APPLICATION OF CONTROL CHART BASED RELIABILITY ANALYSIS IN PROCESS INDUSTRIES

Jose K Jacob¹ and ² Dr. Shouri P.V.
¹Ph.D Research Scholar, Anna University Coimbatore, Tamilnadu.
E-mail: jkjsolutions@yahoo.com
² Head, Dept. of Mechanical Engineering, Govt. Model Engineering College, Cochin, Kerala, India. E-mail: pvshouri@yahoo.com

ABSTRACT

In any case failures cannot be eliminated. 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 arrive at a benchmark value in terms of component failure rate and reliability and thereby arrive at the net effect of modification that is required for a system up-gradation. The method involves plotting control charts for individual components using the time to fail. The central line of the control chart corresponds to the Mean Time Between Failure (MTBF) and are placed at a distance of \( \pm 3\sigma \) from the mean line and is based on t-distribution. The components requiring an improvement in respect of failure rate is identified by analysing the control charts. The desired change in the component availability 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.

Key words: Availability, Control chart, Failure rate, Mean Time Between Failure (MTBF), Process reliability.

1. INTRODUCTION

Reliability of any component or system is its probability of success. Reliability and availability place a vital role in deciding the economic feasibility of any system [Shouri and Sreejith, 2008]. A process system typically will be made up of a number of components and the system reliability will depend upon the system configuration as well as the individual component reliability. That is, how good a
system is will depend upon how good the individual components are. Hence it is important that each and every component or forms up to its maximum capable limit without failure. No industry can progress effectively without the knowledge of implementation of reliability engineering. Today it has developed to a high degree of refinement and quantification. Reliability engineering provides the theoretical and practical tools whereby the probability and capability of parts, components, equipment, products, sub-systems and systems to perform their required functions without failure for desired periods of specified environments. Reliability and risk analyses have traditionally been conducted in order to provide information for stakeholders as basis for, or aid in, decision-making [Apostolakis 2004].

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Process availability is a critical driver for the economic performance of a production plant [Shouri and Śreejith, 2008]. Over the years efforts have been made to address plant reliability and maintainability issues at the conceptual stage of design so as to improve the plant availability at the operational stage [Vassiliadis &
Pistikopoulos, 1999; Grievink et al., 1993. Davidson [1998] pointed out three factors to achieve growing availability: increasing the time to failure; decreasing down-time due to repairs or scheduled maintenance; and accomplishing the above two in a cost-effective manner. As availability increases, the capability for making money increases because the equipment is in service for longer periods of time. The common approach to improve inherent availability at the design stage is to use different reliability analysis tools such as a reliability block diagram [Henley & Gandhi, 1975], a Petri net simulation [Cordier et al., 1997], a fault tree analysis [Thangamani et al., 1995], etc. all of which allow for availability assessments on a selected process system with given unit/component reliability and maintainability data. The results of these availability studies provide useful qualitative and quantitative information that can be used later to evaluate operational performance and can be further used in improving achievable availability.

Understanding the dynamic behaviour of system reliability becomes an important issue in either scheduling the maintenance activities or dealing with the improvement in the revised system design. In doing so the failure or hazard rate function should be addressed. Bathtub curve is usually adopted to represent the general trend of hazard rate function. Many studies were concentrated on depicting the geometric shape of bathtub curve. The early contributors in this area include Shooman [1968], Thomas [1973], Bain [1974], Smith & Bain [1975], Gaver[1979], Hijroth [1980], Dhillon [1981], Lawless[1982], Jaisingh et al [1987].

One of the decision making tools employed in total quality management (TQM) is statistical process control (SPC). When applied successfully to manufacturing processes, SPC improves product quality and productivity, reduces production costs and increases profits. In its simplest form SPC is applied directly to a process variable obtained from a process which is to be controlled. The process variable is plotted on a statistical control chart (cc). The cc is comprised of the mean of the process variable, an upper control limit (UCL) and a lower control limit (LCL). If observations on the process variable fall above the UCL or below the LCL, the process is considered to be out of control. This condition is regarded as being due to a special cause affecting the process mean. Duncan[1956] introduced the design of $\bar{x}$ control chart on the basis of economic criteria. He developed a model to find the control chart parameters for a continuous process, which goes out-of-control due to a single assignable cause. Panagos etal. [1985] describe a continuous process as a process in which the manufacturing activities continue during the search for an assignable cause. Surtihadi and Raghavachari [1994] have shown that for control charts with fixed sampling intervals, the exponential process failure mechanism provides a good approximation even though the real process follows any non-exponential process failure mechanism. Control charts can be designed to have constant parameters; time varying parameters and adaptive parameters. Prabhu et al. [1994] designed $\bar{x}$ control charts with adaptive parameters and showed that they are superior to conventional control chart designs. In general, the complexity of the models has grown from single assignable cause models to multiple assignable cause models and exponential failures to Weibull and gamma distributions. The quality characteristics considered in the models have grown from monitoring a single quality characteristic (univariate) to multiple quality characteristics (multivariate). Control charts that can use present and past information effectively have been introduced.
The present work attempts to adopt control chart method in identifying the performance of components in terms of its life. A methodology is also developed to arrive at the benchmark component reliability values under the existing environment using control charts. The control charts are plotted for all the process components separately using the time to failure values that are collected during a predefined time period. The central line is placed corresponding to MTBF and the control limits are at a distance of $\pm 3\sigma$ and are based on $t$– distribution. The benchmark value corresponds to the reliability obtained using the MTBF value by deleting the time to failure points that lie outside the control limits. A model is also developed for evaluating the economic feasibility of raising the individual component reliabilities to the benchmark standards. This is obtained by weighing the expenditure towards upgradation of system components to the benchmark values on one hand and the benefits resulting from improvement in system availability on the other. Minute improvements in component reliability values can be obtained by proper maintenance and providing appropriate process environment. However, improvements beyond a particular level will require a change in design, replacement of existing components or even both. The model can also be used to arrive at the pay back period in case of system modification. The developed model could prove to be a powerful tool in reliability analysis as well as in framing equipment replacement policies. The present model takes into account the change in availability as a result of upgrading the components to the benchmark values in addition to the conventional cost elements that are considered in conventional payback calculations. The developed model was applied in different industrial situations and was also validated using the actual plant data. It is found that the error involved is of negligible magnitude.

2. 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.
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:

$$LCL = \frac{1}{\lambda} - t_{\alpha/2} \sqrt{\frac{\sum_{i=1}^{N} \left(\frac{1}{\lambda} - T_{f_i}\right)^2}{N}}$$  \hspace{1cm} (7)$$

$$UCL = \frac{1}{\lambda} + t_{\alpha/2} \sqrt{\frac{\sum_{i=1}^{N} \left(\frac{1}{\lambda} - T_{f_i}\right)^2}{N}}$$  \hspace{1cm} (8)$$

Where $\lambda$ 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 benchmark 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:

\[ N_E = H(P/A,i,n)[R \times U(A_f - A_i) - O_f \times A_f + O_i \times A_i] - (C_1 + C_2 + C_3 + \ldots + C_n) \]  

(9)

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

\[(P/A,i,n) = \frac{(1+i)^n - 1}{i(1+i)^n}\]  

(10)

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

\[ N_E = H \left[ \frac{(1+i)^n - 1}{i(1+i)^n} \right] [R \times U(A_f - A_i) - O_f \times A_f + O_i \times A_i] - (C_1 + C_2 + C_3 + \ldots + C_n) \]  

(11)

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

3. 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(7) and (8).
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 (11).

**4. APPLICATION OF CONTROL CHART METHOD FOR RELIABILITY ANALYSIS IN A GELATIN PLANT**

The model was applied to the concentrator part of the plant. Dilute gelatin solution is received in a feed tank. A circulation stream is maintained through the first effect of the concentrator consisting of heat exchanger HE 1 and separator SEP 1 by the circulation pump 2. Gelatin solution from feed tank is pumped to this circulation stream by pump 1. This solution is heated by steam coming from steam header through pressure reducing valve (PRV). The heated solution gets concentrated by the evaporation of water. A part of this medium concentration gelatin is fed to the circulation stream of second effect of the evaporator. Again the second effect of the concentrator consists of heat exchanger HE 2 and separator SEP 2 and the circulation is maintained by pump 3. The feeding quantity to first effect is balanced with the sum of water quantity evaporated and gelatin quantity bled out. The heating medium for second evaporator is the vapour generated by the first effect. In second effect evaporated vapour is removed from separator to a condenser HE 3, where it is condensed. Here the concentration maintained is higher and part of this concentrated gelatin solution is taken out by pump 4 and fed to next section. The steam condensate together with the vapour condensates are removed from system by pump 5. All this evaporation is carried out at vacuum pressure so as to keep temperatures down. This vacuum is maintained by pump 6 by removing non condensable gases from condenser. The heat rejected at condenser is removed by circulating water pumped by pump 7. Steam at a pressure of 40kgf/cm\(^2\) was brought down to 3 kgf/cm\(^2\) by means of a pressure reduction valve (PRV) and then further supplied to the heat exchanger HE 1.

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 heat exchanger, separator, pump, boiler feed water pump, boiler and pressure reducing valve to find out the benchmark value of MTBFs, 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
Figure 2 Concentrator part of a gelatin plant before modification
The points outside the control limits were discarded and based on the remaining values the MTBF is calculated. If this new value of MTBF is less than the initial value, then the existing value of the MTBF itself is taken as the benchmark value. If new MTBF is greater than the initial value, then this is taken as the
benchmark MTBF and necessary steps need to be taken for reducing the failure rate of this particular component. It is evident from the above control charts that suitable remedial measures must be taken in the case of heat exchanger 1, heat exchanger 2, pump2, pump4, pump5, boiler and pressure reducing valve. Based on the analysis it is observed that there should be 0.487901% increase in MTBF or 0.485532% decrease in failure rate of heat exchanger 1, 9.510315% increase in MTBF or 8.684401% decrease in failure rate in heat exchanger 2, 0.669812% increase in MTBF or 0.665355% decrease in failure rate in pump 2, 2.688915% increase in MTBF or 2.618505% decrease in failure rate in pump4, 1.519608% increase in MTBF or 1.4968612% decrease in failure rate in pump5, 15.419% increase in MTBF or 13.35915328% decrease in failure rate in boiler and 27.97562% increase in MTBF or 21.860114% decrease in failure rate in pressure reducing valve. Modification required in heat exchanger 1, pump2, pump4 and pump5 are less than 5% and can be done by corrective maintenance.

The modification required in heat exchanger 2 is high and decided to replace HE2 and its pipes. The boiler used was a high pressure boiler and produces high pressure steam which is much more than the required pressure. There for a pressure reducing valve was used to reduce the pressure to the required value. The improvement required for achieving the benchmark value for boiler and pressure reducing valve are much higher. Further there is also a huge loss in energy and there for as a part of energy conservation policy the company decided to install a thermocompressor and also to replace the existing high pressure boiler with a low pressure one and also to eliminate the pressure reduction valve. Thermo compressors use a high-pressure steam source to recover the energy from the low-pressure source, thereby providing considerable savings in energy cost. This is accompanied by change in circulation flow rates maintained in the two effects and varying heat transfer areas. Part of the vapour generated in first effect at low pressure is sucked by the thermocompressor to generate medium pressure steam. This process is powered by high pressure steam that is the motive force from steam header. The modification costed about Rs. 2 crores including the cost of thermocompressor, replacement of old boiler by a new one and replacement of old heat exchanger 2 by a new one.. The savings based on fuel consumption is about 33 kg per hour of furnace oil. The new design results in an increase in overall energy efficiency by 11.91%. After modification the PRV was replaced by a thermocompressor and the corresponding MTBF and MTTR is 6000 hours and 36 hours respectively. Also the old boiler was replaced by a new boiler with MTBF and MTTR equal to 4500 and 18 hours respectively.

The net effect of modification thus obtained is using equation (11) as:

\[
N_E = \frac{20000000 + 7000 \left[ (1+0.1)^{15}-1 \right]}{0.1(1+0.1)^{15}} \times [215 \times 50 \times 0.000598943 - 55469.48 \times 0.97997 + 57470.77 \times 0.979371]
\]

\[
= Rs. 84524091.5
\]

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. 4.
Fig. 4 Variation of net effect of modification with system life

The actual production values after adopting the suggestions is shown in Fig. 5. It is evident that the output in terms of production increased as well as the operation and maintenance costs decreased as a result of the change in process availability, the change in component efficiencies and the change in plant design. It can be seen that the pay back period as per the model is 1.6502171 years or 19.80 months. This value is very close to the actual pay back and lies between the sixteenth and seventeenth month.

Fig. 5 Actual production data after modification

5. CONCLUSIONS

The control chart method was used to monitor the failure of components and thereby arrive at the benchmark value. Process reliability study was conducted at different industrial situations using the developed model. The major research findings are listed below.

1) Control chart method can be applied to any process industry to obtain the benchmark values.

2) 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.

3) 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 $N_E$.

4) 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.

5) Achieving the benchmark reliability value can have a significant impact in production and in the case of gelatin plant about 0.06% increase in availability will result in an increase of production amounting to about 3 lakhs per year

6) The modification of a system results in system availability which in turn affects production as well as operation and maintenance costs. In some cases the change in operation and maintenance will be much more predominant than the change in production. In the gelatin company the reduction in operation and maintenance cost is quite significant and the resulting gain works out to be around 1.4 crores as compared to an increase in production of about 3 lakhs.

7) The net effect of modification depends on the expected life of the system after modification and $N_E = 0$ corresponds to the break even value or the pay back period. In the case of gelatin plant, the payback works out to be around 1.65 years.

REFERENCES


