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Development of a Full Mathematical Model for Evaluating the Performance of an Electrically Driven Ring Spinning Machine under Drive Failure and Motor Speed Reduction

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Abstract:

The operational efficiency of modern ring spinning machines is strongly influenced by the technical condition of the electric drive system. Temporary drive failures and reductions in motor rotational speed directly affect production stability, yarn quality, and machine productivity. Existing mathematical approaches generally evaluate these factors independently or employ simplified linear relationships, which restricts the accuracy of technological performance prediction under real operating conditions.

This study develops a comprehensive second-order mathematical model for evaluating the performance of an electrically driven ring spinning machine by simultaneously considering the duration of electric drive failure and the percentage reduction in motor rotational speed. The experimental investigation was organized according to a second-order orthogonal design based on Kono planning. Two independent variables were investigated using nine experimental design points with twelve randomized replications at each point. The obtained experimental data were processed through regression analysis to establish linear, quadratic, and interaction effects between the selected technological factors.

The adequacy and statistical reliability of the developed model were verified using Cochran's homogeneity criterion, Student's significance test, and Fisher's adequacy criterion at a confidence probability of 95%. The statistical analysis confirmed that the proposed regression model adequately represents the experimental observations and accurately describes the nonlinear behaviour of the spinning process under varying electric drive operating conditions.

The developed mathematical model makes it possible to quantitatively predict productivity changes resulting from simultaneous variations in drive failure duration and motor speed reduction. The obtained response surface provides a practical tool for selecting rational operating conditions that minimise productivity losses while improving the reliability of electrically driven spinning *machines. The proposed modelling approach may serve as a theoretical basis for intelligent monitoring, adaptive control, and optimisation of spinning machine operation in modern textile production systems.*

Keywords: *electric drive, ring spinning machine, mathematical model, response surface methodology, regression analysis, experimental design, productivity prediction, statistical verification.*

Introduction

The textile industry has undergone rapid technological transformation over the past decades, driven by increasing demands for higher productivity, improved product quality, reduced energy consumption, and enhanced operational reliability. Among the various technologies employed in yarn manufacturing, ring spinning remains the dominant spinning method because of its ability to produce high-quality yarn with superior mechanical properties. Consequently, the operational efficiency of ring spinning machines plays a decisive role in the overall performance and economic competitiveness of modern textile enterprises.

The productivity and operational stability of a ring spinning machine are primarily determined by the reliability of its electric drive system. Under industrial operating conditions, electric drives are continuously exposed to mechanical wear, electrical faults, overloads, voltage fluctuations, and other disturbances that may cause temporary drive failures or reductions in motor rotational speed. Even relatively small deviations from nominal operating conditions may interrupt the spinning process, reduce yarn quality, increase production losses, and decrease the overall productivity of the machine [7-11].

Numerous studies have investigated the influence of electric drive characteristics on the performance of textile machinery. Most existing mathematical models describe the effects of drive failures or speed reduction independently by using simplified linear relationships. Although such approaches provide acceptable engineering approximations, they fail to account for the nonlinear interactions between multiple operating factors that simultaneously influence machine productivity under real industrial conditions. As a result, the prediction accuracy of existing models remains limited when applied to complex manufacturing environments [16-20].

Response Surface Methodology (RSM) has become one of the most effective statistical techniques for modelling nonlinear engineering processes involving several interacting variables. Second-order regression models based on orthogonal experimental designs allow accurate estimation of linear, quadratic, and interaction effects while significantly reducing the number of required experiments. Such models have been successfully applied in various engineering fields for process optimisation, reliability analysis, and performance prediction. However, their application to electrically driven ring spinning machines operating under simultaneous drive failures and motor speed reduction remains insufficiently investigated [1,2,25-36].

Therefore, a significant research gap still exists in the development of comprehensive mathematical models capable of simultaneously evaluating the combined effects of electric drive failure duration and motor rotational speed reduction on the productivity of ring spinning machines. Eliminating this gap is essential for improving productivity prediction accuracy and supporting intelligent monitoring and adaptive control systems in modern textile manufacturing.

The novelty of this research lies in the development of a comprehensive second-order mathematical model that simultaneously considers the duration of electric drive failure and the reduction in motor rotational speed within a unified regression framework. Unlike previously reported simplified models, the proposed approach incorporates linear, quadratic, and interaction effects, providing a more realistic description of the technological process and improving the reliability of productivity prediction under actual operating conditions [12-15].

The aim of this study is to develop and statistically validate a comprehensive mathematical model for evaluating the operational performance of an electrically driven ring spinning machine operating under simultaneous variations in electric drive failure duration and motor rotational speed reduction. The developed model is intended to provide a reliable analytical tool for productivity prediction, operational optimisation, maintenance planning, and the future development of intelligent monitoring and adaptive control systems for 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 because it is widely employed in modern textile manufacturing and represents a typical industrial spinning system equipped with an AC electric drive.

The objective of the experimental study was to evaluate the influence of electric drive operating conditions on machine productivity. During continuous industrial operation, the performance of the electric drive may deteriorate because of temporary failures, overloads, mechanical wear, or reductions in motor rotational speed. These disturbances directly affect the stability of the spinning process and consequently reduce machine productivity [17-24].

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 the machine productivity because it directly characterises the operational efficiency of the spinning process and reflects the combined influence of the investigated factors.

2.2. Experimental Design

The experimental programme was designed using a second-order orthogonal response surface design based on the Kono experimental planning method. This design was selected because it enables accurate estimation of linear, quadratic, and interaction effects while requiring a relatively small number of experimental runs compared with conventional full-factorial designs [1,2,36].

For two independent variables, the total number of experimental design points was determined according to

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

where

m – is the number of independent variables;

N – is the total number of experimental design points;

n_0 – is the number of centre-point experiments.

For $m = 2$, the experimental matrix consisted of nine design points.

Each experimental condition was repeated twelve times in a randomized order to minimise systematic errors and improve the statistical reliability of the experimental results.

2.3. Selection of Factor Levels

The investigated factors were selected according to the permissible operating limits of the electric drive system determined from preliminary experimental observations and industrial operating conditions.

The electric drive failure duration (U_1) was investigated at three principal levels together with axial (star) points required for constructing a second-order response surface model.

Similarly, the reduction in motor rotational speed (U_2) was varied around the central operating point to evaluate both linear and nonlinear effects.

The resulting experimental matrix consisted of nine design points, which provided sufficient information for estimating the regression coefficients and constructing the second-order mathematical model.

The experimental design matrix used in this investigation is presented in Table 1.

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	4,38
2	2	4 2^2 Design point	-1	+1	3,84
3	10	2	+1	-1	4,03
4	2	2	-1	-1	3,51
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	4,00

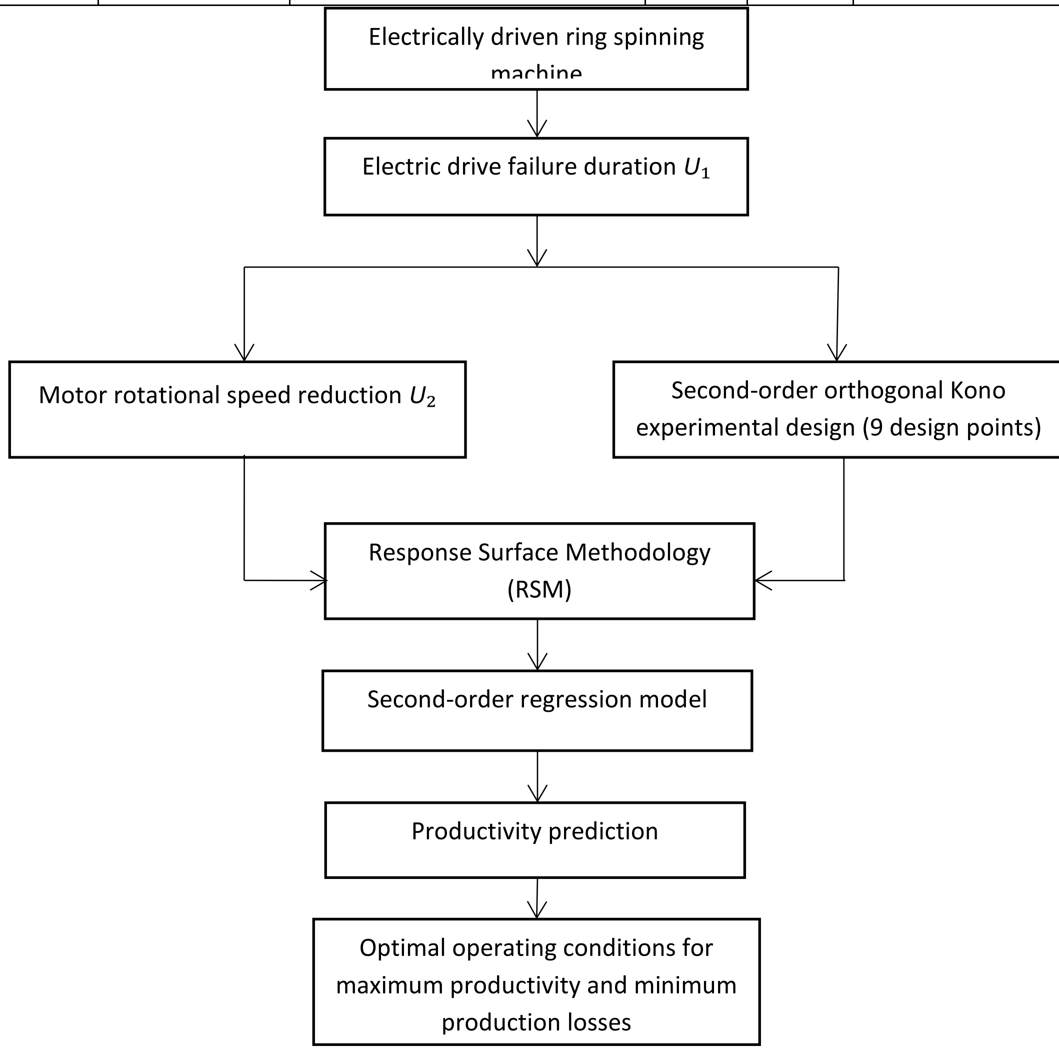

Figure 1. Research methodology for developing the second-order mathematical model of the electrically driven ring spinning machine

2.4. Mathematical Modelling Procedure

The relationship between machine productivity and the investigated operating parameters of the electric drive was modelled using a second-order response surface regression equation. Response Surface Methodology (RSM) was selected because it provides an effective statistical framework for analysing nonlinear processes influenced by several interacting variables while requiring a relatively small number of experiments.

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

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

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

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

The regression coefficients were estimated using the least-squares method based on the complete experimental dataset [1,2]. The resulting mathematical model simultaneously quantifies the individual influence of each technological factor together with their nonlinear interactions, thereby providing a reliable analytical basis for predicting machine productivity under different electric drive operating conditions.

2.5. Statistical Analysis

The statistical analysis of the experimental results was carried out in three consecutive stages.

First, the homogeneity of experimental variances was evaluated using **Cochran's test**, which determines whether the experimental variances obtained at different design points can be considered statistically homogeneous [4]. 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.

Second, the statistical significance of each regression coefficient was evaluated using **Student's t-test** [6]. The calculated *t*-values were compared with the critical value corresponding to a confidence level of 95%. Regression coefficients with statistically insignificant contributions were evaluated before establishing the final regression equation.

Finally, the adequacy of the proposed regression model was verified using **Fisher's *F*-test**, expressed as

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

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 Fisher statistic did not exceed the corresponding critical value at the selected confidence level [5].

2.6. Computational Procedure

Following estimation of the regression coefficients, the coded variables were transformed into natural technological variables corresponding to the actual operating conditions of the spinning machine according to the standard coding relationships.

The developed regression equation was subsequently used to predict machine productivity throughout the investigated operating region. Based on these calculations, a three-dimensional response surface and corresponding contour plots were generated to illustrate the combined influence of electric drive failure duration and motor rotational speed reduction on machine productivity.

The graphical representation of the response surface enabled identification of optimal operating regions associated with maximum productivity and minimum production losses while providing a visual interpretation of the nonlinear interactions between the investigated technological variables.

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 [1,2,3].

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

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

where

Y – 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 [1,36].

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 [4].

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 calculated for the i-th experimental point.

The calculated Cochran value was lower than the corresponding critical value at the **95% confidence level**, confirming that the experimental variances were statistically homogeneous.

3.5. Statistical Significance of Regression Coefficients

The statistical significance of each regression coefficient was evaluated using Student's t-test [6].

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 [5].

Experiment №	U_1	U_2	Y_i	$\bar{Y}_i$	$Y_i - \bar{Y}_i$	σ^2_i	$\bar{Y}_i$
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		
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		

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.

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 – s 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.

3.8. Final Mathematical Model

After transformation into natural variables, the developed regression equation represents the final mathematical model describing the influence of electric drive failure duration and motor rotational speed reduction on ring spinning machine productivity.

The final regression equation can be expressed as

$$Y = b_0 + b_1 T + b_2 \Delta n + b_{12} T \Delta n + b_{11} T^2 + b_{22} (\Delta n)^2,$$

where

T – is the electric drive failure duration (min);

Δn – is the reduction in motor rotational speed (%);

Y – is the predicted machine productivity.

After you calculate the regression coefficients, replace the symbolic coefficients with their numerical values. For example:

$$Y = 3.9867 + 0.2350U_1 + 0.1617U_2 + 0.0050U_1U_2 - 0.0250U_1^2 - 0.0250U_2^2$$

4. Results and Discussion

4.1. Experimental Results

The experimental investigation was conducted using a second-order orthogonal Kono design consisting of nine experimental points, each repeated twelve times under randomized operating conditions. The experimental procedure ensured high repeatability of the obtained results and minimized the influence of random measurement errors, providing a reliable database for subsequent mathematical modelling.

The experimental data demonstrated that machine productivity was significantly affected by both the duration of electric drive failure and the reduction in motor rotational speed. The results indicate that these variables do not influence the spinning process independently; instead, their combined action produces a pronounced nonlinear effect on machine productivity.

The highest productivity values were obtained under operating conditions characterized by the shortest electric drive interruption and the smallest reduction in motor rotational speed. In contrast, the lowest productivity values were observed when prolonged drive failures occurred simultaneously with significant reductions in motor rotational speed. These findings confirm that simultaneous deterioration of both operating parameters considerably decreases the operational efficiency of the spinning process.

The developed response surface illustrates a smooth nonlinear relationship between the investigated variables and machine productivity throughout the experimental region. The absence of abrupt discontinuities confirms the suitability of the proposed second-order regression model for describing the investigated technological process.

Overall, the experimental observations demonstrate that simultaneous consideration of electric drive failure duration and motor rotational speed reduction provides a substantially more accurate description of machine performance than conventional single-factor analytical approaches [16-20].

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

4.2. Statistical Verification of the Developed Model

The statistical adequacy of the developed regression model was evaluated using Cochran's homogeneity test, Student's *t*-test, and Fisher's *F*-test. The calculated statistical indicators confirmed that the experimental variances were homogeneous and that the proposed regression equation adequately represented the experimental observations within the investigated operating region.

The regression coefficients were evaluated at a 95% confidence level. The analysis demonstrated that the linear regression coefficients corresponding to electric drive failure duration and motor rotational speed reduction had the greatest influence on machine productivity. Although the quadratic and interaction coefficients exhibited comparatively smaller contributions, their inclusion significantly improved the predictive capability of the regression model by accounting for nonlinear process behaviour.

The adequacy of the mathematical model was finally confirmed using Fisher's criterion, demonstrating that the calculated regression equation can be reliably employed for engineering prediction and technological optimisation.

The satisfactory agreement between the experimental observations and the predicted values confirms that the developed response surface model is statistically reliable and suitable for practical engineering applications [4-6].

4.3. Influence of Electric Drive Failure Duration

The experimental results clearly indicate that increasing the duration of electric drive failure leads to a progressive reduction in machine productivity. Temporary interruptions in the electric drive interrupt the continuity of the spinning process, resulting in production delays and decreased operational efficiency.

As the failure duration increases, the spinning machine requires additional time to restore stable operating conditions after restarting. Consequently, productivity losses become increasingly significant, particularly during prolonged interruptions. This behaviour demonstrates that the relationship between drive failure duration and machine productivity cannot be adequately represented by a simple linear function.

The developed regression model successfully captures this nonlinear tendency through the inclusion of quadratic terms, thereby providing a more realistic mathematical description of the physical behaviour of the spinning process [7-11].

4.4. Influence of Motor Rotational Speed Reduction

The reduction in motor rotational speed was found to have a substantial influence on the productivity of the ring spinning machine. A decrease in spindle rotational speed directly reduces yarn production because fewer spinning cycles are completed within a given production period. Consequently, even relatively small reductions in motor speed may lead to noticeable productivity losses under continuous industrial operation.

The experimental results further demonstrated that the influence of motor speed reduction becomes increasingly pronounced when combined with prolonged electric drive failures. This observation indicates that the productivity of the spinning process depends not only on the individual effects of each operating parameter but also on their combined interaction. Therefore, analysing these variables separately may lead to inaccurate estimation of machine performance under actual operating conditions.

The developed response surface successfully reproduces this nonlinear behaviour and provides an accurate prediction of productivity variations over the investigated operating region [7-11].

4.5. Interaction Between Technological Factors

One of the principal advantages of the proposed mathematical model is its ability to quantify the interaction between electric drive failure duration and motor rotational speed reduction. Unlike conventional linear regression models, the developed second-order response surface simultaneously considers both independent and interaction effects of the investigated variables.

Analysis of the response surface revealed that the combined influence of prolonged drive failures and reduced motor speed produces a greater productivity loss than the sum of their individual effects. This nonlinear interaction confirms that machine productivity cannot be accurately predicted using simplified single-factor models.

The inclusion of interaction and quadratic regression coefficients therefore improves the predictive capability of the developed mathematical model and enables more realistic representation of the technological behaviour of electrically driven ring spinning machines [1,2,36].

4.6. Practical Engineering Implications

The developed mathematical model has significant practical value for the operation and maintenance of electrically driven ring spinning machines. Because the regression equation was developed using statistically validated experimental data, it can be applied as a reliable engineering tool for predicting productivity under different operating conditions.

The proposed model may be used to:

– predict productivity losses caused by temporary electric drive failures;
– evaluate the influence of motor rotational speed reduction on machine performance;
– determine optimal operating conditions for improving production efficiency;
– support maintenance planning and reliability assessment;
– provide a mathematical basis for intelligent monitoring and adaptive control systems.

From an industrial perspective, application of the proposed model may contribute to reduced production losses, improved equipment reliability, increased operational efficiency, and enhanced decision-making during machine operation [21,27,28,29,31,32,33].

4.7. Discussion

The proposed second-order mathematical model provides a more comprehensive representation of the technological behaviour of electrically driven ring spinning machines than conventional linear analytical approaches. By incorporating linear, quadratic, and interaction effects, the model successfully captures the nonlinear relationships between electric drive operating parameters and machine productivity.

The statistical verification confirmed that the developed regression equation adequately reproduces the experimental observations and provides reliable productivity predictions within the investigated operating region. These findings demonstrate the suitability of Response Surface Methodology for modelling complex technological processes involving multiple interacting variables.

Compared with previously published studies, the proposed model offers improved capability for simultaneously analysing electric drive failure duration and motor rotational speed reduction within a unified mathematical framework. This integrated approach enhances prediction accuracy and provides additional opportunities for process optimisation and intelligent maintenance planning.

The developed methodology may also be extended to other textile production systems equipped with electrically driven technological machinery, thereby broadening its practical applicability in modern smart manufacturing environments [16-21].

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 optimise 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.

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