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Research Article

Reliability, Availability and Maintainability Analysis to Improve the Operational Performance of Soft Water Treatment and Supply Plant

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Abstract

The purpose of this paper is to provide results for reliability, availability and maintainability (RAM) measures to improve the operational performance of a soft water treatment and supply plant (SWTS-Plant) through the illustrative case study. RAM analysis of SWTS plant installed in a high-rise society ABC, Jaipur was performed. The descriptive analysis of time to failure and repair has been made along with trend analysis and goodness-of-fit test. The best fitted distributed and parameters have been identified from the existing theoretical distributions using the maintenance data of ABC plant. Reliability and maintainability measures also calculated for the entire plant. It is observed that (i) the plant availability decline from 97.96% to 92.67% (ii) failures of five subsystems dominant with 81.5 % failures and (iii) average failure rate is 937.4 minutes. This study will be supportive to identify the occurring complications in the plant.

Keywords: Soft water treatment and supply plant, Parameter Estimation, Failure Rate, Trend and Serial Correlation, Goodness-of-Fit.

1. Introduction

India is a developing country having second largest population in the world. Till 1980, most of the Indian population residing in rural areas but after industrialization and economic reforms urbanization started rapidly in India. and According to World bank report, 34% population in India residing in cities. During last four decades, population in cities explosively increasing and town planners face the problem of accommodating these persons. The advanced technology helps the town planners and construction of multi-story buildings initiated in the cities. Supply of water and electricity are essential for survival in these multi-story buildings. Though, water is essential for life but up till now knowledge construction of water supply system is mainly based on practical approach and any standardized guidelines are not available. Real estate players establish the water supply system according to demand and experience of their engineers. In many areas, quantity of fluoride is very high in underground water. So, to remove it soft water treatment plant is also established with water supply system. The combination of these two systems formulate a very complex system having several components. In soft water treatment and supply plant (SWTS-Plant) all components are configured in a series system and failure of any component causes the complete system failure. Manufacturer and management always focusing on the proper working on these plants and supply of water. Irregular water supply may spoil the name of the real estate company. In such situations, to improve the efficiency of the plant manufacturer should focus on the reliability, availability and maintainability of the plant. In SWTS-Plant a desired level of reliability is required for satisfactory operation. To confirming or achieving a desired level of reliability thrust should be given on design of the plant. Though the reliability in itself very complex and many additional intertwining factors also included at the evaluation time of reliability. Deficient reliability causes to severe glitches like extraordinary maintenance rate, hazardous working conditions, and ultimate downfall in the quality of products. Such type of failures happened due to these glitches spoil the company's reputation that is built in years. Regattieri et al. [1] appended in detail the methods of reliability, availability, safety, dependability and maintainability analysis for industrial and non-industrial complex systems. Researchers developed lot of methods and models for performing maintenance of the systems. Manzini et al. [2] proposed aa model for determining the best frequency of maintenance and optimization of spare parts consumption. Many studies have been carried out about reliability, availability and maintainability investigation (Dia and Jia [3]; Wang and Pham [4]; Smith [5]; Liu et al. [6]). RAM-index has been developed as aggregate measure for assessing the performance of industrial systems by Rajpal et al. [7]. Adhikary et al. [8] made a significant effort to investigate the reliability measures of a power plant operating using coal situated in India. It is observed from various studies that the statistical analysis plays key role in the RAM evaluation of complex industrial systems. Many researchers analysed the failure and repair data of industries using statistical techniques. Zhang et al. [9] proposed a fault identification technique in reliability assessment by considering piston manufacturing plant as a case study. Tsarouhas [10] statistically analysed the reliability and availability of food production line. Tsarouhas [11] used FMEA methodology along with statistical analysis in RAM investigation of wine packaging plant. Dahiya et al. [12] proposed a numerical method approach for reliability analysis of complex industrial systems. Kumar et al. [13] developed a stochastic model for reliability evaluation of non-identical unit's system using regenerative point technique. Kumar et al. [14] analyzed randomly performance measures of a system where failure

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and repairs follows Weibull distribution. Wang et al. [15] studied the reliability of a two-dissimilar-unit warm standby repairable system with priority in use. Saini and Kumar [16] proposed a stochastic model of a single-unit system operating under different environmental conditions subject to inspection and degradation. Yusuf et al.[17] carried out the reliability assessment of a repairable system under online and offline preventive maintenance. Barak et al. [18-19] used the concept of abnormal weather conditions in profit analysis of a two-unit cold standby system model. Dahiya et al. [20] developed a mathematical model for A-pan crystallization system in a sugar industry. Goyal et al. [21] analysed a sewage water treatment plant by adopting the component wise analysis approach. Recently, Gupta et al. [22] studied the operational availability analysis of generators in steam turbine power plants. Gupta et al. [23] performed the behavioral analysis of cooling tower in steam turbine power plant using reliability, availability, maintainability and dependability approach. But according to best knowledge, in existing literature no effort has been made to carry out RAM analysis of SWTS-plant.

Here, a RAM investigation has been conducted for the SWTS-Plant. The descriptive analysis of time to failure and time to repair has been carried out. The best fitted distribution of failure and repair has been identified among the existing theoretical distributions and conforming parameters have been identified. The plots for survival rate and hazard rate have been depicted. Moreover, reliability, availability and maintainability for the entire line was derived. These results were possibly helpful for assessing the current situation of plant and to predict reliability for improving the functioning of SWTS-Plant

2. System Description & Data Collection

The soft water treatment and supply plant work in two shifts every day, the duration of one shift is 5 hours. So, failure and repair time data of the plant has been recorded for a duration of two years. For this duration total number of failures, total time to repair and total time between failures has been recorded with the help of maintenance person through exact repair time is available for line SWTSP but time between failure has been calculated by MS Excel by rearranging the data. During the complete duration system suffers 419 times by minor and major failures on various subsystems namely fourteen subsystems are Raw water (S1), Electricity (S2), Electric Panel (S3), Raw Water Tank (S4), Valve (S5), Electric Motor (S6), MCF (S7), Valve (S8), ACF (S9), Treated water tank (S10), Electrical Motor (S11), Valve (S12), Pipe (S13), Storage tank on roof (S14). All flow chart of the plant is appended in Fig 1.

The diagram of soft water treatment and supply plant is appended below in Fig-1.

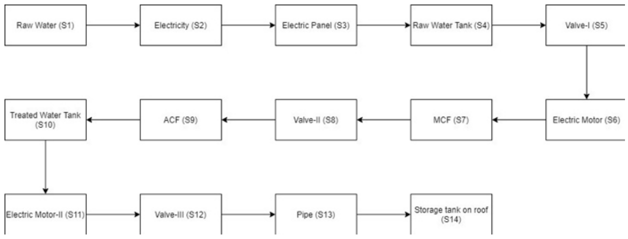


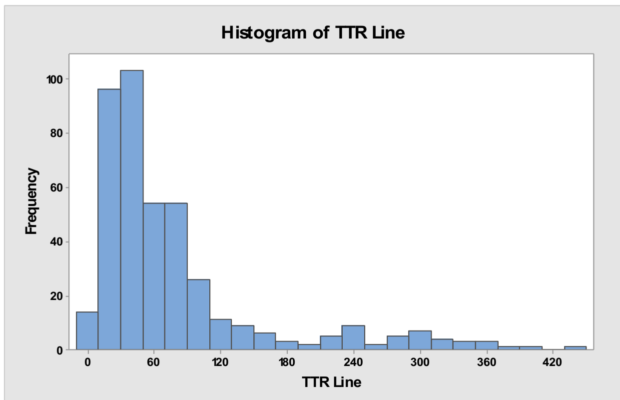
Fig. 1. Reliability Block Diagram of SWTS-Plant

The total number of failures, total TBF, total TTR and availability of subsystems and system are given in Table 1.

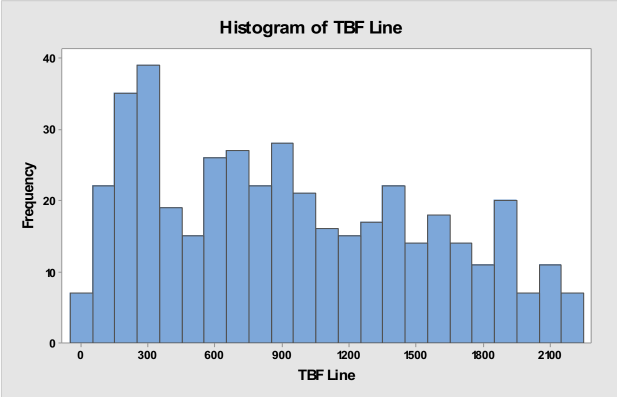
Table 1. Total number of failures, total TBF, total TTR and availability of Soft Water Treatment and Supply Plant

System	No. of Failures	TBF	TTR	Availability
S1	198	429090	8910	0.979657534
S2	57	432780	5220	0.988082192
S3	24	436500	1500	0.996575342
S4	4	437680	320	0.999269406
S5	13	437480	520	0.998812785
S6	35	431520	6480	0.985205479
S7	2	437890	110	0.999748858
S8	19	437240	760	0.99826484
S9	3	437850	150	0.999657534
S10	2	437820	180	0.999589041
S11	34	431880	6120	0.986027397
S12	20	437200	800	0.998173516
S13	6	437460	540	0.998767123
S14	2	437520	480	0.99890411
Line	419	405910	32090	0.92673516

In Figure 2 a) and b), histograms of TBF and TTR of soft water treatment and supply plant (SWTSP) has been depicted. After observing the histogram, it is identified that the approximate shape of the TBF and TTR will be anyone from Exponential, Lognormal, Weibull and Normal distribution that will be identified in later sections. The boxplots and scatter plot of TBF and TTR data has been shown in figures 4.a), 4.b) and 5 respectively.



a)



b)

Fig. 2. a) Histogram of TTR of SWTSP and b) Histogram of TBF of SWTSP

The Pareto chart appended in figure 3, investigated the frequency of failures of each subsystem. It is revealed that S1 is the most frequent failed subsystem and it is amounting 46% failures, the second most failed component is S2 having 13.4% failure and successive failed components are S6, S2, S3, S12, S8, S5, S13 and all these as a cumulative accounted for 95.8% of total number of failures.

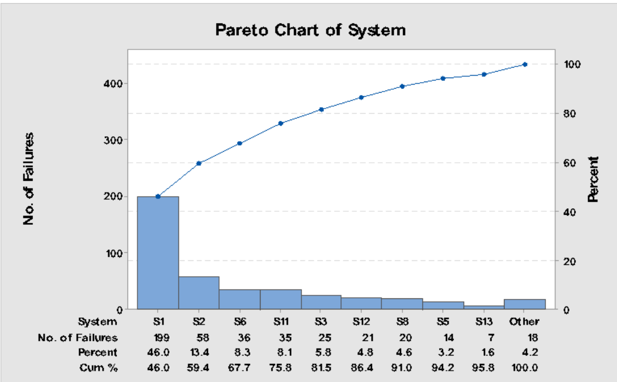
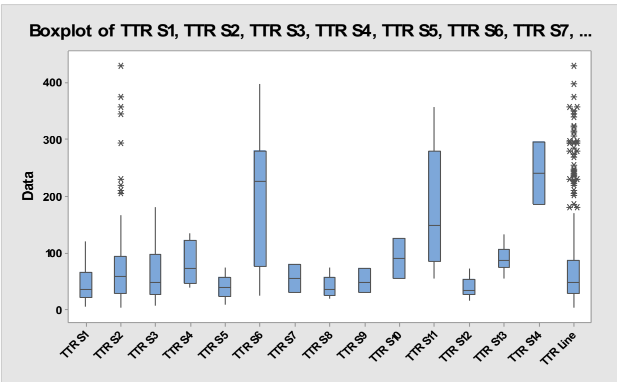
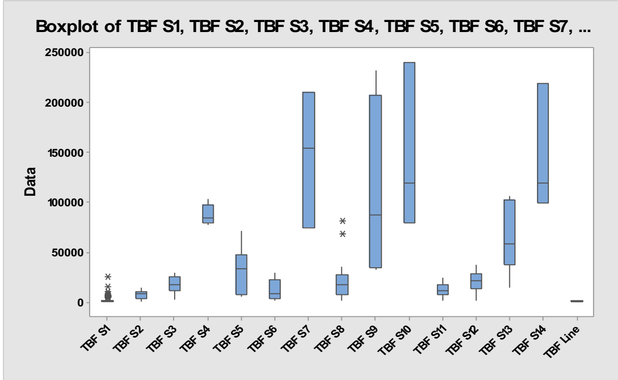


Fig. 3. Pareto Chart of SWTSP



a)



b)

Fig. 4. a) Box plot of TTR of SWTSP and b)Box plot of TBF of SWSTP

3. Descriptive Analysis

In this section, descriptive analysis of quantitative variables has been performed with the help of Minitab-version 17. To depict the nature of frequency distribution of TBF and TTR various descriptive statistical measures have been derived. Some most common measures like Minimum and Maximum value, Average value, Standard deviation, coefficient of variation, Skewness and Kurtosis for each subsystem and entire line were extracted. It is a well-known fact that skewness and kurtosis are helpful for measuring the nature and shape the distribution of the failure and repair data. Normal distribution has skewness and kurtosis values are respectively 0 and 3. Table 2 and 3, comprises all descriptive measures of subsystems and plant. It is observed that mean TBF & TTR of line is 934.4 & 76.59 minutes. It means approximately 3 failures in 4 days. Whereas average time to repair of failure is 76.59 minutes. Second important observation from descriptive analysis that minimum TBF is 4 minutes. It means that the system does not continuous operate due to continuous failure. For TBF and TTR the coefficient of variation value is greater than 1, which represents that there is high variability and maintenance staff devotes different interval for repair of various subsystem. All the failure mode and entire line for TBF and TTR shows positively skewed behavior. So, mode < median < mean and finally from Table 1, it is also observed that line is available for 92.6% times and subsystem S1 is the most sensitive subsystem of the plant.

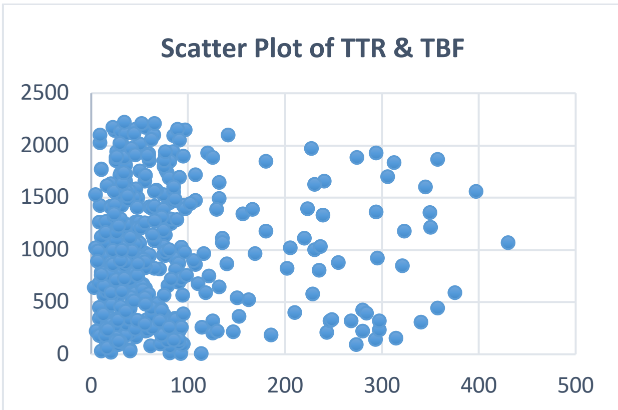


Fig. 5. Scatter plot of TBF & TTR of Plant

Table 2. Descriptive Analysis of TBF

Variable	Count	Mean	StDev	CoefVar	Min	Median	Max	Skewness	Kurtosis
TBF S1	199	2156	2916	135.26	4	1150	25319	3.55	20.97
TBF S2	58	7462	3976	53.29	235	8708	14689	-0.28	-0.90
TBF S3	25	17460	7957	45.57	2871	17844	29455	-0.12	-0.99

TBF S4	5	87536	10079	11.51	77071	84671	103196	1.03	0.89
TBF S5	14	31249	21963	70.29	5190	33629	71658	0.29	-0.99
TBF S6	36	11987	9065	75.63	1663	8075	29204	0.63	-1.24
TBF S7	3	145963	68344	46.82	74010	153870	210010	-0.51	*
TBF S8	20	21862	20856	95.40	1888	17817	81829	1.85	3.52
TBF S9	4	109463	93171	85.12	32373	86889	231700	0.88	-1.10
TBF S10	3	145940	83288	57.07	79475	118975	239370	1.30	*
TBF S11	35	12339	6639	53.81	1913	11065	24742	0.49	-0.78
TBF S12	21	20819	10482	50.35	1823	21995	37964	-0.41	-0.75
TBF S13	7	62494	33616	53.79	14427	58639	106474	0.12	-0.97
TBF S14	3	145840	64051	43.92	99433	119170	218917	1.55	*
TBF Line	433	937.5	604.5	64.49	4.0	861.0	2223.0	0.36	-1.01

3.1 Trend and Serial Correlation Analysis

The trend and serial correlation test have been performed on TBF and TTR data of subsystem and line. To identify the nature of TBF and TTR, Table 4 comprise the result of trend test for TBF and TTR, while Figure 6(a and m) shows the serial correlation of TBF and TTR of the line, after observing both the graph it is identified that no serial correlation present in the TBF and TTR line. Analytically it is revealed that 5% level of significance most of the subsystem reject H_0 i.e not IID's and only for TBF of S1, S8, TBF line and TTR of S1, S2, S3 and TTR line, not reject H_0 i.e IID's. In the next step all the subsystem which rejected H_0 has been tested for correlation. In Figure 6(b) to Figure 6(h) illustrate the correlation diagram of TBF and TTR line diagram, this is calculated by correlation coefficient of legs 1-10. It is observed that TBF of subsystems S2, S3.

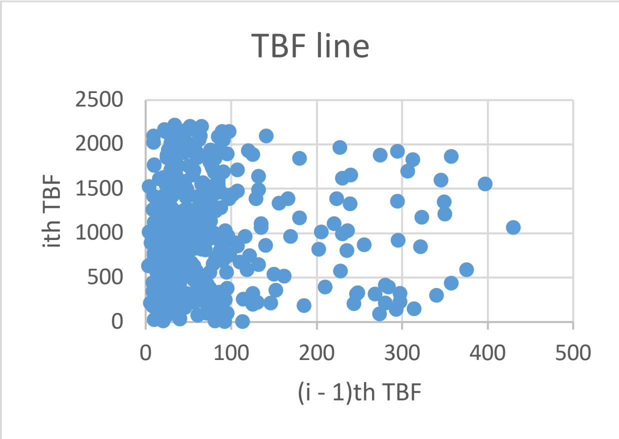
Table 3. Descriptive Analysis of TTR

Variable	Count	Mean	StDev	CoefVar	Min.	Median	Max.	Skewness	Kurtosis
TTR S1	198	45.00	28.25	62.77	5.00	35.00	120.00	0.70	0.58
TTR S2	57	91.6	101.4	110.68	3.0	58.0	430.0	1.86	2.87
TTR S3	24	62.50	48.40	77.44	8.0	48.50	180.00	1.08	0.09
TTR S4	4	80.0	40.2	50.26	40.0	72.5	135.0	1.02	1.50
TTR S5	13	40.00	20.00	49.99	10.00	40.00	75.0	0.19	0.86
TTR S6	35	185.1	106.9	57.75	25.0	227.0	397.0	-0.06	1.29
TTR S7	2	55.0	35.4	64.28	30.0	55.0	80.0	*	*
TTR S8	19	40.00	16.68	41.70	20.0	35.00	74.00	0.64	0.89
TTR S9	3	50.0	21.1	42.14	30.0	48.0	72.0	0.42	*
TTR S10	2	90.0	49.5	55.00	55.0	90.0	125.0	*	*
TTR S11	34	180.0	102.6	57.00	55.0	148.0	357.0	0.42	1.38
TTR S12	20	40.00	16.92	42.29	17.00	33.50	72.00	0.72	0.73
TTR S13	6	90.0	25.2	28.01	55.0	87.5	132.0	0.57	1.77
TTR S14	2	240.0	77.8	32.41	185.0	240.0	295.0	*	*
TTR Line	419	76.59	80.00	104.45	3.00	48.00	430.00	2.11	4.06

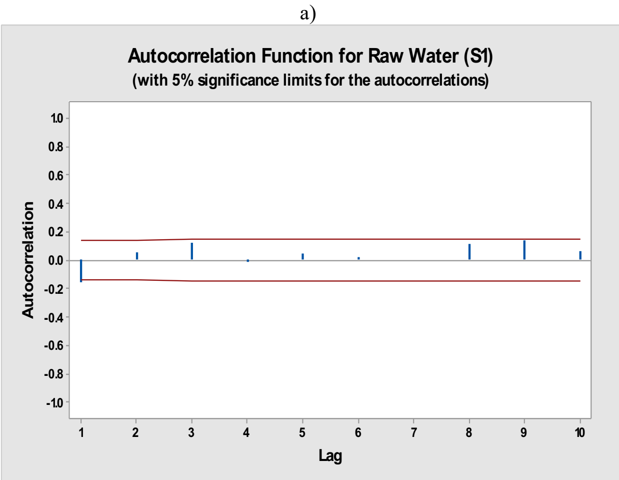
S5, S6, S11, S12 and TTR of subsystems S5, S6, S8, S11, S12 shows trend and serial correlation. Thus, for all these non-homogeneous Poisson process/ power law process in the best fitted distribution.

Table 4. Trend analysis of TBF & TTR of soft water treatment and supply plant

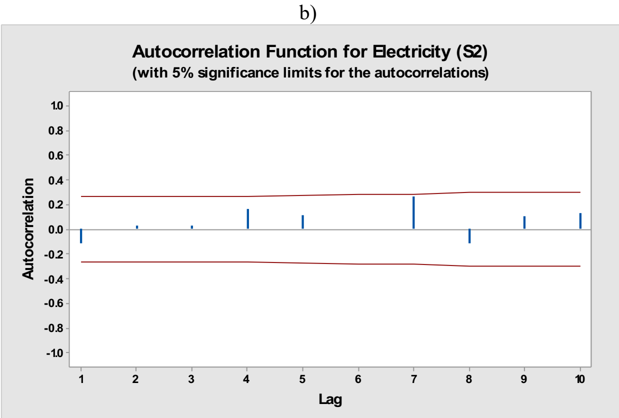
Variable	Degree of freedom	Calculated Statistic U	x^2 with $2(n-1)$	Rejection of H_0 at 5% level of significance
S1	396	1311.16	443.399	Not rejected(IID)
S2	114	111.95	139.92	Rejected(Not-IID)
S3	48	33.24	65.17	Rejected(Not-IID)
S5	26	32.6	38.88	Rejected(Not-IID)
S6	70	87.14	90.53	Rejected(Not-IID)
S8	38	70.85	53.38	Not rejected(IID)
S11	68	60.39	88.25	Rejected(Not-IID)
S12	40	34.59	55.75	Rejected(Not-IID)
TBF Line	864	1021.91	933.49	Not rejected(IID)
S1	394	475.27	441.28	Not rejected(IID)
S2	112	241.95	137.7	Not rejected(IID)
S3	46	65.27	62.83	Not rejected(IID)
S5	24	20.1	36.42	Rejected(Not-IID)
S6	68	70.34	88.25	Rejected(Not-IID)
S8	36	26.43	51	Rejected(Not-IID)
S11	66	58.4	85.96	Rejected(Not-IID)
S12	38	26.81	53.38	Rejected(Not-IID)
TTR Line	836	1798.14	904.38	Not rejected(IID)


TBF line
ith TBF
2500
2000
1500
1000
500
0
0
100
200
300
400
500
(i - 1)th TBF

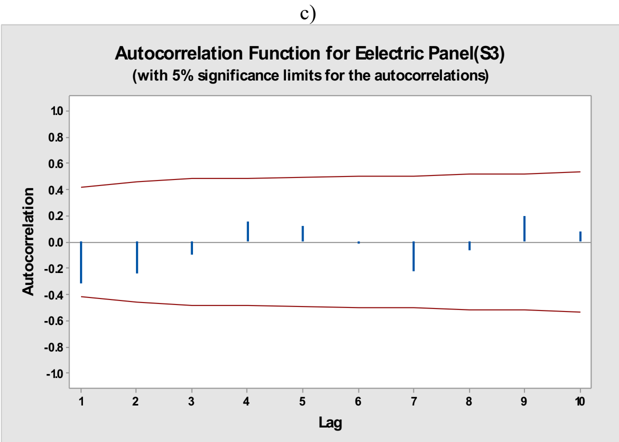
a)


Autocorrelation Function for Raw Water (S1)
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

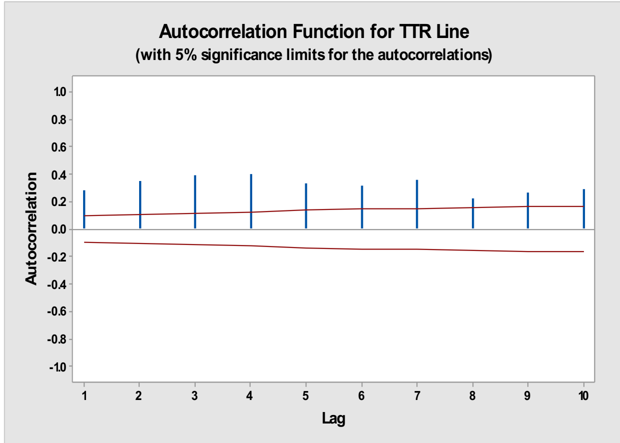
b)


Autocorrelation Function for Electricity (S2)
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

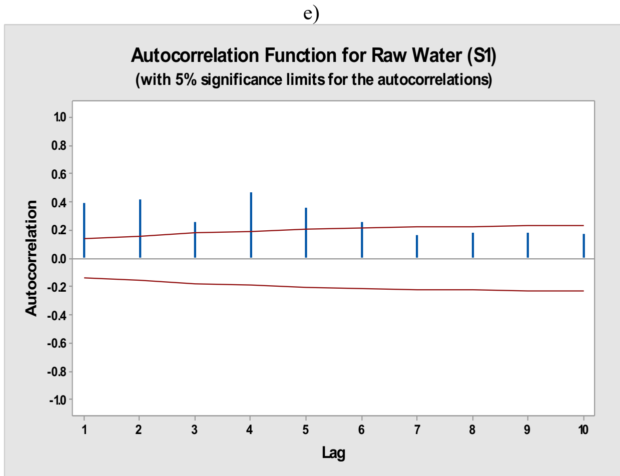
c)


Autocorrelation Function for Eelectric Panel(S3)
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

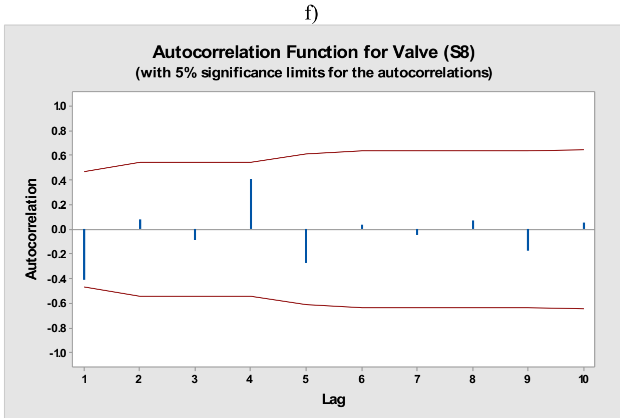
d)


Autocorrelation Function for TTR Line
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

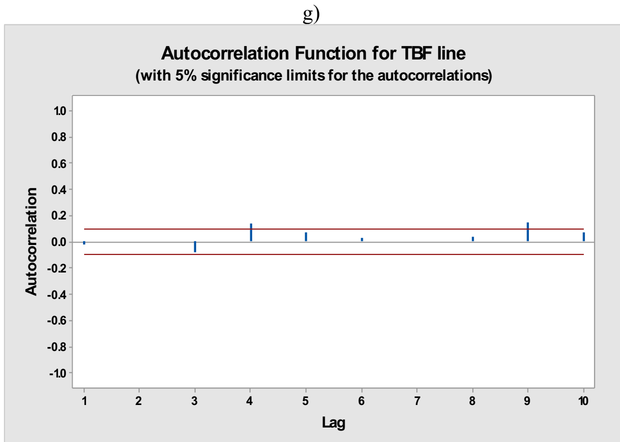
e)


Autocorrelation Function for Raw Water (S1)
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

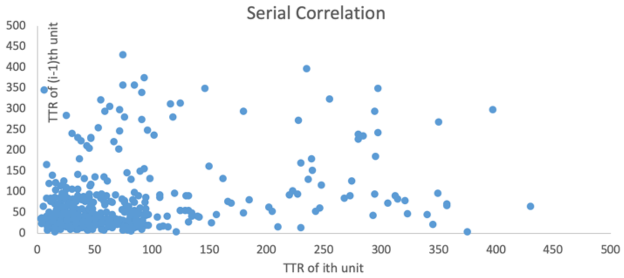
f)


Autocorrelation Function for Valve (S8)
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

g)


Autocorrelation Function for TBF line
(with 5% significance limits for the autocorrelations)
Autocorrelation
Lag

h)



m)

Fig. 6. a) Serial Correlation of TBF, b) TTR of Raw Water 6, c) TTR of Electricity, d) TTR of Electric Panel, e) TTR of WTP, f) TBF of Raw water, g) TBF of Valve, h) TBF of WTP and m) Serial Correlation of TTR of the Water treatment plant

3.2 Reliability and Maintainability Analysis

Reliability of an equipment/unit/component is defined as the probability that it performs its intended work under stated environmental conditions for a period, i.e., probability of no failure period. The best fitted distribution is identified using maximum likelihood method of estimation and values of parameters are obtained using Anderson-Darling test. The Anderson-Darling values of various subsystems and Soft water treatment & supply plant are given in table 5&6 for TTR and TBF with respect to various theoretical distributions. Figure- 7(a),7(b), 8(a) & 8(b) comprises the values of various shape and scale parameters for the best estimated distributions. Weibull distribution is the best fitted distribution for TBF of all the subsystems, Soft water treatment & supply plant while TTR of Soft water treatment and supply plant follows the lognormal distribution. In figure 8 & 9, the hazard rate curve and survival plot of all TBF are depicted and a decreasing behavior is observed. The hazard rate function and the values of parameter were given. The hazard rate for S1 decrease while for S8 and TBF line it is increase, so the maintenance in S8 and line must be optimized in order to eliminate the increase failure rate. The graphical representation of survival function, probability density function and hazard rate function are shown in fig. 9, 10(a) & 10(b). The numerical results of reliability and maintainability are given in table 7 & 8 and obtained a decreasing behaviour in reliability.

Table 5. Anderson-Darling statistics for TTR

Distribution	S1	S2	S3	S5	S6	S8	S11	S12	S13	TTR Line
Weibull	1.92	0.803	1.063	1.096	1.857	1.21	1.387	1.254	2.244	8.425
Lognormal	1.512	0.637	0.902	1.233	2.239	1.12	1.314	1.018	2.208	1.201
Exponential	11.85	0.85	1.539	2.424	3.068	3.772	3.33	3.939	3.307	9.335
Normal	5.684	5.165	1.963	1.118	1.522	1.368	1.756	1.457	2.24	39.225

Table 6. Anderson-Darling statistics for TBF

Distribution	S1	S2	S3	S5	S6	S8	S11	S12	S13	TBF Line
Weibull	2.732	2.507	0.877	1.499	1.599	0.934	0.666	1.387	1.914	3.366
Lognormal	4.236	4.637	1.322	1.71	1.322	1.125	0.737	2.093	1.982	10.064
Exponential	7.289	5.396	3.733	1.629	1.811	1.029	3.697	2.903	2.486	16.407
Normal	20.18	1.244	0.844	1.321	2.652	1.927	1.062	0.975	1.933	6.215

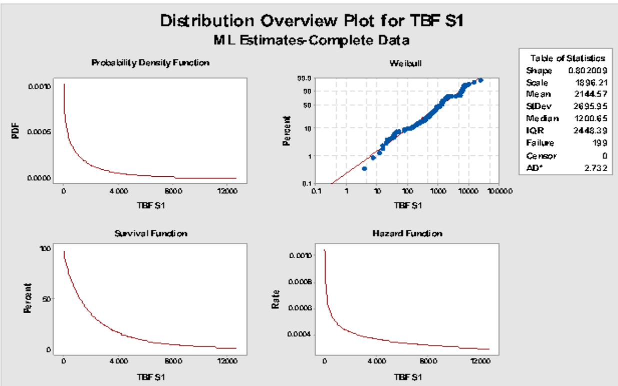
Table 7. Reliability of soft water treatment and supply plant (SWTSP)

Time	Electricity (S2)	Electric Panel(S3)	Valve -I (S5)	Electric Motor(S6)	Electrical Motor (S11)	Valve-III (S12)	Plant
0	1	1	1	1	1	1	1
90	0.98678512	0.9956476	0.998245	0.99188147	0.99500789	0.996964	0.876984
180	0.97374487	0.9913142	0.996494	0.98382885	0.99004069	0.993938	0.7691
270	0.96087695	0.9869996	0.994746	0.9758416	0.9850983	0.99092	0.674488
360	0.94817908	0.9827038	0.993	0.9679192	0.98018057	0.987912	0.591515
450	0.93564901	0.9784266	0.991258	0.96006112	0.9752874	0.984913	0.518749
540	0.92328452	0.9741681	0.989519	0.95226684	0.97041866	0.981923	0.454934
630	0.91108343	0.9699282	0.987783	0.94453583	0.96557422	0.978942	0.39897
720	0.89904357	0.9657067	0.98605	0.93686759	0.96075396	0.97597	0.34989
810	0.88716282	0.9615035	0.98432	0.9292616	0.95595777	0.973008	0.306848
900	0.87543907	0.9573187	0.982593	0.92171736	0.95118552	0.970054	0.269101
990	0.86387025	0.9531521	0.980869	0.91423437	0.94643709	0.967109	0.235997
1080	0.85245431	0.9490036	0.979148	0.90681213	0.94171237	0.964173	0.206965
1170	0.84118923	0.9448731	0.97743	0.89945015	0.93701123	0.961246	0.181505
1260	0.83007301	0.9407607	0.975715	0.89214793	0.93233356	0.958328	0.159177
1350	0.8191037	0.9366661	0.974003	0.884905	0.92767925	0.955419	0.139596
1440	0.80827934	0.9325894	0.972294	0.87772087	0.92304817	0.952518	0.122423
1530	0.79759803	0.9285304	0.970588	0.87059507	0.91844021	0.949627	0.107363
1620	0.78705787	0.924489	0.968885	0.86352712	0.91385525	0.946744	0.094156
1710	0.77665699	0.9204653	0.967185	0.85651654	0.90929318	0.94387	0.082573
1800	0.76639356	0.9164591	0.965488	0.84956289	0.90475388	0.941004	0.072415
1890	0.75626577	0.9124703	0.963794	0.84266569	0.90023725	0.938148	0.063507

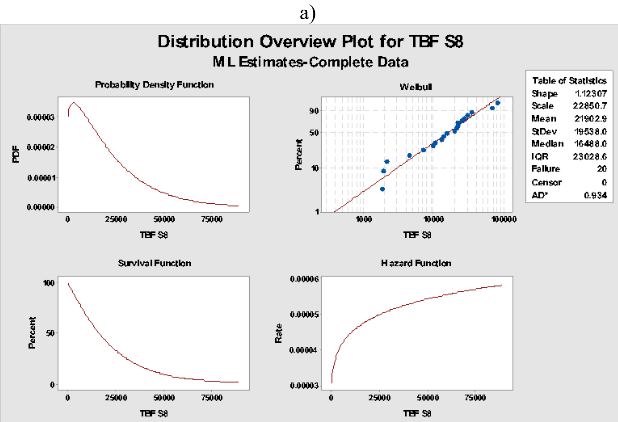
Table 8. Maintainability of soft water treatment and supply plant (SWTSP)

Time	Valve (S5)	Electric Motor(S6)	Valve (S8)	Electrical Motor (S11)	Valve (S12)	TTR Line
90	0.212005	0.479577	0.897771	0.362908	0.836154	0.1853

180	0.379064	0.72916	0.989549	0.594114	0.973154	0.336263
270	0.510706	0.859049	0.998932	0.741413	0.995601	0.459253
360	0.614439	0.926646	0.999891	0.835257	0.999279	0.559453
450	0.69618	0.961825	0.999989	0.895043	0.999882	0.641086
540	0.760591	0.980133	0.999999	0.933133	0.999981	0.707593
630	0.811347	0.989661	1	0.9574	0.999997	0.761776
720	0.851342	0.994619	1	0.97286	0.999999	0.805919
810	0.882859	0.9972	1	0.982709	1	0.841882
900	0.907693	0.998543	1	0.988984	1	0.871181
990	0.927263	0.999242	1	0.992982	1	0.895051
1080	0.942683	0.999605	1	0.995529	1	0.914498
1170	0.954835	0.999795	1	0.997151	1	0.930342
1260	0.96441	0.999893	1	0.998185	1	0.943249
1350	0.971955	0.999944	1	0.998844	1	0.953765
1440	0.977901	0.999971	1	0.999263	1	0.962332
1530	0.982586	0.999985	1	0.999531	1	0.969312
1620	0.986278	0.999992	1	0.999701	1	0.974999
1710	0.989187	0.999996	1	0.99981	1	0.979631
1800	0.991479	0.999998	1	0.999879	1	0.983406
1890	0.993286	0.999999	1	0.999923	1	0.986481

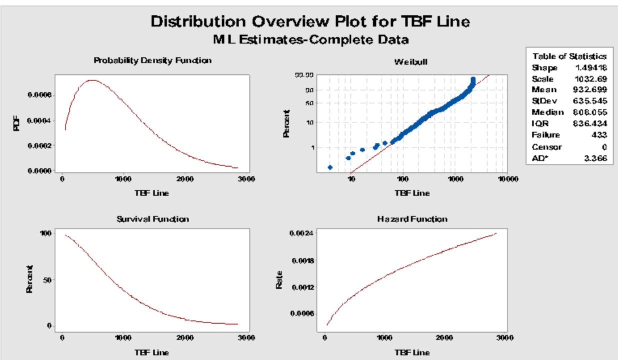


a)



b)

Fig. 7. a) Distribution overview of TBF (S1) and b: Distribution overview of TBF (S8)



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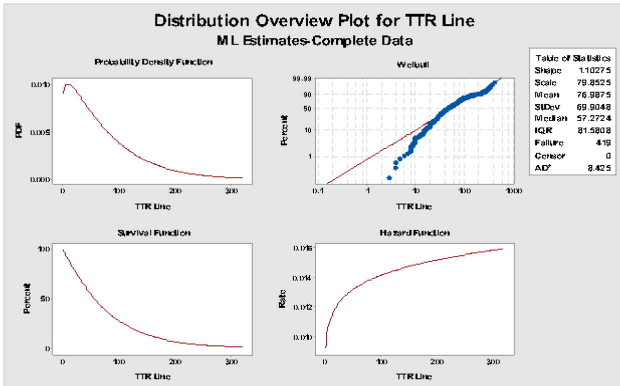


b)

Fig. 8. a) Distribution identification of TBF of SWTSP and b) Distribution identification of TTR of SWTSP

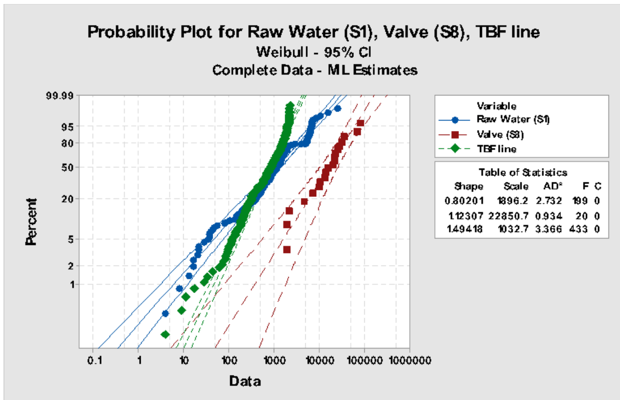
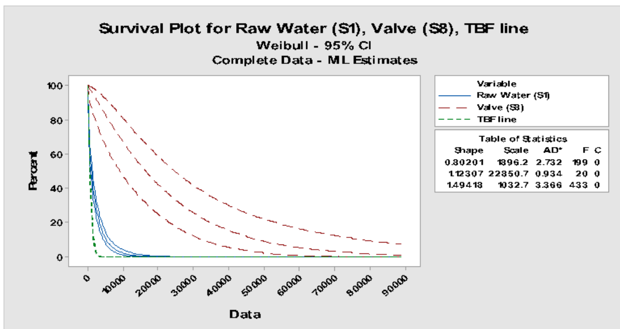
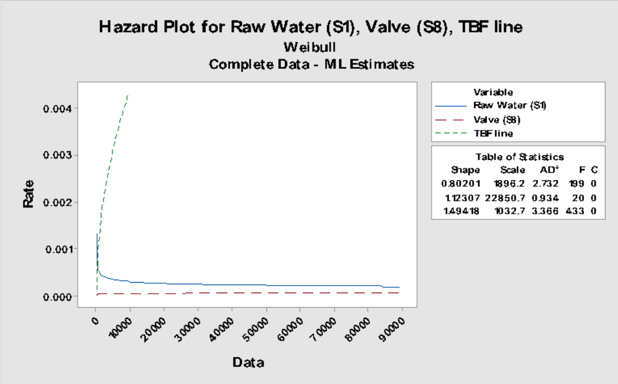


Fig. 9. Probability density plot of Raw water, valve-II and SWTSP w.r.t Weibull distribution



a)



b)

Fig. 10. a) Survival probability plot of Raw water, valve-II and SWTSP and b) Hazard rate plots of Raw water, valve-II and SWTSP

3.3 Failure Mode and Effect Analysis (FMEA)

Failure mode and effect analysis is developed as a powerful tool to analyze the reliability and maintainability of industrial systems. Sharma and Sharma [24] suggested that the results of FMEA analysis are helpful for identification of faults, their causes and correction methods that are helpful for system designers to design the systems. Strong [25] used FMEA to identify the faults, evaluate the effect of these faults on system and to propose the possible solution to remove the faults. Here, after observing the reliability and maintainability measures of the SWTSP appended above, FMEA methodology has been applied. It includes hardware, human and functional parts of the system and find the possible ways of system failures. In our study, an effort has been made to identify the most relevant factors and relevant failure modes using FMEA approach. A committee was constituted to identify the reasons of failure of the SWSTP. The committee includes secretory of RWA of society, site manager, electrician, plumber of society and the researcher as an expert. The complete FEMA analysis has been shown in tables 9-11. The committee discriminates methodologies to vacate the key issues through intellectualizing and developing the ideas and suggestions of individuals. The detailed description is as follows:

- The investigated key failure modes and their effect: raw material availability, maintenance agency planning, and manpower management. The available manpower and management of maintenance agency does not focus on the availability of raw water. According to geographical location of society, water is outsourced by tankers most of the times because only one submersible pump is available in society and on average 10 tankers of water is outsourced. Many times, available manpower does not call for raw water and system faces failures. No systematic planning is available for maintenance.
- The investigated key causes of failure modes: For each failure mode potential causes have been identified. Proper preventive maintenance/corrective maintenance must be planned. The time of ground staff must be appointed according to shift-wise. During day shift three personals are available while in night only one person is there. There are two black spots in morning and evening where no personal is there. No electrician is available in night shift.
- No efficient current fault detection methodology is available.
- Risk priority number (RPN) for each type of failure mode has been calculated. RPN is an indicator of seriousness of faults and to determine proper corrective action. The RPN is calculated by multiplying the severity (1-10), occurrence (1-10), and detection ranking (1-10) levels resulting in a scale from 1 to 1,000:

  RPN= Severity X Occurrence X Detection

  A small value of RPN is always better. It is always recommended to plan proper and rapid corrective maintenance planning strategies for the components of high RPN. Also, it is recommended to engineering team to maintenance first high RPN components instead of analyzing all failure modes.
- The committee recommended to schedule a maintenance of the whole SWTSP in the society. The reassigning the duties of ground staff and to arrange some components in redundancy for smooth functioning. The feasibility of the scheduled maintenance plan is shown by evaluating new RPN.

Hence, carelessness of the maintenance agency regarding providing water supply, non-availability of raw material, unskilled staff and unorganized manpower allocation, were the most factors that influence the reliability and availability of soft water treatment and supply plant.

Table 9, 10 and 11: Failure Mode and Effect Analysis

Table 9. FEMA Analysis Raw Material Availability

Procedure function	**Key failure mode**	**Key effect of failure**	**Sev**	**Key cause (s) of failure**	**Occur**	**Current procedure controls**	**Detec**	**RPN**	**Recommendations**	**Accountability and aim**	**Sev**	**Occ**	**Det**	**RPN**
Raw material Availability	Low ground water & disruption in supply of water by vendor & society Pump	No water in storage water tank and no supply	9	No proper outsourcing of raw water	8	None	10	720	Hire better outsourcing agency and maintain the society pump	Supply department	9	6	6	324

				Electric equipment failure	8	None	10	720	Avail spare electric equipment's	Electrical and purchase departments		5	4	180
	Low availability of water as well spare parts	High cost to buy water and high repair cost of electric and other devices	9	Economic factors	8	None	10	720	Increase the price	Account department	9	5	4	180
				High demand	6	None	10	540	Aware the residents about limited consumption	Customer relation officer		5	4	180
				Equipment failures	7	None	10	630	Spare items like valve and one spare electric motor, pipes	purchase department		3	4	108

Table 10. FEMA Analysis Manpower Organization

Procedure function	Key failure mode	Key effect of failure	Sev	Key cause (s) of failure	Occur	Current procedure controls	Detec	RPN	Recommendations	Accountability and aim	Sev	Occ	Det	RPN
Manpower organization	Shortage of manpower	Extra workload	8	Less pay scale and unsecure future	7	HR Department	8	448	HR department is ordered to increase the salary of workers	HR department	8	5	3	120
	Shortage of skilled and experienced workers	Takes more time on repairing major faults	7	Unequal staff distribution on site	9	HR department	10	630	Equally distribute the staff for operation	HR and maintenance department	7	3	4	84
				No proper AMC management of heavy equipment's	7	None	8	392	Properly maintain all the AMC and other systems	Maintenance department		4	3	84
				untrained employees	7	None	6	294	HR is ordered to appoint sled personals	HR department		5	4	140

Table 11. FEMA Analysis- Maintenance Scheduling

Key failure mode	Key effect of failure	Sev	Key cause (s) of failure	Occur	Current procedure controls	Detec	RPN	Recommendations	Accountability and aim	Sev	Occ	Det	RPN
No analysis of past data and not planned any maintenance strategy	Maintenance department not ready to plan any immediate maintenance scheduling	8	Insufficient quality system	7	Maintenance department only focus on current failures reported by residents	10	560	Training of workers	M & QA department	8	6	6	288

4. Conclusion

The key findings of the above analysis are pointed as follows:

- The most sensitive component is raw water supply as its availability is 97.9%.
- System availability was 92.67% having 7.33% down time.
- TBF and TTR of the SWST-Plant does not show any correlation
- To optimize the SWST-Plant reliability management must focus on subsystems S1, S2, & S6.
- The best fitted distribution for TTR of the plant is lognormal while plant's TBF follows Weibull distribution.
- Non-homogenous Poisson process/Power law process is the best fitted distribution for subsystems which shows serial and trend correlation in their TTR and TBF times.

- The average TBF time is 937.5 minutes while average TTR is 76.59 minutes.
- From FEMA technique, it is observed that resource unavailability, unskilled manpower and unstructured maintenance planning are the key factors that affects the maintenance process of plant.

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