[International Journal of Applied Research in Mechanical Engineering](https://www.interscience.in/ijarme)

Volume 3 | Issue 1 Article 1

July 2013

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FORMULATION OF MATHEMATICAL MODEL FOR MAINTENANCE COST OF A STONE CRUSHING PLANT BASED ON DIMENSIONAL ANALYSIS AND MULTIPLE REGRESSION

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Abstract- This paper presents the approach for the mathematical modeling of maintenance cost for the set up of new Stone Crushing Plant based on the dimensional analysis and multiple regression. Presented maintenance cost mathematical model is derived based on the generated design data. Design data is generated from actual design of all stone crushing plants followed by static and dynamic analysis. Estimation of design data is carried out based on the assumed plant layout. Dimensional analysis is used to make the independent and dependent variables dimensionless and to get dimensionless equation. Later, multiple regression analysis is applied to this dimensionless equation to obtain the index values based on the least square method. The mathematical model of maintenance cost is formulated using these obtained index values. Finally, the formulated model is evaluated on the basis of correlation and root mean square error between the computed values by model and the estimated values.

Keywords- *Stone Crushing plant, Dimensional Analysis, Multiple Regression, Mathematical Model*

I. INTRODUCTION

The most important reason for interest in developing a small capacity stone crusher is that till today for reducing sizes of stones from 10 cm x 10 cm to 2.5 cm x 2.5 cm in quarries is a laborious job and is done manually. Main issue in the production of stones with a desired size is the design of stone crushing plant and is one of the important challenges. The scope of research exists in this typical area for the mechanical and industrial engineering researchers.

This paper presents an approach for mathematical modeling of maintenance cost for the set up of new small capacity stone crushing plant. Plant design is the main issue for any manufacturing plant .Present work is based on the assumed stone crusher plant design. Concerned plant includes many resources and the optimal use of these resources with certain constrains is the focal issue. Stone crusher plant layout is prepared based on certain assumptions. Based on the plant layouts, various design data is estimated and further the design data is generated which later used in formulation of mathematical model which is based on the dimensional analysis and multiple regression.

II. APPROACH FOR STONE CRUSHING PLANT DESIGN

The suggested approaches for design of stone crushing plant with maintenance cost consist of following steps.
Step-1: Identification of input and output parameters.
Step-2: Estimation and Generation of Design data for various capacities.
Step-3: Formulation of the mathematical model for the stone crushing plant.
Step-1: Identification of input and output parameters

In this step, input and output parameters are identified with following assumptions:
1) All stone crushers are design based on capacity of 3Tonnes.
2) All stone crushers are design for reducing sizes of stones from 10 cm x 10 cm to 2.5 cm x 2.5 cm. in cross section.
3) All stone crushers are design for maximum torsional stress of 58 N/mm^2.
4) All stone crushers are design based on combined effect of static and dynamic forces into account [ref.1, 2, 3].

Present work is concern with the following input and output parameters. Input and output parameters are identified as the inputs and responses of the stone crushing plant.
Inputs: Area Occupied, Space Occupied, Cost of Brought Out Items, Design Time, Design Cost, Weight of the System, Acceleration due to Gravity, Moment of Inertia of Flywheel.
Area Occupied: This includes area required for various major component of the stone crushing plant such as motor, input shaft, pulley mounted on input shaft, v-belt ,pulley mounted on output shaft, output shaft, flywheel, couplings, bearings, worm gears, mechanism's area occupied.[ref.1,2,3]
Space Occupied: This includes volume required for various major component of the stone crushing plant such as motor, input shaft, pulley mounted on input shaft, v-belt ,pulley mounted on output shaft, output shaft, flywheel, couplings, bearings, worm gears, mechanism's area occupied.[ref.1,2,3]

Cost of Brought out Items: This includes cost of major components like motor, Gear Box, V-belt assembly, miscellaneous items like bearings, couplings, flywheel material, and Mechanism's material etc.

Design Time: This includes time required for literature survey, design of crank and rocker mechanism, design for transmission angle, design of double rocker mechanism, Static force Analysis, Dynamic force Analysis, flywheel design, Gear-Box selection, V-belt design, Motor Design, Selection of couplings & Bearings, Drawings.

Design Cost: Designer's salary is considered as approximately Rs.2000/- per day. In a day working hours are considered to be 6hours.Then design cost is calculated by multiplying design cost by design time in hours.

Weight of the System: This includes weight of all major components like motor, gear box, V-belt assembly, bearings, couplings, flywheel, Mechanism
Acceleration due to Gravity: It is taken as 9.81 m/s^2
Moment of Inertia of Flywheel: It is calculated as per designs of stone crushing plant; some are presented in papers [ref.1, 2, 3].

Responses: Productivity, maintenance cost, system efficiency, life, fabrication time, fabrication cost, maximum torsional stress.

In this paper we are taking maintenance cost as a response variable. Table. I gives all the input and response parameters.

TABLE: I SUMMERY OF INPUTS AND RESPONSES

Specification	Unit	Parameters	Estimation Based on
Area Occupied – A	cm^2	Input	Design of Stone crusher
Space Occupied –V	cm^3	Input	Design of Stone crusher
Cost of brought out items -C_{BI}	Rs. In Lacs	Input	Design and suppliers Quotations
Design Time -D_T	Hours	Input	Human efficiency and Design
Design Cost -C_D	Rs. In Lacs	Input	Human efficiency and Design
Weight of system -W_S	N	Input	Design of Stone crusher
Accelaration due to gravity–g	m/s^2	Input	Standard for Earth
Moment of Inertia of flywheel- I_F	Kg-mm^2	Input	Design of Stone crusher
Productivity	-	Response	Efficient conversion of inputs to outputs
maintenance cost	Rs. In Lacs	Response	Expected failures, Preventive maintenance of each equipment
system efficiency	-	Response	Combined efficiencies of all major Parameters
Life	Years	Response	Average Life of all major Parameters
fabrication time	Hours	Response	Fabrication of suggested design
fabrication cost	Rs. In Lacs	Response	Human resources availability
maximum torsional stress	N/mm^2	Response	Type of stresses exerting during loading condition

Step-2: Estimation and Generation of Design data for various capacities

Various inputs and responses with their unit of measure and the estimation of based on are summarized in the Table II. The data related to the inputs and response i.e. maintenance cost is generated based on the stone crushing plant capacity and the estimated data of inputs respectively.

Estimation of all the inputs for all eight designs is generated with certain assumptions. Few of them are published in the articles [ref. 1, 2, 3].All the response variables are also evaluated independently. Basic requirements of the stone crushing plant may get change as per desired capacities. Estimation of some of the input parameters is also changed due to the varying specification requirements for different capacities of plant.

Design data is generated using the estimated values of the input and response variables. The design data is already generated [ref.1, 2, 3].

TABLE: II DATA GENERATED FROM EIGHT PROPOSED DESIGNS OF STONE CRUSHERS:

Sr.No	Area Occupied	Space Occupied	Cost of brought out items	Design Time	Design cost	Weight of System	Accelaration Due to gravity	Moment of Inertia of Flywheel
	(cm^2)	(cm^3)	(Rs)	(Hrs)	(Rs)	(N)	(N/mm^2)	($Kg\text{-}mm^2$)
1	20,000	10,00,000	49.8 Lacs	600	2 Lacs	30,088	9.81	33.22
2	19,000	8,00,000	13.38 Lacs	500	1.67 Lacs	15,508	9.81	12.95
3	19,500	9,00,000	21.03 Lacs	450	1.5 Lacs	20,017	9.81	26
4	18,500	7,80,000	9.74 Lacs	300	1 Lacs	10,100	9.81	11.55
	22,500	10,50,000	49.13 Lacs	550	1.84 Lacs	32,155	9.81	8.3
6	22,000	9,50,000	12.75 Lacs	400	1.34 Lacs	16,500	9.81	3.23
7	22,500	9,75,000	21.42 Lacs	450	1.5 Lacs	21255	9.81	6.7
8	21,500	9,25,000	9.34 Lacs	320	1.06 Lacs	11700	9.81	2.88

Step-3: Formulation of the mathematical model for the stone crushing plant.

To start stone crushing plant, one will have to decide what should be the capacity of plant in order to get maximum productivity and minimum maintenance cost. These issues can be addressed if quantitative relationship between the inputs and responses of the plant is formulated in terms of mathematical model. Relationship amongst the inputs and response (maintenance cost) is established first, by doing the dimensional analysis of independent and dependent variables and followed by formulating multiple-linear-regression model. Formulated mathematical model is based on the generated designed data [ref.1, 2, 3]. In this paper, the mathematical model is formulated for maintenance cost.

III.DIMENTIONAL ANALYSIS

Formulation of dimensional equation is the first step to formulate the model of stone crushing plant. The variables to be predicted are called the responses or dependent variables and the variables predicting the responses are called the inputs or independent variables. The functional relationship amongst the inputs and response (maintenance cost) affecting the stone crushing plant is formulated using dimensional analysis. Following are the two methods for dimensional analysis:

1. Buckingham's π – theorem
2. Rayleigh's method

Above two methods provides the same results, in most of the cases but having slightly different approach of formulation. Rayleigh's method of dimensional analysis is used in this work and it expresses a functional relationship of inputs and response (maintenance cost) in the form of an exponential equation. The method involves the following steps:

1) Identification of the inputs those are likely to influence the response.
2) If X is a variable that depends upon input variables X_1, X_2, X_3,…… X_n then the functional equation can be written as

$$X = F(X_1, X_2, X_3, \ldots\ldots X_n)$$

3) Write the above equation in the form where C is a dimensionless constant and a, b, c,…….. m are arbitrary exponents.
4) Express each of the quantities in the equation in some fundamental units in which the solution is required.
5) By using dimensional homogeneity, obtain a set of simultaneous equations involving the exponents a ,b, c,…….. m.
6) Solve these equations to obtain the value of exponents a,b,c,…….m .
7) Substitute the values of exponents in the main equation, and form the non-dimensional parameters by grouping the inputs with like exponents.

Dimensional equation so obtained can be formulated into model using multiple-linear-regression analysis. Multiple-linear-regression analysis is a statistical tool that utilizes the relation between two or more quantitative variables so that one variable can predict from another. By using this methodology the dimensional equation and model is formulated for the maintenance cost. The formulated model is evaluated on the basis of correlation and root mean square error between the computed values by model and the estimated values.

Variables with Symbols and Dimensions:
Various inputs like equipments Area Occupied, Space Occupied, Cost of Brought Out Items, Design Time, Design Cost, Weight of the System, Acceleration due to Gravity, Moment of Inertia of Flywheel that affects the maintenance cost of stone crushing plant. Dimensional analysis is used to reduce the complexity of phenomenon of the maintenance cost. at initial stage and to deduce various inputs in non-dimensional form. Inputs involved in stone crushing plant is expressed dimensionally in terms of three fundamental quantities i.e. mass [M], length [L], time [T] and cost parameter represented as rupee [Rs] in dimensional form in presented work. List of various inputs (dependent variables) and responses (independent variables) with their symbol and dimensions is given in Table III.

TABLE III: LIST OF VARIABLE WITH SYMBOL AND DIMENSIONz

Sr.No	Name of Variable	Symbol	Type of Variable	Dimensions	Units
1	Area Occupied	A	Independent	L^2	mm^2
2	Space Occupied	V	Independent	L^3	mm^3
3	Cost of brought out items	C_{BI}	Independent	-	Rs
4	Design Time	D_T	Independent	T	Hrs.
5	Design Cost	C_D	Independent	-	Rs
6	Weight of system	W_S	Independent	MLT^{-2}	N
7	Accelaration due to gravity	G	Independent	LT^{-2}	N/mm^2
8	Moment of Inertia of flywheel	I_F	Independent	ML^2	$Kg\text{-}mm^2$
9	Productivity	P_R	Dependent	-	-
10	Maintenance cost	M_C	Dependent	-	Rs
11	System efficiency	S_E	Dependent	-	-
12	Life	L	Dependent	-	-
13	Fabrication time	F_T	Dependent	T	Hrs
14	fabrication cost	F_C	Dependent	-	Rs
15	maximum torsional stress	σ_T	Dependent	$ML^{-1}T^{-2}$	N/mm^2

IV. FORMULATION OF DIMENTIONAL EQUATION FOR THE RESPONSE AS THE MAINTENANCE COST

Formulation of dimensional equation for the response as the maintenance cost is based on the inputs identified for stone crushing plant .The maintenance cost is a function of inputs is represented in equation (1)

$C_M = f\,(A, V, C_{BI}, D_T, C_D, W_S, G, I_F)$…………(1)

As per methodology (dimensional analysis, as previously discussed), it is assumed that the relationship between these quantities exits and which is written as given in equation (2)

$C_{MI} = f_I\,[(A^3/V^2), (C_{BI} / C_D), (W_S\, G\, D^4_T / I_F)]$……(2)

Equation (2) represents the groups of non-dimensional parameter for the response variable (maintenance cost).Eight inputs for the stone power plant reduced to three dimensionless groups. Each group is represented as π term and is given table IV.

TABLE IV : NON-DIMENSIONAL GROUPS AS π TERMS

Variable Term	Dimensionless Groups	π terms
Inputs	A^3/V^2	π_1
Inputs	C_{BI} / C_D	π_2
Inputs	$W_S\, G\, D^4_T / I_F$	π_3
Response	C_{MI}	π

We have gathered the data of eight designs of stone crusher as given in table II, Then eight independent variables we convert into three π terms. Table V given below shows the values calculated for all eight design.

TABLE V: GENERATED VALUES OF π TERMS FOR ALL EIGHT DESIGNS

Sr.No	π 1	π 2	π 3
	A=A^3/V^2	B=CBI/ CD	$C = Ws \times g \times DT^4 / IF$
1	8.000	24.91	$1.151 * 10^{15}$
2	10.717	8.028	$7.34 * 10^{14}$
3	9.154	14.02	$3.097 * 10^{14}$
4	10.400	9.74	$6.94 * 10^{13}$
5	10.330	26.7	$3.478 * 10^{15}$
6	11.798	9.51	$1.28 * 10^{15}$
7	12.870	14.28	$1.276 * 10^{15}$
8	11.615	8.756	$4.178 * 10^{14}$

V. FORMULATION OF MODEL FOR MAINTENANCE COST

Formulation of dimensional groups for maintenance cost is given in equation (2) and is represented using π term as given in table IV to get equation (3) as follows:

$\pi = f\,[(\pi_1)^a, (\pi_2)^b, (\pi_3)^c]$………………(3)

Where, the all π terms are calculated from generated design data (table V) for stone crushing plant .Equation (3) represents the relationship of the response term π with the dimensionless group terms π_1,π_2,π_3.Therefore, the multiple regression model for maintenance cost as a function of various inputs is written as equation (4)

$\pi = k \times (\pi_1)^a \times (\pi_2)^b \times (\pi_3)^c$ ………………(4)

Where k, a, b and c are the constant exponent or called as an index of respective π terms or regression coefficients. Equation (4) represents a nonlinear relationship between inputs and response. The logarithmic transformation of response provides log-linear form, which is commonly used in linear regression analysis. Equation (4) is simplified by taking log of both the sides, and is expressed in equation (5).

$[\log \pi] = \log k + a \log (\pi_1) + b \log (\pi_2) + c \log(\pi_3)$ …(5)

Equation (5) is multiple-linear-regression model with three regressor variables and is linear function of nknown parameters are calculated from the generated designed data using least squares method.

Therefore, above equation (6)

$$\sum Y = nK1 + a\sum A + b\sum B + c\sum C$$

$$\sum YA = K1\sum A + a\sum A^2 + b\sum AB + c\sum AC$$
$$\sum YB = K1\sum B + a\sum AB + b\sum B^2 + c\sum BC$$
$$\sum YC = K1\sum C + a\sum AC + b\sum BC + c\sum C^2$$
……………… (6)

Where Y = log π, k1 = log k, A = log (π_1), B = log (π_2), C = log (π_3) are calculated by using the π terms values and is given in table VI. Constants k1, a, b and c are calculated from using MATLAB the generated designed data using least square method. Therefore above equation (6) is solved for k, a, b and c using least square method and the calculations are worked out by using the equation (7), where n=8, is total number of data samples. Equation (7) is solved using MATLA

$$\begin{pmatrix} \sum Y \\ \sum YA \\ \sum YB \\ \sum YC \end{pmatrix} = \begin{pmatrix} n & \sum A & \sum B & \sum C \\ \sum A & \sum A^2 & \sum AB & \sum AC \\ \sum B & \sum AB & \sum B^2 & \sum BC \\ \sum C & \sum AC & \sum BC & \sum C^2 \end{pmatrix} x \begin{pmatrix} k1 \\ a \\ b \\ c \end{pmatrix} \quad \text{.........(7)}$$

TABLE :VI LOG EVALUATION OF π TERMS FOR ALL EIGHT DESIGNS

Sr.No	LOG (π_1)	LOG (π_2)	LOG (π_3)	LOG(π_1xπ_1)	LOG(π_2x π_2)	LOG(π_3x π_3)	LOG(π_1xπ_2)	LOG(π_2xπ_3)	LOG(π_1xπ_3)
1	0.903089987	1.396373728	15.061	0.815571525	1.949859587	226.833721	1.261051	21.03078	13.60143
2	1.030073231	0.904607364	14.865	1.061050861	0.818314483	220.968225	0.93181	13.44698	15.31203
3	0.961610908	1.146748014	14.49	0.924695539	1.315031007	209.9601	1.102725	16.61637	13.93374
4	1.017033339	0.988558957	13.841	1.034356813	0.977248811	191.573281	1.005397	13.68264	14.07675
5	1.014100322	1.426511261	15.541	1.028399462	2.034934379	241.522681	1.446625	22.16941	15.7601
6	1.071808392	0.978180517	15.107	1.148773229	0.956837124	228.221449	1.048422	14.77737	16.19180
7	1.109578547	1.154728207	15.105	1.231164552	1.333397233	228.161025	1.281261	17.44216	16.76018
8	1.065019214	0.942305753	14.62	1.134265926	0.887940132	213.7444	1.003573	13.77651	15.57058
Total	$\sum$A = **8.172313939**	$\sum$B= **8.9380138**	$\sum$C = **118.63**	$\sum A^2$ = **8.378277906**	$\sum B^2$= **10.27356276**	$\sum C^2$= **1760.984882**	$\sum$AB= **9.080868**	$\sum$BC= **132.9422**	$\sum$AC= **121.2066**

Sr.No	Mainte-nance Cost	LOG (π)	LOG (π π_1)	LOG (π π_2)	LOG (π π_3)
	Y2 (Rs)				
1	250000	5.397940	4.874825572	7.537541611	81.29837447
2	80000	4.903089	5.050541743	4.435371308	72.88443266
3	110000	5.041392	4.847858198	5.781207048	73.04978001
4	50000	4.698970	4.779009155	4.645208886	65.03844383
5	250000	5.397940	5.474052698	7.700222211	83.88938567
6	65000	4.812913	5.158520925	4.707898075	72.70868208
7	110000	5.041392	5.59382117	5.821438338	76.15023651
8	50000	4.698970	5.004493341	4.427866468	68.69894146
Total	---	$\sum$Y= **39.99260**	$\sum$YA= **40.7831228**	$\sum$YB= **45.05675394**	$\sum$YC= **593.7182767**

The following matrix represents the equations, which is used for programming

[$\sum$Y; $\sum$YA; $\sum$YB; $\sum$YC] = [39.99260874; 40.7831228; 45.05675394; 593.7182767]

[n, $\sum$A, $\sum$B, $\sum$C;$\sum$A, $\sum A^2$, $\sum$AB, $\sum$AC; $\sum$B, $\sum$AB, $\sum B^2$, $\sum$BC; $\sum$C, $\sum$AC, $\sum$BC, $\sum C^2$] =

[8, 8.172313939, 8.9380138, 118.63; 8.172313939, 8.378277906, 9.080868771, 121.2066847; 8.9380138, 9.080868771, 10.27356276, 132.9422607; 118.63, 121.2066847, 132.9422607, 1760.984882]

Solving, the above matrix equation by using MATLAB software, following values are obtained.

k1 = 2.2800
a = -1.1364
b = 0.8287
c = 0.1992

Implementation Results and Discussion

After solving equation in MATLAB, the following values of constants are found out. Since k1 is LOG k , hence k = 190.546.The values of a,b,c are as it is .Solving, the above matrix equation by using MATLAB software, the values of different indices have been found out. Using above values of constant and indices the following model is obtained

$\pi = 190.546 \text{ x } (\pi_1)^{-1.1364} \text{ x } (\pi_2)^{0.8287} \text{ x } (\pi_3)^{0.1992}$ …. (8)

VI. CONCLUSION AND FUTURE SCOPE

The key points for formulating mathematical modeling is to keep in mind the maintenance cost are the important response variables. As per process flow and the specifications of the desired maintenance cost, the dependency and independency of the resources can be established. Once the relational model is prepared, the objectives of desired mathematical modeling can be identified, which then make the concern problem as the single or multi objective problem. Later it can be solved by classical or non- classical methods. Different models can be possible according to the desires of the individuals, perspective of the engineer involved in designing of the plant.

In present work, an approach for mathematical model of maintenance cost is discussed. This paper deals with the dimensional analysis and multiple regression analysis. Formulated mathematical model provides the detail of dependency of the maintenance cost on the inputs. It is found that there are three groups on which the maintenance cost depends out of which some typical group have the dominant role in deciding the quantity of maintenance cost. From equation (8), it is clear that the second group (π_2) plays very important role in the evaluation of the maintenance cost, as the power of the second group is largest. The generated design data is used for the mathematical model formulation for the stone crushing Plant. All this work is carried out with certain assumptions. If the data range is other than the range which is used in mathematical model formation, then, the curve for the dependent variable deviates for the other data range. This is happening because the model is developed using multiple linear regression analysis. Therefore, presented model is suitable for the range of the identified capacities. Mathematical formulation can be carried out by using different existing mechanisms and/or techniques. This paper provides the new direction of work for the researchers to optimize the design of any plant by generating design data which then be used for the formulation of mathematical model.

In future, different mathematical model can be formulated, such as, productivity model ,system efficiency, life ,fabrication cost, fabrication time, torsional stress model etc. Presented work deals with the multiple linear regression analysis, but one can go for the same problem as the multiple-nonlinear regression problem. Presented model can be enhanced or evaluated against the other models which can be developed by considering other techniques of regression. Presented model can be evaluated by using the neural network. For this, one has to go for the formation neural network based on the generated data for the typical model, here for instance, maintenances cost. Reliability of the presented model can be evaluated based on the evaluation of the actual values of the group terms and the evaluated values of the group terms using the proposed mathematical model. Correlation of these two values can be evaluated, based on which the reliability of the presented model can be predicted.

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