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Improving Productivity of Concreting Equipment: Failure Modeling

Case Study on New Hot Strip Mill, Rourkela, India

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Abstract

There is a growing reliance on concrete batching plants and ready-mix concrete presently due to faster work, uniform quality of concrete, eco-friendly nature and reduction in wastage. Rapid changes in the type of equipment and technological advancement has restructured the dynamics of the construction industry. Hence improving the productivity of Concrete Batching Plants and their supporting equipment will ensure better quality, durable and robust infrastructure development economically and sustainably. The high variability in site concreting operations, complex problems in logistical and combinational optimization are major hindrance factors that affect effective management strategies/procedures. Overall Reliability of the System (Concrete Batching Plant and Transit Mixer) is calculated using k out of n method algorithm developed by Barlow Heidman. A regression model is then developed for each of the equipment that tries to find out the factors on which the time to failure of a concrete batching plant depends upon and establishes a mathematical relationship with an acceptable level of accuracy. The model will act as a tool for future forecasting so that effective maintenance strategies can be duly formulated, and maintenance crew allotted/kept on standby just before the next failure to minimize loss of productivity due to equipment breakdown.

Keywords

Failure Modelling, Ready Mix Concrete, Overall Equipment Efficiency, Reliability.

1. Introduction

Since its inception in 1905 in Germany, the Concrete Batching Plant has undergone many modifications, and technological improvements to now serve as the backbone for infrastructural development. In the Indian context, it all started with the commencement of RMC plant in Pune in 1993. Although cement and concrete consumption is forecast to increase approximately at 3% to 4% globally, higher growth of about 6% to 8% is estimated to take place during the next decade in India. The construction industry is the backbone towards the proper growth and development of any nation. According to the Global Construction 2030 report, the amount of construction output will grow by 85% to $15.5 trillion globally by 2030, with primarily three countries, US, India, and China, taking the lead and explaining 57% of the global growth. The Global Construction 2030 report forecasts the average global construction growth to be 3.9% per annum till 2030 leaving behind even the global GDP by over one point (Global Construction 2030 Report, GCP, Oxford Economics, Mazloumian *et al.,*2015). The primary force behind this prediction is the continued industrialization of emerging countries and the developed nations coping with economic instability. Improving productivity of concrete batching and production has been the continuous striving force behind numerous studies and equipment improvement techniques in the construction industry (Elazouni, 1997; Sawhney, 2003; Cheng, 2016; Seeman, 2016*).* Continuous monitoring and control is also an essential ingredient towards understanding key issues hampering productivity. Productivity translates the input directly into cost savings and profitability (Proverbs *et al.,* 1998).

India today is a thriving economy undergoing rapid infrastructural growth. This growth translates to a massive increase in large and multifaceted complex projects -high rise towers, metros, city complexes, smart cities, elevated corridors, factory projects to name a few. India's construction market is estimated to be almost double that of China by 2030 (Global Construction Report 2030, GCP, Oxford Economics, Mazloumian *et al.,*2015). A staggering figure of 165 million more people will be added to India's population by 2030 with Delhi itself adding another 10.4 million people to become the world's second-largest city. The success and functionality of any project are primarily dependent on its concreting operations, hence improving their effectivity and productivity acts as a vital factor towards determining the project success. According to Mishra (2012), if the right kind of maintenance is not chosen, then it may lead to over maintenance or under maintenance which might increase the cost and reduce the productivity. Therefore, the cost-effective and right maintenance at the right time will boost the productivity of a system by reducing the total breakdown time and by reducing the frequency of breakdowns.

2. Objective and scope

The primary objective of this study is to calculate system reliability and analyze the factors which affect the time to failure of a concrete batching plant system consisting of two batching plants with a fleet of four transit mixers. A model that will provide a mathematical relationship and provide a tool for failure forecasting is subsequently developed with an acceptable level of accuracy.

3. Failure data modeling concepts

Maintenance is a support group function which is essential to support the production-related processes. Frequent breakdowns in the equipment of the production line affect the overall productivity. The usage of maintenance differs among the companies. Maintenance is of three categories: preventive, corrective and predictive maintenance.

One of the essential strategies to carry out effective and efficient maintenance is forecasting the breakdown patterns of the machines. The two critical aspects of the maintenance capacity are the number of people involved in the maintenance and the skill set of those people to carry out the maintenance activities (Daya *et al*., 2009). The breakdowns are highly uncertain in nature and hence the corrective maintenance load and higher repair time, and due to this uncertainty, the forecasting of the breakdown of the machines are essential (Daya *et al*., 2009). There are two approaches on which the forecasting is based on. One is quantitative data, and the other one is qualitative data. Qualitative data is collected in the form of interviews and expert personnel opinion, and this is done when the historical data on breakdowns cannot be collected for the machine. On the other hand, the quantitative data approach is used when this historical data on the machines are available. The forecasting model could be built by using this quantitative data. The following steps are suggested when developing a quantitative forecasting model (Daya *et al*., 2009):

- Define the variables and identify the causality
- Collect and validate the data
- Locate significant trends and seasonality
- Propose different forecasting models
- Validate the models and select the best one
- Improve its performance

MTBF: Mean Time Between Failure is defined as the average time between two successive failures.
There are two methods for determining the value of MTBF (Rahman and Kadirgama, 2009):
1. Estimate MTBF: The value of MTBF could be found from the historical data.
2. Predict MTBF: This method is used when the historical data is not available. The value of MTBF is found out based on the reliability design of the system.

$$MTBF = \frac{1}{Failure} = \frac{Total\ running\ time\ during\ the\ period\ of\ investigation}{Total\ number\ of\ failures\ within\ the\ system}$$

…...**Equation 1**

$$MTBF = MTTF + MTTR$$

……**Equation 2**

MTTR: Mean Time to Repair (Average amount of Time the equipment has spent in the workshop/repair yard)
MTTF: Mean Time to Failure (Ratio between number of total hours of service of all equipment to the number of equipment.

4. Research Methodology

A three-phase methodology was used to develop a failure modeling tool to forecast the next failure of the concreting equipment (batching plants, transit mixers, boom placers). Primary data was collected from the construction site (New Hot Strip Mill, Rourkela) with breakdown hours, time to failure, daily concrete consumption and time to repair as the parameters. From this data, the Mean Time Between Failure(MTBF), Mean Time to Repair(MTTR) and Mean Time to Failure(MTTF) is calculated as given in Equation 1 and 2. The reliability of the concreting system can be calculated utilizing the "*k out of n*" algorithm with the assumption that minimum one concrete batching plant and two transit mixers need to be in working condition for the site to continue its operations smoothly. Now, ANOVA (analysis of variance) is performed to determine the interdependent factors and then choose suitable dependent and independent variables and create a multivariable regression model. Validation of the model can be done with F-test, t-test and ANOVA analysis to test the goodness of fit, adequate sampling, and other necessary parameters. Numerical relationships are obtained to express time to failure as a function of cumulative time to repair and cumulative concrete produced for various concreting equipment utilized on site. The third phase consists of interpretation of the results found and significance of results obtained and their practical implications. This model will provide an invaluable tool to site officials to allocate necessary resources based on future concrete batching plant failures and devise effective maintenance strategies to minimize such failures.

5. Analysis: Reliability of the System (k out of n method)

5.1 Concrete Batching System

The Batching Plant System can be thought of as a 1 out of 2 systems. We shall apply the k out of n method to calculate the overall system reliability for the batching plant only as given by the Barlow and Headman Algorithm. From data collected at the site, it was observed that Batching Plant 1(BP01) had 3164 working hours out of which it was out of service for 34 hours; whereas Batching Plant 2(BP02) had 2584 working hours out of which it was out of service for 31 hours due to break down.

Hence probability of failure of BP01=34/3164=0.011

Reliability of BP01=1-0.011=0.989

the probability of failure of BP02=31/2684=0.012

Reliability of BP02=31/2864=0.988

The probabilities of failure and their individual reliabilities are given in Table 1.

Table 1: Probabilities of Failure and Reliabilities of BP01 and BP02

		BP01	**BP02**
R	Reliability	0.989	0.988
(1-R)	Failure	0.011	0.012

Since this is a 1 out of 2 combinations only one failure is allowed which allows for the following cases:

Case 1: Both Batching Plants in working condition

Case 2: Either of the Batching plants in working condition.

Hence the reliability of the batching plant system will be:

$$R_{BP}=R_1 R_2+(1-R_1)R_2+(1-R_2)R_1 \qquad \text{............ Equation 3}$$

R_{BP}= Overall Reliability of the concrete batching plant system.

R_1= Reliability of concrete batching plant 1.

R_2= Reliability of concrete batching plant 2.

The reliability of the batching plant system has been calculated in Table 2.

Table 2: Analysis of Various Cases

Cases	*Both Batching Plants Working*	*Only 1 Batching Plant Working*
	0.977	0.012
		0.011
	Total reliability of the system	**0.999**

5.2 Transit Mixer System

There are 4 transit mixers available at the site of which two must always be in working condition to ensure the smooth running of concreting operations. Hence this system can be thought of as a 2 out of 4 system. We shall apply the k out of n method to calculate the overall system reliability for the transit mixer system. From data collected at the site, it was observed that Transit Mixer 1(TM01) had 2650 working hours out of which it was out of service for 510 hours; whereas Transit Mixer 2(TM02) had 2868 working hours out of which it was out of service for 218 hours due to break down, Transit Mixer 3(TM03) had 2823 working hours with 162 breakdown hours,Transit Mixer 4(TM04) had 518 breakdown hours among a total of 2428 working hours.

Hence, probability of failure of TM01 =510/2650=0.011

Reliability of TM01=1-0.011= 0.808

Similarly, we calculate the values for TM02, TM03, TM04 and summarize the contents of Table 3 given below.

Table 3: Probabilities of Failure and Reliabilities of BP01 and BP02

		TM01	**TM02**	**TM03**	**TM04**
R	Reliability	0.808	0.924	0.943	0.766
(1-R)	Failure	0.192	0.076	0.057	0.234

Since this is a 2 out of 4 combinations only one failure is allowed which allows for the following cases:
Case 1: All four transit mixers working
Case 2: Only three transit mixers in working condition
Case 3: Only two transit mixers in working condition
Hence the overall reliability of the system will be:

$$\mathbf{R_{TM}=R_1R_2R_3R_4+(1-R_1)R_2R_3R_4+R_1(1-R_2)R_3R_4+R_1R_2(1-R_3)R_4+R_1R_2R_3(1-R_4)+(1-R_1)(1-R_2)R_3R_4+(1-R_1)R_2(1-R_3)R_4+(1-R_1)R_2R_3(1-R_4)+R_1(1-R_2)(1-R_3)R_4+R_1(1-R_2)R_3(1-R_4)+R_1R_2(1-R_3)(1-R_4)}$$

…. Equation 3

R_{TM}= Overall Reliability of the transit mixer system.
R_1= Reliability of transit mixer 1.
R_2= Reliability of transit mixer 2.
R_3= Reliability of transit mixer 3.
R_4= Reliability of transit mixer 4.

Table 4: Analysis of Various Cases

Cases	*All four transit mixers working*	*Only three transit mixers in working condition*	*Only two transit mixers in working condition*
	0.539	**0.128**	**0.011**
		0.044	**0.008**
		0.033	**0.039**
		0.165	**0.003**
			0.014
			0.010
	Total Reliability of the Transit Mixer System		**0.993**

5.3 Overall Reliability of the Concreting System

Since the concrete batching plant system and the transit mixer system are linked serially, the overall reliability of the concreting system can be calculated as $R_c=R_{BP}$ X R_{TM} = 0.999 X 0.993 = 0.992 or 99.2%.

R_c= Reliability of the Concreting System.

From "Nines" chart for "three nines," we obtain that the system will have a mean downtime of 8.76 hours per year, equivalent to 1.44 minutes of downtime per day. This result is an acceptable level of reliability for a high variability operation like concreting and shows efficient site management.

5.4 Development of Regression Models

From the raw data obtained at the site, the following Table 5 is formulated to calculate the Mean Time to Failure, Mean Time to Repair as given in Equations 1 and 2. Consequently one can get a brief idea as to what parameters are responsible for affecting the breakdown of an equipment.

Table 5: Calculation of MTBF, MTTR, Analysis of Batching Plant 1

No. of breakdowns	*Time to Failure*	*Time Between Failure*	*Cumulative MTBF*	*Cumulative MTTR*	*Cumulative Production Quantity (in cum.)*
1	**219.00**	**219.00**	**219.00**	**3.00**	**4706.26**
2	**596.00**	**377.00**	**298.00**	**6.50**	**21243.09**
3	**612.00**	**16.00**	**204.00**	**9.00**	**29222.37**
4	**3123.00**	**2511.00**	**780.75**	**8.20**	**34090.80**
5	**3222.00**	**99.00**	**644.40**	**9.20**	**53564.51**
6	**6408.00**	**3186.00**	**1068.00**	**10.20**	**58432.94**
7	**6442.00**	**34.00**	**920.29**	**10.80**	**68169.79**
8	**6564.00**	**122.00**	**820.50**	**11.40**	**73038.22**

Now a simple correlation analysis, as given in Table 6, shall be performed to determine which parameters are strongly linked with each other and to identify the dependent and independent variables for regression analysis. This analysis will give us a basic idea towards the formulation of the final model.

Table 6: Correlation table for Batching Plant 1

	No. of breakdowns	**Time to Failure**	**Time Between Failure**	**Cumulative MTBF**	**Time to Repair**	**Cumulative MTTR**	**Cumulative Production Qty (in cum.)**
No. of breakdowns	1.000						
Time to Failure	0.955	1.000					
Time Between Failure	0.108	0.306	1.000				
Cumulative MTBF	0.846	0.942	0.553	1.000			
Time to Repair	0.796	0.714	0.082	0.654	1.000		
Cumulative MTTR	0.911	0.812	0.123	0.725	0.887	1.000	
Cum. Production Qty (in cum.)	0.989	0.934	0.078	0.831	0.844	0.932	1.000

From correlation table (Table 6) for Batching plant 1, a strong positive correlation is obtained between Time to failure and Cumulative Production Quantity (=0.934), between Cumulative Mean Time Between Failure(MTBF) and Cumulative Production Quantity (=0.831), Cumulative Production Quantity and Cumulative Mean Time to Repair(MTTR) (=0.932), Cumulative MTBF and Time to Failure (=0.942), Cumulative Mean Time to Repair and Time to Failure (=0.812),Number of Breakdowns with Time to Failure (=0.955),Cumulative MTTR(=0.911),Cumulative Production Quantity(=0.989). Hence, Time to Failure is chosen as the dependent variable and Cumulative MTTR and Cumulative Production Quantity as independent variables to perform a multivariable regression analysis and obtain a failure model. Now, an ANOVA (Analysis of Variance) analysis, as given in Table 7, is performed with the following hypothesis:

Let, H_0 = Hypothesis that cumulative MTTR, cumulative production quantity does not affect time to failure
H_a = Hypothesis that cumulative MTTR, cumulative production quantity affect time to failure

Table 7: ANOVA Analysis for Batching Plant 1
(Dependent Variable: - Time to Failure; Independent Variables: -Cum. MTTR, Cum. Prod. Qty.)

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	48658481	16219494	22.050	0.006
Residual	5	5516753	1103351		
Total	8	54175234			

From ANOVA analysis given in Table 7, we obtain the total degrees of freedom(n-1) as 8, the regression degree of freedom(k) as 5 and residual degree of freedom(n-k-1) as 3.The regression sum of squares(SSR) is obtained as 48658481 and the sum of squared errors of prediction (SSE) is obtained as 5516753 with the total sum of squares or total variability(SST) to be 54175234.The mean sum of residuals(MSR) is obtained as 16219494, and the mean sum of errors(MSE) obtained is 1103351 From this we obtain the value of F^*=22.05033 which is higher than F(0.95,1,6)=5.99[from F-table]. Hence H_a holds which means there is a definite relationship between Time to Failure on Cumulative Time to Repair and Cumulative Concrete Produced for Batching Plant 1. Now we perform multivariable regression model taking Time to Failure as a function of cumulative time to repair and cumulative concrete produced. A confidence limit of 95% was taken for all the above calculations. The obtained coefficient of determination R^2=0.8981 with a standard error of 2.742 and the regression equation obtained is:

$$T_f = 645.104 + 0.118C_p - 455.047T_r \qquad \text{………… } \textbf{Equation 4}$$

where, T_f = Time to Failure
C_p = Cumulative Concrete Produced
C_t = Cumulative Concrete Transported
T_{ry} = Time to Repair

We shall repeat the procedure with the data obtained from Batching Plant 2, Transit Mixer 1(TM01), Transit Mixer 2(TM02), Transit Mixer 3(TM03), Transit Mixer 4(TM04). The comprehensive list of concrete equipment studied, their regression model equations with standard errors and coefficient of determination along with F-test values and significance values are summarized in Table 8 below.

Table 8: Summary of Regression Analysis of Concreting Equipment

Equipment Name	**Capacity**	**Regression Equation**	**R^2**	**Standard error**	**$F \leq F^*$**	**Significance value($p<0.05$)**
Concrete Batching Plant 1	**30 m^3/hr**	**$T_f = 645.104 + 0.118C_p - 455.047T_r$**	**0.898**	**2.742**	**F^*=22.05033 F(0.95,1,6)=5.99**	**0.006**
Concrete Batching Plant 2	**30 m^3/hr**	**$T_f = 92.592 + 0.086C_p - 51.186T_r$**	**0.996**	**82.981**	**F^*=3467.409 F(0.95,1,6)=5.99**	**3.96443E-16**

Transit Mixer 1	**6 m^3**	**$T_f = 86.912 + 0.58C_t - 9.821\ T_r$**	**0.999**	**2.741**	**F^*=303631.7** **F(0.95,2,2)=19**	**3.29345E-06**
Transit Mixer 2	**6 m^3**	**$T_f = 87.173 + 0.591C_t + 3.742T_r$**	**0.996**	**63.274**	**F^*=521.284** **F(0.95,1,10)= 4.96**	**7.74014E-11**
Transit Mixer 3	**6 m^3**	**$T_f = 230.520 + 0.635C_t - 28.230T_r$**	**0.993**	**71.300**	**F^*= 844.972** **F(0.95,1,11) =4.82**	**9.09632E-13**
Transit Mixer 4	**6 m^3**	**$T_f = -329.112 + 0.330C_t + 3.639T_r$**	**0.993**	**95.267**	**F^*=521.6566** **F(0.95,1,4)=5.96**	**1.46E-05**

6. Discussion and Conclusion

It is found that although the availability of Batching Plant 1**(**=86.99%) is higher, its productivity (24.727%) is lower than that of Batching Plant 2 **(**availability=73.08%; productivity=29.939%**).** This is due to the higher failure rate of Batching Plant 1 **(**=0.002) as compared to Batching Plant 2**(**=0.001**)** and exhaustion of its useful service life. Also, its overall equipment efficiency could also be less which can only be verified by further analysis in the future. From the overall reliability of the system, we find that the total reliability of the overall concreting system is found to be around 99.2% which translates to an effective downtime of 8.76 hours per year of the overall system. This percentage is a relatively acceptable level of reliability for a high variability operation like concreting and shows efficient site management. What is noteworthy is that the greater availability of a construction equipment does not guarantee a higher productivity as evidenced in this case study. Availability was calculated as the ratio between actual working hours and total working hours, whereas productivity was calculated as the ratio between actual quantity produced to that given in the specification of the equipment. A value of 24.727% and 29.939% suggests that the productivity output of the batching plants is quite low and better management and maintenance is necessary to improve its productivity. From the regression analysis of all the concreting equipment separately, it can be concluded that there is a significant relationship between Time to Failure on cumulative concrete produced/transported and cumulative mean time to repair. The value of R^2 for all the linear regression models was found to be within the range of 0.896 to 0.996 which suggests that the models accurately describe the hypothesized relationship. Also, the goodness of fit tests is satisfied as verified by the f-test performed on all the models. Furthermore, the significance value of all models is well below 0.05 which suggests that we can safely accept our hypothesis. To obtain a generalized equation rigorous data analysis from multiple sites is necessary, but there are specific barriers to such data collection since contractors and construction firms are usually hesitant sharing the breakdown data of their equipment to hide inefficient practices. It is interesting to note that while the cumulative time to repair had a negative coefficient in 50% of the cases, the cumulative concrete produced/transported always had a positive coefficient. This seems to suggest that while in half the cases a significant amount of time spent in the yard resulted in improvement of the machine and lowered frequency of breakdown, but the other half had entirely different results. Hence the subjective factors like mechanic skill, maintenance strategy followed, quality of spare parts, yard infrastructure does play a crucial role in determining the time to failure of the concreting equipment.

In this analysis, we only consider quantifiable factors for which data was available. There are many more factors such as operator skill, quality of raw materials, site conditions, climatic conditions which also affect the time to failure but are challenging to quantify numerically. Further research can be done to quantify them through questionnaire survey and inculcate them in the model.

7. References

Ben-Daya, M., Duffuaa, S.O., Raouf, A., Knezevic., J., and Ait-Kadi, D. (2009). *Handbook of Maintenance Management and Engineering*. Vol. 27, No. 2, Springer-Verlag London, London.

Betts M., Robinson G., Leonard J. (2015). *Global Construction 2030.* Global Construction Perspectives and Oxford Economics, London.

Kutner, Michael H., Nachtsheim, Christopher J., Neter John, Li, William (2005). *Applied Linear Statistical Models*. 5th ed., McGraw-Hill Irwin, Singapore.

Mishra, R. C., and Pathak K. (2012). *Maintenance Engineering and Management*.2nd ed., PHI Learning, New Delhi.

Rahman, M. M., & Kadirgama, K. (2009). *Proceedings of the National Conference on Postgraduate Research (NCON-PGR)*, Editors: M.M. Noor; M.M. Rahman and K. Kadirgama (October), Universiti Malaysia Pahang, Malaysia, pp. 165–175.

Sawhney, A., Walsh, K. and Mulky, A.R. (2003), “Agent-based modeling and simulation in construction.” *Proceedings of the 2003 Winter Simulation Conference*, Editors: S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, LA, USA, pp.1541-1547