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The Impact of Dimensional Analysis on Corrugated Sheet Manufacturing Process using Buckingham Pi Theorem

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Abstract- ***Studies carried out for corrugated sheet box manufacturing industries having man machine system revealed the contribution of many independent parameters on cycle time and human energy. The independent parameters include anthropometric data of workers, personal data, machine specification, workplace parameters, product specification, environmental conditions and mechanical properties of corrugated sheet. Their effect on dependent parameters cycle time and human energy was totally unknown. The present study focuses on Dimensional Analysis (DA), formulating a mathematical model in terms of Pi terms using Buckingham's Pi theorem between independent and dependent parameters. The objective of this study is to minimize the error between the experimental values and computed values obtained from mathematical model using dimensional analysis. In order to get the clear picture of this manufacturing process, it is decided to study the actual scene of manufacturing of three different industries. All other conditions remaining same, it will enable to estimate the influence of running practices at three different organizations.***

Index Terms **- Buckingham's Pi Theorem, Corrugated Sheet Box, Coefficient of Correlations, Dimensional Analysis (DA), Mathematical Model, Regression Analysis.**

I. INTRODUCTION

Machine like movement of the man and there synchronization is commonly seen with majority of industries. Corrugated sheet boxes are packaging products used worldwide. Manufacturing of these boxes involves inseparable activities between man and machine. Manufacturing units for such boxes are generally from small scale and exhibit poor housekeeping. The production of corrugated sheet boxes is influenced by number of factors of industrial importance. To straight some of them are machines, tools, work stations, environment, operators, skill set and management perspective. It is the dream of any industry to maximize the profit, produce large quantity of high quality as output. The operational strategies of any industry are reasonable blend of available resources, management attitude and routine operations. This work aims at study of man machine system in the manufacturing process of corrugated sheet boxes. Further to analyze various contributors and there effects on productivity. It also aims at minimization of human energy as one of the resource. In order to get the clear picture of this manufacturing process, it is decided to study the manufacturing process at three different industries. All other conditions remaining same, it will enable to estimate the influence of management practices at three different organizations. The objective of improving production rate is equivocal to reduction of per piece cycle time. The work involves setting of two functions as below, Minimize t = f1 (x1, x2, x3, x4-----------xn) and Minimize E = f2(x1, x2, x3, x4-----------xn) Where t= Cycle time and E= Human energy.

II. LITERATURE REVIEW

The Buckingham Pi theorem may sometimes be misused as a general solution method for complex engineering problems. Dimensional analysis can not necessarily solve general problems, nor can it even add to understanding unless it is used to some legitimate purpose [1]**.** In attempting to solve a problem, an engineer often tries analytic mathematical methods first. Equations stating the relations that must be satisfied are set up. Solution of these equations then gives the desired relations existing between the different variables in the problem. Very often, however, it happens that it is very difficult or even impossible to set up and solve analytical equations. In such cases dimensional analysis will frequently give a solution. The Buckingham pi theorem is a very powerful tool of dimensional analysis. This theorem is particularly well adapted for use by engineers since little mathematical knowledge is necessary. The underlying physical principles, however, must be well known. This theorem was formulated by Dr. Edgar Buckingham of the Bureau of Standards. The pi theorem is somewhat more sophisticated and may be applied to more intricate problems [2]. Dimensional analysis is a method for reducing complex physical problems to their simplest (most economical) forms prior to quantitative analysis or experimental investigation. Its use in science and engineering is ubiquitous. Applications are many, including astrophysics, electromagnetic theory, radiation, aerodynamics, ship design, heat and mass transfer, explosions, chemical reactions and processing etc. dimensional analysis reduces a problems degree of

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freedom to the minimum and thus suggests the most economical scaling laws. It can be particularly useful in exploratory investigations of novel phenomena for which the equations and boundary conditions have not yet been fully articulated. Simply omitting the quantities that have fixed values and performing dimensional analysis on the rest will not answer the question. Dimensional analysis must be based on a complete set of independent quantities that define the quantity of interest, that is, all quantities with values that may affect the quantity of interest must be included regardless of whether some have invariant values in the cases that are under consideration. Omitting even one relevant independent variable can fatally damage the analysis. We show when and how some such problems can be simplified further, that is, when their Π-groups can be reduced below the number predicted by Buckingham's theorem [3]. "Buckingham – Π theorem is a mathematical theorem used in dimensional analysis that predicts the number of non-dimensional groups that must be functionally related from a set of dimensional parameters that are thought to be functionally related"[4]. In real life engineering problem, when equations for a system are unavailable and experimentation is the only the method of obtaining reliable results, tests are performed on a geometrically scaled model, rather than a full-scale prototype. This saves both time and money. For modeling up the system, dimensional analysis is a powerful tool with primary purpose of: Generating non – dimensional parameters that help in the design of experiments (physical and / or numerical) and in the reporting of experimental results. Predict prototype performance from model performance. Predict (sometimes) the trends in the relationships between parameters. **Buckingham's – Π theorem** provides the relation for the number of independent non – dimensional parameters also referred to as Πs. There are several quite simple ways in which a given test can be made compact in operating plan without loss in generality or control. The best known and most powerful of these is dimensional analysis. Some fifty years ago, dimensional analysis was used primarily as an experimental tool and specifically as a means whereby several experimental variables could be combined to form one. As the technique gradually became a part of engineering curriculums, the original purpose behind the methods slipped away [5]. Dimensional Analysis (DA) is a well-known methodology used in physics and traditional engineering areas in order to empower the model formulation and to cut efforts in the empirical assessment phases. The highest achievement of DA is the Buckingham theorem (or pi-theorem or P-theorem), which states that any equation modeling a physical problem can be rearranged and simplified using a set of dimensionless variables (or numbers, or ratios) so that the number of variables originally used to describe the problem can be reduced by the number of independent fundamental physical quantities used in the original equation. In this way, the modeler can save variables to handle and, above all, get a richer knowledge of the studied phenomenon. Once we are confident of the proposed dimensionless set, the study moved to the development of a regression relation to estimate the FMS throughput. In this regard, it is pretty evident the advantage brought about by the BT, since we moved from the original equation $Th=f(N_{PAL},N_{WC},N_{LUS},T_{PRO},N_{PCS},T_{LU},T_{LUPA},T_{ROR},V,D,T_{TC},N_{TC})$ to the simplified equation: $\Pi1=F(\Pi1,\Pi2,\Pi3,\Pi4,\Pi5,\Pi6,\Pi7,\Pi8,\Pi9)$. Stemming from the numerical analysis, the following regression model was obtained: $\Pi1=0.263-0.0416\Pi_2-0.0922\Pi_3-0.0477\Pi_4-0.087\Pi_5- \Pi_6+0.144\Pi_7+0.0326(\Pi_2\Pi_3)+0.0745(\Pi_3\Pi_5)-0.0802(\Pi_3 . \Pi_7)$ whose performances are convincing, as testified by $R^2adj=94.1\%$ and $R^2pred=92.8\%$ [6].

III. CORRUGATED SHEET BOX MANUFACTURING PROCESS

Cardboard packaging is one of the most widely used forms of packaging. The corrugated cardboard is stiff, strong and light in weight material made up of layers of brown craft paper. These brown craft paper rolls are transported to a corrugation machine where this paper gets crimped and glued to from corrugated cardboard called as single face corrugated board and then this single face corrugated board is cut according required dimension on the cutting machine. According to requirement by adding another corrugating medium and a third flat printed liner creates a double wall corrugated board or triple wall corrugated boards on gluing or bonding machine called as 3ply 5ply and 7ply.

Then these cardboards are transferred to creasing and cutting machine where extra material is removed and creasing operation is performed (i.e., from where the box get folded). The next operation is slotting operation where the strip plate is slotted for stitching and finally with stitching operation corrugated box is manufactured. The entire sequence of corrugation sheet box manufcturing operation is shown in Fig. 1.

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Reel Decal Inventory WS1 Printing WS2Corrugation WS3 Gluing/Pasting

WS4 Horizontal Creasing WS5 Vertical Creasing WS6 Stitching WS7 Slotting

Fig. 1 Snap Shot of Manufacturing Process of Corrugated Sheet Box

IV. IDENTIFICATION OF VARIABLES

The term variables are used in a very general sense to apply any physical quantity that undergoes change. If a physical quantity can be changed independent of the other quantities, then it is an independent variable. If a physical quantity changes in response to the variation of one or more number of variables, then it is termed as dependent or response variable as shown in Table I.

Table I. Independent Variables

Sr. No.	Description of Variables	Symbol	MLT Indices	Unit of Measurement
1	Arm span(X1)	As	$M^0 L^1 T^0$	cm
2	Foot breadth(X2)	Fb	$M^0 L^1 T^0$	cm
3	Height(X3)	Ht	$M^0 L^1 T^0$	cm
4	Arm reach(X4)	Ar	$M^0 L^1 T^0$	cm
5	Qualification grade(X5)	Qgr	$M^0 L^0 T^0$	dimensionless
6	BMI prime(X6)	BMI prime	$M^0 L^0 T^0$	dimensionless

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Sr. No.	Description of Variables	Symbol	MLT Indices	Unit of Measurement
7	Age(X7)	Ag	$M^0 L^0 T^1$	Years
8	Experience(X8)	Exp	$M^0 L^0 T^1$	Months
9	Power HP(X9)	P	$M^1 L^2 T^{-3}$	H.P.
10	Stroke/Seconds(X10)	Sps	$M^0 L^0 T^{-1}$	Hz
11	Age of Machine(X11)	Aom	$M^0 L^0 T^1$	Years
12	Machine down time(X12)	Mc_dt	$M^0 L^0 T^1$	hours
13	Production rate of Machine(X13)	P_{rate} of Mc	$M^0 L^0 T^{-1}$	/sec
14	Roller speed(X14)	Rs	$M^0 L^1 T^{-1}$	mm/sec
15	Weight of Machine(X15)	Wt	$M^1 L^0 T^0$	kg
16	Machine Width(X16)	Mc_ wth	$M^0 L^1 T^0$	mm
17	Height of stool(X17)	Hos	$M^0 L^1 T^0$	cm
18	Height of work table(X18)	Htw	$M^0 L^1 T^0$	cm
19	Spatial distance between centroid of stool top and work table(X19)	Sd1	$M^0 L^1 T^0$	cm
20	Area of tabletop(X20)	Areattop	$M^0 L^2 T^0$	cm^2
21	Spatial distance between centroid of stool top and WIP table(X21)	Sd2	$M^0 L^1 T^0$	cm
22	Thickness(X22)	t	$M^0 L^1 T^0$	mm
23	Length(X23)	L	$M^0 L^1 T^0$	mm
24	Breadth(X24)	B	$M^0 L^1 T^0$	mm
25	Part Weight(X25)	Part_Wt	$M^1 L^0 T^0$	kg
26	Mc_criticality(X26)	Mc.criti.	$M^0 L^0 T^0$	dimensionless
27	Volume of Box(X27)	V	$M^0 L^3 T^0$	cm^3
28	Bursting strength(X28)	Bs	$M^1 L^{-2} T^0$	Kg/cm^2
29	Bursting Factor(X29)	Bf	$M^0 L^0 T^0$	dimensionless
30	Illumination sight range (Average)(X30)	Isr	$M^1 L^3 T^{-1}$	Lux
31	Noise level with Operation(X31)	dBopr	$M^0 L^0 T^0$	dBA
32	Dry bulb temperature(X32)	DBT	$M^0 L^0 T^0 K^1$	^{O}C
33	Illumination at work table(X33)	Iwt	$M^1 L^3 T^{-1}$	Lux
34	Noise level without Operation(X34)	dB	$M^0 L^0 T^0$	dBA
35	Wet bulb temperature(X35)	WBT	$M^0 L^0 T^0 K^1$	^{O}C
36	Caliper(X36)	Cal	$M^0 L^1 T^0$	mm
37	Puncture Resistance Test(X37)	PRT	$M^1 L^1 T^0$	Kg-cm
38	Edge Crushing Test (X38)	ECT	$M^1 L^{-1} T^0$	kN/m
39	Flat Crushing Test(X39)	FCT	$M^1 L^{-2} T^0$	Kg/cm^2
40	Cobb(X40)	Cob	$M^1 L^{-2} T^0$	g/m^2
41	Moisture (%)(X41)	Mois.	$M^0 L^0 T^0$	dimensionless
42	Box Compression Test Peak Load in Kg(X42)	PL	$M^1 L^0 T^0$	kg
43	Box Compression Test Peak Load / Perimeter(X43)	PLP	$M^1 L^{-1} T^0$	Kg/cm

Table II. Dependent Variables

Sr. No.	Description of Variables	Symbol	MLT Indices	Unit of Measurement
1	Cycle time(Y1)	cytime	$M^0 L^0 T^1$	Seconds
2	Human Energy input at end of the shift(Y2)	pulse	$M^0 L^0 T^0$	RMVBITS

If a physical quantity that affects our test is changing in random and uncontrolled manner, then it is called an extraneous variable. The variables affecting the effectiveness of the phenomenon under consideration are anthropometric data of operators, personal factors of an operator, workstation machine specification, workplace parameters, specification of the products, environmental conditions and mechanical properties of corrugated sheet boxes. The dependent or the response variables in this case is cycle time and human energy recorded at the end of the shift as shown in Table II.

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V. REDUCTION OF INDEPENDENT VARIABLES / DIMENSIONAL ANALYSIS (DA)

There are several quite simple ways in which a given test can be made compact in operating plan without loss in generality or control. The best known and the most powerful of these is dimensional analysis. In the past dimensional analysis was primarily used as an experimental tool whereby several experimental variables could be combined to form one. The field of fluid mechanics and heat transfer were greatly benefited from the application of this tool. Almost every major experiment in this area was planned with its help. Using this principle modern experiments can substantially improve their working techniques and be made shorter requiring less time without loss of control. Deducing the dimensional equation for a phenomenon reduces the number of independent variables in the experiments. The exact mathematical form of this dimensional equation is the targeted model. This is achieved by applying Buckingham's π theorem (Hilbert, 1961).When we apply this theorem to a system involving n independent variables, (n minus number of primary dimensions viz. L, M, T, and π) i.e. (n-4) numbers of π terms are formed. When n is large, even by applying this theorem number of π terms will not be reduced significantly than number of all independent variables. Thus much reduction in number of variables is not achieved. It is evident that, if we take the product of the terms it will also be dimensionless number and hence a π term. This property is used to achieve further reduction of the number of variables. Dimensional analysis is used to reduce the variables and following Pi terms were evolved out of it as shown in Table III and Table IV.

Table III. Pi Term Formulation for Independent Variables

Pi term relating to Anthropomorphic Data		
Arm span	As	$\pi 1 = (As \times Fb) \div (Ht \times Ar)$ In terms of MLT Indices $\Pi 1 = \frac{(M^0L^1T^0 \text{ x } M^0L^1T^0)}{(M^0L^1T^0 \text{ x } M^0L^1T^0)}$
Foot breadth	Fb	
Height	Ht	
Arm reach	Ar	
Pi term relating to Personal factors of an Operator		
Qualification grade	Qgr	$\pi 2 = (Qgr \times BMI\ prime \times Ag \times S) \div (Exp)$ In terms of MLT Indices $\Pi 2 = \frac{(M^0L^0T^0 \text{ x } M^0L^0T^0 \text{ x} M^0L^0T^1 \text{ x } M^0L^0T^0)}{(M^0L^0T^1)}$
BMI prime	BMI prime	
Age	Ag	
Experience	Exp	
Sex	S	
Pi term relating to Machine Specification		
Power HP	P	$\pi 3 = (P \times P_{rate}\ of Mc \times Aom \times Mc\_dt) \div (Wt \times Sps \times Mc\_Wth \times rps)$ In terms of MLT Indices $\Pi 3 = \frac{(M^1L^2T^3 \text{ x } M^0L^0T^{-1} \text{ x} M^0L^0T^{-1} \text{ x } M^0L^0T^1)}{(M^1L^0T^0 \text{ x } M^0L^1T^1 \text{ x } M^0L^1T^0 \text{ x } M^0L^0T^1)}$
Stroke/Seconds	Sps	
Age of Machine	Aom	
Machine Down Time	Mc_dt	
Roller Speed	rps	
Production rate of Machine	P_{rate} of Mc	
Machine Width	Mc_ wth	
Weight of Machine	Wt	
Pi term relating to Workplace Parameters		
Height of stool	Hos	$\pi 4 = (Hos \times Htw \times Sd1) \div (Areattop \times Sd2)$ In terms of MLT Indices $\Pi 4 = \frac{(M^0L^1T^0 \text{ x } M^0L^1T^0 \text{ x } M^0L^1T^0)}{(M^0L^2T^0 \text{ x } M^0L^1T^0)}$
Height of work table	Htw	
Spatial distance between centroid of stool top and work table	Sd1	
Area of tabletop	Areattop	
Spatial distance between centroid of stool top and WIP table	Sd2	
Pi term relating to Specification of the Product		
Thickness	t	$\pi 5 = (Bs \times Vol \times Bf \times t) \div (Part\_Wt \times Mc\_criti \times B \times L)$
Length	L	

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Breadth	B	In terms of MLT Indices $\Pi5 = \frac{M^1L^{-2}T^0 \times M^0L^3T^0 \times M^0L^0T^0 \times M^0L^1T^0}{M^1L^0T^0 \times M^0L^0T^0 \times M^0L^1T^0 \times M^0L^1T^0}$
Part Weight	Part_Wt	
Mc_criticality	Mc_criti.	
Volume	V	
Bursting Strength	Bs	
Bursting Factor	Bf	
Pi term relating to Environmental Condition		
Illumination sight range (Average)	Isr	$\pi6 = (Isr \times dBopr \times DBT) \div (Iwt \times dB \times WBT)$ In terms of MLT Indices $\Pi6 = \frac{M^1L^3T^{-1} \times M^0L^0T^0 \times M^0L^0T^0K^1}{M^1L^3T^{-1} \times M^0L^0T^0 \times M^0L^0T^0K^1}$
Noise level with Operation	dBopr	
Dry bulb temperature	DBT	
Illumination at work table	Iwt	
Noise level without Operation	dB	
Wet bulb temperature	WBT	
Pi term relating to Mechanical Properties of a Corrugated Box		
Caliper	Cal	$\pi7 = (Cal \times ECT \times FCT \times Mois \times PL) \div (PRT \times Cob \times PLP)$ In terms of MLT Indices $\Pi7 = \frac{M^0L^1T^0 \times M^1L^{-1}T^0 \times M^1L^{-2}T^0 \times M^0L^0T^0 \times M^1L^0T^0}{M^1L^1T^0 \times M^1L^{-2}T^0 \times M^1L^{-1}T^0}$
Puncture Resistance Test	PRT	
Edge Crushing Test	ECT	
Flat Crushing Test	FCT	
Cobb	Cob	
Moisture (%)	Mois.	
Box Compression Test Peak Load in Kg	PL	
Box Compression Test Peak Load / Perimeter	PLP	

Table IV. Pi Term Formulation for Dependent Variables

Pi term relating to Cycle Time		
Cycle Time	cytime	$\pi8 = (cytime) \div (m/coptime)$ In terms of MLT Indices $\Pi8 = \frac{M^0L^0T^1}{M^0L^0T^1}$
Machine Operation Time	m/coptime	
Pi term relating to Human Energy		
Pulse	pulse	$\pi9 = (pulse) \div (rmvbits)$ In terms of MLT Indices $\Pi9 = \frac{M^0L^0T^0}{M^0L^0T^0}$
RMV Bits	rmvbits	

VI. MODEL FORMULATION

The data of the independent and dependent parameters of three similar corrugated sheet box industries having same man machine system has been gathered during experimentation. In this case there are two dependent and seven independent pi terms involved in the experimentation. It is necessary to correlate various independent and dependent pi terms involved in this system quantitatively. This correlation is nothing but a mathematical model as a design tool for such workstation. Based on the experimentation work performed on the actual scene of manufacturing, using classical plan of experimentation, Deduction of generalized Experimental Models for the dependent π terms is discussed.

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A. Formulation of Experimental Data Based Model

Seven independent pi terms (Π1, Π2, Π3, Π4, Π5, Π6, Π7) and two dependent pi terms (Π8, Π9) have been considered in the design of experimentation and are available for the model formulation.

Independent Π terms = (Π1, Π2, Π3, Π4, Π5, Π6, Π7), Dependent Π terms = (Π8, Π9)

Each dependent Π term is assumed to be function of the available independent Π terms,

t = f (Π1, Π2, Π3, Π4, Π5, Π6, Π7)

Where, t = Π8, Dependent pi term "f (Π8) = function of (Π1, Π2, Π3, Π4, Π5, Π6, Π7)"

E= Π9, Dependent pi term "f (Π9) = function of (Π1, Π2, Π3, Π4, Π5, Π6, Π7)"

A probable exact mathematical form for this phenomenon could be the empirical relationships in between dependent dimensionless ratio and independent dimensionless ratio and are assumed to be exponential.

Following eighteen mathematical relationships or models are formed for three industries and three products with respect to dependent variable cycle time and human energy i.e. (Pr1 Vs Ct, Pr1 Vs Pul, Pr2 Vs Ct, Pr2 Vs Pul and Pr3 Vs Ct, Pr3 Vs Pul).

$\Pi8 = k \times (\Pi1)^{a} \times (\Pi2)^{b} \times (\Pi3)^{c} \times (\Pi4)^{d} \times (\Pi5)^{e} \times (\Pi6)^{f} \times (\Pi7)^{g}$ (1)

Considering Equation 1 to simplify

$\Pi8 = k \times (\Pi1)^{a} \times (\Pi2)^{b} \times (\Pi3)^{c} \times (\Pi4)^{d} \times (\Pi5)^{e} \times (\Pi6)^{f} \times (\Pi7)^{g}$ (2)

Taking log of both the sides

$\text{Log}\,[\Pi8] = \text{Log}\,[k \times (\Pi1)^{a} \times (\Pi2)^{b} \times (\Pi3)^{c} \times (\Pi4)^{d} \times (\Pi5)^{e} \times (\Pi6)^{f} \times (\Pi7)^{g}]$

Using logarithmic rule,

Log [A x B] = Log A + Log B

$\text{Log}\,[\Pi8] = \text{Log}\,[k] + \text{Log}\,[(\Pi1)^{a}] + \text{Log}\,[(\Pi2)^{b}] + \text{Log}\,[(\Pi3)^{c}] + \text{Log}\,[(\Pi4)^{d}] + \text{Log}\,[(\Pi5)^{e}] + \text{Log}\,[(\Pi6)^{f}] + \text{Log}\,[(\Pi7)^{g}]$

Using logarithmic rule,

$\text{Log}\,[A^{B}] = B \times \text{Log}\,A$

Log (Π8) = Log (k) + a x Log (Π1) + b x Log (Π2) + c x Log (Π3) + d x Log (Π4) + e x Log (Π5) + f x Log (Π6) + g x Log (Π7)

Z = K + [a A] + [b B] + [c C] + [d D] + [e E] + [f F] + [g G] (3)

Equation (3) is a regression equation of Z on A, B, C, D, E, F and G in a dimensional co-ordinate system.

In above equation, a, b, c, d, e, f, g are unknowns whose value are to be find out, while A, B, C, D, E, F and G are set of values obtained during experimentation.

To solve the above equation, multiply coefficient of a, b, c, d, e, f and g individually,

Multiplying by A, $AZ = AK + [a A^2] + [b AB] + [c AC] + [d AD] + [e AE] + [f AF] + [g AG]$

Multiplying by B, $BZ = BK + [a AB] + [b B^2] + [c BC] + [d BD] + [e BE] + [f BF] + [g BG]$

Multiplying by C, $CZ = CK + [a AC] + [b BC] + [c C^2] + [c CD] + [e CE] + [f CF] + [g CG]$

Multiplying by D, $DZ= DK + [a AD] + [b BD] + [c CD] + [d D^2] + [e DE] + [f DF] + [g DG]$

Multiplying by E, $EZ = EK + [a AE] + [b BE] + [c CE] + [d DE] + [e E^2] + [f EF] + [g EG]$

Multiplying by F, $FZ = FK + [a AF] + [b BF] + [c CF] + [d DF] + [e EF] + [f F^2] + [g FG]$

Multiplying by G, $GZ= GK + [a AG] + [b BG] + [c CG] + [d DG] + [e EG] + [f FG] + [g G^2]$

Above Set of equations are valid for the number of reading taken during experimentation, therefore taking summation of these for n values,

The equations become,

$\sum (Z) = n*K + [a \sum (A)] + [b \sum (B)] + [c \sum (C)] + [d \sum (D)] + [e\sum (E)] + [f \sum(F)] + [g \sum(G)]$

$\sum (AZ) = K*\sum A + [a \sum (A^2)] + [b \sum (AB)] + [c \sum (AC)] + [d \sum (AD)] + [e \sum (AE)] + [f \sum (AF)] + [g \sum (AG)]$

$\sum (BZ) = K*\sum B + [a \sum (AB)] + [b \sum (B^2)] + [c \sum (BC)] + [d \sum (BD)] + [e \sum (BE)] + [f\sum (BF)] + [g \sum (BG)]$

$\sum (CZ) = K*\sum C + [a \sum (AC)] + [b \sum (BC)] + [c \sum (C^2)] + [d \sum (CD)] + [e \sum (CE)] + [f \sum (CF)] + [g \sum (CG)]$

$\sum (DZ) = K*\sum D + [a \sum (AD)] + [b \sum (BD)] + [c \sum (CD)] + [d \sum (D^2)] + [e \sum (DE)] + [f \sum (DF)] + [g \sum (DG)]$

$\sum (EZ) = K*\sum E + [a \sum (AE)] + [b \sum (BE)] + [c \sum (CE)] + [d \sum (DE)] + [e \sum (E^2)] + [f \sum (EF)] + [g \sum (EG)]$

$\sum (FZ) = K*\sum F + [a \sum (AF)] + [b \sum (BF)] + [c \sum (CF)] + [d \sum (DF)] + [e \sum (EF)] + [f \sum (F^2)] + [g \sum (FG)]$

$\sum (GZ) = K*\sum G + [a \sum (AG)] + [b \sum (BG)] + [c \sum (CG)] + [d \sum (DG)] + [e \sum (EG)] + [f \sum (FG)] + [g \sum (G^2)]$

(4)

To solve these equations, reducing it to matrix form

[P] = [Z] *[Indices Matrix]

Therefore

[Indices Column Matrix] = Inverse [Z] *[P]

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By putting the values for various parameters in the matrices shown below the following indices in Table V are obtained.

$$
\begin{pmatrix} \Sigma Z1 \\ \Sigma Z1A \\ \Sigma Z1B \\ \Sigma Z1C \\ \Sigma Z1D \\ \Sigma Z1E \\ \Sigma Z1F \\ \Sigma Z1G \end{pmatrix} = [P] \quad
\begin{pmatrix}
N & \Sigma A & \Sigma B & \Sigma C & \Sigma D & \Sigma E & \Sigma F & \Sigma G \\
\Sigma A & \Sigma A^2 & \Sigma AB & \Sigma AC & \Sigma AD & \Sigma AE & \Sigma AF & \Sigma AG \\
\Sigma B & \Sigma AB & \Sigma B^2 & \Sigma BC & \Sigma BD & \Sigma BE & \Sigma BF & \Sigma BG \\
\Sigma C & \Sigma AC & \Sigma BC & \Sigma C^2 & \Sigma CD & \Sigma CE & \Sigma CF & \Sigma CG \\
\Sigma D & \Sigma AD & \Sigma BD & \Sigma CD & \Sigma D^2 & \Sigma DE & \Sigma DF & \Sigma DG \\
\Sigma E & \Sigma AE & \Sigma BE & \Sigma CE & \Sigma DE & \Sigma E^2 & \Sigma EF & \Sigma EG \\
\Sigma F & \Sigma AF & \Sigma BF & \Sigma CF & \Sigma DF & \Sigma EF & \Sigma F^2 & \Sigma FG \\
\Sigma G & \Sigma AG & \Sigma BG & \Sigma CG & \Sigma DG & \Sigma EG & \Sigma FG & \Sigma G^2
\end{pmatrix} = [Z] \quad
\begin{pmatrix} K \\ a \\ b \\ c \\ d \\ e \\ f \\ g \end{pmatrix}
$$

= Indices column Matrix

Table V. Abbreviations Used For Mathematical Modeling

Log (Π8) = Z
Log (k) = K
Log (Π1) = A
Log (Π2) = B
Log (Π3) = C
Log (Π4) = D
Log (Π5) = E
Log (Π6) = F
Log (Π7) = G

Using Scilab-5.3.3 following values are obtained

p =

$$
\begin{pmatrix} 63.546015 \\ -131.20789 \\ 263.35425 \\ -491.26092 \\ -68.39491 \\ 271.34501 \\ 45.611855 \\ 52.849909 \end{pmatrix}
$$

z =

84.	- 173.08107	351.96666	- 657.5656	- 73.316369	369.15461	60.667432	70.062288
- 173.08107	356.90434	- 724.76542	1352.7115	151.79889	- 759.17741	- 125.1063	- 144.36257
351.96666	- 724.76542	1537.6495	- 2765.4825	- 203.27228	1523.9906	280.36073	293.56654
- 657.5656	1352.7115	- 2765.4825	5263.4253	501.36826	- 2922.9979	- 483.01637	- 548.67925
- 73.316369	151.79889	- 203.27228	501.36826	305.63105	- 339.40751	- 11.560775	- 61.15134
369.15461	- 759.17741	1523.9906	- 2922.9979	- 339.40751	1656.0891	257.25962	307.90258
60.667432	- 125.1063	280.36073	- 483.01637	- 11.560775	257.25962	59.052975	50.019236
70.062288	- 144.36257	293.56654	- 548.67925	- 61.15134	307.90258	50.019236	64.330347

-->inv (z)*p

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Ans =

10.712741	(Antilog 10.712741 = 44924.563=K)
2.8315571	= a
- 0.5026113	=b
- 0.1035394	=c
0.0153408	=d
- 0.6965155	=e
0.3389875	=f
0.0037730	=g

Industry 1

Table VI. Mathematical Model Indices Using DA for Industry 1

Model	K (Constant)	a	b	c	d	e	f	g
M1(Pr1 Vs Π8)	44924.563	2.831	-0.502	-0.103	0.015	-0.696	0.338	0.003
M2(Pr1 Vs Π9)	0.864	-0.116	0.005	-0.009	-0.004	-0.011	-0.015	0.002
M3(Pr2 Vs Π8)	569708.439	3.563	-0.665	-0.105	0.055	-0.834	0.346	0.015
M4(Pr2 Vs Π9)	0.734	-0.178	0.007	-0.012	-0.005	-0.009	-0.013	-0.005
M5(Pr3 Vs Π8)	43424.974	3.234	-0.290	-0.064	-0.034	-0.599	0.191	0.005
M6(Pr3 Vs Π9)	1.240	-0.006	-0.014	-0.007	0.0008	-0.020	0.002	0.002

Putting the values of indices from Table VI in the equation (3) we get mathematical model.
The various mathematical models for three products are stated below.

$\Pi 8$ (**M1**) $=44924.5637*\Pi 1^{2.8315571}*\Pi 2^{-0.5026113}*\Pi 3^{-0.1035394}*\Pi 4^{0.0153408}*\Pi 5^{-0.6965155}*\Pi 6^{0.3389875}*\Pi 7^{0.003773}$

$\Pi 9$ (**M2**) $=0.864062651*\Pi 1^{-0.1167155}*\Pi 2^{0.0058204}*\Pi 3^{-0.0098635}*\Pi 4^{-0.0047379}*\Pi 5^{-0.0114402}*\Pi 6^{-0.0152789}*\Pi 7^{0.0023288}$

$\Pi 8$ (**M3**) $=569708.4399*\Pi 1^{3.5633325}*\Pi 2^{-0.6656638}*\Pi 3^{-0.1057087}*\Pi 4^{0.055631}*\Pi 5^{-0.8340323}*\Pi 6^{0.3462495}*\Pi 7^{0.0153582}$

$\Pi 9$ (**M4**) $= 0.734981463*\Pi 1^{-0.1789282}*\Pi 2^{0.007433}*\Pi 3^{-0.0120809}*\Pi 4^{-0.0055131}*\Pi 5^{-0.0095751}*\Pi 6^{-0.0130512}*\Pi 7^{-0.0051806}$

$\Pi 8$ (**M5**) $=1.240198317*\Pi 1^{-0.0069027}*\Pi 2^{-0.0144753}*\Pi 3^{-0.0078644}*\Pi 4^{0.0008706}*\Pi 5^{-0.0201663}*\Pi 6^{0.0021459}*\Pi 7^{0.0022971}$

$\Pi 9$ (**M6**) $=1.240198317*\Pi 1^{-0.0069027}*\Pi 2^{-0.0144753}*\Pi 3^{-0.0078644}*\Pi 4^{0.0008706}*\Pi 5^{-0.0201663}*\Pi 6^{0.0021459}*\Pi 7^{0.0022971}$

Computed values based on above sited mathematical model could be readily possible by just putting the values of corresponding Pi terms.

Using IBM SPSS Statistical 20.0 software for windows the coefficient correlations for experimental and computed values of cycle time and pulse are computed as below:

Table VII. Coefficient of Correlations and Root Mean Square Error for Industry 1

Dimensional Analysis Result		
Model	**Coefficient of Correlations**	**R.M.S. Error**
M1(Pr1 Vs Cycle Time)	0.820	0.346
M2(Pr1 Vs Pulse)	0.804	0.020
M3(Pr2 Vs Cycle Time)	0.825	0.412
M4(Pr2 Vs Pulse)	0.701	0.013
M5(Pr3 Vs Cycle Time)	0.839	0.297
M6(Pr3 Vs Pulse)	0.686	0.020

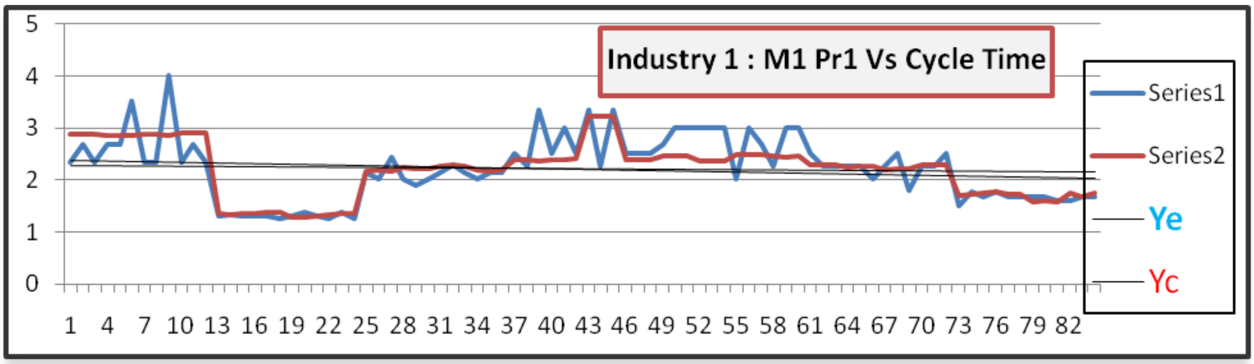

Fig. 2 DA Y experimental Vs Y computed Industry 1

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VII. INTERPRETATION OF MODEL: PRODUCT 1 VS CYCLE TIME

DA is a method for reducing complex physical problems to their simplest (most economical) forms prior to quantitative analysis or experimental investigation. Out of 43 independent variables, using Buckingham's Pi Theorem it has been reduced to 7 dimensionless Pi term. Indices depicted in the model 1(Pr1 Vs Cycle Time) divulge clear cut scenario about influential group of variables which will have substantial impact on cycle time reduction. Term Π1 bears the index with absolute value 2.831, this Pi term represents anthropomorphic data of the operator, as it is already proved by previous researcher that anthropomorphic data plays critical role for overall productivity improvement, here this term will have momentous impact to reduce cycle time . One unit increase in the sited index will lead to increase cycle time on the contrary decrementation is possible with one unit reduction. Π5 represents specification of product which bear index of -0.6960, Π2 represents personal factors of the operators bears the index of -0.502, Π6 represents environment conditions bears the index of 0.338 will have a significant impact on cycle time. Other dimensionless groups such as machine specification (Π3), workplace parameters (Π4) and mechanical properties of corrugated sheet box (Π7) will also lead to reduce cycle time but with very less impact.

Table VIII. Model Summary $Y_{experimental}$ V_s $Y_{computed}$

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics: R Square Change	F Change	df1	df2	Sig. F Change
1	.820[a]	.672	.668	.2947	.672	167.956	1	82	.000

a. Predictors: (Constant), YEXPT

b. Dependent Variable: YCOMPU

R-square:

This model represents the value of the coefficient of determination, "R Square" and of $s = \sqrt{MSE}$, the "standard error of the estimate. The coefficient of multiple determinations is 0.672; therefore, about 67.2 % of the variation in the Cycle Time (CTIME) is explained by independent pi term variables. The standard error of the estimate s = 0.2947. Precise prediction of cycle time would be possible from the depicted model as the coefficient of correlation is adequately concise as shown in Table VIII.

Table IX. ANOVA Table

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	14.584	1	14.584	167.956	.000[a]
	Residual	7.120	82	8.683E-02		
	Total	21.705	83			

a. Predictors: (Constant), YEXPT

b. Dependent Variable: YCOMPU

The last column of the ANOVA table shows the goodness of fit of the model. Lower this number, the better is the fit. Typically, if "Sig" is greater than 0.05, we conclude that our model could not fit the data. If Sig < 0.01, then the model is significant at 99%, if Sig < 0.05, then the model is significant at 95%, and if Sig < 0.1, the model is significant at 90%. Significance implies that we can accept the model. If Sig>0.1 then the model was not significant (a relationship could not be found) or "R-square is not significantly different from zero." In this case Sig = 0.000 hence the model is accepted as shown in Table IX.

One of the next useful pieces of the output is the histogram of the residuals as shown in Fig. 3 and Fig.4:

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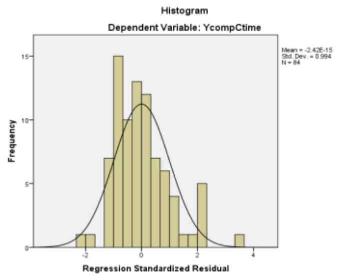

Fig. 3 Histogram Ye Vs Yc

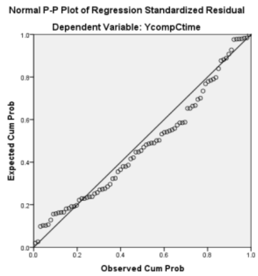

Fig. 4 Normal P-P Plot Ye Vs Yc

Idealized Normal Curve: In order to meet the classical assumptions the residuals should roughly follow this curves shape. The thick curve should lie close to the diagonal. The next interesting piece of the output is the P-P plot to check on whether the residuals are normally distributed. Cycle Time appears to be linearly related to each of the predictor variables with no visible potential outliers or influential observations i.e. any points away from the main cluster of points.

Industry 2

Table 1 Mathematical Model Indices Using DA for Industry 2

Model	K (Constant)	a	b	c	d	e	f	g
M1(Pr1 Vs Π8)	1.716	-0.999	-0.383	0.142	-0.127	-0.095	1.186	0.055
M2(Pr1 Vs Π9)	0.960	-0.078	-0.014	-0.009	-0.010	-0.026	0.020	0.007
M3(Pr2 Vs Π8)	0.503	-2.358	-0.680	0.123	-0.158	-0.219	0.731	0.089
M4(Pr2 Vs Π9)	0.982	-0.072	-0.012	-0.009	-0.010	-0.025	0.020	0.010
M5(Pr3 Vs Π8)	26.738	-0.118	-0.120	-0.006	-0.069	-0.518	-0.170	-0.017
M6(Pr3 Vs Π9)	0.984	-0.069	-0.012	-0.009	-0.010	-0.025	0.021	0.011

Putting the values of indices from Table X in the equation (3) we get mathematical model.
The various mathematical models for three products are stated below.

Π8 (**M1**) $=1.716257*\Pi1^{-0.99968}*\Pi2^{-0.38311}*\Pi3^{0.142025}*\Pi4^{-0.12799}*\Pi5^{-0.09577}*\Pi6^{1.186915}*\Pi7^{0.055545}$

Π9 (**M2**) $=0.960376*\Pi1^{-0.07818}*\Pi2^{-0.01411}*\Pi3^{-0.0096}*\Pi4^{-0.01099}*\Pi5^{-0.02672}*\Pi6^{0.020029}*\Pi7^{0.00747}$

Π8 (**M3**) $=0.503455*\Pi1^{-2.35808}*\Pi2^{-0.68086}*\Pi3^{0.123206}*\Pi4^{-0.15845}*\Pi5^{-0.21923}*\Pi6^{0.731248}*\Pi7^{0.089632}$

Π9 (**M4**) $=0.982092*\Pi1^{-0.07202}*\Pi2^{-0.01278}*\Pi3^{-0.00948}*\Pi4^{-0.01003}*\Pi5^{-0.02527}*\Pi6^{0.020255}*\Pi7^{0.010797}$

Π8 (**M5**) $=26.73801*\Pi1^{-0.11843}*\Pi2^{-0.12057}*\Pi3^{-0.00633}*\Pi4^{-0.06982}*\Pi5^{-0.51888}*\Pi6^{-0.17017}*\Pi7^{-0.01791}$

Π9 (**M6**) $=0.984501*\Pi1^{-0.06952}*\Pi2^{-0.01283}*\Pi3^{-0.00956}*\Pi4^{-0.01072}*\Pi5^{-0.02535}*\Pi6^{0.021717}*\Pi7^{0.011002}$

In the above Dimensional Mathematical Model put the values of Π terms and computed output variables cycle time and pulse for three different products is found.
Using SPSS 20.0 for windows the coefficient correlations for experimental and computed values of cycle time and pulse are found as below.

Table XI. Coefficient of Correlations and Root Mean Square Error for Industry 2

Dimensional Analysis Result		
Model	**Coefficient of Correlations**	**R.M.S. Error**
M1(Pr1 Vs Cycle Time)	0.707	0.917
M2(Pr1 Vs Pulse)	0.744	0.011
M3(Pr2 Vs Cycle Time)	0.665	0.615
M4(Pr2 Vs Pulse)	0.763	0.011
M5(Pr3 Vs Cycle Time)	0.704	0.440
M6(Pr3 Vs Pulse)	0.768	0.011

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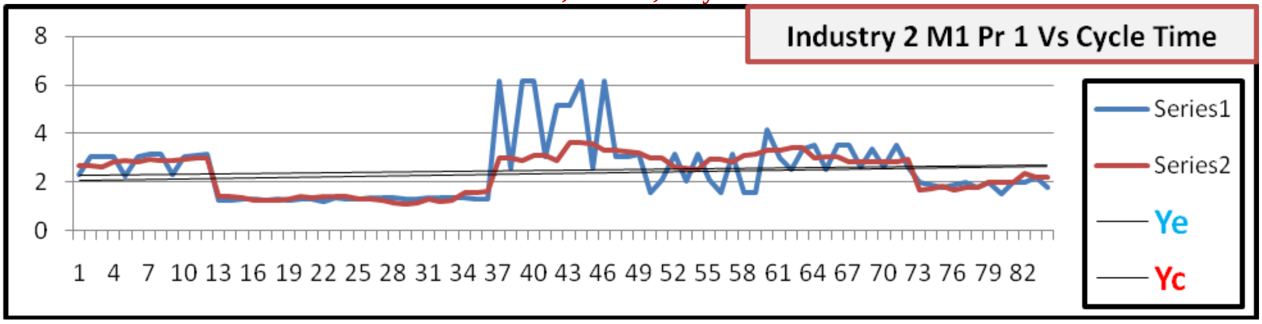

Fig. 5 DA Y experimental Vs Ycomputed Industry 2

Industry 3

Table XII. Mathematical Model Indices Using DA for Industry 3

Model	K (Constant)	a	b	c	d	e	f	g
M1(Pr1 Vs Π8)	199.301	0.882	-0.168	0.016	-0.006	-0.428	-0.069	-0.049
M2(Pr1 Vs Π9)	1.995	0.203	-0.011	0.006	0.00003	-0.016	-0.007	0.002
M3(Pr2 Vs Π8)	18.045	0.824	-0.058	-0.105	-0.014	-0.235	-0.092	0.015
M4(Pr2 Vs Π9)	2.035	0.2007	-0.011	0.006	-0.0003	-0.019	-0.012	0.007
M5(Pr3 Vs Π8)	51207.946	3.587	-0.349	-0.008	0.046	-0.440	0.157	0.030
M6(Pr3 Vs Π9)	1.995	0.204	-0.010	0.006	0.0002	-0.017	-0.012	0.007

Putting the values of indices from Table XII in the equation (3) we get mathematical model.
The various mathematical models for five products are stated below.

$\Pi 8\ (\mathbf{M1}) = 199.3015491*\Pi 1^{0.8821287}*\Pi 2^{-0.1685043}*\Pi 3^{0.0167341}*\Pi 4^{-0.0060449}*\Pi 5^{-0.4282205}*\Pi 6^{-0.0697533}*\Pi 7^{-0.0492393}$

$\Pi 9\ (\mathbf{M2}) = 1.995742178*\Pi 1^{0.2037712}*\Pi 2^{-0.0114446}*\Pi 3^{0.0065818}*\Pi 4^{0.0000398}*\Pi 5^{-0.0166827}*\Pi 6^{-0.0078184}*\Pi 7^{0.0022812}$

$\Pi 8\ (\mathbf{M3}) = 18.0450781*\Pi 1^{0.8249335}*\Pi 2^{-0.0586876}*\Pi 3^{-0.1058562}*\Pi 4^{-0.0144956}*\Pi 5^{-0.2355941}*\Pi 6^{-0.0920099}*\Pi 7^{0.0150288}$

$\Pi 9\ (\mathbf{M4}) = 2.035071595*\Pi 1^{0.2076665}*\Pi 2^{-0.0114769}*\Pi 3^{0.0064827}*\Pi 4^{-0.000343}*\Pi 5^{-0.0190182}*\Pi 6^{-0.0123499}*\Pi 7^{0.0075835}$

$\Pi 8\ (\mathbf{M5}) = 51207.94629*\Pi 1^{3.5870063}*\Pi 2^{-0.3490271}*\Pi 3^{-0.0081689}*\Pi 4^{0.0469004}*\Pi 5^{-0.4404392}*\Pi 6^{0.1577948}*\Pi 7^{0.0307684}$

$\Pi 9\ (\mathbf{M6}) = 1.995442839*\Pi 1^{0.2041128}*\Pi 2^{-0.0107404}*\Pi 3^{0.0065768}*\Pi 4^{0.0002942}*\Pi 5^{-0.0178484}*\Pi 6^{-0.0120317}*\Pi 7^{0.0077803}$

In the above Dimensional Mathematical Models put the values of Π terms and computed output variables cycle time and pulse for three different products is found as shown in Table VII, Table XI and Table XIII.
From this computed values the graph is plotted between the Y experimental Vs Ycomputed as shown in Fig.2, Fig. 5 and Fig.6
Using SPSS 20.0 for windows the coefficient correlations for experimental and computed values of cycle time and pulse are found as below

Table 2. Coefficient of Correlations and Root Mean Square Error for Industry 3

Dimensional Analysis Result		
Model	**Coefficient of Correlations**	**R.M.S. Error**
M1(Pr1 Vs Cycle Time)	0.940	0.144
M2(Pr1 Vs Pulse)	0.631	0.018
M3(Pr2 Vs Cycle Time)	0.848	0.206
M4(Pr2 Vs Pulse)	0.634	0.018
M5(Pr3 Vs Cycle Time)	0.847	0.152
M6(Pr3 Vs Pulse)	0.637	0.018

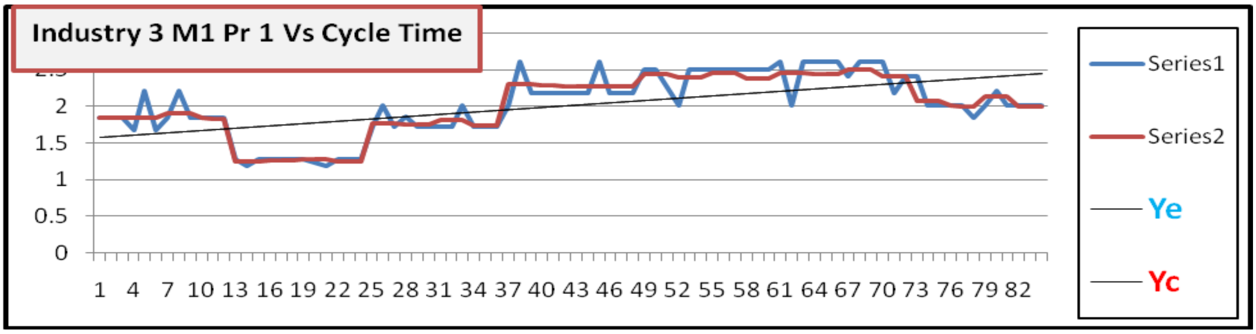

Fig. 6 DA Y experimental Vs Ycomputed Industry 3

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VIII. DISCUSSION

In this study three corrugated sheet boxes for three industries is studied and a generalized field data base mathematical model using Buckingham's Pi Theorem is developed to simulate its process cycle time and human energy of operator (pulse) to improve the productivity and profit. The approach to formulate a generalized mathematical model is to provide excellent and simple way to analyze the corrugated sheet box manufacturing complex process where the impact of field data is dominating the performance. It can be seen from the mathematical model equation that this model containing cycle time and human energy as response variables depends on Pi term. The following primary conclusion appear to be justified from the above models

1. Industry 1

The absolute index of π1 for cycle time as response variable is highest viz. 2.831, 3.563, 3.234. This π1 term represents anthropomorphic data of the operator. Thus the dimensionless term π1 is the most influencing factors which affects the cycle time. The value of this index is positive indicating cycle time π8 is directly varying with respect to π1. The absolute index of π7 is lowest viz. 0.003, 0.015, 0.005. Π7 term represents mechanical properties of corrugated box are having least influence on cycle time in the model. The value of the index is negative indicating cycle time is inversely varying with respect to π2 and π5. The sequence of influence of the additional independent pi terms π3, π4, π6, is having absolute indices as shown in table 5 is having less impact on cycle time respectively. The absolute index of π1 for pulse as response variable is highest viz. -0.116, -0.178, -0.006. The value of the index is negative indicating pulse is inversely varying with respect to π1.

2. Industry 2

The absolute index of π1 for cycle time as response variable is highest viz. -0.999, -2.358, -0.118. This π1 term represents anthropomorphic data of the operator. Thus the dimensionless term π1 is the most influencing factors which affects the cycle time. The value of this index is negative indicating cycle time π8 is inversely varying with respect to π1. The absolute index of π7 is lowest viz. 0.055, 0.089, -0.017. Π7 term represents mechanical properties of corrugated box are having least influence on cycle time in the model. The sequence of influence of the additional independent pi terms π2, π3, π5, π6 is having absolute indices as shown in table 5 is having less impact on cycle time respectively. The absolute index of π1 for pulse as response variable is highest viz. -0.078, -0.072, -0.069. The value of the index is negative indicating cycle time π8 is inversely varying with respect to π1. The absolute index of π3 is lowest viz. -0.009, -0.009, -0.009. Π3 term represents machine specifications are having least influence on pulse in the model.

3. Industry 3

The absolute index of π1 for cycle time as response variable is highest viz. 0.882, 0.824, 3.587. This π1 term represents anthropomorphic data of the operator. Thus the dimensionless term π1 is the most influencing factors which affects the cycle time. The value of this index is positive indicating cycle time π8 is directly varying with respect to π1. The absolute index of π4 is lowest viz. -0.006, -0.014, and 0.046. Π4 term represents workplace parameters are having least influence on cycle time in the model. The value of the index is negative indicating cycle time is inversely varying with respect to π4. The sequence of influence of the additional independent pi terms π2, π3, π5, π6, π7 is having absolute indices as shown in table 5 is having less impact on cycle time respectively. The absolute index of π1 for pulse as response variable is highest viz. 0.203, 0.2007, 0.204. The value of the index is positive indicating pulse is directly varying with respect to π1.

IX. CONCLUSION

The mathematical model formulated is used to analyze the data and to establish relationship between different variables of corrugated sheet box manufacturing process. The dimensional equations are established in reduced or compact mode in order to make the complete experimentation process less time taking having generation of optimum data. The experimental data is generated for formulation of the mathematical model. The experimental data from three different industries having similar manufacturing process and man machine system for three products is gathered. These include the measurement of cycle time and human energy as response variable using specially designed electronic stop watch and SPO_2 pulse oxymeter etc. The indices of mathematical model were formulated using regression analysis. The DA for the above sited models suggest that π1 the anthropometric data is the most influencing parameters for all three industries and all three products affecting the cycle time and pulse as response variables.

Π1	Π2	Π3	Π4	Π5	Π6	Π7	Π8= Y_1=Ye(Ct)	Π8= Yc(Ct)
0.116107	31.08	0.001846	0.069998	39.12133	1.382881	1.845239	2.3333333	2.8797416

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0.116107	31.08	0.001938	0.069998	39.12133	1.382881	1.845239	2.6666667	2.8652307
0.116107	31.08	0.001892	0.069998	39.12133	1.382881	1.845239	2.3333333	2.8723885
0.116107	31.08	0.001892	0.069998	39.12133	1.342271	2.867886	2.6666667	2.8482476
0.116107	31.08	0.001846	0.069998	39.12133	1.342271	2.867886	2.6666667	2.855539
0.116107	31.08	0.001846	0.069998	39.12133	1.342271	2.867886	3.5	2.855539
0.116107	31.08	0.001846	0.069998	39.12133	1.367723	1.702743	2.3333333	2.8681327
0.116107	31.08	0.001892	0.069998	39.12133	1.367723	1.702743	2.3333333	2.8608093
0.116107	31.08	0.001938	0.069998	39.12133	1.367723	1.702743	4	2.8536803
0.116107	31.08	0.001892	0.069998	39.12133	1.410234	3.120132	2.3333333	2.8972602
0.116107	31.08	0.001892	0.069998	39.12133	1.410234	3.120132	2.6666667	2.8972602
0.116107	31.08	0.001846	0.069998	39.12133	1.410234	3.120132	2.3333333	2.904677
0.129645	24.75	0.000358	0.144643	273.8493	1.328125	1.845239	1.3	1.3449223
0.129645	24.75	0.000418	0.144643	273.8493	1.328125	1.845239	1.3157895	1.3236269
0.129645	24.75	0.000358	0.144643	273.8493	1.328125	1.845239	1.3	1.3449223
0.129645	24.75	0.000418	0.144643	273.8493	1.4	2.867886	1.3	1.3497311
0.129645	24.75	0.000358	0.144643	273.8493	1.4	2.867886	1.3	1.3714465
0.129645	24.75	0.000358	0.144643	273.8493	1.4	2.867886	1.25	1.3714465
0.129645	24.75	0.000418	0.144643	273.8493	1.1945	1.702743	1.3	1.2765052
0.129645	24.75	0.000418	0.144643	273.8493	1.1945	1.702743	1.3684211	1.2765052
0.129645	24.75	0.000358	0.144643	273.8493	1.1945	1.702743	1.3	1.2970425
0.129645	24.75	0.000418	0.144643	273.8493	1.346154	3.120132	1.25	1.3323284
0.129645	24.75	0.000358	0.144643	273.8493	1.346154	3.120132	1.3684211	1.3537639
0.129645	24.75	0.000358	0.144643	273.8493	1.346154	3.120132	1.25	1.3537639
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.172414	1.845239	2.125	2.1640714
0.132669	68.26667	3.29E-05	0.886824	136.9246	2.172414	1.845239	2	2.1732376
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.172414	1.845239	2.4285714	2.1640714
0.132669	68.26667	3.02E-05	0.886824	136.9246	2.274784	2.867886	2	2.2311117
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.274784	2.867886	1.8888889	2.2017758
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.274784	2.867886	2	2.2017758
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.434411	1.702743	2.125	2.2485539
0.132669	68.26667	3.02E-05	0.886824	136.9246	2.434411	1.702743	2.2857143	2.2785131
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.434411	1.702743	2.125	2.2485539
0.132669	68.26667	3.29E-05	0.886824	136.9246	2.153846	3.120132	2	2.1712218
0.132669	68.26667	3.43E-05	0.886824	136.9246	2.153846	3.120132	2.125	2.1620641
0.132669	68.26667	3.29E-05	0.886824	136.9246	2.153846	3.120132	2.125	2.1712218
0.136734	41.65	0.000449	0.266709	91.28309	1.067479	1.845239	2.5	2.3692822
0.136734	41.65	0.000449	0.266709	91.28309	1.067479	1.845239	2.25	2.3692822
0.136734	41.65	0.00046	0.266709	91.28309	1.067479	1.845239	3.3333333	2.3632325
0.136734	41.65	0.000472	0.266709	91.28309	1.094381	2.867886	2.5	2.3812749

Appendix: Prediction of Cycle Time using DA

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