Minimizing Defects in Tufting Process Using Full Factorial Design

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Abstract: - In this paper, a full factorial design is used to show the statistical significance of an effect that four specific factors exerts on the size of defect in a tufting process. The objective is to minimize the size of defect by adjusting these four factors. An equation is also developed to be used for predicting the size of defect in the tufting process.

Key-Words: Tufting, Design Of Experiments, Optimization.

1 Introduction
The problem at hand is a realistic quality problem in tufting process. There exists , an empty space in the fabric measured in inches squared. For this study, the yield is chosen as the size of this defect space (empty space in the fabric). The major factors influencing the size of defect are:

A. The number of threads per square inch (factor A),
B. The number of twists per inch of thread (factor B),
C. The size content of the fabric (factor C) and
D. The thickness of the needle (factor D).

2 The Experimental Setup
The major factors influencing the size of defect were selected according to the recommendation of experts in this field. In conducting the full factorial experiments, two levels were found to be enough to represent the range of variability related to each factor. Table 1 shows the related factors and the levels selected (Data shown below was all adopted from previous work done by the authors).

Table 1: Factors & levels selected

Factors	Level 1	Level 2
Number of thread/inch^2	2704	3025
Twist/inch of Thread	15	18
Fabric Size Content	5%	7%
Thickness of Needle	0.75 mm	1.5 mm

3 Analysis of Results
Using full factorial design, 16 independent experiments were performed; the results of these actual experiments are shown in Table 2. The objective is to determine the level of each factor that would result in minimum defective area in the fabric. The order of running the experiment was randomized. This randomization was necessary, in order to reduce the effects of any other outside uncontrollable factors.

Table 2: Results of experiments showing size of defect (Yield) in square inch

Experiment No.	Random Run	Factors				Yield (sq. inch) Y_i
		A	B	C	D	
1	15	2704 (-)	15 (-)	5 (-)	0.75 (-)	1.20
2	8	3025 (+)	15 (-)	5 (-)	0.75 (-)	1.35
3	7	2704 (-)	18 (+)	5 (-)	0.75 (-)	1.42
4	14	3025 (+)	18 (+)	5 (-)	0.75 (-)	1.98
5	1	2704 (-)	15 (-)	7 (+)	0.75 (-)	1.51
6	12	3025 (+)	15 (-)	7 (+)	0.75 (-)	2.21
7	3	2704 (-)	18 (+)	7 (+)	0.75 (-)	2.03
8	11	3025 (+)	18 (+)	7 (+)	0.75 (-)	3.57
9	16	2704 (-)	15 (-)	5 (-)	1.5 (+)	1.07
10	6	3025 (+)	15 (-)	5 (-)	1.5 (+)	2.19
11	9	2704 (-)	18 (+)	5 (-)	1.5 (+)	2.27
12	5	3025 (+)	18 (+)	5 (-)	1.5 (+)	3.09
13	2	2704 (-)	15 (-)	7 (+)	1.5 (+)	2.25
14	13	3025 (+)	15 (-)	7 (+)	1.5 (+)	3.16
15	4	2704 (-)	18 (+)	7 (+)	1.5 (+)	3.23
16	10	3025 (+)	18 (+)	7 (+)	1.5 (+)	3.78

3.1 Effects of Main Factors on Yield

In order to determine the effect of each factor on the yield, we have 8 estimates for the effects of each factor as follows:

Average Effect of Factor A = (1/8) Σ (Y_{i+1}-Y_i) ; i = 1, 3, 5, 7, 9, 11, 13, 15.
= (1/8) {(1.35 – 1.20) + (1.98 – 1.42) + ….. + (3.78 – 3.23)} = 0.79375

The effects of the remaining three factors (B, C, and D) can be calculated similarly. The results are listed in Table 3.

Table 3: Calculated effects of all factors & interactions

FACTORS & INTERACTIONS	AVERAGE EFFECT	FACTORS & INTERACTIONS	AVERAGE EFFECT
A	0.79375	BD	0.12125
B	0.80375	CD	0.05375
C	0.89625	ABC	0.04625
D	0.72125	ABD	-0.2388
AB	0.07375	ACD	-0.2513
AC	0.13125	BCD	-0.1913
AD	0.05625	ABCD	-0.0613
BC	0.06625		

OVERALL AVERAGE = 2.26937

3.2 Effects of Interactions on Yield

In addition to the effects of main factors, interactions of two or more factors may also contribute to the yield. These can be estimated as follows:

Average Effect of Factor A when B is Low
= (1/4) {(1.35–1.20) + (2.21–1.51) + (2.19-1.07)+ (3.16-2.25)} = 0.72
Average Effect of Factor A when B is High
= (1/4) {(1.98–1.42) + (3.57–2.03) + (3.09-2.27)+ (3.78-3.23)} = 0.88
Interactions between factors A and B (AB)
= (1/2) {(Average Effect of Factor A when B is High) – (Average Effect of Factor A when B is Low)} = 0.07375

The values of the effects of remaining interactions are listed in Table 3. As can be seen in Table 3, any third order interaction involving factor D has a negative effect on the yield, while all the other factors have positive effect on the yield. Furthermore, the overall average effect is about 2.27 indicating a significant effect of the considered factors on the yield.

3.3 Analysis of Variance Results

The ANOVA results (table 4) showed that only main factors were statistically significant and all other interactions were not statistically significant. The sum of squares for all non-significant factors is included in the error term. The significant factors were used to develop a prediction equation for the yield.

Table 4: (ANOVA) Analysis Of Variance Results for Significant Factors

Source of variation	Sum of Squares	Degrees Of freedom	MSE	F_0
A	0.169124	1	0.16912	12.7399
B	0.180457	1	0.18046	13.5936
C	0.229617	1	0.22962	17.2968
D	0.092152	1	0.09215	6.94172
Error	0.146026	11	0.01328	
Total	0.817376	15		

3.4 Prediction Equation for Yield

A prediction equation is developed for the yield based on the average effects of significant factors. The Y-intercept in the prediction equation is obtained from the overall average of the yield for all experiments. This prediction model (equation) can be used to estimate the yield, which is the expected area of a defect on the fabric for a specified combination of levels of all factors considered. It turns out that to minimize the defective area on the fabric, all main factors, A-D, should be at their low levels as can be seen from the equation (1) below:

Yield (in square inches)
$$=2.269375+0.396875*A+0.401875*B + 0.448125*C + 0.360625*D \quad (1)$$

To validate the prediction model, the residuals should be plotted versus the run order of experiments as shown in Figure 1.

Since the residuals plot (in Figure 1) forms a funnel, it indicates that outside uncontrollable factors are interfering with the experiment results. This may also indicate that some factors, which are not found to be significant by ANOVA, may in fact be significant; and those that are found to be significant may actually be insignificant. One way to sort out this problem is to remove the trend in residuals by transforming the data and then repeating the ANOVA to see if the list of significant factors remains the same. If it does, then the analysis is correct and the prediction equation is valid, otherwise another prediction equation must be formed.

3.5 Transformed Model

The interference of uncontrollable factors will also cause the variance of the error not to be constant (as it should be). Not having a constant variance implicates that all results based on ANOVA are not reliable. To stabilize the variance (constant variance) a transformation to the yield is needed. The most common transformation to remove the funnel shape distortion is a power transformation. The suggested power is given by equation (2):

$$y' = y^x \qquad (2)$$

Where, y' = The transformed value of the yield and y = The original value of the yield. Trying several values for the power x, it was found that the best value is x= -1.5. Applying the transformation to the yield resulted in the yields given in Table 5.

Table 5: Transformed values for the yield

Exp No	Transformed Yield	Exp No	Transformed Yield
1	0.7607	9	0.9035
2	0.6375	10	0.3085
3	0.5909	11	0.2924
4	0.3589	12	0.1841
5	0.5389	13	0.2963
6	0.3044	14	0.1780
7	0.3457	15	0.1723
8	0.1483	16	0.1361

ANOVA analysis resulted in the same list of significant factors as for the original data, and the prediction equation for the transformed yield was found by equation (3):

$$y' = 0.38479 - 0.10281*A - 0.10620*B - 0.11980*C - 0.07589*D \qquad (3)$$

Plotting the residuals versus the run order (Figure 2), shows no apparent pattern, thus the transformation had successfully removed the outside uncontrollable factors. Thus, confirming that the original list of significant factors remains the same. It is of interest to know which factor has the most influence; these are readily available from the ANOVA analysis, since ANOVA lists the variations in the yield due to each factor under the term "Sum of Squares (SS) ". The contribution of each factor on the yield can be calculated by comparing the "Sum of Squares (SS_x)" due to that factor (say x) divided by the "Total Sum of Squares (SS_T)". Therefore, the percent contribution of (x) = (SS_X / SS_T) * 100

Fig.1 Residual Plots

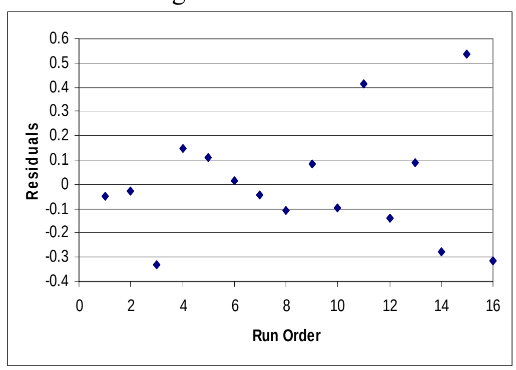
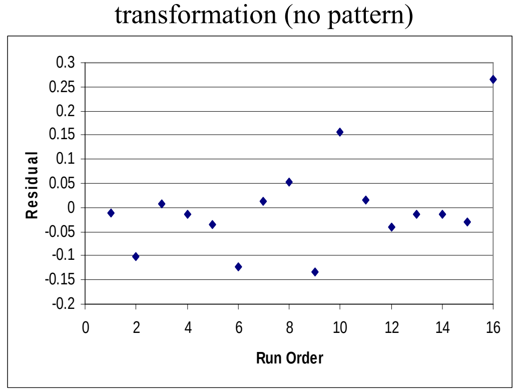


Fig.2 Residuals versus run order after transformation (no pattern)



The contribution of factors before and after transformation is as shown in Table 6.

Table 6: Yield before & after transformation.

Factor	The % Contribution before transformation	The % Contribution after transformation
A	= (2.5202 / 11.23969) *100 = 22.42 %	20.69 %
B	= (2.5841 / 11.23969) *100 = 22.99 %	22.07 %
C	= (3.2131 / 11.23969) *100 = 28.59 %	28.09 %
D	= (2.0808 / 11.23969) *100 = 18.51 %	11.27 %

The most influential factor on the yield is still factor C (size content of the fabric).

4 Conclusion

The significant effects were identified by utilizing ANOVA, from which the prediction equation was found. Because of the non-constant variance of the error, there was a need to transform the values of the yield to remove the influence of any unknown outside uncontrollable factors. After the yield was transformed, the error was reduced and a constant variance was obtained. Thus the original model given by equation (1) was found to be valid. This model can be used to determine the level of factors that minimize the magnitude of defects. As it is seen from the model, all factors should be at their low level (-1) in order for the yield to be minimum. This in turn means that Factor A (Number of threads in the fabric) should be 52x52, Factor B (Number of twists per inch of the thread) should be 15, Factor C (Size content of the fabric) should be 5% and Factor D (Thickness of the needle) should be 0.75 mm. This would result in a minimum defect area of:

$$\text{Yield} = 2.269375 + 0.396875*A + 0.401875*B + 0.448125*C + 0.360625*D$$

$$= 2.269375+0.396875*(-1) +0.401875*(-1) +0.448125*(-1) +0.360625*(-1)$$

$$= 0.661875 \text{ inches square}$$

The model presented in this paper can be used by production and quality managers to predict the related quality characteristic in their system. Also, the methodology given in this paper can be used to develop other prediction equations for other quality characteristics in the textile industry.

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