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Investigation of reliability, maintainability and availability of a paper machine in an integrated pulp and paper mill

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Abstract

Continuous production of an integrated pulp and paper mill depends on the availability of paper machines. Reliability and maintainability are essential for accomplishing the availability of paper machines. This study investigates the reliability, availability and maintainability (RAM) characteristics of a 120 tonnes per day paper machine from a paper mill in southern region of India. The paper machine is divided into five subsystems for failure analysis. The data was analyzed for trend and serial correlation tests for validating the inference of independent and identical distribution of failure and repair information before each sub system is best fitted to the theoretical probability distributions. Reliability and maintainability of the paper machine has been evaluated at various times which are useful for establishing the preventive maintenance schedules for improving availability of the paper machine. Wire part is found to be more critical subsystem from all points of view and require improvement by 4% and 1.5% in maintainability and availability point of view. The results of the analysis are presented to maintenance department for their active consideration.

Keywords: Paper machine, reliability, maintainability, availability, mean time between failures (MTBF), mean time to repair(MTTR), independent and identically distributed(IID)

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1. Introduction

The Indian paper industry plays a substantial function in the economic development of the nation and has since been adopted as an elevated main concern industry with a promising socio-economic impact on India. Included in the topmost 15 worldwide player in today's paper industry, the industry is credited with over six million tonnes as annual output together with a projected turnover in the order of Rs 150,000 millions and an estimated demand of 13 million tons in the year 2020 (Sundrakumar and Marimuthu, 2012). Large integrated mills have set new benchmarks in technology up gradation with state-of-the-art pulp and paper machines. From the perspective of installed capacity, the paper mills in India are roughly grouped into two: large (of more than 100 tonnes per day (TPD) mills and small (less than 100 TPD). The paper industry being a continuous process industry, the availability of paper machines are heavily rely on the reliability and maintenance of sub systems to meet the targeted production. The necessity of running reliable operations has been acknowledged in paper plants. To attain elevated productivity and availability, it is essential that all systems/sub-systems maintain an up-state for extended period of time. Nevertheless, these systems or sub-systems are under the influence of failures that are random in nature because of inadequate design, shortage of operating skills and inappropriate manufacturing methods, etc., leading to substantial losses of production. These systems that have failed can be restored to their operation conditions after repairs or component replacements within the least probable down-time. The operating situations and repair policies occupy a significant function to maintain the working systems, operate with the utmost duration i.e. the most advantageous system availability. This could be achieved merely by means of accomplishment appraisal and examination of all the working systems of the plant. The system's accomplishment can be measured from the perspective of availability if the working system is modelled mathematically and analysed in ideal operating situations.

Reliability examination is a vital instrument to guage the effectiveness of a scheme with capacity to adopt a maintenance plan (Wang *et al*., 2011).The probability of equipment failure is impacted upon by the adopted engineering design, the working situations, maintenance schedules and policy of an organization. RAM analysis was conducted idea to carried to incorporate the design modification of press unit of après unit of a paper plant in India by adopting Lambda-Tau approach and genetic procedures, fault tree are employed to model the system and the outcomes will assist plant workers to examine the scheme's behaviour (Komal and Kumar.,2009). To enhance the availability of an equipment or plant, it requires an in depth analysis of existing maintenance practices to minimize the down time (Hall and Daneshmend., 2003; Ghodrati and Kumar., 2005). Reliability, availability and maintainability analysis of repairable system were carried out in the past which includes a 500MW combined cycle power plant (Carazas and Souza., 2009), on steam generating system (Khan *et al*., 2008), on steam and power generation systems in a thermal power plant (Arora and Kumar., 1997), on coal conveyor system(Arora *et al*., 1995), on coal crushing system (Arora and Kumar., 1993), on naphtha fuel oil system in a thermal power plant(Kaushik and Singh., 1994).

The results of the study on reliability and maintainability analysis conducted at crushing plants of bauxite mine of Iran affirm that it is useful to frame maintenance schedules (Barabady and Kumar., 2008). RAM analysis was conducted on distinct subsystems including mechanical, electrical, hydraulic, pneumatic, and water systems of an earth pressure balance tunnel boring machine established that the highest failure frequency, lowest reliability and maintainability is pertaining to the mechanical systems (Hasel *et al*., 2015).The reliability of conveyor belt system in a cement factory in Iran was analysed and suggested appropriate maintenance policies for sub systems (Ali *et al*., 2015). RAM analysis was conducted to compare the characteristics of two units of thermal power plant in India and concluded that the results are useful in finding critical subsystems and deciding their preventive maintenance programme (Adhikary *et al*., 2012). From the literature it is observed that RAM analysis has been carried out on individual subsystems particularly from thermal power, coal handling and crushing plants. It is evident from the literature, RAM studies relating to critical systems of continuous process industries have not been carried out previously. The gap in the literature has given enough confidence to conduct the RAM analysis of paper machine in an integrated pulp and paper mill in India. The study is useful to the maintenance team of paper machine to improve its performance by adopting appropriate maintenance strategies.

2. Methodology

It is not practical for an engineer to analyze reliability in a qualitative form. Therefore, the reliability should be analyzed in a quantitative method to bestow practical implications. The flowchart of the present study is presented in Figure 1(Pritam., 2016).

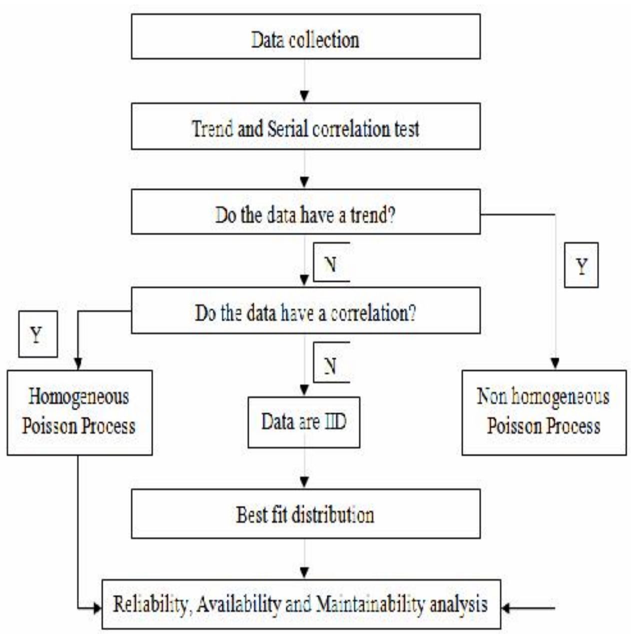

Figure 1. Step by step procedure of RAM analysis

The step by step procedure involved in the reliability, availability, and maintainability (RAM) analyses are as follows (Hasel *et al*., 2015).

- Identification of system and data collection
- Data evaluation
- Data analysis

- TBF and TTR data analysis
- Goodness-of-fit test

2.1. Data Collection: The first step of the study is the data collection. The failure and repairable data of the system are continuously recorded for the analysis. The present study monitors the failure and repair time data of the paper machine in an integrated pulp and paper mill.

2.2. Data Valuation: It describes the approach needed for evaluation of the collected data to select appropriate probability and statistical analyses techniques. The main assumption of the data is that the collected data are independent and identically distributed (IID). This assumption needs verification by pertinent statistical tests such as the trend and serial correlation test.
2.2.1. IID Assumption: The assumption that the data sets are IID implies that probability distributions can be used to model the subsystems. If the data sets do not fulfil the IID requirement; and probability distributions are used for modelling, the results and the conclusions of the analysis can be totally wrong (Adhikary *et al*., 2012). The assumption that the data sets are independent means that one failure is not dependent on the previous one, which implies that the parameters of the chosen distribution do not change with time. The assumption that the data sets are identical means that the different data points follow the same distribution.
2.2.2. Trend Test: In the trend test, the cumulative time between failures (TBF) or time to repair (TTR) is plotted against the cumulative failure or repair number. If a line drawn through the data points either resembles a concave upwards or concave downwards trend in the data, the system is respectively an improving or deteriorating system. However, if the line drawn through the data points is approximately a straight line, then the data is free from the trend, which implies that the data set is identically distributed (Kumar et al., 1989; Rigdon and Basu., 2000).
2.2.3. Serial Correlation Test: In the serial correlation test, the $(i-1)^{th}$ TBF/TTR is plotted against the i^{th} TBF/TTR. If the data points are randomly scattered without any clear pattern, it implies a data set free from serial correlation, which again implies that the data points in the data set are independent of each other (Kumar et al., 1989; Rigdon and Basu., 2000).

2.3. Data Analysis: The system under study is modelled by TBF and TTR data analysis. The best-fit probability distributions are identified by a goodness-of-fittest and parameters for the best fit distribution estimated through the maximum likelihood estimation method.

2.4. TBF and TTR Data Analysis: For a repairable system, the analysis is concerned with modelling both the times as it takes from a performed repair action (or restoration) to the next system failure (life of the system) and the time it takes to restore the system (repair of the system) back to operating state. The main goal of the TBF and TTR data analysis is to model the failure and repair processes of the different subsystems. It is done by fitting a probability distribution that best represent the failure data, and fitting a distribution that best represent the repair data, and estimating parameters to fit the distributions to the different data sets. It is common to assess the time between failures for analysis of repairable systems. In this case, the downtime duration, and more specific, the repair duration, is considerably lower than the uptime duration. For that reason, the analysis considers the time from restoration to system failure, denoted TBF, and the significant smaller repair duration denoted TTR.

2.5. Goodness-of-Fit Test: To select a suitable probability distribution function, its goodness-of-fit should be identified by the appropriate test. Most commonly used are the p-value test, the Chi-squared test, Kolmogorov-Smirnov test and Anderson-Darling test (Rigdon and Basu., 2000). The principle behind goodness-of-fit tests is to verify how far the chosen distribution is matched with the actual data set, or in other words, how well the chosen distribution represents the observed distribution. One goodness-of-fit test often used in RAM analysis is the Kolmogorov-Smirnov (K-S) test. The original K-S test is only applicable for distributions with known parameters. After fitting distributions to the data sets the parameters of the specific distributions, it needs to be estimated. Six common probability distribution functions (Weibull 3-parameter, Weibull 2-parameter, Lognormal 3-parameter, Lognormal 2-parameter, Exponential 2-parameter, and Normal distribution) were examined for modelling the failure data and repair data for each subsystem. These six distributions are well known to be appropriate for modelling failures of mechanical systems. In the present study; the maximum likelihood estimation (MLE) method is used. The reliability software easy-fit 5.6 was used to perform both the goodness-of-fit test and the parameter estimation by MLE method.

3. Case study

In the present investigation, a case study has been considered describing the reliability, maintainability and availability analysis of a 120 tonnes per day (TPD) paper machine in southern region of India. The paper machine is divided into five subsystems for categorizing the failures and analysis of reliability, maintainability and availability. The classification of the power plant is presented in Table 1. The five subsystems are arranged in a series configuration, as shown in Fig.2 (Durgan, 2018). This implies that the paper machine is in its operating situation merely as every subsystem is functioning.

Table 1. Sub systems and codes

Sub system	Code	Equipments
Wire section	WP	Couch drive, wire return rolls and breast roll vacuum pumps couch pit and head box.
Press section	PP	I, II, and III press rolls and drives, fabric blower.
Dryers section	DY	I, II, III, IV and V group dryers and drives.
Calendars	CL	I and II stack calendars and drives, doctor system.
Pope reel , Primary & secondary arms	PA	Pope reel drive, primary and secondary arms

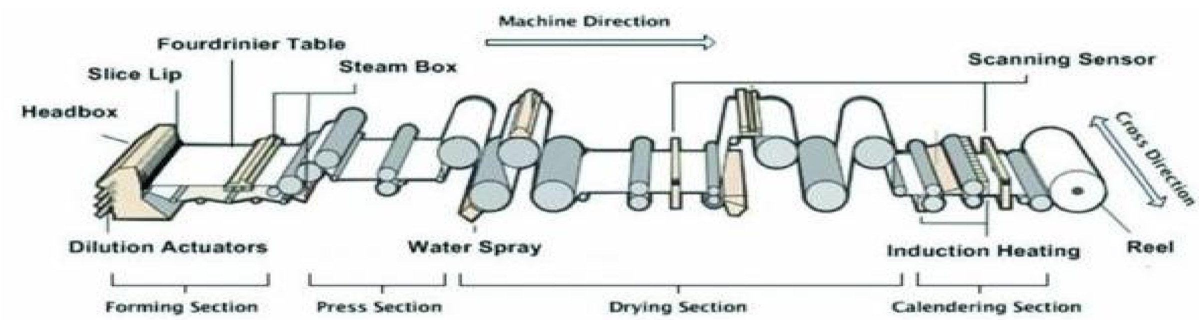

Figure 2. Line diagram of paper machine

3.1. Data Collection: Gathering of essential failure data is often important in the analysis of system reliability for obtaining dependable and precise outcomes. The data pertaining to time between failures (TBF) and time to repair (TTR) has been collected from the machine process register and maintenance log report of the paper machine for the period 2014 to 2016, which are sorted and classified for analysis. Then data of each subsystem has been classified in the form required for analysis (i.e. TBF, TTR, frequency, total breakdown hours, total working hours, total maintenance hours, etc).

3.2. Critical Sub Systems and Failures: To establish the "substantial few with the insubstantial many" sub-systems, the Pareto analysis has been carried out and depicted in Fig.3 and it indicates that the wire part(WP) is the most frequent failure subsystem and the pope reel and arms(PA) has the lowest frequency of failures. The aim is to find out the significant components since their failure seriously affects the failure of the whole plant (Adhikary *et al*., 2012). It is noted in Figure 3 that the subsystems WP and DY reveals extra failure frequency when weighed against other sub-systems. The failure of the plant was 68 times because of the subsystem's failure from a sum of 100 failures in the course of the period that the research is conducted. Consequently, plant failure of 68% happens because of failure of 40% of its mechanical sub-systems arranged in series. Consequently, these sub-systems ought to be checked extra times for maintenance compared with other sub-systems.

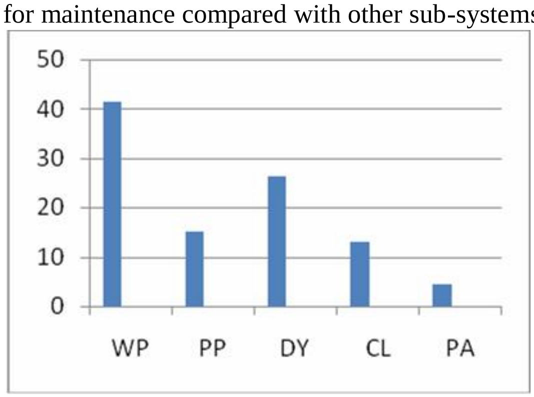

Figure 3. Failure frequency of sub systems

3.3. Validation of IID Assumption: The TBF and TTR data of all subsystems are ordered in sequential form for statistical examination to establish the movement of failure. The soundness of postulation of self-reliant and matching spreading of data set was established employing movement and sequential correlation trials. The movement for TBF/TTR data set is achieved through scheming the cumulative frequency alongside the cumulative time between failures (CTBF)/cumulative time to repair (CTTR) respectively. The sequential correlation test is achieved by scheming the i^{th} TBF/TTR against $(i-1)^{th}$ TBF/TTR. The movement trial for TBF and TTR data of WP, PP, DY, CL and PA of the paper machine are displayed in Fig. 4(a, b, c ,d ,e) and Fig.5 (a, b ,c, d, e) correspondingly.

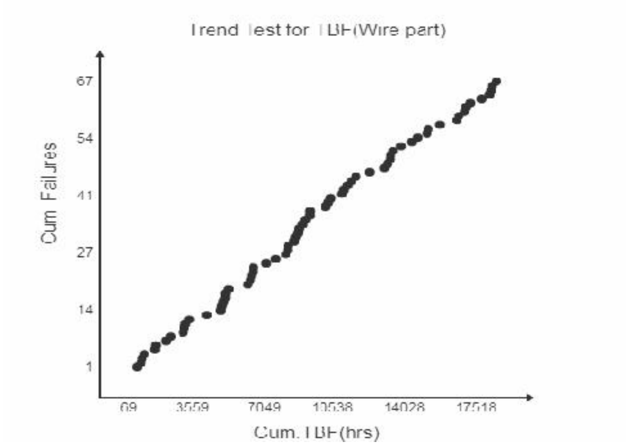

Figure. 4(a). Trend Test for TBF (WP)

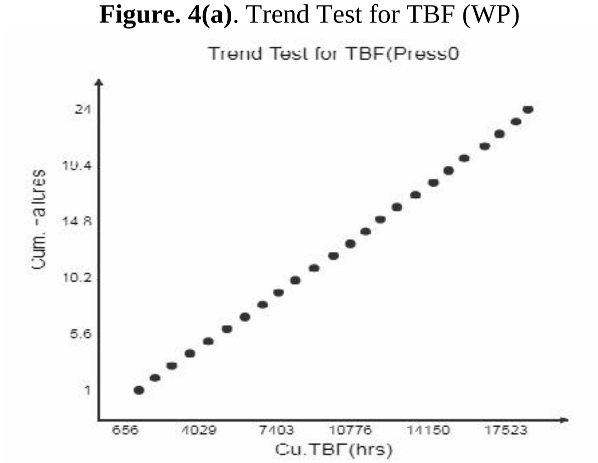

Figure 4(b). Trend Test for TBF (PR)

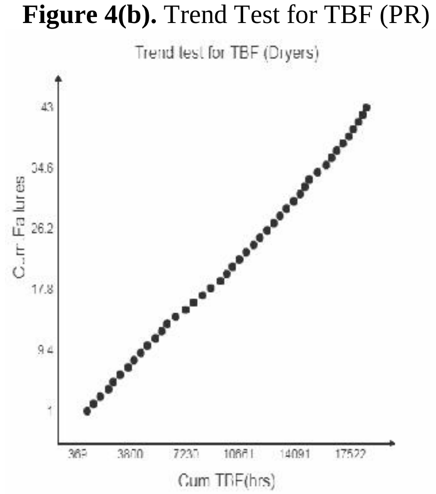

Figure 4(c). Trend Test for TBF (DY)

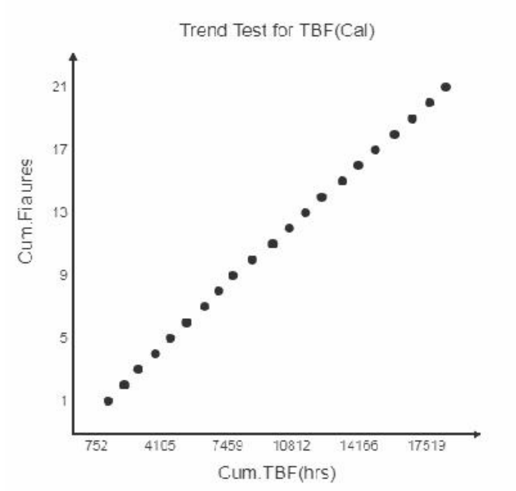

Figure 4(d). Trend Test for TBF (CL)

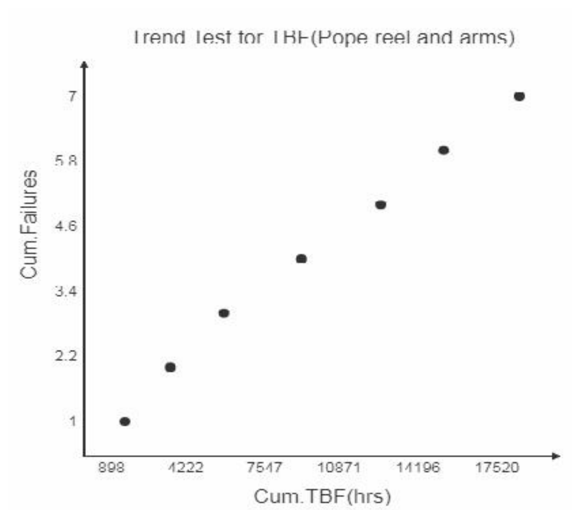

Figure 4(e). Trend Test for TBF (PA)

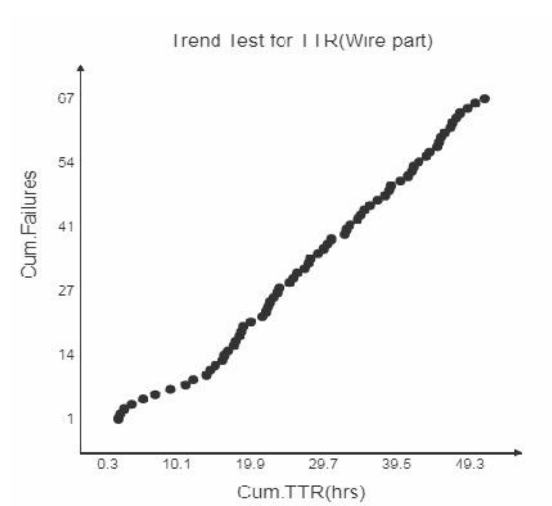

Figure 5(a). Trend Test for TTR (WP)

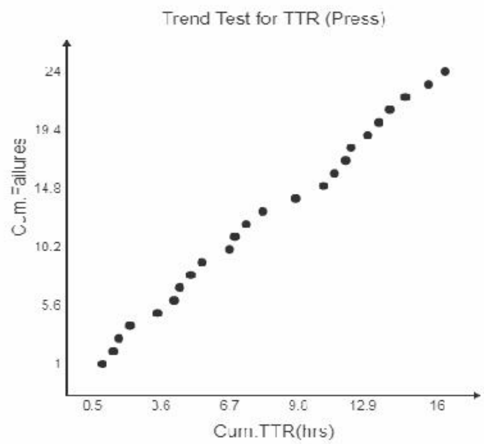

Figure 5(b). Trend Test for TTR (PP)

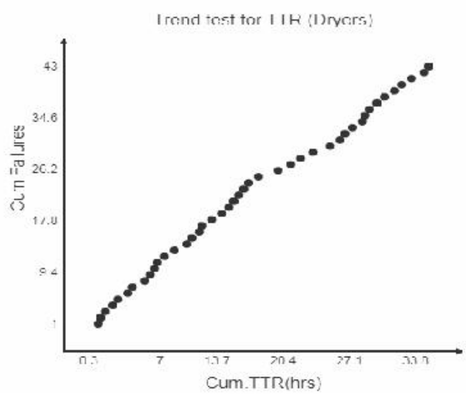

Figure 5(c). Trend Test for TTR (DY)

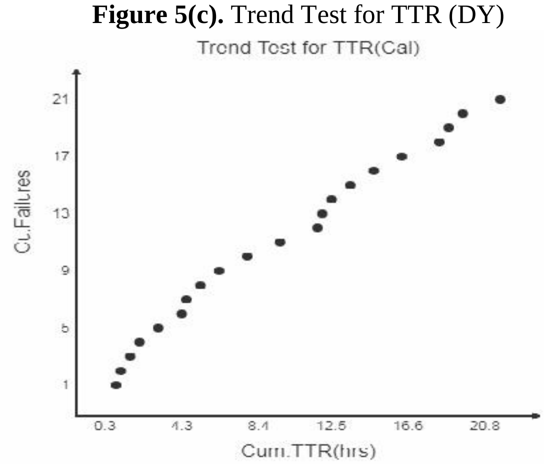

Figure 5(d). Trend Test for TTR (CL)

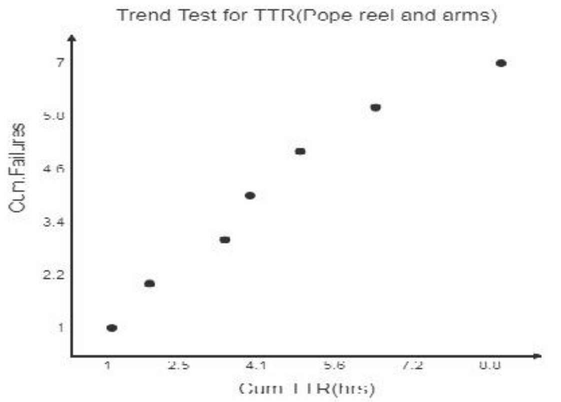

Figure 5(e). Trend Test for TTR (PA)

It is observed from Fig.4 (a, b, c, d e) & Fig.5 (a, b, c, d, e) that the trend plots for TBF/TTR data set of respective subsystems exhibit approximate straight line. This indicates that there are weak or no absolute trend in the TBF/TTR data set of respective sub systems. The serial correlation test for both TBF and TTR data of the subsystems are shown in Fig.6 (a, b, c, d, e) and Fig.7 (a, b, c, d, e) respectively.

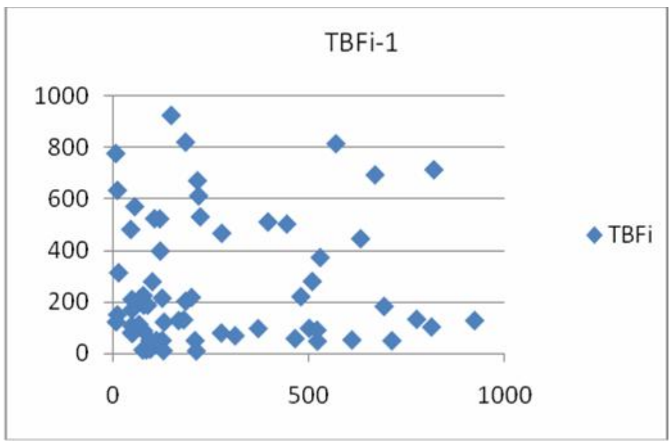

Figure 6(a). Serial Correlation test for TBF (WP)

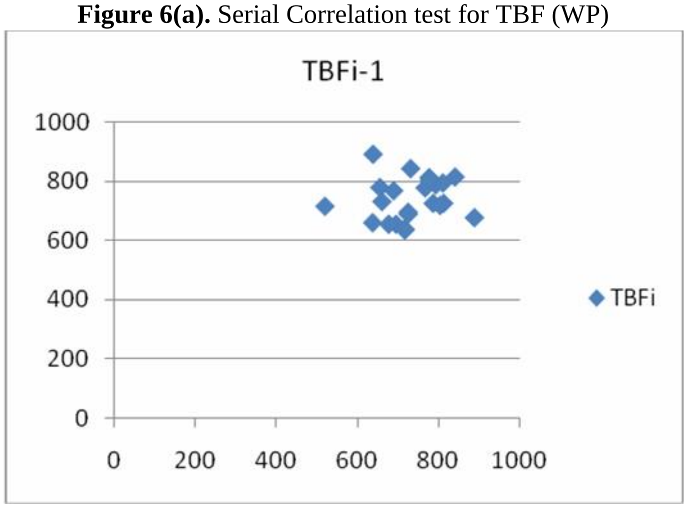

Figure 6(b). Serial Correlation test for TBF (PP)

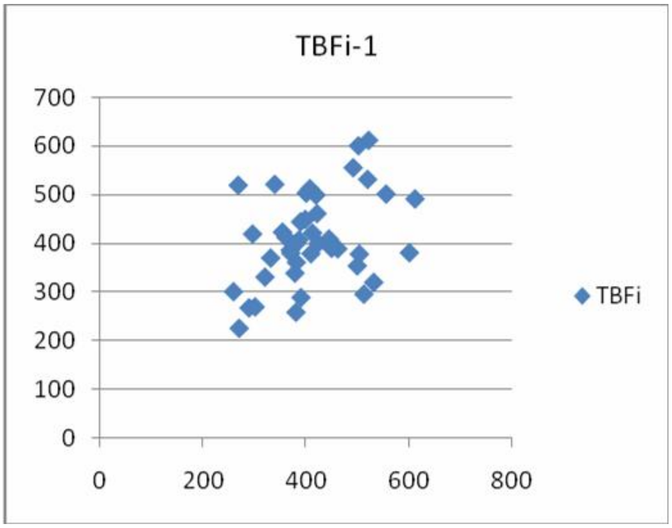

Figure 6(c). Serial Correlation test for TBF (DY)

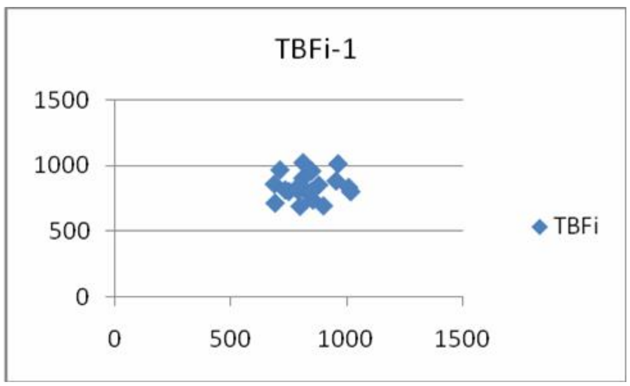

Figure 6(d). Serial Correlation test for TBF (CL)

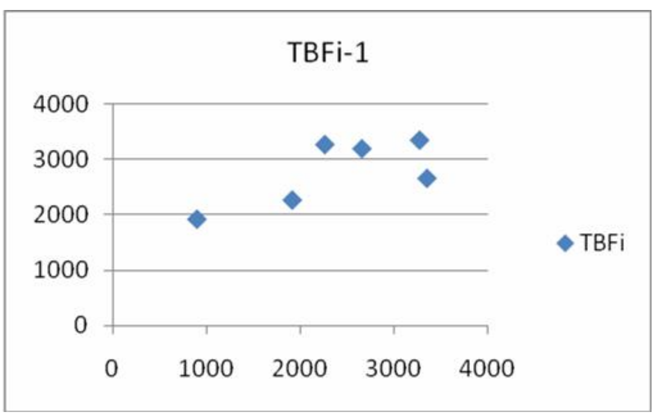

Figure 6(e). Serial Correlation test for TBF (PA)

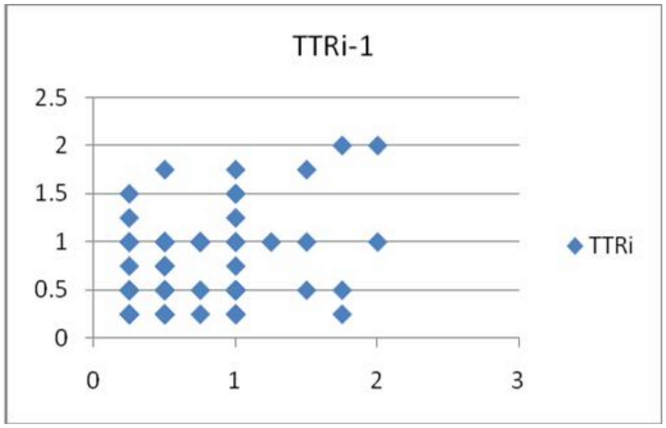

Figure 7(a). Serial Correlation test for TTR (WP)

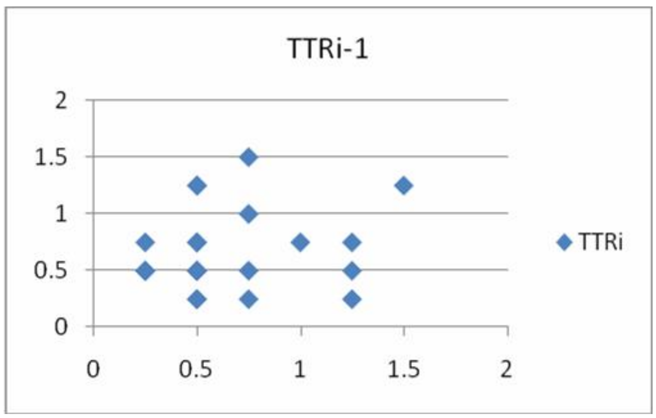

Figure 7 (b). Serial Correlation test for TTR (PP)

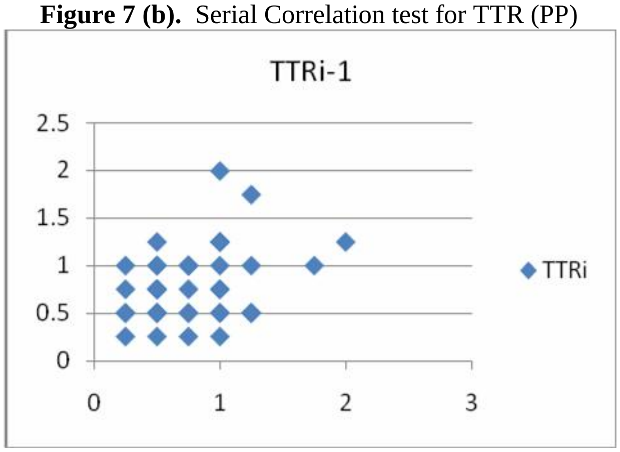

Figure 7(c). Serial Correlation test for TTR (DY)

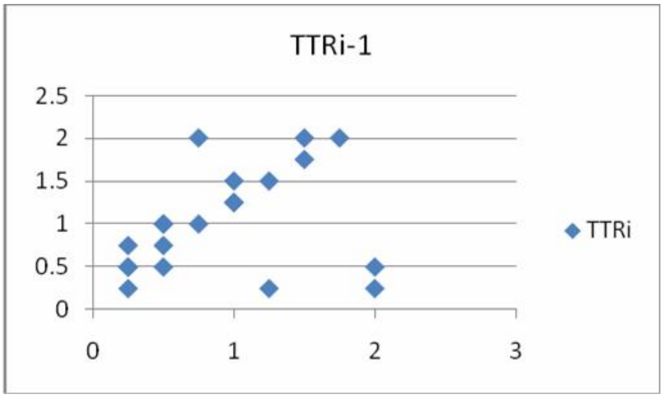

Figure 7(d). Serial Correlation test for TTR (CL)

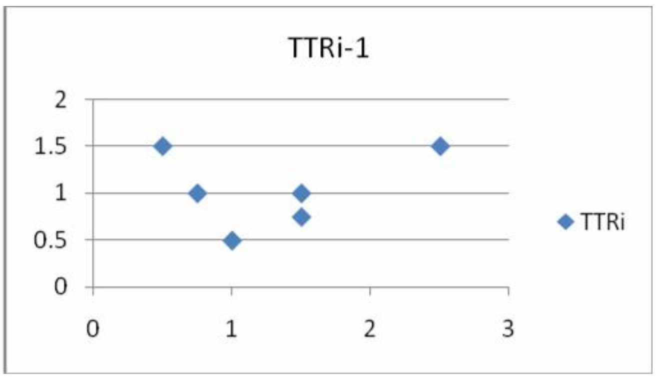

Figure 7(e). Serial Correlation test for TTR (PA)

From Fig.6 (a, b, c, d, e) and Fig.7 (a, b, c, d, e) it is observed that the points are randomly scattered, which indicates that the data set are independent or free from serial correlation. So the data set (TBF/TTR) can be assumed to be independent and identically distributed.

3.4. Fitting Theoretical Distribution and Estimation of Reliability: The data free from trend was further analyzed to find the precise characteristics of failure or repair time distribution. The two most commonly used goodness of fit tests for data points are chi-square and Kolmogorov–Smirnov test. The chi-squared test is applied in case of samples having size greater than 50. The Kolmogorov–Smirnov test is less restrictive, since the size of the sample has no lower limit (Adhikary *et al*., 2012). Therefore Kolmogorov–Smirnov test has been used for goodness of fit test of TBF/TTR data set using Easy Fit 5.6 professional software (ReliaSoft., 2007).The best fit distribution for time between failures is presented in Table 2.

Table 2. Best fit distribution for TBF

Sub system	K-S value	Best fit	Parameters
WP	0.08909	Log normal	σ =1.1521 μ =5.0394 t_{med} = 154.38
PP	0.10041	Weibull 3P	α = 5.7582 β = 430.93 t_{med} = 331.12
DY	0.08632	Log normal	σ = 0.106 μ = 6.7449 t_{med} = 447.02
CL	0.10087	Log normal	σ = 0.11075 μ = 6.7204 t_{med} = 829.15
PA	0.19905	Log normal	σ = 0.43242 μ = 7.7479 t_{med} = 2316.7

Where σ is shape parameter, μ is mean, t_{med} is median time to failure for lognormal distribution and α is shape parameter and β is scale parameter for weibull distribution respectively. It is observed from Table 2 that all the subsystems except PP follow weibull distribution with shape parameter greater than one , which indicates increasing failure rate due to aging process.WP is best fitted to lognormal distribution with shape parameter greater than one and for this system preventive maintenance is required for reducing the failures (Samanta *et al* ., 2000).DY, CL and PA follow the lognormal distribution with shape parameter less than one , is indicating decreasing failure rate before it reaches its useful life. Therefore corrective maintenance will be economical for these subsystems. The results of best-fit distributions and the estimated parameters for time to repair (TTR) are presented in Table 3 and it indicates that the TTR of WP is decreasing with shape parameter less than one which support the concave upward curve in the trend test plot (Fig 5a).

Table 3. Best fit distribution for TTR

Sub system	K-S value	Best fit	Parameters
WP	0.1619	Log normal	σ = 0.62855 μ = 0.47247 t_{med} = 1.604
PP	0.2125	Log normal	σ = 0.51437 μ = 0.53501 t_{med} = 1.707
DY	0.1558	Log normal	σ = 0.52159 μ = 0.36919 t_{med} = 1.446
CL	0.2578	Weibull	α = 1.4598 β = 1.077
PA	0.1593	Log normal	σ = 0.4858 μ = 0.10663 t_{med} = 1.112

3.5. Estimation of Reliability of Paper Machine: The theoretical reliability for all subsystems at the end of different mission time has been estimated according to the best-fit distribution of their TBF data set. In case of Weibull distribution neglecting location parameter reliability has been calculated according to equation 1 whereas in lognormal distribution it is calculated by equation 2.

$$R(t)=e^{-(t/\beta)*\alpha} \tag{1}$$

$$R(t)=1-\phi\{(1/\sigma)\ln(t/t_{med})\} \tag{2}$$

Where ϕ is the probability density function. All the subsystems are functionally arranged in a series configuration, as shown in Fig.2. This signifies that the paper machine will work only when all the subsystems are working satisfactorily. The reliability of the whole plant is calculated according to equation 3. The values of reliability of the subsystems and overall paper machine are presented in Table 4.

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{3}$$

Where, R_i is reliability of the different subsystems and R_s is the reliability of the whole systems and n is total number of subsystems.

Table 4. Reliability of paper machine at times

Time(hrs)	WP	PP	DY	CL	PA	Total
0	1	1	1	1	1	1
200	0.412	0.988	1	1	1	0.408
400	0.203	0.522	0.85	1	1	0.090
600	0.119	0.001		0.998	0.999	
800	0.076			0.625	0.992	
1000	0.052			0.045	0.973	
1200	0.037				0.935	
1400	0.028				0.877	
1600	0.021				0.805	
1800	0.016				0.719	
2000	0.013				0.633	
2200	0.010				0.547	
2400	0.009				0.206	

From Table 4, it is seen that DY, PP and CL are more critical with respect to reliability point of view than the other subsystems as their reliability becomes zero within 400,600 and 1000 hours respectively. Therefore existent measures are to be reviewed so that the critical subsystems (DY, PP and CL) reliability gets improved in order to enhance the overall reliability of the paper machine.

3.6. Maintainability Analysis of the Sub Systems: The theoretical maintainability (M) for all subsystems at the end of different given time (t) has been estimated according to the best-fit distribution of their TTR data set. The maintainability of the subsystems has been calculated according to equations 4 and 5 for weibull or lognormal distribution [16] of TTR data set respectively.

$$M(t)=1-e^{-(t/\beta)*\alpha} \quad (4)$$

$$M(t)=\phi \{(1/\sigma)\ln(t/t_{med})\} \quad (5)$$

The calculated maintainability of all sub systems as well as of the paper machine for different times is presented in Table 5. It is observed that maintainability of WP is much lower than other subsystems and it requires more time to repair than the other subsystems.

Table 5. Maintainability at time intervals

Time (hrs)	WP	PP	DY	CL	PA
5	0.535	0.42	0.96	0.99	0.99
10	0.961	1	1	1	1

3.7. Availability Analysis of the Paper Machine: Finally the inherent availability (A_{in}) and operational availability (A_{op}) for all subsystems has been computed following equations 6 and 7 respectively and presented in Table 6

$$A_{in}=MTBF/(MTBF+MTTR) \quad (6)$$

$$A_{op}=MTBF/(MTBF+MDT) \quad (7)$$

Where, MTBF is mean time between failures, MTTR is mean time to repair and MDT is mean down time.

Table 6 shows that the availability of WP is less than the other subsystems and is treated critical sub system in the paper machine. The availability of the WP has to be improved in order to improve the availability of the paper machine.

Table 6. Availability of sub systems

Sub Systems	MTBF (hrs)	MTTR (hrs)	A_{in}	MDT (hrs)	A_{op}
WP	261.46	0.735	0.997	3.50	0.986
PP	730.13	0.667	1	1.59	0.998
DY	407.49	0.785	0.998	1.12	0.997
CL	834.24	0.988	0.998	1.93	0.998
PA	2502.86	1.250	1	2.97	0.998

4. Conclusions

In the present study reliability, maintainability and availability of a paper machine has been investigated. All the TBF/TTR data sets of the paper machine subsystems are found to be independent and identically distributed. All the subsystems except press part follow the lognormal distribution. Press part follows the weibull distribution with shape parameter greater than one, which indicates increasing failure rate due to aging process. Wire part is best fitted to lognormal distribution with shape parameter greater than one and for this subsystem preventive maintenance is required. Driers, calendar and pope reel follow lognormal distribution with shape parameter less than one, is indicating the decreasing failure rate and these subsystems require corrective maintenance.

Driers, press part and calendar are more critical with respect to reliability point of view than the other subsystems as their reliability becomes zero within 400,600 and 1000 hours respectively. Therefore existent measures are to be reviewed so that the critical subsystems (DY, PP and CL) reliability gets improved in order to enhance the overall reliability of the paper machine. Wire part is found to be critical from maintainability and availability point of view and requires improvement by 4% and 1.5% respectively. The availability of press, dryers, and calendar and primary arms requires improvement by 0.5%. Therefore the repair times are to be reduced by adopting preventive maintenance program. Wire part is found to be more critical subsystem from all points of view.

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