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Significance of control chart based reliability monitoring and benchmarking in process industries in decision making

Jose K Jacob[1] and Shouri P.V[2]
[1]Anna University Coimbatore, Tamilnadu, India
[2]Department of Mechanical Engineering, Government Model Engineering College, Cochin, Kerala, India.

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ABSTRACT
Failures of equipments and process costs money. The reasons for failure could be either a bad design, improper working conditions, failure of system components as they approaches the wear out stage or a combination of these factors. There is no way of completely eliminating failures. However, a better understanding of the causes and mechanisms of equipment failure can allow failure control measures to be developed and implemented. Unreliability is the costly part of the economic equation and adopting measures to improve reliability and availability of the system will ultimately result in economic gain. The present work attempts to provide an estimate of the net effect of modification that is required for a system by using the control chart procedure. The method involves plotting control charts for each of the components using the time to fail. The central line of the control chart corresponds to the Mean Time Between Failure (MTBF) and the control limits are placed at a distance of $\pm 3\sigma$ from the mean line and is based on t- distribution. The components that require an improvement with regard to failure rate is identified by analysing the control charts. The desired change in the component availabilities as well as the system availability can be obtained and an estimate of the net effect of modification is also arrived. The model can provide a measure of the performance of the components as well as that of the system. The quantification of the improvements required, if any, can be obtained using the model. A 11 step algorithm is also developed based on the model. It is hoped that the developed model and algorithm will prove to be a powerful tool in process reliability analysis.

Introduction

One of the most powerful tools in statistical quality control is control chart. Since 1924 when Dr. Shewhart presented the first control chart, various control chart techniques have been developed and widely applied as a primary tool in statistical process control. Control chart based process monitoring and maintenance procedures are available in the literature.

Xie M (2002) developed some effective control chart methods for reliability monitoring. Katter et al. (1998) used the control chart to monitor the on-line welder condition. Steiner and Mackay (2001) showed the use of control chart to detect process changed for censored data. Cassady et al. (2000) introduced a combined control chart-preventive maintenance strategy. Haworth (1996) showed how the multiple regression control charts could be used to manage software maintenance processes

Any engineered equipments has the potential to eventually cease the operation due to the failure.

Failure with regard to the process can be defined as an event when as process equipment or machinery is not available to produce outputs at specified conditions when scheduled or is not capable of producing outputs or perform scheduled operations to specifications. In order to define failure correctly for a particular piece of equipment, the equipment functions or requirements must be firstly defined. These functions may vary depending upon the applications.

For a given process, RBD can be drawn and can be used to derive the analytic expression for system availability and reliability. In arriving at the process system reliability and availability normally the following considerations are made.

1) All component failures that occur are assumed to be independent of each other.
2) The process unit, depending upon the case, is logically represented by a series, parallel, or a mixed configuration.
3) Equipments or components with short service periods or components that do not affect the process continuity and can be repaired or replaced within a reasonable time are omitted from the logical configuration.

Model Development

This section describes the development of a model for benchmark reliability assessment of system components using control chart technique.

An algorithm is also developed to make an assessment of the cost benefits, in case the component MTBF and reliability falls below the benchmark value and needs improvement.

The model is based on the following assumptions:

1) Process components are assumed to have a constant failure rate as well as a constant repair rate.
2) Availability under consideration is steady state availability.
3) Interest rate is constant throughout.
4) Depreciation of the plant is not considered.

Tele:
E-mail addresses: jkjsolutions@yahoo.com

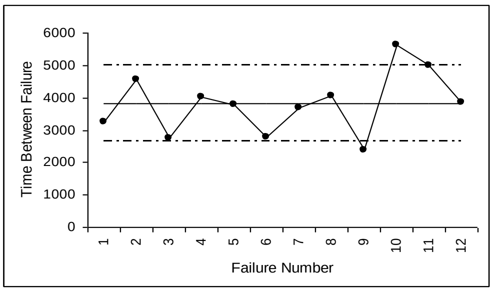


Fig .1 Control chart based model for reliability analysis

The procedure involves plotting the Time to Failure (TTF) Vs the failure number for a pre-determined time for each of the components separately. The mean time between failures (i.e., the average of TTF's) represents the central line of the control chart. The upper control limit and lower control limit are calculated on the basis of Student's t – distribution as given by the following equations:

$$LCL = \frac{1}{\lambda} - t_{\alpha/2}\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{1}{\lambda} - T_{f_i}\right)^2}{N}} \quad (1)$$

$$UCL = \frac{1}{\lambda} + t_{\alpha/2}\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{1}{\lambda} - T_{f_i}\right)^2}{N}} \quad (2)$$

Where λ is the failure rate based on the MTBF, T_f is the time to fail, N is the total number of failures, $t_{\alpha/2}$ is the critical value corresponding to the number of degrees of freedom.

The points corresponding to the TTF's that lie above and below the control limits are discarded and the revised value of MTBF is calculated. This is taken as the bench mark value. If the benchmark value is more than the existing MTBF, then suitable steps must be taken to bring down the failure rate of the respective components. If the improvements in the component MTBF required are not too big, this can be achieved by proper maintenance or even by upgrading the existing maintenance procedures. On the other hand if the improvement in component MTBF required are too large, the situation demands either the use of a more superior component or even a change in design. In either case there is an additional expenditure in the form of maintenance or superior design. On arriving the economic feasibility the expenditure towards upgrading the existing maintenance procedures or change in design should be weighed with the effect of change in availabilities. The operating and maintenance cost also vary with the plant availability and this element of cost also need to be considered. The net effect of modification by incorporating these factors can be expressed as:

$$N_E = H(P/A,i,n)\left[R \times U(A_f - A_i) - O_f \times A_f + O_i \times A_i\right] - (C_1 + C_2 + C_3 + ... + C_n) \quad (3)$$

In the above equation the parameter $(P/A,i,n)$ is called as uniform series present worth factor and is expressed as

$$(P/A,i,n) = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (4)$$

The equation for the net effect of modification thus reduces to:

$$N_E = H\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]\left[R \times U(A_{fs} - A_{is}) - O_f \times A_{fs} + O_i \times A_{is}\right] - (C_1 + C_2 + C_3 + ... + C_n) \quad (5)$$

A positive value for N_E suggests that the modification will work out to be a feasible one.

Algorithm for arriving at the net effect of modification

A 11- step algorithm has been developed for arriving at the benchmark reliability values of the system components and arriving at the net effect of modification that is required for the system. The total cost of modification is obtained by considering the cost that is associated with the cost of various system components that require an improvement in the base value of MTBF.

1. Based on the actual process system configuration draw the corresponding reliability block diagram (RBD).
2. Fix the time period or note down the time interval during which the failure data for a specific component is available. This time period should be preferably as long as possible.
3. Obtain the time to failure of each component during the fixed time period and also count the number of failures during the interval.
4. Calculate MTBF by taking the average of time to failure for each of the components.
5. Calculate the control limits for all the components using the equations (1) and (2).
6. Plot control chart for all the components with central line as respective MTBF and the calculated values of LCL and UCL as obtained in step 5.
7. Find out the points (or TTF's) that lie beyond the control limits.
8. Discard the points (or TTF's) that lie out side the control limits and then calculate the revised MTBF (i.e., $MTBF'$) and obtain the revised failure rate. If all points are lying within the control limits, there will not be any change in MTBF. $MTBF'$ represents the attainable value of the mean time between failure and always attempts must be made to ensure that the existing component MTBF is either equal to or more than this value.
9. Obtain the steady state availability using the old value and new value of MTBF. Find out the improvement in MTBF, $(i.e., MTBF' - MTBF)$
10. Estimate the cost required to improve the MTBF for each of the components and also calculate the total cost using the equation $TC = \sum_{i=1}^{N} C_i$.
11. Estimate the net effect of modification using the equation (5).

Application of control chart technique in a captive power plant to study the impact of system modification

The ability to improve continually is desirable. In recent years, the reliabilities of power plants have become increasingly important issues in most developed and developing countries [Eti et al., 2007]. As a result the recent works are focused on integrating reliability, availability, maintainability and supportability (RAMS), as well as risk analysis related with power plants. On the other hand, prevailing low efficiency of the power plants, especially that of captive power plants is a matter of concern. With the growing need for energy conservation most of the process plants are being modified and it is important that in decision making regarding plant modifications and redesigns reliability and energy efficiency have to be considered together. A comparative study between the following two options was conducted.

Option 1: Present MTBF is to upgrade to the benchmark value obtained from the control chart technique.

Option 2: As a part of energy conservation program the two 25 kW parallel pumps by a single 30 kW pump which runs at nearly full load.

The valuation model is applied to arrive at the net effect of modification resulting from system modification. The effect variation of various parameters like steam flow rate, valuation period, interest rate and power price on process system value was also studied.

Description of the captive power plant

The process flow diagram of the captive power plant is shown in Figs.2. The capacity of the power plant is 2.5 MW. The boiler is of Thermax design and is a panel type water tube boiler capable of burning oil and by product gas. The steam is generated at 39 kgf/cm^2 and 350°C.

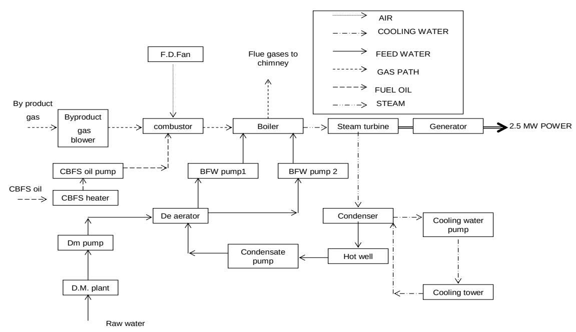
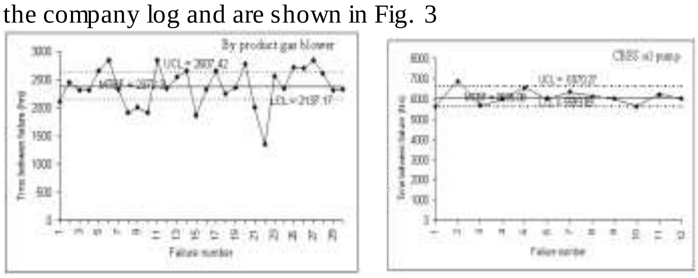


Figure 2. Process flow diagram for the captive power plant

During the normal course of operation the boiler is fired by the byproduct gas and only if the supply of gas is insufficient the oil is supplied and the oil used is carbon black feed stock oil. A heater is also used for heating the oil. Different equipments present in the system are represented as series and parallel configuration in RBD. It should be noted that the connectivity between equipment in RBD is based on logic and differs from the actual physical configuration. Feed water pumping is carried out by two 25 KW pumps connected in parallel and are running at half loads. The pumping system will fail only if both the pumps fail simultaneously.

Application of control chart technique in captive plant

First step in applying the model was identifying the components and their mean time between failure and mean time to repair. The components of concentrator part of the gelatin plant are Byproduct gas blower, CBFS oil pump, CBFS oil heater, Combustor, boiler, Boiler feed water pump, Generator, Steam turbine, Piping, Condenser, Cooling tower, Draft fan, Cooling water pump, and Condensate pump. To find out the benchmark value of MTBF's, control charts for each of the components are drawn based on the failure data available from the company log and are shown in Fig. 3



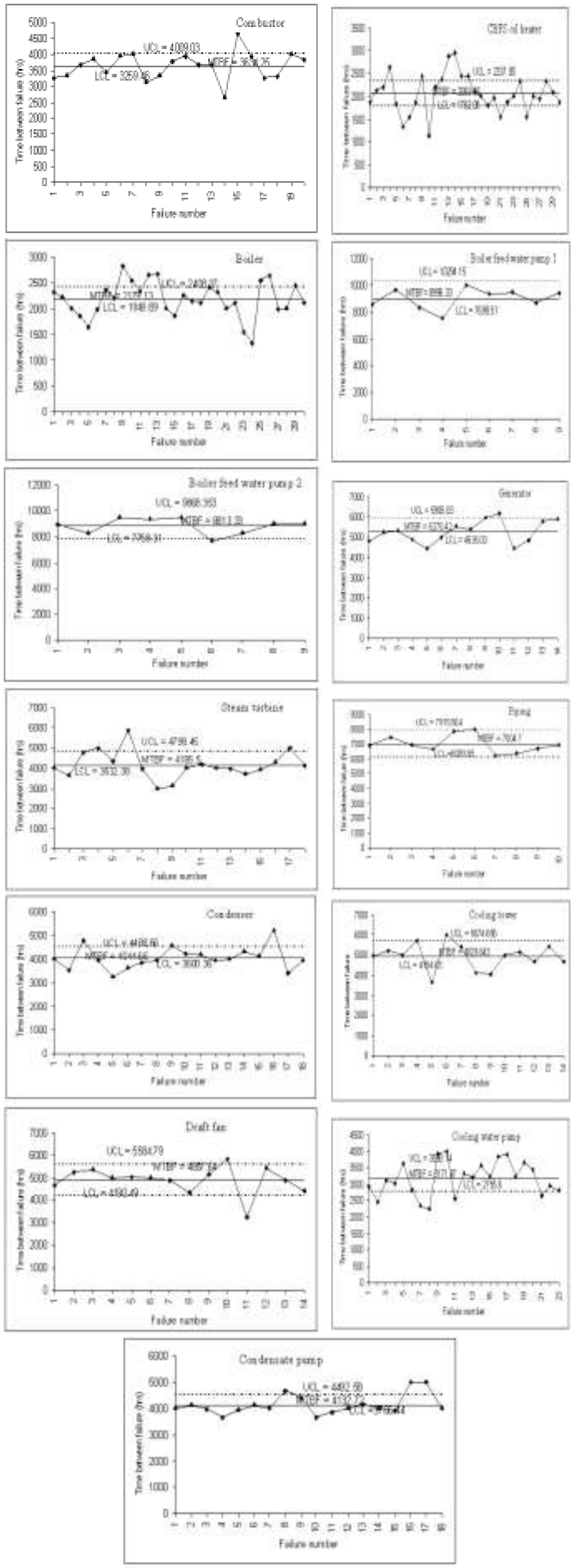


Fig. 3 Control chart for the components

System modification

By discarding the points outside the control limits the benchmark values of MTBF are obtained and are shown in Table 1

From the analysis it can be seen that necessary steps should be taken to improve the reliability and availability in the case of combustor, boiler feed water pump, cooling tower, draft fan and cooling water pump. There are different options to modify the system, out of which two are compared below to find the economic feasibility.

Option 1

The modification can be done without changing the configuration of the components. Decrease in failure rate required to achieve the benchmark value in combustor, boiler feed water pump 1, boiler feed water pump2, and draft fan are less than 2% and can be obtained by corrective maintenance measures. Decrease in failure rate required to achieve the benchmark value for cooling water pump is 2.70339 % and can be achieved by replacing the existing one with a new pump. Decrease in failure rate required to achieve the benchmark value for cooling tower is 2.42625 % and can be achieved by refilling the gas and corrective maintenance. The total cot expected for these works is rupees 1 lakh. There is 0.6057429% reduction in operating cost as result of the modifications is also expecting. The system reliability and availability before and after modification of option 1 is shown in Fig. 4. It is clear from the figure that there is 1.157367119% improvement in system reliability and 0.596260034% improvement in system availability due to this modification.

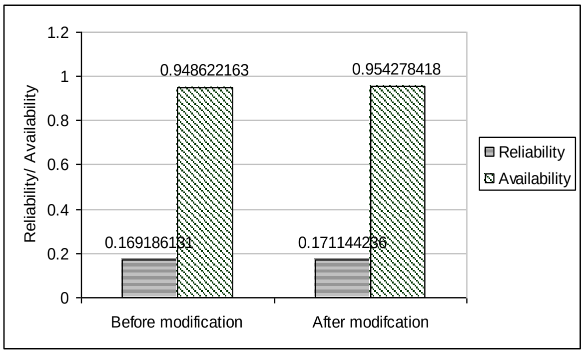


Fig. 4 System reliability/ availability before and after modification

A simple tradeoff between the cost of modification and the projected savings will show that the pay back period will only be a few months. However, a more realistic approach will be to take reliability aspects also into consideration and develop valuation model that can be used to check the economic feasibility of this modification.

The net effect of modification thus obtained is:

$$N_E = -(C_1 + C_2 + C_3 + ... + C_n) + H\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]\left[m \times \Delta h \times U(A_{fs} - A_{is}) - O_f \times A_{fs} + O_i \times A_{is}\right]$$

$$N_E = -200000 + 7000 \times \left[\frac{(1+0.1)^{15} - 1}{0.1 \times (1+0.1)^{15}}\right]\left[3 \times 775.2 \times 3.5 \times 0.005656255 - 880.57 \times 0.954278418 + 885.94 \times 0.948622163\right]$$

= Rs. 1884989.6

The above calculation assumes an interest rate of 10% and the system life of 15 years after modification. The variation of N_E with system life is given in Fig.5. It is evident from the figure that the pay back period is only 0.329920 years (3.95904 months).

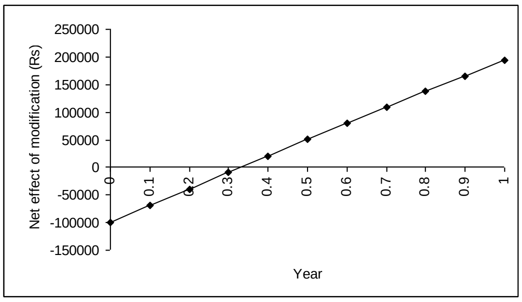


Fig 5 Variation of net effect of modification with system life

Option 2

The modification can be done by replacing the two 25 kW parallel pumps by a single 30 kW pump which runs at nearly full load. Decrease in failure rate required to achieve the benchmark value in combustor and draft fan can be obtained by corrective maintenance procedures. Decrease in failure rate required to achieve the benchmark value for cooling water pump is 2.70339 % and can be achieved by replacing the existing one with a new pump. Decrease in failure rate required to achieve the benchmark value for cooling tower is 2.42625 % and can be achieved by refilling the gas and corrective maintenance. The modification resulted in an expenditure of Rs.2 lakhs.. There is 3.088973062 % reduction in operating cost as result of the modifications is also expecting. The reliability block diagram of the captive plant after modification is shown in Fig. 6.

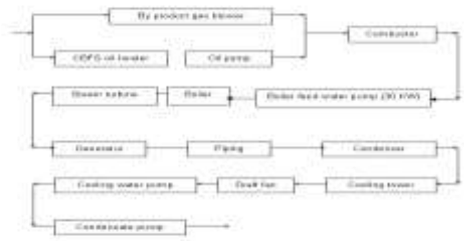


Fig 6 RBD of captive plant after modification

The system reliability and availability before and after modification of option 2 is shown in Fig. 7. It is clear from the figure that there is 44.11127074% decrease in system reliability and 0.340038812% decrease in system availability due to this modification. The decrease in reliability and availability is due to the loss of redundancy.

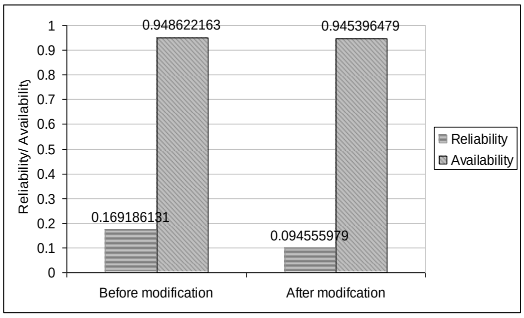


Fig. 7 System reliability/ availability before and after modification

A simple tradeoff between the cost of modification and the projected savings will show that the pay back period will only be a few months. However, a more realistic approach will be to take reliability aspects also into consideration and develop valuation model that can be used to check the economic feasibility of this modification.

The net effect of modification thus obtained is:

$$N_E = -200000 + 7000 \times \left[\frac{(1+0.1)^{15} - 1}{0.1 \times (1+0.1)^{15}} \right] \left[3 \times 775.2 \times 3.5 \times -0.00323 - 858.57 \times 0.945396 + 885.94 \times 0.948622 \right]$$

= Rs. -68266

The above calculation assumes an interest rate of 10% and the system life of 15 years after modification. The variation of N_E with system life is given in Fig. 8.

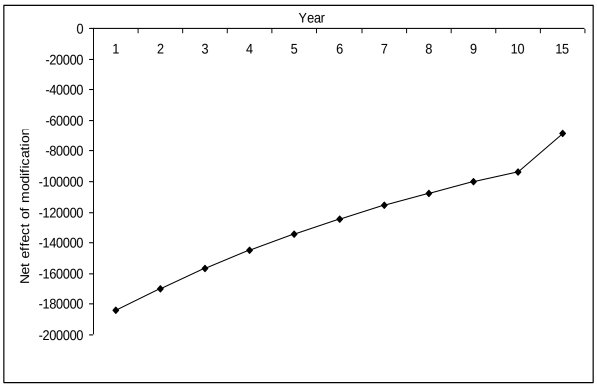


Fig 8 Variation of net effect of modification with system life

It is evident from Fig. 8 that the pay back period has not arrived even after 15 years. The net effect of modification after 15 years of operation is Rs. -68266/- even though there is savings due to decrease in operating and maintenance cost.

Conclusions

The control chart method was used to monitor the failure of components and there by arrive at the benchmark value. Process reliability study was conducted at a captive power plant using the developed model. The economic feasibility of elevating the existing components to the benchmark standards is evaluated by considering the investment needed on one hand and the change in production as well as the operating and maintenance cost on the other. The net effect of elevating the existing components to the benchmark standards need not necessarily be positive. It depends upon factors like change in availability, years of operation after modification and also time value of money. The savings that can be generated over a period of time can be quantified by considering factors like initial investment, operation and maintenance and interest and is represented by NE. In case of systems that are modified for reasons like improvement in energy efficiency, the model can be used as a method of comparison of alternatives. The methodology involves comparing the production and maintenance figures by incorporating availability before and after modification. The availability figures corresponding to the benchmark values are considered in each case. In the case of captive power plant wherein the pumping system has been modified for improving energy efficiency, the net effect works out to be negative.

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Table 1 Benchmark values using control chart method

Component number	Component name	MTBF before modification	Benchmark MTBF
1	Byproduct gas blower	2372.30	2372.30
2	CBFS oil pump	6085.08	6085.08
3	CBFS oil heater	2059.57	2059.57
4	Combustor	3634.25	3638.81
5	Boiler	2179.13	2179.13
6	Boiler feed water pump 1	8996.33	9176.63
7	Boiler feed water pump 1	8813.33	8956.88
8	Generator	5270.43	5270.43
9	Steam turbine	4165.50	4165.50
10	Piping	7004.70	7004.70
11	Condenser	4044.67	4044.67
12	Cooling tower	4929.64	5052.22
13	Draft fan	4887.64	4944.92
14	Cooling water pump	3171.87	3260.00
15	Condensate pump	4132.72	4132.72