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DEVELOPMENT OF MATHEMATICAL MODELS FOR OPTIMAL PREVENTIVE MAINTENANCE POLICY IN A STEEL INDUSTRY : SIX SIGMA APPROACH

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Abstract: *This paper deals with a critical evaluation of the Preventive Maintenance system in steel industry. This study helps in implementing Six Sigma solutions to reduce the down time of two critical machines i.e., Electric Arc Furnace (EAF) and Billet Casting Machine (BCM). It is clear from the analysis of EAF and BCM respectively that, variations in output are quite possible because the machines output not only depend on maintenance time but also on several other variables. Further, the objective is to design a preventive maintenance programme on the same equipment situated in the plant using Six Sigma. The breakdown of these equipments could very well affect the production rate. For this, the mathematical models have been developed and these models are used to obtain the optimum preventive maintenance frequency for minimizing the down time and maximizing the profits.*
Keywords: *Six Sigma, Preventive Maintenance, Correlation and Regression, Optimal policy.*

1. INTRODUCTION

In a developing economy like India, plant maintenance has acquired paramount importance for maintaining the plant and equipment in a state of high operating efficiency and to achieve enhanced productivity in any Steel industry. The present study deals with the equipment maintenance and related aspects in a Steel industry. There are many steel industries in India, which are making very low profits due to improper maintenance of both plant and equipment.

The study deals with important aspects of applying Six Sigma methodology for maintenance of critical process machines which is as important as improving the manufacturing process and the quality of raw material. As there is no scientific system or method to maintain the critical process machines in the production line, the authorities concerned generally arrive at breakdown maintenance, attending the machines only when the machines fail. In doing so, they neglected the maintenance pattern which is basis for the perfect maintenance management. This study helps in implementing six sigma solutions to reduce the down time of the two critical process machines.

2. METHODOLOGY

2.1.Define/Measure Phase

In order to compute various parameters affecting the production process, both primary and secondary data are obtained from maintenance department. The primary data deals with critical parts or sub systems, appropriate costs of inspection and repair has been obtained by conducting a series of brain storming sessions with the maintenance personnel and works director. The secondary data mainly deals with number of breakdowns in each month, the average inspection time, and the average repair time for each component are obtained from the records maintained by the maintenance department.

2.2. Analyze Phase

A cross functional team has been formed to prepare a process map to identify the important subsystems/parts for each machine which are mainly responsible for the majority of breakdowns (Table.1). The monthly data that is collected for three years related to the number of breakdown of each part is thoroughly analyzed and the average breakdown per year is computed. Further by using quantitative Pareto principle to identify important causes that are responsible for the most of the problems are shown in Figure.1 and the shut down time of different machines are computed.

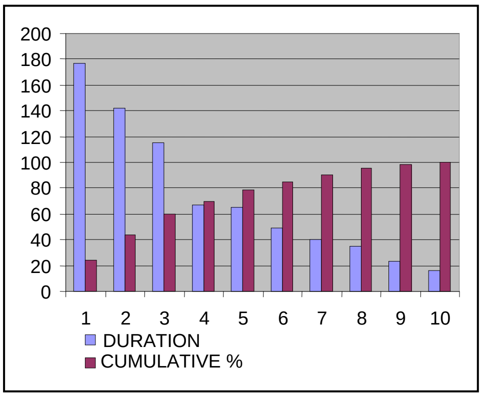
Table. 1. Causes for Breakdown

Electric Arc Furnace (EAF)		**Billet Casting Machine (BCM)**	
Sl No	*Problem Elements*	*Sl No*	*Problem Elements*
1	Roof Pond Water Leakage	1	Gear box problem
2	Furnace On/Off	2	Bearings problem

	Problem		
3	EBT Jam	3	Water line unit
4	Changing Tap	4	Mould tube
5	Furnace Bottom Repair	5	Oscillations problem(dummy bar)
6	Electrode Problem	6	DC motor
7	EBT flap problem		
8	VCB problem		
9	Gunning		
10	S I Chute Jam		

2.3. Improve Phase

Results of analysis show that 60% of shutdown time occurs due to the roof pond water leakage, Furnace break on /off problem and EBT hole jam in the furnace. On the other hand 58% of the shut down occurs due to gear box problem, bearings and oscillation problems in billet casting machines. Appropriate measures should, be taken initially to reduce the duration of these problems by having the proper maintenance strategy with a maintenance schedule concentrating much on these problems. The proposed methodology was piloted on the two machines.



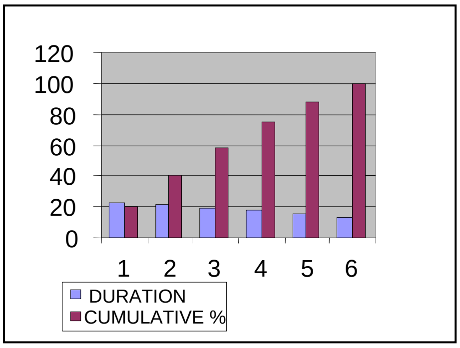


Figure 1: Contribution of each problem in EAF and BCM

2.4. Control Phase

To monitor and control the on-going performance of the machines, the company implemented a database to track each problem and monitor the key subsystems. A concise scheduling format is developed to track the weekly progress of maintenance within each subsystem and the overall performance of the machine.

The Correlation – Regression model is used in order to obtain the linear regression equation for the machine output(Y) and the maintenance time (X) for the Electric arc furnace and the Billet casting machine. After obtaining the linear regression equation, predicted or expected values of 'Y' for different values of 'X' are obtained.

In order to carryout simple Correlation and Regression analysis in single cause variable X has been assumed to have a linear association with the effect variable Y. The data concerning maintenance time (X) and machine outputs (Y) are tabulated for EAF and BCM respectively in Table 2.

3. CORRELATION – REGRESSION MODEL FOR THE PRESENT WORK

The different variables appearing in industrial and business problems are often found to exhibit a "Cause effect" relationship among them.

E.g., the output of a machine may depend among other variables like availability of power and raw materials, time spent on machine maintenance etc. are generally denoted by X_1, X_2 etc. The effect variable i.e., machine output is indicated by Y.

We know that if 'r' denotes the coefficient of correlation between X and Y,

$$\text{then } r = S_{xy} / S_x S_y \qquad (1)$$

where S_x- Standard deviation of X.
S_y - Standard deviation of Y.

$$S_x = \sqrt{\sum (X_i - \bar{X})^2 / n}$$

where $\bar{X}$ is mean of X_1, X_2, -----X_n.

$$S_y = \sqrt{\sum (Y_i - \bar{Y})^2 / n}$$

where $\bar{Y}$ is mean of Y_1, Y_2,-----Y_n.

S_{xy} = Covariance between X and Y.

$$S_{xy} = \sqrt{\sum (X_i - \bar{X})(Y_i - \bar{Y}) / n}$$

The linear relationship between X and Y called the 'linear regression equation' of Y on X is given by the straight line.

$$Y = a + bx \qquad (2)$$

Where Y is the predicted or expected value corresponding to the 'Cause' variable X.

Where, $a = \frac{\sum X^2 \sum Y - \sum X \sum XY}{n\sum X^2 - \left(\sum X\right)^2}$ and

$$b = \frac{n\sum XY - \sum X \sum Y}{n\sum X^2 - \left(\sum X\right)^2}$$

The quantity r^2 is known as the 'Coefficient of determination'.

Eg, r = - 0.8 ($-1 < r < +1$), then $100r^2 = 64$ in percentage

Let r_1 and r_2 denote the Co-efficient of correlation between X and Y for the machines 1 and 2 respectively. The values of r_1 and r_2 are likely to be negative because with increase (decrease) in maintenance time, one normally expects a decrease (increase) in machine output.

Suppose $r_1 = -0.5$ and $r_2 = -0.7$ so, the corresponding coefficients of determination are $100r_1^2 = 25$ and $100\ r_2^2 = 49$. These values indicate that 25% and 49% of the variations in machines 1 and 2 respectively are described to maintenance time. Hence higher priority is given to the maintenance of machine 2.

It is also possible to use the linear regression equation of Y on X as given in equation (2) to predict the machine output for different duration of maintenance time. The importance of this information lies in the fact that it enables one to ascertain the maintenance time needed for achieving a given output target. The maintenance manager may then explore the possibility of organizing activities of the maintenance crew in such a way that the output target is me

Table.2. Maintenance time & Machine output

	Electric Arc Furnace (EAF)		Billet Casting Machine (BCM)	
Sl No	**Maintenance time in hrs(X)**	**Machine O/P in tones (Y)**	**Maintenance time in hrs(X)**	**Machine O/P in tones (Y)**
1	71.25	8600	7.50	8593
2	62.51	8640	5.16	8620
3	92.42	8325	7.58	8312
4	47.40	8468	7.50	8455
5	43.00	8770	7.57	8760
6	72.59	8380	9.32	8350
7	54.67	8560	11.90	8541
8	59.00	7980	9.60	7952
9	79.91	8585	9.08	8574
10	155.95	8267	12.42	8255
11	67.92	8482	9.41	8470
12	57.09	8280	11.41	8270

3.1. Data analysis

It is clear from the Table.2

- The coefficient of correlation 'r' between X and Y for furnace is -0.3146 and for BCM is -0.408.
- Maintenance time decreases(X) from 92.42 in period '3'to 59 in period '8', Furnace output(Y) instead of increasing ,has decreased from 8325 tones to 7980 tones .
- It is further observed that, as the maintenance increases from 59 in period '8' to 67.92 in period 11, the furnace output instead of decreasing, it has increased.
- For same maintenance time of 7.5 hrs in periods 1 and 5, the BCM outputs was 8593 tones and 8455 tones respectively.
- Similarly the BCM outputs are 8312 tones and 8760 tones in periods 3 and 5 respectively although the maintenance time is almost same .i.e., 7.57 hrs.
- Such variations are quite possible because the machine output not only depends on maintenance time but also on several other variables.

4. LINEAR REGRESSION EQUATION

- Linear Regression Equation of machine output (Y) on maintenance time (X) is obtained and the predicted or expected values of Y for different values of X=40,60,80,100,120,140,160 hrs for EAF and X=2,4,6,8,10,12,14,16 hrs for BCM are computed in Table.3.
- Linear Regression Equation for machine output (Y) on maintenance time (X) is given by $Y = a + bX$

Table.3 Predicted Furnace output for Different values of Maintenance time.

Electric Arc Furnace (EAF)		**Billet Casting Machine (BCM)**	
(Y = 8605.55 – 2.2341X.)		**(Y = 8839.95 – 45.43X)**	
Maintenance time (X) (hrs)	**Expected Furnace output(tons) Y=a+bX**	**Maintenance time (X) (hrs)**	**Expected m/c output(tons) Y=a+bX**
40	8515.00	2	8515.00
60	8470.96	4	8470.96
80	8426.28	6	8426.28
100	8381.60	8	8381.60
120	8336.92	10	8336.92
140	8292.24	12	8292.24
160	8247.56	14	8203.93
		16	8113.23

It is very clear from Table 3

- Production output decreases with increase in maintenance time.
- Since it is statistically significant, the maintenance manager should intensify his efforts to ensure that the maintenance job is to be carried out in the shortest possible time so that the machine output increases significantly.
- Depending upon the significance or insignificance of the coefficient of correlation, the maintenance department has to decide upon the priorities to be attached to the different maintenance jobs.

5. PREVENTIVE MAINTENANCE

Further objective is to design a preventive maintenance programme on the same equipments situated in the plant using Six Sigma methodology.

As a first step, a thorough study of equipments were made in the define phase of Six Sigma DMAIC methodology. Subsequently the factors which justify the application of preventive maintenance programme to the machines under consideration have been identified. Since the inspection is integral part of the preventive maintenance programme, the optimum inspection frequency is obtained by using the mathematical models by analyzing the breakdown details of the equipments. Based on this, Preventive Maintenance inspection schedule for the next year is also proposed.

5.1. Preventive Maintenance Frequency for Minimization of Cost

5.1.1. Statement of the problem

Breakdown of the equipments from time to time requires men and materials to repair which results in production loss. In order to reduce number of break downs, we can periodically inspect the equipment and rectify minor defects leading to ultimate failure. Hence an inspection policy is determined which will give us the correct balance between the number of inspections and the profit per unit time from the equipment availability is maximized.

5.1.2. Model Development

- Equipment failure occur according to the negative exponential distribution with mean time between failure (MTBF) = 1/λ, Where λ is the mean arrival rate of failures.

- The value of the output in an uninterrupted unit of time has a profit value 'V' i.e., profit value if there are no down time losses.
- The average cost of inspection per uninterrupted unit of time is 'I'.
- The average cost of repair per uninterrupted unit of time is 'R'.
- The breakdown rate of the equipment 'λ' is a function of 'n' the frequency of inspection ie. the breakdowns can be influenced by the number of inspections.
- The objective is to choose 'n' in order to maximize the expected profit per unit time for operating the equipment.

The profit per unit time for operating the equipment will be a function of the number of inspections. Therefore profit per unit time P(n),

P(n) = Value of output per uninterrupted unit of time - Output value lost due to repairs per unit time - Output value lost due to inspections per unit time - Cost of repairs per unit time - Cost of inspections per unit time.

Output value lost due to repairs per unit time = Value of output per uninterrupted unit of time x No. of repairs per unit of time x mean time to repair.

$$= \frac{V\lambda(n)}{\mu}$$

Output value lost due to inspections per unit time = Value of output per uninterrupted unit of time x No. of inspections per unit of time x mean time to inspection.

$$= \frac{Vn}{i}$$

Cost of repairs per unit time = Cost of repairs per uninterrupted unit of time x Mean time to repair x No. of repairs/unit time

$$= \frac{R\lambda(n)}{\mu}$$

Cost of inspections per unit time = Cost of inspections per uninterrupted unit of time x Mean time to inspect x No. of inspections/unit time

$= \frac{In}{i}$ Therefore,

$$P(n) = V - \frac{V\lambda(n)}{\mu} - \frac{Vn}{i} - \frac{R\lambda(n)}{\mu} - \frac{In}{i} \quad (3)$$

This becomes the model of the problem, relating to the frequency of inspection 'n' to profit P(n). To get an approximate answer, P(n) is assumed to be a continuous function of 'n'.

On differentiating w.r.t n, we have

$$\frac{dp(n)}{dn} = -\frac{V\lambda'(n)}{\mu} - \frac{V}{i} - \frac{R\lambda'(n)}{\mu} - \frac{I}{i}$$

Where, $\lambda'(n) = \frac{d[\lambda(n)]}{dn}$

Therefore, $0 = \frac{\lambda'(n)[V+R]}{\mu} + \frac{1[V+I]}{i}$ (4)

Maximum $\lambda'(n) = -\frac{\mu[V+I]}{i[V+R]}$ Since values of μ, i , V, R,I and λ(n) are known, the optimal frequency to maximize profit per unit time is that value of 'n' which makes the LHS of equation (4) equal to its RHS.

5.2. Preventive Maintenance Frequency for Minimization of down time

5.2.1. Statement of the Problem

The problem, here, is determining the inspection policy which minimizes the total down time per unit time incurred due to breakdowns and inspection rather than to determine the policy which maximizes profit per unit time**.**

5.2.2. Model Development

F (t), λ' (n), n, 1/μ., and 1/i are already defined.

The objective is to choose 'n' to minimize total down time per unit time. The total down time per unit time will be a function of the inspection frequency 'n' denoted as D (n).

Therefore, D (n) = Down time incurred due to repairs per unit time + Down time incurred due to inspection per unit time.

$$D(n) = \frac{\lambda(n)}{\mu} + \frac{n}{i} \quad (5)$$

Equation (5) is a model of the problem relating inspection frequency 'n' to the total down time D (n). Assuming, D (n) to be a continuous function of 'n'.

$\frac{d[D(n)]}{dn} = \frac{\lambda'(n)}{\mu} + \frac{1}{i}$ **i.e.,** $0 = \frac{\lambda'(n)}{\mu} + \frac{1}{i}$

Threfore, $\lambda'(n) = -\frac{\mu}{i}$ *(6)*

Optimal inspection frequency to minimize down time is that value of 'n' which makes LHS of the equation (6) equal to its RHS.

Eg. Let $\lambda(n) = \frac{K}{n}$ we have $\lambda'(n) = -\frac{K}{n^2}$ (7)

The constant 'K' is the arrival rate of breakdowns per unit time.

Substituting equation (7) in (4) gives

$n = \sqrt{\frac{Ki[V+R]}{\mu[V+I]}}$ for minimizing the cost. Similarly, Substituting (7) in (6) we get $n=\sqrt{\frac{Ki}{\mu}}$ for minimization of down time.

6. DATA COLLECTION AND ANALYSIS

The objective of the study deals with equipment maintenance and related aspects using Six Sigma. In order to minimize the equipment downtime and the down time cost for the furnace and billet casting machines, the above mathematical models are used. In order to compute various parameters affecting these models both primary data and the secondary data are obtained from the Maintenance department.

The data mainly deals with the number of breakdowns in each month, the average inspection time and the average repair time for each component are obtained for three consecutive years ie., 2006, 2007, and 2008 from the records maintained by the maintenance department and the average number of breakdowns per year and per month is computed. Further by using weighted average method the forecasted number of breakdowns for each part of the machine is estimated by giving 20%, 30% and 50% weightage for the above mentioned three years data respectively. Thus information regarding time taken to inspect as well as repair is obtained from the records of maintenance department from which the average time for inspection and repair was computed.

After carefully examining the various details pertaining to the type of inspection/repair, average number of people employed for each type of inspection/repair, the amount of supervision necessary, the approximate cost of breakdown, the cost of inspection and the cost of repairs are calculated.

In order to compute the optimum number of inspections so as to reduce the total number of breakdowns as well as to minimize the cost of maintenance using Six Sigma, mathematical models are employed. For this purpose, one of the important factors i.e., the value output for an uninterrupted month is calculated by taking into consideration the standard time to produce a billet, the cost of a billet and the number of billets that can be casted in a month. The optimum inspection frequency has been determined for each part by using the mathematical models. The details of the optimum inspection frequency for the Electric arc furnace and billet casing machine have been calculated for the year. The average inspection frequency has been calculated for both the machines and is given in Table 5. By adapting this, the down time is reduced to considerable extent which in turn reduces the cost of maintenance and are indicated in table 6.

Table 5: Preventive Maintenance Frequency for Minimizing the Cost and down time

Electric Arc Furnace (EAF)		**Billet Casting Machine (BCM)**	
Parts	*Minimizing the cost or Minimizing the down time*	*Parts*	*Minimizing the cost or Minimizing the down time*
Roof Pond Water Leakage	15	Gear Box Problem	4
Furnace On/Off Problem	3	Bearing Problem	3
EBT jam	3	Water line Unit	3
Changing Tap	2	Mould tube	2
Furnace bottom repair	2	Oscillations Problem (Dummy Bar)	2
Electrode Problem	1	D.C.Motor	1
EBT flap Problem	1		

Table 6: Details of Cost Benefit Analysis

Production Increased	2 tons/hr
Increased Production / day	48 tons/day
Cost of Billets	Rs 12000 /ton
Cost benefit per day	Rs 576000/-
Total Cost benefit / month	**Rs 1,72,80,000/-**
Power saving of EAF & BCM (15 Kw x 24 hrs x 365 days)	**131400 Kw / annum**
Cost saving of EAF & BCM (15 Kw x Rs 3/- x 24 hrs x 365 days)	**Rs 3.94 lacs / annum**

7. CONCLUSIONS

The study highlights the implementation of Six Sigma solutions to reduce the downtime of the two critical machines EAF and BCM. It is clear from the analysis of EAF and BCM that variations in output are quite possible because the machine output not only depend on maintenance time but also on several other variables and predicted output for both the machines are obtained for different values of maintenance time. For this, the mathematical models have been developed and these models were used to obtain the optimum preventive maintenance frequency for minimizing the down time and cost..

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