2P_4(t) = \lambda_2P_0(t) \quad (5)$$

$$P_5^{'}(t) + \mu_3P_5(t) = \lambda_3P_0(t) \quad (6)$$

$$P_6^{'}(t) + \mu_5P_6(t) = \lambda_5P_0(t) \quad (7)$$

$$P_7^{'}(t) + \mu_1P_7(t) = \lambda_6P_1(t) \quad (8)$$

$$P_8^{'}(t) + \mu_2P_8(t) = \lambda_2P_1(t) \quad (9)$$

$$P_9^{'}(t) + \mu_3P_9(t) = \lambda_3P_1(t) \quad (10)$$

$$P_{10}^{'}(t) + \mu_5P_{10}(t) = \lambda_5P_1(t) \quad (11)$$

$$P_{11}^{'}(t) + \mu_2P_{11}(t) = \lambda_2P_2(t) \quad (12)$$

$$P_{12}^{'}(t) + \mu_3P_{12}(t) = \lambda_3P_2(t) \quad (13)$$

$$P_{13}^{'}(t) + \mu_4P_{13}(t) = \lambda_7P_2(t) \quad (14)$$

$$P_{14}^{'}(t) + \mu_5P_{14}(t) = \lambda_5P_2(t) \quad (15)$$

$$P_{15}^{'}(t) + \mu_1P_{15}(t) = \lambda_6P_3(t) \quad (16)$$

$$P_{16}^{'}(t) + \mu_2P_{16}(t) = \lambda_2P_3(t) \quad (17)$$

$$P_{17}^{'}(t) + \mu_3P_{17}(t) = \lambda_3P_3(t) \quad (18)$$

$$P_{18}^{'}(t) + \mu_4P_{18}(t) = \lambda_7P_3(t) \quad (19)$$

$$P_{19}^{'}(t) + \mu_5P_{19}(t) = \lambda_5P_3(t) \quad (20)$$

where

$$K_0 = (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)$$

$$K_1 = (\lambda_6 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)$$

$$K_2 = (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_7 + \lambda_5)$$

$$K_3 = (\lambda_6 + \lambda_2 + \lambda_3 + \lambda_7 + \lambda_5)$$

with initial conditions at time t = 0

$$P_i(t) = 1 \text{ for } i=0,$$
$$= 0 \text{ for } i \neq 0$$

VI. Steady State Availability

The Yarn Dyeing System of Textile Industry is required to be available for a long duration of time. So, the long-run or steady state availability of the Yarn Dyeing System is obtained

by putting d/dt=0 as $t\rightarrow\infty$, into all differential (1) to (20). The steady state availability of the system can be analyzed by setting $t\rightarrow\infty$ and d/dt=0;

The limiting probabilities from (1) to (20) are:

$$K_0P_0(t) = \mu_1P_7(t) + \mu_2P_4(t) + \mu_3P_5(t) + \mu_4P_{13}(t) + \mu_5P_6(t) \quad (21)$$

$$K_1P_1(t) = \lambda_1P_0(t) + \mu_2P_8(t) + \mu_3P_9(t) + \mu_4P_{18}(t) + \mu_5P_{10}(t) \quad (22)$$

$$K_2P_2(t) = \mu_1P_{15}(t) + \mu_2P_{11}(t) + \mu_3P_{12}(t) + \lambda_4P_0(t) + \mu_5P_{14}(t) \quad (23)$$

$$K_3P_3(t) = \lambda_1P_2(t) + \mu_2P_{16}(t) + \mu_3P_{17}(t) + \lambda_4P_1(t) + \mu_5P_{19}(t) \quad (24)$$

$$\mu_2P_4(t) = \lambda_2P_0(t) \quad (25)$$

$$\mu_3P_5(t) = \lambda_3P_0(t) \quad (26)$$

$$\mu_5P_6(t) = \lambda_5P_0(t) \quad (27)$$

$$\mu_1P_7(t) = \lambda_6P_1(t) \quad (28)$$

$$\mu_2P_8(t) = \lambda_2P_1(t) \quad (29)$$

$$\mu_3P_9(t) = \lambda_3P_1(t) \quad (30)$$

$$\mu_5P_{10}(t) = \lambda_5P_1(t) \quad (31)$$

$$\mu_2P_{11}(t) = \lambda_2P_2(t) \quad (32)$$

$$\mu_3P_{12}(t) = \lambda_3P_2(t) \quad (33)$$

$$\mu_4P_{13}(t) = \lambda_7P_2(t) \quad (34)$$

$$\mu_5P_{14}(t) = \lambda_5P_2(t) \quad (35)$$

$$\mu_1P_{15}(t) = \lambda_6P_3(t) \quad (36)$$

$$\mu_2P_{16}(t) = \lambda_2P_3(t) \quad (37)$$

$$\mu_3P_{17}(t) = \lambda_3P_3(t) \quad (38)$$

$$\mu_4P_{18}(t) = \lambda_7P_3(t) \quad (39)$$

$$\mu_5P_{19}(t) = \lambda_5P_3(t) \quad (40)$$

Solving the above equations, we get:

$$P_1 = L_1P_0 \qquad P_2 = L_2P_0$$
$$P_3 = L_3P_0 \qquad P_4 = H_2P_0$$
$$P_5 = H_3P_0 \qquad P_6 = H_5P_0$$
$$P_7 = H_4L_1P_0 \qquad P_8 = H_2L_1P_0$$
$$P_9 = H_3L_1P_0 \qquad P_{10} = H_5L_1P_0$$
$$P_{11} = H_2L_2P_0 \qquad P_{12} = H_3L_2P_0$$
$$P_{13} = H_1L_2P_0 \qquad P_{14} = H_5L_2P_0$$
$$P_{15} = H_4L_3P_0 \qquad P_{16} = H_2L_3P_0$$
$$P_{17} = H_3L_3P_0 \qquad P_{18} = H_1L_3P_0$$
$$P_{19} = H_5L_3P_0$$

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$$H_1 = \frac{\lambda_7}{\mu_4}, \quad H_2 = \frac{\lambda_2}{\mu_2}, \quad H_3 = \frac{\lambda_3}{\mu_3}, \quad H_4 = \frac{\lambda_6}{\mu_1}, \quad H_5 = \frac{\lambda_5}{\mu_5}$$

$$P_1 = L_1 P_0, \quad P_2 = L_2 P_0, \quad P_3 = L_3 P_0$$

$$L_1 = N_1 + N_2 L_3, \quad L_2 = N_4 + N_3 L_3, \quad L_3 = \frac{(\lambda_1 + \lambda_4 - \lambda_6 N_1 - \lambda_7 N_4)}{\lambda_6 N_2 + \lambda_7 N_3}$$

$$N_1 = \frac{\lambda_1}{\lambda_6 + \lambda_4}, \quad N_2 = \frac{\lambda_7}{\lambda_6 + \lambda_4}, \quad N_3 = \frac{\lambda_6}{\lambda_1 + \lambda_7}, \quad N_4 = \frac{\lambda_4}{\lambda_1 + \lambda_7}$$

Now using Normalizing condition, i.e., sum of all the state probabilities is equal to one, we get:

$$\sum_{i=1}^{19} P_i = 1$$

$$P_0 = \left[1 + L_1 + L_2 + L_3 + H_2 + H_3 + H_5 + H_4 L_1 + H_2 L_1 + H_3 L_1 + H_5 L_1 \right.$$
$$+ H_2 L_2 + H_3 L_2 + H_1 L_2 + H_5 L_2 + H_4 L_3 + H_2 L_3$$
$$\left. + H_3 L_3 + H_1 L_3 + H_5 L_3 \right]^{-1}$$

Now, the Steady State Availability of the Yarn Dyeing system may be obtained as the summation of all the working state probabilities, i.e.

$$A_v = P_0 + P_1 + P_2 + P_3 = P_0 + L_1 P_0 + L_2 P_0 + L_3 P_0 = [1 + L_1 + L_2 + L_3] P_0$$

VII. PERFORMANCE ANALYSIS

The effects of failure and repair rates of various subsystems comprising Yarn Dyeing System of the Textile Industry are examined. Their impacts on system availability are given in decision matrices as shown in Tables I-V. These tables reveal the various availability levels for different combinations of failure and repair rates.

TABLE I
EFFECT OF FAILURE AND REPAIR RATES OF PRE WINDING MACHINE ON SYSTEM AVAILABILITY

λ_1, μ_1	0.0028	0.0029	0.0030	0.0031	0.0032
0.0142	0.6974	0.6972	0.6970	0.6969	0.6967
0.0152	0.6990	0.6988	0.6986	0.6984	0.6983
0.0162	0.7003	0.7001	0.7000	0.6998	0.6997
0.0172	0.7015	0.7014	0.7012	0.7010	0.7009
0.0182	0.7026	0.7024	0.7023	0.7021	0.7020

Constant Parameters: λ_2=0.0004, μ_2=0.0034, λ_3=0.0015, μ_3=0.0073, λ_4=0.0036, μ_4=0.0250, λ_5=0.0004, μ_5=0.0102, λ_6=0.0009, λ_7=0.0007

Table I reveals the effect of failure and repair rates of Pre Winding Machine on the availability of Yarn Dyeing System of the Textile Industry, as the failure rate (λ_1) increases from 0.0028 to 0.0032, the system's availability reduces by 0.10%. Similarly as the repair rate (μ_1) increases from 0.0142 to 0.0182, the system's availability increases by 0.74%.

TABLE II
EFFECT OF FAILURE AND REPAIR RATES OF DYEING MACHINE ON SYSTEM AVAILABILITY

λ_2, μ_2	0.0004	0.0005	0.0006	0.0007	0.0008
0.0034	0.6974	0.6834	0.6699	0.6570	0.6445
0.0044	0.7107	0.6994	0.6884	0.6778	0.6675
0.0054	0.7200	0.7098	0.7006	0.6916	0.6829
0.0064	0.7263	0.7172	0.7092	0.7015	0.6939
0.0074	0.7309	0.7227	0.7157	0.7088	0.7021

Constant Parameters: λ_1=0.0028, μ_1=0.0142, λ_3=0.0015, μ_3=0.0073, λ_4=0.0036, μ_4=0.0250, λ_5=0.0004, μ_5=0.0102, λ_6=0.0009, λ_7=0.0007

Table II reflects the effect of failure and repair rates of Dyeing Machine on the long run availability of the system. As the failure rate (λ_2) increases from 0.0004 to 0.0008, the system availability reduces considerably by 7.5%. Similarly as the repair rate (μ_2) increases from 0.0034 to 0.0074, the availability of the system increases by 4.8%.

TABLE III
EFFECT OF FAILURE AND REPAIR RATES OF RAPID DRYER ON SYSTEM AVAILABILITY

λ_3, μ_3	0.0015	0.0016	0.0017	0.0018	0.0019
0.0073	0.6974	0.6908	0.6843	0.6780	0.6717
0.0083	0.7097	0.7037	0.6977	0.6919	0.6862
0.0093	0.7196	0.7141	0.7086	0.7033	0.6980
0.0103	0.7278	0.7227	0.7177	0.7127	0.7078
0.0113	0.7347	0.7300	0.7253	0.7206	0.7161

Constant Parameters: λ_1=0.0028, μ_1=0.0142, λ_2=0.0004, μ_2=0.0034, λ_4=0.0036, μ_4=0.0250, λ_5=0.0004, μ_5=0.0102, λ_6=0.0009, λ_7=0.0007

Table III highlights the effect of failure and repair rates of Rapid Dryer on the long run availability of the system. As the failure rate (λ_3) increases from 0.0015 to 0.0019, the system availability reduces considerably by 3.68%. Similarly as the repair rate (μ_3) increases from 0.0073 to 0.0113, the availability of the system increases by 5.34%.

TABLE IV
EFFECT OF FAILURE AND REPAIR RATES OF POST WINDING MACHINE ON SYSTEM AVAILABILITY

λ_4, μ_4	0.0036	0.0037	0.0038	0.0039	0.0040
0.0250	0.6974	0.6974	0.6973	0.6973	0.6972
0.0260	0.6979	0.6978	0.6978	0.6977	0.6977
0.0270	0.6983	0.6982	0.6982	0.6981	0.6981
0.0280	0.6986	0.6986	0.6986	0.6985	0.6985
0.0290	0.6990	0.6990	0.6989	0.6989	0.6988

Constant Parameters: λ_1=0.0028, μ_1=0.0142, λ_2=0.0004, μ_2=0.0034, λ_3=0.0015, μ_3=0.0073, λ_5=0.0004, μ_5=0.0102, λ_6=0.0009, λ_7=0.0007

Table IV shows the effect of failure and repair rates of Post Winding Machine on the long run availability of the system. As the failure rate (λ_4) increases from 0.0036 to 0.0040, the system availability reduces by 0.02%. Similarly as the repair rate (μ_4) increases from 0.0250 to 0.0290, the availability of the system increases by 0.22%.

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TABLE V
EFFECT OF FAILURE AND REPAIR RATES OF CONDITIONING MACHINE ON
SYSTEM AVAILABILITY

λ_5, μ_5	0.0004	0.0005	0.0006	0.0007	0.0008
0.0102	0.6974	0.6927	0.6880	0.6834	0.6789
0.0112	0.6991	0.6948	0.6905	0.6863	0.6821
0.0122	0.7006	0.6966	0.6926	0.6887	0.6848
0.0132	0.7018	0.6981	0.6944	0.6908	0.6872
0.0142	0.7028	0.6994	0.6959	0.6926	0.6892

Constant Parameters: λ_1=0.0028, μ_1=0.0142, λ_2=0.0004, μ_2=0.0034, λ_3=0.0015, μ_3=0.0073, λ_4=0.0036, μ_4=0.0250, λ_6=0.0009, λ_7=0.0007

Table V depicts the effect of failure and repair rates of Conditioning Machine on the long run availability of the system. As the failure rate (λ_5) increases from 0.0004 to 0.0008, the system availability reduces considerably by 2.65%. Similarly as the repair rate (μ_5) increases from 0.0102 to 0.0142, the availability of the system increases by 0.77%.

VIII. CONCLUSION

The performance modeling and availability analysis of Yarn Dyeing System of the Textile Industry have been carried out using Probabilistic Approach and decision matrices. Table VI clearly specifies that the Rapid Dryer is the most critical subsystem as far as maintenance aspect is concerned and given top priority. The Dyeing Machine should be given second priority as the effect of its failure and repair rate on the system performance is much higher than that of Conditioning Machine, Pre Winding Machine and Post Winding Machine. Therefore, on the basis of above performance analysis, the maintenance priorities should be given as per following order:

TABLE VI
MAINTENANCE PRIORITIES FOR VARIOUS SUBSYSTEMS OF YARN DYEING
SYSTEM

Sr. No.	Subsystem	Maintenance Priorities
1.	Rapid Dryer	I
2	Dyeing Machine	II
3	Conditioning Machine	III
4.	Pre Winding Machine	IV
5.	Post Winding Machine	V

The findings of this paper are discussed with the concerned Textile Industry Management. These results are found to be highly beneficial to the plant management for the evaluation of performance and analysis of availability of Yarn Dyeing System and hence to decide about the maintenance repair priorities of various subsystems of the system concerned in a Textile Industry.

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