Rizvan Erol,
***Aysun Sağbaş**

Multiple Response Optimisation of the Staple-Yarn Production Process for Hairiness, Strength and Cost

Department of Industrial Engineering, Cukurova University,
Adana 01330, Turkey
E-mail: rerol@cu.edu.tr

***Department of Mechanical Engineering, Mersin University,**
Mersin 33343, Turkey
E-mail: asagbas@mersin.edu.tr

Abstract
It is generally desirable to reduce yarn hairiness as much as possible since it causes serious problems in both yarn production and use of yarn in subsequent textile operations. On the other hand, the cost of yarn production should be minimised while satisfying yarn hairiness and yarn strength specifications. In this study, a multiple response optimisation model based on empirical regression models is developed to determine the best processing conditions for spindle speed, yarn twist, and the number of travelers with yarn hairiness, yarn strength and production cost being multiple response variables. Experimental levels for process variables are selected according to a Central Composite Design (CCD) due to its good statistical properties, such as orthogonality and rotatability. Regression analysis of experimental results indicates that the second-order regression model adequately represents yarn hairiness in terms of process variables. Finally, the yarn production cost model and regression models for yarn hairiness and yarn strength are combined into a multiple response optimisation model to determine optimum processing conditions for different yarn quality levels.

Key words: *process optimisation, yarn production, hairiness, strength, yarn cost.*

Introduction

In yarn production, yarn hairiness is kept as low as possible except for a few special cases. High yarn hairiness causes serious problems in both yarn production and use of yarn in subsequent textile operations [1]. Such problems include higher friction during spinning, greater fly fibre, and increased yarn breakage during weaving [2 - 4]. A study published in Textile World (1989) states that 46% of yarn breakages in weaving are due to high yarn hairiness. Another adverse effect of hairiness in weaving is greater pilling in fabric. Differences in the hairiness properties of weft yarns result in a band forming in fabric [5]. High hairiness in bobbin machines results in a loss of productivity, and dark lines form where high hairiness exists in warp yarn [3, 6]. These examples show that it is critical to reduce yarn hairiness in order to improve the quality of yarn used in knitting, weaving and finishing operations. This also brings significant cost reductions in the production of yarn by eliminating additional operations to reduce hairiness. On the other hand, the cost of yarn production should be minimised while maintaining yarn hairiness and yarn strength within desirable limits.

Process optimisation through statistical regression models is common practice in many industries. Ozkan et al. [7] use the Box-Wilson optimisation method to determine the best production conditions for partially oriented yarn properties. Altas and Kadoglu [8] build a multiple regression model to analyse the effect of linear density on cotton yarn hairiness in ring spinning.

In this study, an optimisation model based on empirical regression models is developed to determine the best processing conditions for spindle speed, yarn twist, and the number of travelers with yarn hairiness, yarn strength and production cost being the multiple responses. Regression analysis is used to build response surface models for yarn hairiness, yarn cost and yarn strength as a function of the process variables under consideration. Finally, the yarn production cost model and regression models for yarn hairiness and yarn strength are combined in a multiple-criteria decision model to determine optimum processing conditions for different quality levels.

Optimisation approach

The basic steps of the multiple-response process optimisation approach used in this study are summarised in a flowchart, shown in ***Figure 1***. A pure cotton blend is prepared to produce 14.75 tex staple yarn on ring machines. Therefore, spindle speeds for the ring spinning frame are selected in this study. Higher spindle speeds could be used for other types of spinning frames, such as open-end. Experimental levels for process variables are selected according to a Central Composite Design (CCD) due to its good statistical properties, such as orthogonality and rotatability [9]. This design has 15 different design points for all combinations of process variables. Yarns produced are tested on Uster

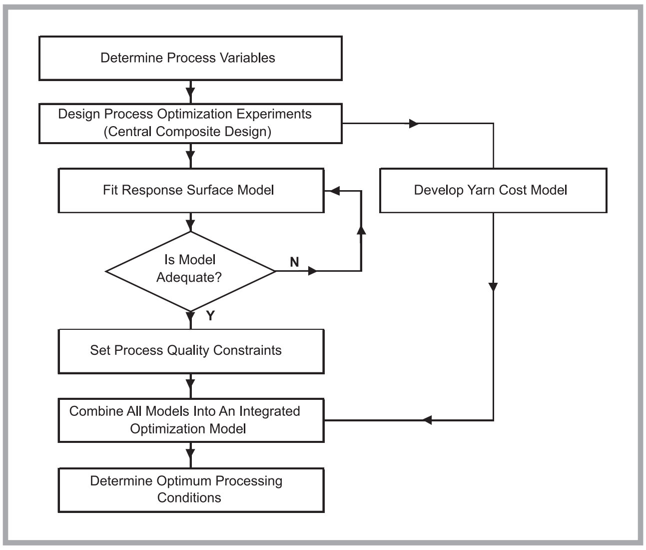

***Figure 1.** Steps of the multiple response process optimisation approach.*

Erol R., Sağbaş A.; Multiple Response Optimisation of the Staple-Yarn Production Process for Hairiness, Strength and Cost.
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Tester 4 and Uster Tensorapid 3 testing equipment [10]. ***Table 1*** shows experimental design points and test results for the response variables. Since this study attempts to find optimal processing conditions by selecting the region of interest as large as possible, some extreme values for the spindle speed and yarn twist are also introduced in experimental runs. Furthermore, central composite designs usually have extreme combinations of processing variables for complete exploration of the region of interest unless there is an infeasibility or safety problem during experiments. Design points at the centre of the CCD correspond to current or more common operating conditions.

The yarn production cost at each design point is estimated using factory data in order to build a regression model that defines the relationship between yarn cost and the process variables of interest. DesignExpert software is used for all statistical analysis and optimisation in this study [11].

A useful approach for optimisation of multiple response variables m proposed by Derringer and Suich makes use of desirability functions [12]. In this approach, each response y_i is expressed in terms of an individual desirability function d_i that takes its values from the following range

$$0 \le d_i \le 1 \quad i = 1, 2, ..., m \qquad (1)$$

When the response variable is at its goal or target, d_i becomes 1, and if the response variable is outside the acceptable range, d_i becomes zero. The overall objective is to set the process variables to such levels that the following overall desirability function is maximised,

$$D = (d_1 d_2 .... d_m)^{1/m} \qquad (2)$$

For yarn hairiness, the desirability function is as follows

$$d = \begin{cases} 1 & y < T \\ \left(\dfrac{U - y}{U - T}\right)^r & T \le y \le U \\ 0 & y > U \end{cases} \qquad (3)$$

where T and U are the target value and the upper limit for yarn hairiness, respectively. In Equation 3, r is the weight assigned to the response variable. Choosing $r > 1$ places greater importance on being close to the target value, whereas choosing $0 < r < 1$ makes this less important.

In similar fashion, as the yarn strength should be maximised, the desirability function should be:

$$d = \begin{cases} 1 & y < T \\ \left(\dfrac{y - L}{T - L}\right)^r & T \le y \le U \\ 0 & y > U \end{cases} \qquad (4)$$

where L is a lower limit for the yarn strength.

Upper and lower limits for the response variables are selected from the Uster statistics published in 2001 for quality of yarn produced worldwide.

Research findings and discussion

Regression analysis of experimental results indicates that the second-order regression models adequately represent yarn hairiness and yarn strength in terms of the process variables considered (p-values for the model significance are 0.0087 and 0.0144 for yarn hairiness and yarn strength, respectively). The analysis of Variance (ANOVA) in ***Table 2*** shows that yarn twist is the most influential factor for yarn hairiness. Least-square regression equations estimated for yarn hairiness and yarn strength are as follows:

$$y_{hairiness} = -19.56 - 0.00109x_1 + \\ + 0.0762x_2 - 0.7655x_3 + \\ - 0.00027x_3^2 + 0.00039x_1x_3 \qquad (5)$$

$$y_{strength} = 14.97 - 0.0004x_1 + \\ + 0.0386x_2 + 0.378x_3 + \\ - 0.0183x_2^2 + 0.0008x_2x_3 \qquad (6)$$

However, the following first-order linear model is found to be adequate for yarn cost

$$y_{cost} = 4.135 - 0.00016x_1 + \\ + 0.0031x_2 - 0.0185x_3 + \qquad (7)$$

Response models for all three response variables are combined into a single multiple-response optimisation model. Search parameters of the multiple response optimisation approach described in the previous section are summarised in ***Table 3*** for various yarn quality levels. The spindle speed and yarn twist values in ***Table 1*** are used to build a regression model that will be used to estimate optimal processing conditions, as shown in ***Table 3***. The best 10 spindle speed and yarn twist values are obtained from the iterative optimisation approach. Actual experiments are not performed at these values since regression model estimates are used in the optimisation. However, experiments at these values could be run for further validation of optimisation results.

As an example, ***Table 4*** shows the best eight solutions of the optimisation approach used to determine optimum processing conditions for the upper 5% in terms of quality. Achieving a maximum overall desirability of 0.79 means that it is not possible to meet all the quality and cost goals for this quality level since the quality of cotton fibres is not high enough for this level. Yarn strength quality limits for upper quality levels of 75%, 50%, 25% and 5% are taken from Uster statistics for the year 2001. ***Table 5***

Table 1. *Central Composite Design(CCD) points and experiment results; x_1 - spindle speed (r.p.m.), x_2 - yarn twist (t.p.m.), x_3 - number of travellers.*

Run	Process variables			Response variables		
	x_1	x_2	x_3	$y_{hairiness}$	$y_{strength}$, cN/tex	y_{cost}, USD/kg
1	12500	1231	35.5	4.54	17.52	5.10
2	12500	1067	35.5	4.98	19.02	4.85
3	10500	1231	35.5	4.37	18.78	5.60
4	10500	1067	35.5	4.33	17.19	5.12
5	10500	1231	28.0	4.41	18.18	5.81
6	10500	1067	28.0	5.09	17.51	5.40
7	12500	1231	28.0	4.41	18.29	5.27
8	12500	1067	28.0	5.15	17.39	4.79
9	11500	1280	31.5	4.03	16.60	5.93
10	11500	1143	40.0	4.47	18.96	5.07
11	9768	1143	31.5	4.81	18.70	5.08
12	11500	1000	31.5	4.03	17.19	4.80
13	11500	1143	25.0	4.89	18.44	5.33
14	13232	1143	31.5	4.92	18.54	4.85
15	11500	1143	31.5	4.78	18.49	5.26
16	11500	1143	31.5	4.78	18.47	5.23
17	11500	1143	31.5	4.76	18.48	5.23
18	11500	1143	31.5	4.79	18.47	5.26

Table 2. *ANOVA Table for yarn hairiness; * significant factors at 5% significance level.*

Source	Sum of squares	df	Mean square	*F* value	*p*-value
Model	1.64	9	0.18	6.18	0.0087*
x_1	0.083	1	0.083	2.82	0.1317
x_2	0.30	1	0.30	10.04	0.0132*
x_3	0.15	1	0.15	5.12	0.0535
x_1^2	0.040	1	0.040	1.37	0.2752
x_2^2	0.74	1	0.74	25.07	0.0010*
x_3^2	0.00027	1	0.00027	0.0089	0.9268
$x_1 x_2$	0.034	1	0.034	1.15	0.3145
$x_1 x_3$	0.76	1	0.76	2.57	0.1479
$x_2 x_3$	0.12	1	0.12	4.06	0.0787
Error	0.24	8	0.030		
Total	1.88	17			

Table 3. *Iterative determination of optimum conditions for the upper 5% in terms of quality; x_1 - spindle speed (r.p.m.); x_2 - yarn twist (t.p.m.); x_3 - number of travellers.*

Best solutions	Process variables			Response variables			Overall desirability
	x_1	x_2	x_3	$y_{hairiness}$	$y_{strength}$, cN/tex	y_{cost}, USD/kg	D
1	9820	1011	38.05	3.40	20.61	4.96	0.790
2	9820	1015	38.05	3.44	20.64	4.97	0.785
3	9820	1017	38.05	3.46	20.60	4.98	0.782
4	9820	1011	38.01	3.40	20.60	4.96	0.780
5	9820	1019	38.05	3.49	20.60	4.99	0.779
6	9820	1023	38.05	3.53	20.59	5.00	0.774
7	9913	1028	38.05	3.60	20.43	5.00	0.681
8	9820	1036	38.05	3.67	20.56	5.04	0.456

Table 4. *Search parameters used in the multiple response optimisation model for different quality levels; L - lower limit, U - upper limit, r - weight of response variable.*

Quality level, (upper %)	$y_{hairiness}$			$y_{strength}$, cN/tex			y_{cost}, USD/kg		
	T	U	r	L	T	r	L	U	r
75	5.1	5.8	2	15.7	16.5	2	4.1	5.0	2
50	4.6	5.0	2	16.5	17.8	2	4.6	5.2	2
25	3.9	4.6	2	18.2	19.6	2	5.0	5.5	2
5	3.6	4.0	2	19.7	21.0	2	5.2	5.8	2

Table 5. *Optimum processing conditions for different quality levels; x_1 - spindle speed (r.p.m.); x_2 - yarn twist (t.p.m.); x_3 - number of travellers.*

Quality level (upper %)	Desirability (d)	Optimum processing conditions			Optimum values for response variables		
		x_1	x_2	x_3	$y_{hairiness}$	$y_{strength}$, cN/tex	y_{cost}, USD/kg
75	0.758	13180	1011	38.05	4.57	19.74	4.41
50	1.000	12139	1011	38.05	4.08	19.09	4.58
25	1.000	10317	1015	37.57	3.59	19.73	4.90
5	0.790	9820	1011	38.05	3.40	20.61	4.96

summarises optimisation results for all quality levels considered.

As shown in ***Table 5***, there is no solution satisfying all the quality and cost goals for the upper 75% in terms of quality, as occurred for the upper 5%. Therefore, we conclude that the quality of raw material selected for this study is too high to produce low quality yarn. On the other hand, it is possible to achieve 100% overall desirability for quality levels of 25% and 50% when we set the process variable at the optimum levels. For instance, in order to achieve a 25% quality level within the desired quality and cost constraints, both the spindle speed and yarn twist should be set at low levels while keeping the number of travellers high. Furthermore, as the quality of yarn desired gets worse, it is necessary to increase the spindle speed.

Conclusions

In this study, a yarn production cost model and regression models for yarn hairiness and yarn strength are combined into a multiple-criteria decision model to determine optimum processing conditions for different yarn quality levels. Optimisation runs indicate that a low spindle speed and yarn twist along with a high number of travellers should be selected to reduce yarn hairiness and production cost while maintaining high yarn strength. Other process variables such as applied draw, ring diameter, temperature and humidity at the workplace can be considered for further optimisation study. Moreover, the process optimisation approach used in this study can be extended for yarn produced in other spinning systems, such as open-end. Other quality parameters (e.g., yarn evenness, breaking force, thin places) could be incorporated into our optimisation model with new experimental runs.

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