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Mathematical Modelling of Ring Spinning Machine Productivity under Electric Drive Failure and Motor Speed Reduction

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Abstract

The operational performance of modern ring spinning machines is closely related to the technical condition and operating stability of their electric drive systems. Temporary drive failures and reductions in motor rotational speed can affect production continuity, machine productivity, and the efficient use of electrical energy. This study develops a second-order mathematical model for evaluating the performance of an electrically driven ring spinning machine by considering the combined effects of electric drive failure duration and motor rotational speed reduction. The experimental investigation was conducted using a second-order orthogonal design based on the Kono experimental planning method. Two independent variables were considered: electric drive failure duration and reduction in motor rotational speed. The experimental programme included nine design points, with twelve randomized replications at each point. The experimental data were processed using regression analysis to determine the linear, quadratic, and interaction effects of the investigated factors on machine productivity. The adequacy and statistical reliability of the developed model were evaluated using Cochran's criterion, Student's t-test, and Fisher's F-test at a 95% confidence level. The obtained results demonstrate that both investigated factors have a measurable effect on machine productivity, while their combined variation produces a nonlinear response. The developed response surface provides a means of identifying operating conditions associated with reduced productivity losses and more efficient use of the machine's operating resources. The proposed mathematical approach can be used to predict productivity under different electric drive conditions and can support the selection of more energy-efficient operating regimes. In this way, the model provides a basis for reducing unnecessary operational losses and improving the sustainability of energy-intensive textile production processes.

Keywords

Electric Drive, Ring Spinning Machine, Mathematical Modelling, Energy Efficiency, Response Surface Methodology, Experimental Design, Productivity Prediction, Sustainable Textile Production

1. Introduction

The textile industry has undergone substantial technological development in recent decades, with increasing attention being given to production efficiency, product quality, energy consumption, and equipment reliability. Among the different technologies used for yarn manufacturing, ring spinning remains an important method because of its ability to produce yarn with high mechanical and quality characteristics. Therefore, the stable operation of ring spinning machines has a direct influence on production performance and the efficient use of energy resources in textile enterprises.

The electric drive is one of the key systems determining the operating performance of a ring spinning machine. During industrial operation, the drive may be affected by mechanical wear, electrical faults, overloads, voltage fluctuations, and other disturbances. Such conditions can cause temporary interruptions or reductions in motor rotational speed. Even relatively small deviations from the normal operating regime may interrupt the continuity of the spinning process, reduce machine productivity, and result in inefficient use of electrical energy [1].

The relationship between electric drive operation and the performance of textile machinery has been investigated in a number of studies. Existing approaches often consider drive failures and motor speed variations separately or use simplified relationships to estimate their influence on machine performance. Although such models can be useful for individual operating conditions, they may not adequately describe the combined effect of several factors acting simultaneously. This limitation becomes particularly important when both drive interruption and motor speed reduction occur during the same operating period [2].

In addition to productivity losses, unstable operation of the electric drive can affect the efficiency with which electrical energy is converted into useful production output. Consequently, assessment of the operating regime should consider not only the direct change in productivity but also the possibility of reducing unnecessary operating losses. From the perspective of sustainable textile production, mathematical models that can identify less efficient operating conditions may therefore provide useful information for improving equipment operation and energy management [3].

Response Surface Methodology (RSM) is an effective statistical approach for studying engineering processes affected by several interacting variables. Second-order regression models based on orthogonal experimental designs make it possible to estimate linear, quadratic, and interaction effects while keeping the number of experimental runs within practical limits. Such approaches have been applied to process process improvement, reliability assessment, and performance prediction in different engineering and manufacturing applications. However, their application to the combined assessment of electric drive failure duration and motor speed reduction in ring spinning machines, particularly in relation to efficient machine operation, remains insufficiently explored [4] [5].

Therefore, a research gap remains in the development of a mathematical model capable of simultaneously evaluating the effects of electric drive failure duration and motor rotational speed reduction on the productivity of ring spinning machines. Addressing this problem can improve the prediction of machine performance and provide a quantitative basis for selecting operating regimes associated with lower production losses and more efficient use of electrical energy.

The novelty of this study is the development of a second-order mathematical model that simultaneously incorporates the duration of electric drive failure and the reduction in motor rotational speed within a unified regression framework. The model includes linear, quadratic, and interaction terms, allowing the combined influence of the investigated factors to be evaluated rather than considering each factor independently [6].

The aim of this study is to develop and statistically validate a second-order mathematical model for evaluating the operational performance of an electrically driven ring spinning machine under simultaneous variations in electric drive failure duration and motor rotational speed reduction. The model is intended to support productivity prediction, identification of less efficient operating conditions, and improvement of energy-efficient operation in textile manufacturing.

2. Materials and Methods

2.1. Research Object

The experimental investigation was carried out using a RIETER G36 electrically driven ring spinning machine designed for the production of 25 tex cotton yarn. The machine was selected as the research object because it represents a widely used type of industrial spinning equipment equipped with an electric drive system [7].

The objective of the experimental study was to determine how changes in the operating condition of the electric drive affect machine productivity. During continuous operation, the drive system can be affected by temporary failures, overloads, mechanical wear, and reductions in motor rotational speed. These changes may disturb the continuity of the spinning process and consequently influence production performance and the efficient use of electrical energy [8].

Two operating parameters were selected as independent variables:

U_1—electric drive failure duration (min);

U_2—reduction in motor rotational speed (% of the nominal speed).

The response variable (Y) was defined as machine productivity. This parameter was selected because it directly represents the production performance of the spinning machine and allows the combined effect of the investigated electric-drive conditions to be evaluated.

To ensure the comparability of the experimental observations, the machine was operated under the same general technological conditions throughout the experimental programme. The nominal motor speed was taken as the reference operating condition, and the investigated speed reductions were imposed relative to this baseline. Temporary drive interruptions were introduced according to the selected duration levels, after which the drive was restored and the machine was allowed to return to the specified operating condition. Each replication represented a separate productivity observation obtained under the same combination of factor levels. The experimental runs were performed in a randomized sequence to minimize the influence of uncontrolled operating variations.

2.2. Experimental Design

The experimental programme was developed using a second-order orthogonal experimental design based on the Kono experimental planning method. This approach was selected because it allows linear, quadratic, and interaction effects to be estimated with a relatively limited number of experimental runs [9] [10].

For m independent variables, the number of experimental design points was determined from the adopted second-order experimental design relationship:

$$N = 2^m + 2m + n_0$$

where

N—total number of experimental design points;

m—number of independent variables;

n_0—number of centre-point experiments.

For two independent variables ($m = 2$), the experimental programme consisted of nine design points. Each experimental condition was repeated twelve times in a randomized sequence. Randomization was used to reduce the possible influence of systematic experimental factors and to improve the statistical reliability of the obtained observations.

2.3. Selection of Factor Levels

The factor levels were selected on the basis of preliminary experimental observations and the permissible operating conditions of the electric drive system. The overall research workflow and methodology are illustrated in **Figure 1**.

The first factor, U_1, represented the duration of electric drive failure. The second factor, U_2, represented the reduction in motor rotational speed relative to its nominal value. Both factors were varied around their central experimental levels so that linear, quadratic, and interaction effects could be identified. The coded values of the independent variables were used in the regression analysis. The corresponding natural values were retained for subsequent engineering interpretation of the mathematical model.

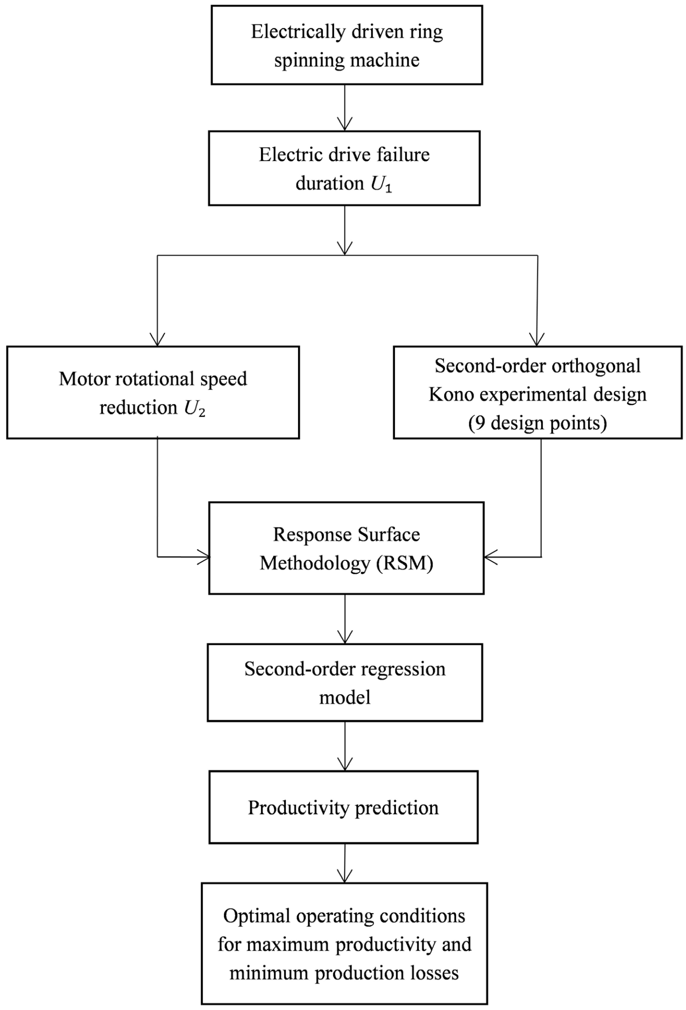

Figure 1. Research methodology for developing the second-order mathematical model of the electrically driven ring spinning machine.

The resulting experimental matrix consisted of nine design points. The experimental conditions and corresponding machine productivity values are presented in **Table 1**.

Table 1. Experimental design matrix and measured productivity values for the ring spinning machine.

Experiment №	Level of variation				Machine productivity, $\bar{Y}_i$, percentage of shift output
	Natural values		Coded values		
	Electric drive failure duration T, min.	Reduction in rotational speed Δn, percentage of nominal value	U_1	U_2	
1	2	3	4	5	
1	10	4	+1	+1	4.33
2	2	4 2^2 Design point	−1	+1	3.84
3	10	2	+1	−1	4.03

Continued

4	2	2	−1	−1	3.78
5	10	3	+1	0	4.13
6	2	3 Axial (star)	−1	0	3.78
7	6	4 points	0	+1	4.10
8	6	2	0	−1	3.81
9	6	3 Centre point	0	0	3.67

2.4. Mathematical Modelling Procedure

The relationship between machine productivity and the investigated electric-drive parameters was described using a second-order response surface regression model. Response Surface Methodology was selected because it allows the simultaneous assessment of linear, quadratic, and interaction effects.

The general form of the second-order regression model is expressed as

$$Y = b_0 + \sum_{i-1}^{m} b_i U_i + \sum_{i-1}^{m} b_{ii} U_i^2 + \sum_{i<j}^{m} b_{ij} U_i U_j$$

where:

Y—is the predicted machine productivity;

b_0—is the intercept coefficient;

b_i—are the linear regression coefficients;

b_{ii}—are the quadratic regression coefficients;

b_{ij}—are the interaction coefficients;

U_i—are the coded independent variables.

For the present investigation involving two independent variables, the regression equation becomes

$$Y = b_0 + b_1 U_1 + b_2 U_2 + b_{12} U_1 U_2 + b_{11} U_1^2 + b_{22} U_2^2$$

where:

Y—predicted machine productivity;

b_0—intercept coefficient;

b_1, b_2—linear regression coefficients;

b_{11}, b_{22}—quadratic regression coefficients;

b_{12}—interaction coefficient;

U_1, U_2—coded values of the independent variables.

The regression coefficients were estimated using the least-squares method based on the experimental observations [11]. The resulting model was used to quantify both the individual influence of each factor and their combined effect on machine productivity.

2.5. Statistical Analysis

The statistical analysis was performed in three stages.

First, the homogeneity of the experimental variances was evaluated using

Cochran's criterion. The test was used to determine whether the variances obtained at the different experimental design points could be considered statistically homogeneous [12] [13].

Second, the significance of the regression coefficients was evaluated using Student's t-test at a confidence level of 95%. Coefficients that did not satisfy the adopted significance criterion were excluded from the final regression equation where appropriate.

Finally, the adequacy of the regression model was evaluated using Fisher's F-test. The model was considered statistically adequate when the calculated Fisher statistic satisfied the corresponding critical-value criterion at the selected confidence level [14].

For the *i*-th experimental point, the Cochran statistic was calculated as:

$$G = \frac{\max S_i^2}{\sum_{i-1}^{n} S_i^2}$$

where S_i^2—is the variance of the *i*-th experimental point.

The statistical significance of a regression coefficient was evaluated using:

$$t_1 = |b_i| / S_{\beta i}$$

where b_i is the estimated regression coefficient and $S_{\beta i}$ *is its standart error*.

The adequacy of the regression model was assessed by comparing the calculated and critical Fisher statistics:

$$F = \frac{S_{ad}^2}{S_e^2}$$

where

S_{ad}^2—is the adequacy variance;

S_e^2—is the experimental variance.

2.6. Computational Procedure

Following estimation and statistical verification of the regression coefficients, the coded variables were transformed into their corresponding natural technological values. The transformation was performed using:

$$U_i = \frac{X_i - X_{0i}}{\Delta X_i}$$

where:

X_i—natural value of the investigated parameter;

X_{0i}—central value of the experimental range;

ΔX_i—variation interval of the corresponding factor;

U_i—coded value used in the regression model.

The developed regression equation was then used to estimate machine productivity throughout the investigated operating region. A response surface was constructed to illustrate the combined influence of electric drive failure duration and motor rotational speed reduction [15].

The response surface was also used to identify operating regions associated with higher productivity and lower production losses. The resulting model provides a quantitative basis for comparing operating conditions and selecting regimes that support more efficient use of the spinning machine and its electric drive system.

3. Mathematical Model Development

3.1. Development of the Response Surface Model

The mathematical model was developed using **Response Surface Methodology (RSM)** to establish a quantitative relationship between machine productivity and the investigated operating parameters of the electric drive. Compared with conventional linear regression models, the second-order response surface model provides a more accurate representation of nonlinear technological processes because it simultaneously accounts for linear, quadratic, and interaction effects [16].

The general second-order regression model adopted in this study is expressed as

$$Y = b_0 + b_1U_1 + b_2U_2 + b_{12}U_1U_2 + b_{11}U_1^2 + b_{22}U_2^2$$

where

Y—is the predicted machine productivity;

U_1—is the electric drive failure duration;

U_2—is the reduction in motor rotational speed;

b_0—is the intercept coefficient;

b_1—and b_2 are the linear regression coefficients;

b_{11}—and b_{22} are the quadratic regression coefficients;

b_{12}—is the interaction coefficient.

This model enables simultaneous evaluation of the independent effects of each factor together with their combined nonlinear influence on machine productivity.

3.2. Experimental Design Matrix

The experimental design matrix was constructed according to the second-order orthogonal Kono design. The total number of experimental design points was determined from

$$N = 2^m + 2m + n_0$$

where

m—is the number of independent variables;

n_0—is the number of centre-point experiments.

For two investigated variables $m = 2$, the experimental programme consisted of nine design points, each repeated twelve times under randomized operating conditions.

This experimental design provides sufficient statistical information for estimating all regression coefficients while significantly reducing the number of required experiments compared with conventional full-factorial designs.

3.3. Estimation of Regression Coefficients

The regression coefficients were estimated using the least-squares method, which minimizes the sum of squared differences between the experimental and predicted productivity values [17] [18].

The linear regression coefficients were calculated according to

$$b_1 = \frac{1}{N}\sum_{k-1}^{N} U_{ik} X_k$$

where

N—is the total number of experimental observations;

Y_k—is the measured productivity;

U_i—is the coded value of the corresponding factor.

The interaction coefficient was determined from

$$b_{12} = \frac{1}{N}\sum_{k-1}^{N} U_{1k} U_{2k} Y_k$$

while the quadratic coefficients were calculated as

$$b_{ii} = \frac{1}{N}\sum_{k-1}^{N} U_{1k} Y_k$$

The estimated regression coefficients form the mathematical basis of the developed response surface model and describe both the independent and combined effects of the investigated operating variables.

3.4. Verification of Experimental Variance

Before estimating the final regression equation, the homogeneity of the experimental variances was evaluated using Cochran's test [19].

The Cochran statistic was calculated as

$$G = \frac{\max\left(S_i^2\right)}{\sum_{i-1}^{n} S_i^2}$$

where S_i^2 is the variance calculated for the i-th experimental point.

The 95% reliability level is retained because all statistical analyses in the experimental study were performed at a 95% confidence level. The calculated Cochran value was lower than the corresponding critical value, confirming the homogeneity of the experimental variances.

3.5. Statistical Significance of Regression Coefficients

The statistical significance of each regression coefficient was evaluated using Student's t-test [20].

The test statistic was calculated as

$$t_i = \frac{|b_i|}{S_{bi}}$$

where

b_i—is the estimated regression coefficient;

S_{bi}—is the standard error of the coefficient.

Regression coefficients satisfying the statistical significance criterion at the 95% confidence level were retained in the final mathematical model.

3.6. Adequacy of the Mathematical Model

The adequacy of the developed regression model was evaluated using Fisher's F-test according to

$$F = \frac{S_{ad}^2}{S_e^2}$$

where

S_{ad}^2 —is the adequacy variance;

S_e^2 —is the experimental variance.

The regression model was considered statistically adequate when the calculated F-value was lower than the corresponding critical value at the selected confidence level [21]. The calculated response values are summarized in Table 2

Table 2. Calculated values of the response within the coded experimental region.

Experiment №	U_1	U_2	Y_i	$\bar{Y}_i$	Y_i - $\bar{Y}_i$	σ_i^2	$\bar{Y}_i$
1	2	3	4	5	6	7	8
1	+1	+1	4.5 4.5 3.5		0.12 0.12 0.88		
			5.0 5.0 3.4		0.62 0.62 0.98		
				4.38		0.53	4.35
			3.5 5.0 5.0		0.88 0.62 0.62		
			3.0 4.5 5.0		1.38 0.12 0.62		
2	−1	+1	3.8 4.0 2.9		0.04 0.16 0.94		
			4.2 5.0 5.0		0.36 1.16 1.16		
				3.84		0.44	3.87
			4.0 4.0 3.0		0.16 0.16 0.84		
			3.6 3.6 3.0		0.24 0.24 0.84		
3	+1	−1	4.2 4.3 5.0		0.17 0.27 0.97		
			3.5 3.0 5.0		0.53 1.03 0.97		
				4.03		0.44	4.02
			4.0 4.0 4.0		0.03 0.03 0.03		
			3.0 4.8 3.5		1.03 0.77 0.53		
4	−1	−1	3.4 3.4 3.8		0.11 0.11 0.29		
			4.0 4.0 4.0		0.49 0.49 0.49		
				3.51		0.34	3.56
			5.0 3.0 3.0		1.49 0.51 0.51		
			4.0 3.8 3.9		0.49 0.29 0.39		

Continued

5	+1	0	3.21 3.09 4.00		0.92 1.04 0.13		
			4.10 4.89 5.02		0.03 0.76 0.89		
				4.13		0.35	4.20
			4.7 4.43 3.93		0.57 0.30 0.20		
			4.23 4.14 3.82		0.10 0.01 0.31		
6	−1	0	4.03 4.78 3.53		0.25 1.00 0.25		
			3.12 3.90 4.32		0.66 0.12 0.54		
				3.78		0.46	3.74
			2.53 4.03 2.60		1.25 0.25 1.18		
			3.78 4.00 4.74		0 0.22 0.96		
7	0	+1	3.81 4.70 4.20		0.29 0.60 0.10		
			3.70 2.70 5.50		0.40 1.40 1.40		
				4.10		0.41	4.13
			4.09 4.00 4.20		0.01 0.10 0.10		
			4.00 4.20 4.10		0.10 0.10 0		
8	0	−1	4.91 3.12 2.90		0.10 0.69 0.91		
			5.01 3.81 3.92		1.20 0 0.11		
				3.81		0.48	3.81
			4.94 3.79 3.78		1.13 0.02 0.03		
			3.18 2.97 3.35		0.63 0.84 0.46		
9	0	0	3.50 4.10 5.00		0.50 0.10 1.00		
			4.30 3.90 4.20		0.30 0.10 0.20		
				4.00		0.36	3.99
			1.10 4.20 2.94		0.10 0.20 1.06		
			3.8 4.20 2.80		0.20 0.20 1.20		

The replicated experimental data were additionally audited by recalculating the mean productivity and experimental variance for each design point. The recalculation was performed using the individual productivity observations obtained from the repeated experimental runs. This verification ensured consistency between the reported mean response values and the corresponding replicate dataset before subsequent regression modelling and statistical analysis.

3.7. Transformation into Natural Variables

Following statistical verification of the regression equation in coded variables, the mathematical model was transformed into natural variables corresponding to the actual operating conditions of the ring spinning machine. This transformation enables direct engineering interpretation of the model and facilitates its practical application under industrial production conditions [22] [23].

The relationship between coded and natural variables is defined as

$$U_i = \frac{X_i - X_{0i}}{\Delta X_i}$$

where

X_i—is the natural value of the investigated parameter;

X_0—is the central value of the experimental range;

ΔX_i—is the variation interval of the corresponding factor;

U_i—is the coded value used in the regression model.

Substituting the transformation equations into the regression model produced the final mathematical equation expressed in natural variables. This representation allows direct prediction of machine productivity using actual operating parameters without additional data conversion [24].

3.8. Final Mathematical Model

Based on the recalculated experimental mean values, the regression coefficients of the second-order response surface model were estimated using the least-squares method. The final regression equation in coded variables was obtained as

$$Y = b_0 + b_1U_1 + b_2U_2 + b_{11}U_1^2 + b_{22}U_2^2 + b_{12}U_1U_2$$

The final form of the regression model was established after estimation of the regression coefficients and evaluation of their statistical significance. The second-order equation includes linear, quadratic, and interaction terms, allowing the individual and combined effects of electric drive failure duration and motor rotational speed reduction to be represented within the investigated experimental region. The statistically verified model was subsequently used for productivity prediction and for constructing the response surface [25].

$$Y = 3.7797 + 0.1805U_1 + 0.1100U_2 + 0.1205U_1^2 + 0.1190U_2^2 + 0.0583U_1U_2$$

4. Results and Discussion

4.1. Experimental Results

The experimental investigation was carried out using a second-order orthogonal Kono design comprising nine experimental points. Each experimental condition was repeated twelve times in randomized order. The obtained observations were used to determine the average productivity values and to develop the second-order regression model. This experimental procedure provided a basis for evaluating the effects of electric drive failure duration and motor rotational speed reduction on the performance of the ring spinning machine [26].

The experimental results show that machine productivity varies with changes in both investigated factors. The response is determined not only by the individual effect of electric drive failure duration or motor speed reduction, but also by their combined variation. This confirms the need to consider the two factors simultaneously when evaluating the operating performance of the spinning machine.

The calculated productivity values obtained from the regression model were used to construct a response surface for the investigated experimental region. The response surface provides a graphical representation of the relationship between the two independent variables and the machine productivity response [27].

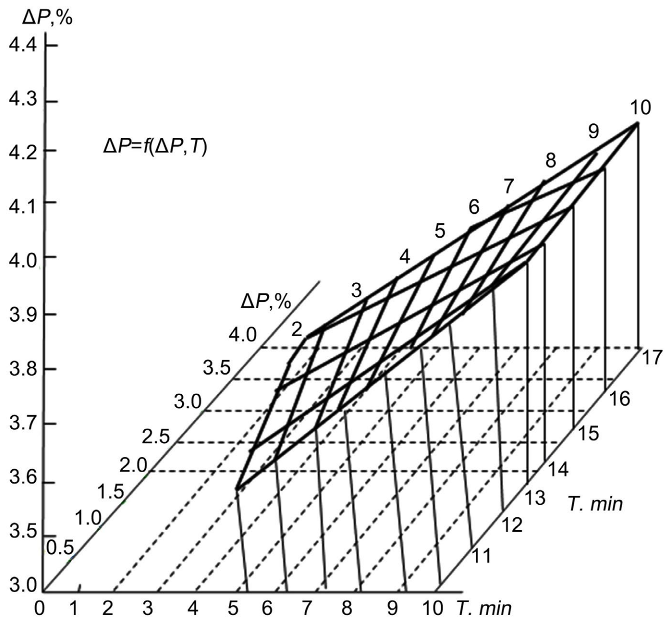

Figure 2. Response surface describing the combined effect of electric drive failure duration and motor rotational speed reduction on the productivity of the RIETER G36 ring spinning machine.

Table 3. Calculated response values at different combinations of the coded variables U_1 and U_2.

U_1	Values of $\bar{Y}$ at different values of U_2								
	0	0.25	0.5	0.75	1.0	−0.25	−0.5	−0.75	−1
0	3.99	4.03	4.07	4.10	4.13	3.96	3.90	3.85	3.81
0.25	4.05	4.09	4.23	4.16	4.19	4.01	3.96	3.91	3.87
0.5	4.10	4.14	4.18	4.22	4.25	4.06	4.01	3.96	3.92
0.75	4.15	4.20	4.24	4.27	4.30	4.12	4.06	4.01	3.97
1.0	4.20	4.25	4.29	4.32	4.35	4.16	4.11	4.06	4.02
−0.25	3.93	3.98	4.01	4.04	4.07	3.89	3.84	3.79	3.75
−0.5	3.87	3.91	3.95	3.97	4.01	3.83	3.78	3.73	3.69
−0.75	3.80	3.85	3.88	3.91	3.94	3.76	3.71	3.67	3.63
−1	3.74	3.77	3.82	3.85	3.87	3.71	3.66	3.60	3.56

The response surface illustrates the variation of machine productivity over the investigated range of the two operating factors. In particular, the figure makes it possible to compare the predicted productivity at different combinations of electric drive failure duration and motor rotational speed reduction [28]. Thus, the graphical representation complements the experimental design and provides an engineering interpretation of the developed regression model (**Table 3**).

The calculated values of the response within the coded experimental region are presented in the corresponding response matrix. The values vary from approximately 3.56 to 4.35 within the investigated range, demonstrating that changes in the electric-drive operating conditions produce a measurable variation in machine productivity [29].

The response surface also demonstrates the importance of considering the interaction between the investigated variables. When the two operating factors change simultaneously, the resulting productivity response cannot always be represented adequately by considering each factor separately. This behaviour is one of the reasons for using a second-order regression model rather than a simple linear relationship.

4.2. Statistical Verification of the Developed Model

The statistical reliability of the developed regression model was evaluated using Cochran's homogeneity criterion, Student's t-test, and Fisher's F-test. These criteria were applied sequentially to assess the homogeneity of experimental variances, the significance of the regression coefficients, and the adequacy of the resulting mathematical model.

The Cochran criterion was used to determine whether the variances obtained at the different experimental points could be considered homogeneous. The analysis indicated that the experimental variances satisfied the adopted homogeneity condition at the 95% confidence level.

Student's t-test was then applied to evaluate the statistical significance of the estimated regression coefficients. The analysis showed that the principal linear effects associated with the investigated operating parameters made the largest contribution to the response. Quadratic and interaction terms were retained where their contribution was statistically justified, allowing the nonlinear behaviour of the process to be represented.

Finally, Fisher's criterion was used to evaluate the adequacy of the regression equation. The calculated result satisfied the adopted adequacy condition, indicating that the mathematical model can be used to describe the experimental response within the investigated range [30].

The statistical verification therefore supports the use of the developed second-order model for predicting machine productivity under different combinations of electric drive failure duration and motor rotational speed reduction [31].

4.3. Influence of Electric Drive Failure Duration

The experimental results demonstrate that electric drive failure duration is an important factor affecting the operating performance of the ring spinning machine. A temporary interruption of the drive disrupts the continuity of the technological process and may result in additional production losses associated with stopping and restarting the machine.

As the duration of the interruption changes, the predicted productivity response also changes. The second-order model accounts for this effect through both the linear and quadratic terms associated with the first factor. Consequently, the model can represent changes in the response that are not necessarily proportional throughout the investigated operating interval.

From an operational perspective, maintaining the electric drive within its normal operating regime is therefore important for avoiding unnecessary interruptions and for ensuring effective use of the machine's available operating time.

4.4. Influence of Motor Rotational Speed Reduction

The second investigated factor was the reduction in motor rotational speed relative to the nominal operating value. The experimental results indicate that changes in motor speed affect the production response of the spinning machine.

A reduction in rotational speed changes the operating conditions of the spinning process and may reduce the amount of yarn produced during a fixed operating period. The influence of this factor becomes particularly important when the speed reduction occurs together with an interruption or deterioration of the electric drive.

The regression model represents this behaviour through the linear and quadratic terms associated with the second factor. The response surface therefore provides a convenient means of evaluating productivity over different combinations of motor speed reduction and drive failure duration.

4.5. Interaction between Technological Factors

An important feature of the developed model is the inclusion of the interaction term between electric drive failure duration and motor rotational speed reduction. This term allows the model to account for the combined effect of the two operating factors.

The response surface indicates that the productivity response depends on the simultaneous state of both variables. Therefore, evaluating the drive failure duration and motor speed reduction independently may not provide the same result as their combined assessment.

The inclusion of the interaction and quadratic terms gives the model greater flexibility in describing the nonlinear behaviour of the spinning process and provides a more informative representation of the operating region than a first-order model.

4.6. Practical Engineering Implications

The developed mathematical model can be used as an engineering tool for estimating machine productivity under different electric-drive operating conditions. Its practical applications include:

- prediction of productivity changes associated with temporary electric drive failures;

- evaluation of the effect of motor rotational speed reduction;
- identification of operating conditions associated with higher production losses;
- support for maintenance planning and reliability assessment;
- comparison of operating regimes from the perspective of efficient use of electrical energy;
- development of mathematical support for intelligent monitoring and adaptive control.

The model can therefore contribute to more informed operation of electrically driven spinning machinery. In particular, identifying operating conditions associated with unnecessary interruptions or inefficient drive operation may help reduce production losses and improve the use of energy resources in textile manufacturing [31].

4.7. Discussion

The developed second-order mathematical model provides a combined description of the relationship between electric drive operating conditions and ring spinning machine productivity. The use of linear, quadratic, and interaction terms makes it possible to represent the response over the investigated experimental region more comprehensively than a simple first-order relationship.

The response surface presented in **Figure 2** provides a visual interpretation of the calculated model values and demonstrates how the productivity response changes with simultaneous variation of the investigated factors. The experimental design and subsequent statistical verification provide a quantitative basis for interpreting these changes.

An additional practical aspect of the model is its potential use in improving the efficiency of textile machinery operation. Although the present experimental response is machine productivity, maintaining stable electric-drive operation can reduce avoidable interruptions and improve the efficient use of the available production period. Therefore, the proposed approach can serve as a basis for further studies in which electricity consumption and specific energy consumption are directly measured together with machine productivity.

Such an extension would make it possible to establish a quantitative relationship between machine productivity, electric-drive operating conditions, and energy efficiency. This direction is particularly relevant for sustainable textile manufacturing, where reducing unnecessary energy use and production losses is an important operational objective.

It should be noted that the present study uses machine productivity as the primary experimental response, while electrical energy consumption was not measured directly. Therefore, the energy-related implications of the developed model should be interpreted in terms of improved utilization of machine operating time and the reduction of avoidable production losses. Future studies may extend the proposed approach by simultaneously measuring productivity and electrical energy consumption, including specific energy consumption per unit of produced yarn.

5. Conclusions

This study developed and experimentally validated a comprehensive second-order mathematical model for evaluating the performance of an electrically driven ring spinning machine operating under simultaneous variations in electric drive failure duration and motor rotational speed reduction.

The developed regression model successfully describes the combined influence of linear, quadratic, and interaction effects of the investigated operating parameters on machine productivity. Application of the second-order orthogonal Kono experimental design made it possible to obtain statistically reliable regression coefficients while significantly reducing the number of required experimental observations.

Statistical verification based on Cochran's homogeneity criterion, Student's t-test, and Fisher's F-test confirmed that the proposed regression equation adequately represents the experimental data at the selected confidence level. The developed mathematical model therefore provides a reliable analytical tool for predicting productivity under different electric drive operating conditions.

The obtained response surface demonstrates that simultaneous increases in electric drive failure duration and motor rotational speed reduction result in substantial productivity losses. Consequently, these operating parameters should be evaluated simultaneously rather than independently when assessing the performance of electrically driven ring spinning machines.

From a practical engineering perspective, the proposed model may be applied to improve machine operating conditions, improve maintenance planning, reduce production losses, and support intelligent monitoring and adaptive control systems in modern textile manufacturing.

Future research will focus on integrating the developed mathematical model with real-time sensor data and artificial intelligence techniques for predictive maintenance, intelligent fault diagnosis, and digital twin technologies for ring spinning machines operating under Industry 4.0 conditions.

Research Highlights

– A comprehensive second-order mathematical model was developed for an electrically driven ring spinning machine.

– The proposed model simultaneously considers electric drive failure duration and motor rotational speed reduction.

– Response Surface Methodology based on the Kono experimental design was successfully applied.

– Statistical validation confirmed the adequacy and reliability of the developed regression model.

– The proposed model provides an effective tool for productivity prediction and intelligent process optimization in textile manufacturing.

Author Contributions

Conceptualization, N.A. and B.T.; methodology, N.A.; software, N.A.; validation, N.A. and B.T.; formal analysis, N.A.; investigation, N.A.; resources, B.T.; data curation, N.A.; writing—original draft preparation, N.A. and B.T.; writing—review and editing, B.T.; visualization, N.A.; supervision, B.T.; project administration, B.T.; funding acquisition, B.T. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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