Modeling the Shrinkage Pattern of Single Layer Synthetic Forming Fabric to reduce the Tight Mounting Problem: A Case Study

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The forming fabric, a woven mesh, plays the role of both a strainer and a conveyor and forms the paper in a paper mill. The usability and versatility of Synthetic forming fabric are much higher than metallic fabrics. The concerned organization has been a pioneer in the manufacture of Synthetic forming fabrics since 1980. In India, since small size paper machines can accommodate a stretch of only 0.4 – 0.8% as compared to 1 - 5% in big size paper mills. Size, spatial dimensions and rigidity of forming fabrics are quite important for small paper mill. The customer of a certain fabric was facing a problem of Tightness on paper machine, even if the final length of the fabric, while dispatching, matched with the required length. As a result of which, the fabric couldn't be mounted on the paper machines due to shrinkage, leading to reduction of market share. Attempts were made to find out the root causes and the shrinkage behavior of a particular design of forming fabric. Later on, adequate process control mechanism was introduced to minimize the tightness problem. It is expected to save time, energy and cost of reworking the tight fabric along with retaining customer satisfaction. This type of study can be extended gradually to other designs of the fabric to exercise stringent process control system in the company.

Keywords : Synthetic Forming Fabric, Tightness, Shrinkage, Supply length, Finish length, Short length, Hypothesis Testing, Multiple Regression, Model Adequacy Checking.

INTRODUCTION

The "Forming Fabric"(aptly named) forms the paper in a paper mill. It is basically a woven mesh and acts like a conveyor belt to form the paper onto it. The holes in the fabric cloth allow water from the dilute water-pulp mixture (ratio 99.99:0.01) to pass through while retaining the pulp fibres on top. It also conveys the mixture from the wet end to dry end of the paper machine. During this period, 80% of water is removed. The resulting wet sheet that forms on the forming fabric is a mixture of 80% fibres and 20% water. So the forming fabric plays the role of both a strainer and a conveyor.

Paper machine fabric design has tremendous effect on paper properties and paper making process. Proper fabric can increase productivity and decrease machine down time [1]. The functions of forming fabric, from design point of view, are retention of fibers and fillers, drainage of water and orientation of celluloid fibers for formation of paper sheet. The mechanical function is that the fabric should have capability of transmission of power and conveyer capacity, dimensional stability at working condition, resistance against abrasion. There are basically two type of forming fabric design – a) Single layer; and b) Multi-layer. Single layer fabrics are simplest in construction. This design is commonly used in manufacture of all variety of paper grades. The drainage through single layer fabric is straight. Single layer fabric also tends to produce least wire mark. A Multi-layer fabric has one warp and two weft strands stacked one over the other. The density of warp is more than 100%. The drainage path through the fabric is diagonal [1].

Earlier, the forming fabric is used to be made of metallic wires (Phosphor Bronze & Stainless Steel). In the 70's Synthetic fabric (Polyester, Polyamide yarns) replaced metallic wires. Synthetic fabrics have much longer life and have more characteristics rather than metallic wires, which are brittle and therefore the usability and versatility of application of Synthetic forming

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fabric are much higher.

The concerned company has been a pioneer in the manufacture of forming fabrics starting its operation in 1962. In the 1980, it started the manufacture of single layer synthetic forming fabric to keep abreast of the latest technological up-gradation in the field. The company has been all along the domestic market leader. Today 40% of its turnover comes from export. The company has managed to hold its ground despite the incursion of major leading world brand in to the domestic market after liberalization. It still commands a healthy 60% market share in a fiercely competitive market in India.

PROCESS DESCRIPTION

The raw materials used for manufacturing forming fabric are Polyester and Polyamide monofilament. The diameter of filaments ranges from 0.17 mm to 0.9 mm. The colour of monofilaments generally looks white, blue, green, red and pink. The process of manufacturing forming fabric is carried out in the following steps.

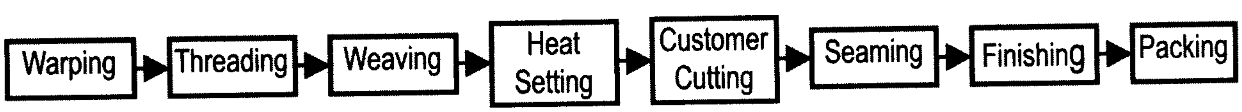

Figure 1: Process Flow of Forming Fabric

Warping

The winding of the warp filament (polyester) in the let-off beam of the loom is called warping. Warping is done in two ways - ring warping and sectional warping / conical warping. In ring warping, the filaments are wound on ring or canister of width about 175mm. After winding the rings, they are inserted through the back beam in the loom. In conical warping, the filaments are laid in sectional way over the warp beam. The sections / bands made on the let off beam in one time are about 50 cm.

Threading

In this process the warp threads/ yarns are passed through the headle eyes and reed as per the requirement of the design.

Weaving

The conversion of filament to fabric is called weaving. Fabric is formed by the interlacement of warp and weft. Warp is supplied from the let-off beam and Weft is supplied from the weft spool through projectile type shuttle or rapier tape drive.

Heat setting

Forming fabrics are set in Warp under tension at high temperature and a small amount of shrinkage is provided along the cross direction. The purpose of heat setting is to release the internal stresses in the fabric after weaving in order to have stable fabric structure. The maximum heat set temperature depends on the fabric material (polyester / Polyamide). In case of polyester yarns, the maximum temperature is around 200°C where as in case of polyamide it is 220°C.

Customer Cutting

In this process the heat-set lot is cut manually by the operators with the help of scissors according to the order size of customer.

Seaming

Seaming is a vital, critical and most time-consuming process in the synthetic forming fabric production process. Its purpose is to make the fabric endless keeping the same design and mesh of the fabrics.

Finishing

The endless fabric is mounted next over a pair of rollers and the rollers are then driven apart to bring the fabric under required longitudinal tension. Pins are mounted at the end of fabric along the length on both sides to resist width wise shrinkage while heating is on. The cross directional load is manually controlled and the pin-marked selvedges are cut off with the help of ultrasonic slitter machine. This is known as edge cutting, which is exactly the supply width. Finally the edges are chemically treated to make them hard, known as plastic edging.

Packing

The final product i.e. endless forming fabric is packed in wooden boxes of length slightly greater than the width of the fabric. In the wooden box, thermocol plates are placed and fabric is placed on the plates to prevent the fabric from rubbing with the inside surface of the box. The boxes are sealed, stickers are affixed and disposed for transportation.

PROBLEM DEFINITION

Size, spatial dimensions and rigidity of a forming fabric are quite important to develop the fabric quality. This is more in the Indian context where small size paper machines have a stretch accommodation of only 0.4% to 0.8% as compared to 1% to 5% in big size paper mills. The Tightness problem on paper machine is defined when the fabric becomes tight during mounting between head roll and tail roll of a paper machine. As a result it takes extra down time for a new fabric to be mounted in forming section. There was a problem of Tightness on paper machine in certain single layer synthetic forming fabrics, where the fabric supply length from the production department is of the required paper machine length, however the same couldn't be mounted on the paper machines at the customer's end due to shrinkage. This problem threatens to be a major one with the potential of eroding the brand value in the market.

GOAL AND OBJECTIVES

The goal of this study is to reduce the uncertainty present between the desired and achieved length of the forming fabric in the manufacturing process through adequate process control system. In order to meet this goal, the following objectives are set.

a) To determine the significant factors responsible for the tightness problem.

b) To set up a mathematical model to know the shrinkage behavior of fabric for a particular design.

c) To institute the necessary control on the process after identifying the controllable parameters and use the set up model.

THE APPROACH

After discussion with the concerned personnel of production and quality departments along with the head of the plant, the following steps are adopted for the study to be carried out in details to meet the aforesaid objectives.

1. Test for significant difference between the supply length and finish length.
2. To identify the sources of short length using brainstorming session and draw a cause-effect diagram.
3. To establish the relationship between shrinkage pattern and measurable process characteristics using experimental study.
4. To develop a mathematical model that is intuitively easy to interpret and predict the shrinkage percentage.

METHODOLOGY

Preliminary Study

At the outset data on Supply length and Average Finish length has been compiled to estimate the length difference (a measure of tightness only during fabric processing stage) from the technical service department of the company. The data set is given below in Table 1.

Table1: Supply length and Average Finish length

Observation	Supply Length (mm)	Average Finish Length (mm)	Shortage Length (mm)
1	25340	25300	-40
2	28360	28325	-35
3	21900	21870	-30
4	22750	22712	-38
5	18680	18645	-35
6	23770	23710	-60
7	22040	21985	-55
8	31220	31140	-80
9	28500	28440	-60
10	23930	23930	0
11	28360	28350	-10
12	25080	25035	-45
13	23480	23445	-35
14	23920	23840	-80
15	23970	23905	-65
16	20930	20845	-85
17	19660	19610	-50
18	19070	19070	0
19	21750	21670	-80
20	28355	28285	-70
21	28540	28485	-55
22	28694	28585	-109
23	31840	31785	-55
24	32320	32235	-85
25	23030	23020	-10
26	35000	34985	-15
27	17950	17938	-12
28	31260	31230	-30
29	28395	28365	-30
30	26230	26164	-66
31	25455	25405	-50
32	32650	32565	-85
33	30250	30190	-60
34	32470	32438	-33
35	28360	28270	-90
36	32660	32605	-55
37	31790	31705	-85
38	21680	21670	-10

The descriptive statistics of the data in Table 2 are tabulated below.

Table 2. Summary Statistics on Shortage Length

Statistics	Shortage Length (mm)
No. of Observations	38
Mean	– 49.68
Median	– 52.50
Standard deviation	24.93
First Quartile (Q1)	– 72.50
Third Quartile (Q3)	– 30.00
Interquartile range (Q1–Q3)	– 42.50

The median value of shortage is –52.50 which indicates that 50% of fabric has 52.50 mm shortage between finish and supply length. The spread of shortage is explained by the Interquartile range value as –42.50.

A Box Plot is done below to depict the Shortage length in graphical form.

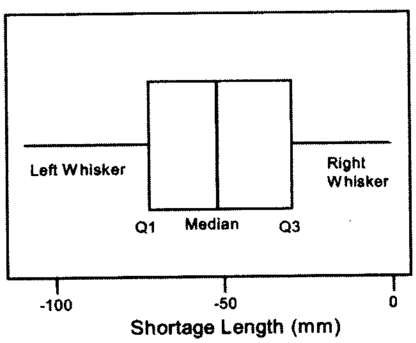

Figure 2: Box Plot for Supply length and Finish length

As from above plot it is observed that Left whisker is larger than Right whisker, so there is a tendency towards more shortage.

Next, statistical hypothesis testing (pair-t test) is carried out to know whether significant difference exists between supply length and finish length exists or not.

Suppose,

Mean Value of Finish length = μ_1

Mean Value of Supply length = μ_2

Then, Mean difference=$\mu_d=\mu_1-\mu_2$

It is interesting to know that whether md < 0 or not [2]. Accordingly, the following hypotheses are formed.

H_0: $\mu_d = 0$

H_1: $\mu_d < 0$

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n}(x_{1i} - x_{2i}) = -49.66$$

$$S_d = \frac{1}{n-1}\sum_{i=1}^{n}(d_i - \bar{d})^2 = 27.95$$

$$\text{Test statistic value=T=} \frac{\bar{d}}{S_d/\sqrt{n}} = -10.95$$

Assuming significance level (α) equal to 0.05, it is observed that the tabulated t-value is $t_{0.05,37} = 2.03$ and | T | >, $t_{0.05,37,}$ so the null hypothesis H_0 is rejected. Therefore, significant difference exists between the finish length and supply length.

A brainstorming session is then held between the production and quality personnel to find out the possible causes of short length. The outcome of the session is accumulated and presented in a Cause-Effect diagram as shown below (ref. Fig.3).

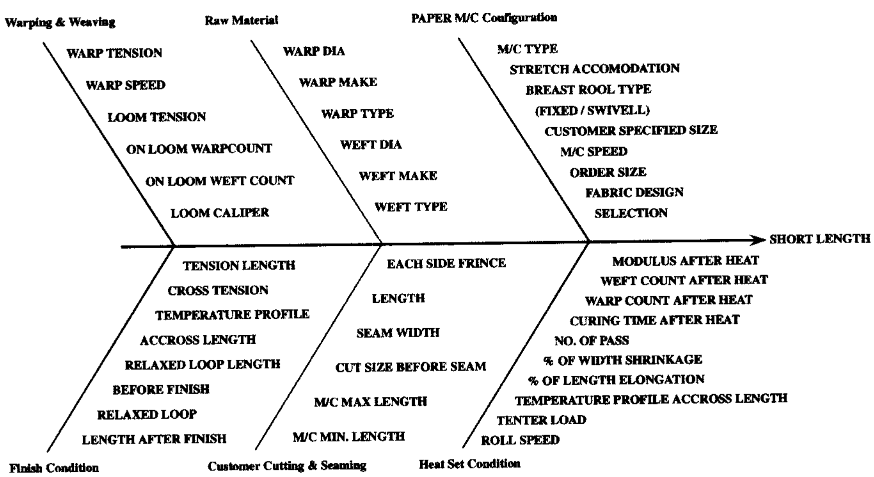

Figure 3: Cause & Effect Diagram for Short length

It has been decided from the diagram that actions on "Heat Set Condition" would be taken and the shrinkage from sample heat set fabric considering two main factors (coded as X_1 and X_2 due to confidential reasons) would be measured.

Model Building

Three data set corresponding to three different batches of production are collected considering two main process variables (X_1 and X_2) from "Heat Set condition".The data are given in Table 3.

The simplest model that enables the prediction of the amount of shrinkage using a data set of continuous predictor variables is a multiple linear regression model.

Table 3: Shrinkage measurement of sample heat set fabric

Obs. No.	Batch No.	Variable X_1	Variable X_2	Shrink%
1	1	18	1124	0.3000
2	1	42	1124	0.4500
3	1	90	1124	0.5000
4	1	114	1124	0.6000
5	1	138	1124	0.6000
6	1	186	1124	0.7000
7	1	216	1124	0.7000
8	1	262	1124	0.8000
9	1	281	1124	0.8000
10	1	334	1124	0.8000
11	1	522	1124	0.8000
12	1	618	1124	0.8500
13	1	1026	1124	0.8500
14	1	1531	1124	0.9000
15	1	3259	1124	1.0000
16	1	5830	1124	1.0000
17	2	54	1110	0.4200
18	2	73	1110	0.5700
19	2	97	1110	0.5700
20	2	121	1110	0.6000
21	2	146	1110	0.6500
22	2	199	1110	0.6500
23	2	243	1110	0.6500
24	2	289	1110	0.7000
25	2	343	1110	0.7000
26	2	410	1110	0.7000
27	2	626	1110	0.7500
28	2	1009	1110	0.8000
29	2	1346	1110	0.8500
30	2	2977	1110	0.8500
31	2	3674	1110	0.8500
32	3	24	1080	0.4500
33	3	49	1080	0.6000
34	3	73	1080	0.6500
35	3	127	1080	0.7000
36	3	170	1080	0.7600
37	3	216	1080	0.8000
38	3	270	1080	0.8600
39	3	337	1080	0.9000
40	3	553	1080	0.9000
41	3	936	1080	0.9000
42	3	1273	1080	1.0000
43	3	2904	1080	1.0000
44	3	3600	1080	1.0000

The response variable (Y), Shrinkage%, is expected to be linearly dependent on a set of explanatory variables (X_1 and X_2) [3, 4]. The multiple linear regression model with interaction effect is assumed here as:

$$Y = a + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2$$

where, α = Constant, β_1 = coefficient of X_1, β_2 = coefficient of X_2, β_3 = coefficient of X_1X_2

Using the data from Table 3 and performing the regression analysis, the following are observed after model adequacy checking (ref. Appendix A for details)

I. Both the coefficients of X_1 and X_2 are significant.

II. Coefficient of X_1X_2 is not significant

III. R^2 value is less (< 0.70).

IV. ANOVA table shows that regression is significant (< 0.05).

V. Y versus X_1 is not in linear form.

VI. Error variance is not constant.

The following actions are taken next to fit an appropriate model:

I. Logarithmic data transformation of X_1 variable. [5]

II. Removal of outlier after data transformation. [6]

Then the best fitted model (*after deleting only one outlier*) is estimated as

$$\text{Shrink \%} = 2.48 + 0.113 \log_e X_1 - 0.00216 X_2$$

with R^2 = 88.1%, adjusted R^2 = 87.5%, standard error = 0.06043.

Model Interpretation

Shrinkage% is logarithmic function of X_1 that indicates if we increase the X_1 term keeping X_2 fixed then Shrinkage% will increase exponentially.

Shrinkage% is a linear function of X_2 that indicates if we increase the X_2 term keeping X_1 fixed Shrinkage% will decrease linearly.

MODEL VALIDATION

An altogether 15 trials are taken by adding extra cut length as per the fitted regression model during customer cutting stage to make up the shrinkage amount considering two factors X_1 and X_2. Subsequently, raw data are collected from SQC department of the company, shortage is measured and performance of the fabric at customers' end is collected from the customers.

It is observed that out of 15 cases only 2 cases faced tight mounting. So the result is found quite satisfactory. The findings of this study were discussed with the production and technical service departments. They become encouraged to use the fitted model to add extra length during cutting stage. The method has been successfully implemented with close monitoring.

CONCLUSION

The statistical model, thus developed, can generally be used to know the shrinkage behavior for a particular design of forming fabric. So, if the supplier of the forming fabric knows the tentative time between customer cutting date and mounting of fabric on a machine, then this type of model for shrinkage would help the supplier to estimate the supply length of a fabric and do the subsequent operations. More accurate model using large number of batches of production can be developed to predict shrinkage. Similar studies can be carried out for other type of forming fabric design.

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Appendix: A

Details on data Analysis and Modeling

The entire analysis of collected data has been carried out using the Minitab statistical software packages in Window Operating environment [7].

Response Variable = Shrink % = Y   Predictor variable X_1 and X_2

Multiple regression model equation with interaction effect:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2$$

Multiple regression model equation without interaction effect:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2$$

Minitab Output

The regression equation is Shrink % = 2.793 + 0.0005335 X_1 – 0.001924 X_2 – 0.0000004 X_1X_2

Test Of Individual Regression Coefficient

Predictor	Coef	SE Coef	T	P
Constant	2.793	1.428	1.96	0.058
X_1	0.0005335	0.0009644	0.55`	0.583
X_2	-0.001924	0.001290	-1.49	0.144
X_1X_2	-0.00000040	0.00000087	-0.46	**0.646**
S = 0.1270		R-Sq = 47.8%		R-Sq(adj) = 43.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	0.59166	0.19722	12.22	0.000
Residual Error	40	0.64559	0.01614		
Total	43	1.23725			

Physical Interpretation:

I. The interaction effect is least significant because p-value of X_1X_2 is highest among all other Predictors.

II. R^2 value is less (< 0.70).

III. ANOVA table shows that Regression is significant (< 0.05).

Note : The p-value is the smallest level of significance (α) that would lead to rejection of the null (H_0).

We remove the interaction term (X_1X_2) and fit the model again without interaction term.

The regression equation Shrink % = 3.17 +0.000087 X_1 – 0.00226 X_2

Test Of Individual Regression Coefficient

Predictor	Coef	SE Coef	T	P
Constant	3.166	1.168	2.71	0.010
X_1	0.00008715	0.00001513	5.76	**0.000**
X_2	-0.002260	0.001056	-2.14	**0.038**
S = 0.1258		R-Sq = 47.5%	R-Sq(adj) = 45.0%	

Analysis of Variance(Anova)

Source	DF	SS	MS	F	P
Regression	2	0.58820	0.29410	18.58	**0.000**
Residual Error	41	0.64905	0.01583		
Total	43	1.23725			

Physical Interpretation:

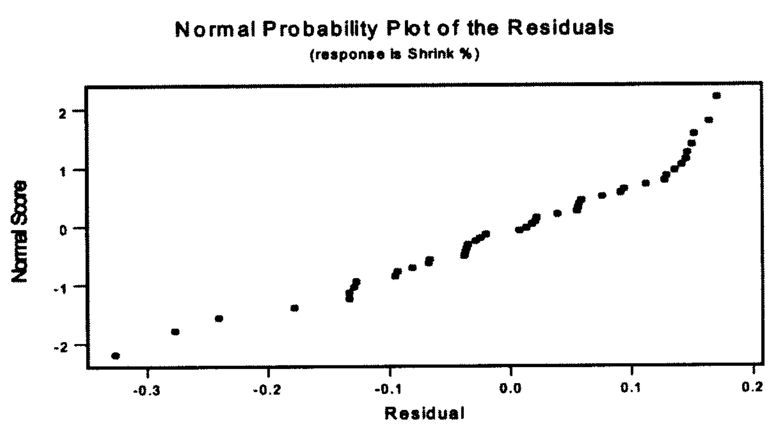
I. Now both the term X_1 and X_2 are significant.

II. R^2 value is less < 0.70).

III. ANOVA table shows that Regression is significant (< 0.05).

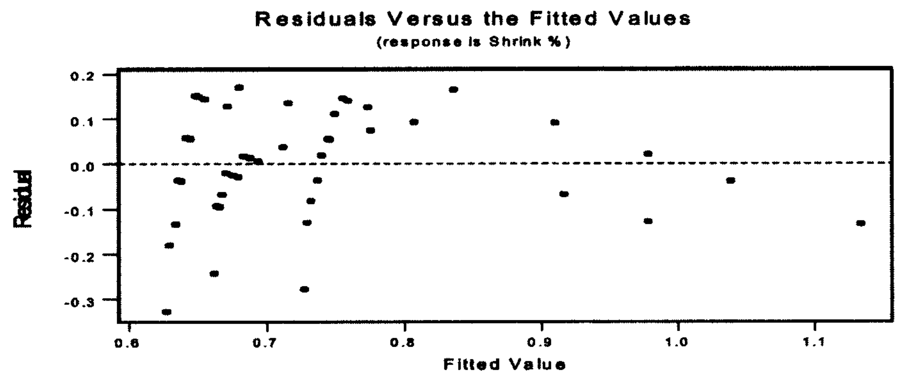
Model adequacy Check:

a) Checking Normality Assumption: Normal Probability Plot (NPP)



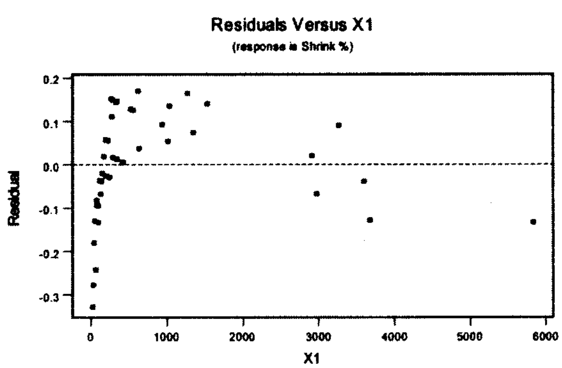
From above NPP plot it is seen that plot resembles nearly a straight line. It might appear that outliers are present.

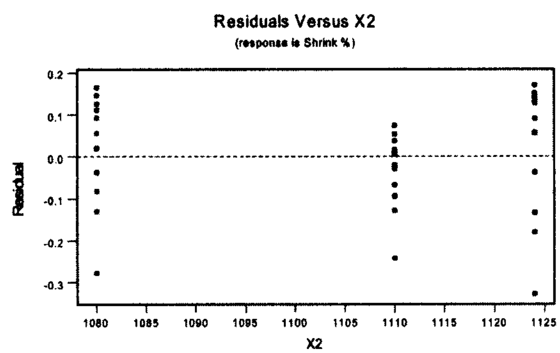
b) Constant error variance check: Scatter Plot of residual vs. the fitted values:



From above graph it is observed that error variance follows non-linear pattern. So error variance is not constant. Data transformation is required.

c) Linearity among Y Vs Xi's: Scatter Plot of residual vs. each of the predictor variables





From above two graphs it is seen that Y vs. X1 is not linear but Y vs. X2 follows linear forms

Interpretation:

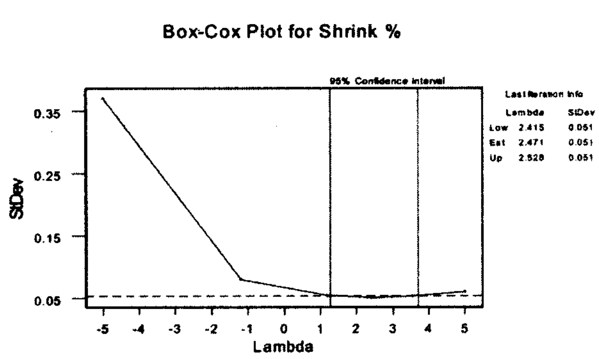
I. Data transformation required

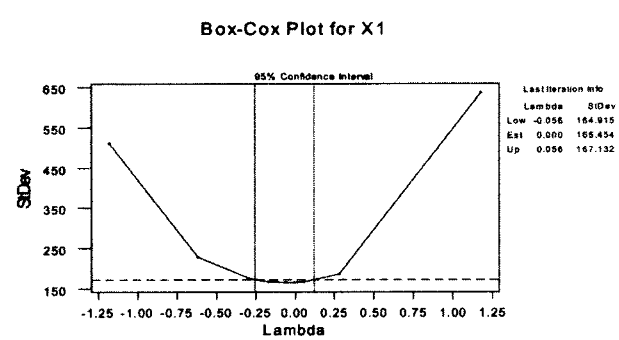
II. Remove outlier after data transformation.

Now, we use the Box-Cox data transformation to meet standard assumptions of the model.

a) Transform the Response to handle unequal variance

b) Transform the predictor to make it in linear form





From the above figure we observe that for Variable X1, λ value is 0.00, so loge transformation is required. No transformation is required for Response (shrink %), as λ value 2.471.

Fitted Model after Data transformation

The regression equation is

Shrink % = 2.54 + 0.108 logeX_1 - 0.00220 X_2

Test Of Individual Regression Coefficient

Predictor	Coef	SE Coef	T	P
Constant	2.5423	0.5957	4.27	0.000
logX_1	0.108152	0.006911	15.65	**0.000**
X_2	-0.0021962	0.0005376	-4.09	**0.000**

S = 0.06408 R-Sq = **86.4%** R-Sq(adj) = **85.7%**

Analysis of Variance (Anova)

Source	DF	SS	MS	F	P
Regression	2	1.06889	0.53445	130.15	**0.000**
Residual Error	41	0.16836	0.00411		
Total	43	1.23725			

Unusual Observations

Obs	logX_1	Shrink %	Fit	SE Fit	Residual	St Resid
31	8.21	0.85000	0.99232	0.01944	-0.14232	-2.33R

R denotes an observation with a large standardized residual

Physical Interpretation

I.Both X_1 and X_2 are highly significant.

II.R^2, R^2(adj) value is high (> 0.70).

III.Anova table shows that Regression is significant (< 0.05).

Now, we remove the outlier and refit the model.

The regression equation is

Shrink % = 2.48 + 0.113 $\log_e X_1$ – 0.00216 X_2

Test Of Individual Regression Coefficient

Predictor	Coef	SE Coef	T	P
Constant	2.4783	0.5623	4.41	0.000
logX_1	0.112570	0.006757	16.66	**0.000**
X_2	-0.0021582	0.0005072	-4.26	**0.000**

S = 0.06043 R-Sq = 88.1% R-Sq(adj) = 87.5%

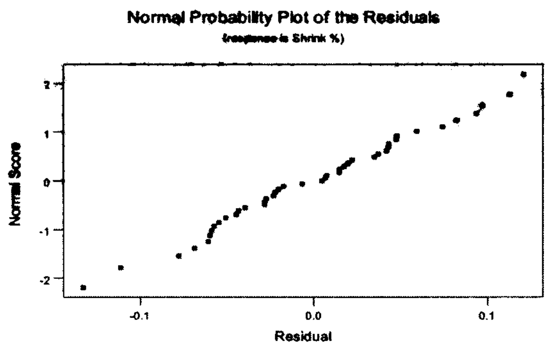
Analysis of Variance (Anova)

Source	DF	SS	MS	F	P
Regression	2	1.07841	0.53920	147.68	**0.000**
Residual Error	40	0.14605	0.00365		
Total	42	1.22446			

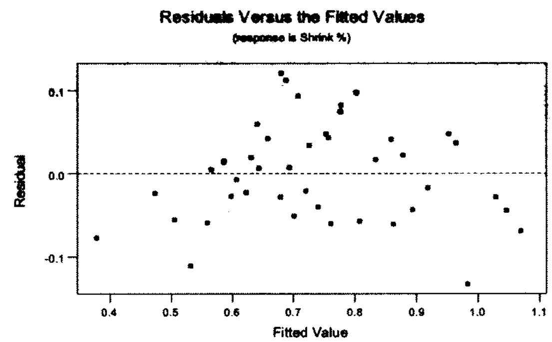
Model adequacy Check:

a) Checking Normality Assumption:

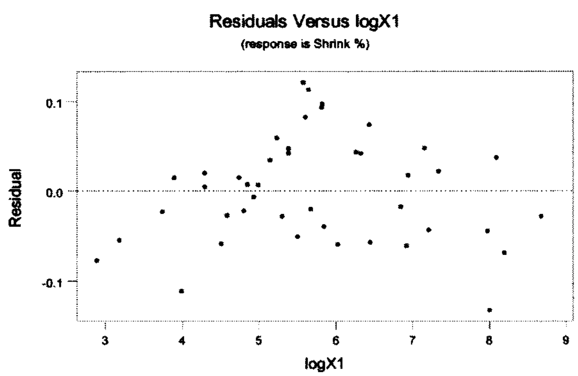
Normal Probability Plot (NPP)

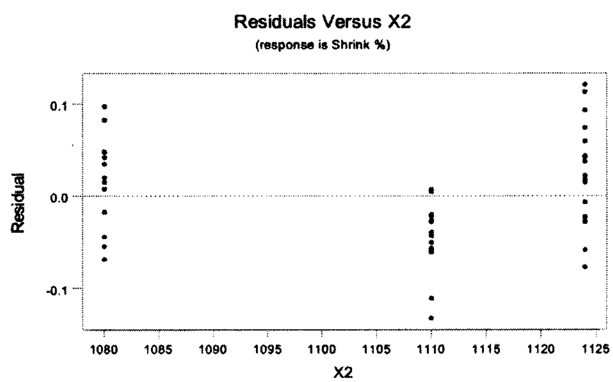


b) Constant error variance check : Scatter Plot of **residual vs. the fitted values:**



c) Linearity among Y vs. Xi's: Scatter Plot of residual vs. each of the predictor variables





Overall Conclusion:

a) Normality assumption is satisfied.

b) Error variance is constant.

c) Linear form exists among Y vs. $\log_e X_1$ and Y vs. X_2

The Fitted regression equation is: Shrink % = $2.48 + 0.113 \log_e X_1 - 0.00216 X_2$

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