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Yarn hairiness versus quality of cotton fibres

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The influence of yarn construction parameters (yarn count and yarn twist) and quality of cotton fibres in terms of HVI parameters on yarn hairiness has been studied. The Uster Tester 4 and Zweigle G 567 are used for yarn hairiness investigation. The statistical methods (correlation analysis and principal component analysis PCA) are applied to verify significance of yarn hairiness parameter in yarn quality control process. The proposed PCA model can be effectively used as a qualitative criterion during yarn quality inspection. The predictive model for yarn hairiness estimation based on fibre and yarn parameters has been successfully designed using the regression analysis and can be used for prediction of yarn hairiness, expressed by hairiness index *H*.

Keywords: Cotton fibres, Multivariate data analysis, Regression model, Yarn quality, Yarn count, Yarn hairiness, Yarn twist

1 Introduction

Yarn quality control usually includes the verification of technological parameters (yarn count and yarn twist) together with study of yarn unevenness and mechanical parameters. There are parameters such as yarn hairiness characteristics, which are analyzed additionally. The yarn hairiness is an important parameter because it gives the information about the arrangement and behavior of fibre in hairiness sphere[1]. The study of yarn structure and fibre arrangement helps us in understanding the spinning process deeply and to describe the changes in yarn parameters occurred during yarn processing. Yarn hairiness has great influence on the weaving process and parameters of textile product such as porosity, permeability, transport of moisture, comfort, aesthetic properties and hand mainly along with wet processing parameters. This knowledge can be used for precise prediction of yarn behavior and design the textile structures according to customers demand[1].

Yarn is a compact complex structure. The arrangement of fibres is related to technology of production, construction of yarn and type of fibre[1,2]. During twisting of the yarn, some fibres are displaced from their central position to the yarn surface (migration effect). The hairiness is given by fibres on the periphery layer of yarn. Hairiness of yarn is usually characterized by the amount of free fibres (fibre loops, fibre ends) protruding from the compact yarn body towards the outer yarn surface[1,2]. There are two instruments commonly used for experimental evaluation of yarn hairiness[1,3]. Uster Tester 4 with additional hairiness sensor represents laboratory testing equipment based on optical system. The cumulative hairiness index *H* used by Uster Tester 4 for yarn hairiness quantification is specified as an average value of hairiness over the total test length. It means, in other words, that the cumulative length of all protruding fibres over 1 cm length of yarn is scanned for all testing yarn segments and row data are statistically processed[1,3]. System Zweigle G 567 is also based on optical system and counts the number of hair ends exceeding 1 mm up to 25 mm length from the compact body of yarn. The internal convention, which takes the variation of light intensity in all optical sensors in to consideration, is used for setting of yarn surface. Output of measurement is the absolute occurrence of hair ends in given length category n_i[1,3]. Sum criteria used for hairiness description (S_{12}, S_3, S) are given below:

$$S_{12} = \sum_{i=1}^{i=2} n_i, \qquad \ldots(1)$$

$$S_3 = \sum_{i=3}^{k} n_i, \qquad \ldots(2)$$

$$S = \sum_{i=1}^{k} n_i, \qquad \ldots(3)$$

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The degree of cotton fibres quality can be determined by using cotton standards, complex criterion mentioned by several authors or by using the utility value[2]. The HVI are usually used for testing basic parameters[4-6]. There are many parameters, which are used for cotton fibre classification. The inter dependencies between cotton parameters lead to the strong multicollinearities. Therefore, the complex quality criterion can be used together with fibre parameters for investigation of their influence on hairiness[4]. The quality index (*FQI)* and Uster spinning consistency index (*SCI*) are based on fibre parameters measured by HVI system [upper half mean length (*UHM)*, fibre bundle strength (*STR)* and micronaire (*MIC*), uniformity index (*UI*), color yellowness (+*b*), reflectance (R_d)]. Definitions of these indexes are given below[3-6]:

$$FQI = \frac{UHM\ STR}{MIC}, \quad \ldots(4)$$

$$SCI = -414.67 + 2.9\,STR - 9.32\,MIC + 49.17\,UHM + 4.74\,UI + 0.65\,R_d + 0.36\,(+b) \quad \ldots(5)$$

Korickij[7] proposed the *IG* criterion based on cotton length in terms of upper half mean length, uniformity index of staple length (*UI)*, short fibre content (*SFC)* and micronaire, as shown below:

$$IG = \frac{UHM\ UI\left(100 - SFC\right)}{10000\sqrt{MIC}} = \frac{UHM\ UI\left(100 - SFC\right)MAT}{10000\sqrt{t}} \quad \ldots(6)$$

More general concept based on the complex utility value was introduced by Militký and Křemenáková[8]. The cotton properties measured by HVI are utility properties *K*, which are based on the direct or indirect measurements. Functional transformation of quality characteristics (based often on the psycho-physical laws) leads to partial utility functions u_i as shown below. K_D is the value of characteristic for just non acceptable cotton ($u_i = 0.01$) and K_H the value of characteristic for just fully acceptable product ($u_i = 1$). Utility value *U* (quality index of cotton fibre) is weighted geometric average of u_i with weights w_i defined by Eq. (8), as shown below. To form the aggregating function *U* from experimentally determined values of individual utility properties, the statistical character of the x_j quantities should be considered and the corresponding variance *D(U)* should be also determined, as shown below[9–11]:

$$u_i = f(x_i, K_{D,} K_H), \quad \ldots(7)$$

$$U = ave(u_i, w_i), \quad \ldots(8)$$

Factors influencing yarn hairiness are type of fibres, yarn twist, yarn count, blending ratio and yarn production technology. This paper reports the influence of cotton fibre properties on yarn hairiness. It is generally accepted that fibre fineness, diameter, shape factor, length, flexural rigidity, torsional rigidity, extension-to-break and friction are fibre parameters influencing yarn hairiness significantly[1,6,9].

Present work is aimed at studying the influence of cotton fibre quality on open-end spun yarns hairiness and developing of prediction model for yarn hairiness estimation, considering the importance of yarn hairiness as the quality criterion of open-end spun yarns by the multivariate analysis. In this case, the correlation analysis and principal component analysis (PCA) are used to check justification of using yarn hairiness parameters as a part of yarn quality criterion.

2 Materials and Methods

Cotton fibres available in the market were used for cotton lots preparation. There exists various methods, which can be used for cotton blending [10,11]. The mixing was realized in respect to quality of cotton lots according to Uster Grade. Seventeen various lots of cotton fibres in whole range of Uster Grade were prepared. The open-end spun yarns were prepared under comparable conditions from set of cottons. The advantage of open-end technology is the shorter pre-spinning process without roving preparation. The earlier experiments were usually based on ring-spun yarns and therefore the realization of this experiment can give interesting results for open end spun yarn. 100% cotton yarns were produced in five levels of yarn count *T* (16.5, 20, 27, 37, and 50 tex) and minimally in two levels of Phrix twist coefficient *a* in respect to the each yarn count.

The HVI system was used for determining different fibre parameters. The micronaire value (*MIC*), length parameters [upper half mean length (*UHM*), mean length (*ML*), uniformity index (*UI*), short fibre index (*SFI*)], bundle strength (*STR*) and elongation (*EL),* color yellowness (*+b*), reflectance (R_d) and trash content (*TRC)* were determined. Vibroskop and Vibrodyn were used to evaluate fibre fineness (*t*) and mechanical parameters of single fibres [absolute strength (*p*), relative strength (*f*) and elongation (e_v)]. The level of yarn count was verified according to international standards. The level of yarn hairiness was measured under standard conditions by Uster Tester 4 and Zweigle G 567. Cumulative hairiness index *H* and its variability was evaluated on 1 km yarn length at 400 $mmin^{-1}$ speed. Absolute occurrence of hair ends in given distances from the yarn surface was analyzed on 100 m yarn length at 100 $mmin^{-1}$ speed. The sum criteria (S_{12} and S_3) were calculated according to Eq. (1) and (2). The analysis of yarn unevenness (*CV*) and number of faults (thin-40%, thin-50%, thick+35%, thick+50%, neps +200%, neps +280%) was done using by Uster Tester 4 and mechanical parameters of yarn. The mechanical parameters like the relative yarn strength (*F*) and yarn elongation (*e*) were measured by Tensorapid under standard conditions, considering the testing length 500 mm, pretension 0.5 $cNtex^{-1}$ and testing speed 5000 $mmmin^{-1}$.

3 Results and Discussion

3.1 Multivariate Data Analysis

Experimental data has been statistically processed and multivariate data analysis is applied. *IG* has been computed according to Eq. (6) and *U* according to Eq. (8) by using weights w_i [$w_{(UI)}$ - 0.21, $w_{(MIC)}$ - 0.17, $w_{(UHM)}$ - 0.15, $w_{(STR)}$ - 0.29, $w_{(EL)}$ - 0.1, $w_{(SFI)}$ - 0.07]. The Mahalanobis distance plot[12] proves that there are no outlying points. The multivariate data analysis confirms the following facts:

- The quality of raw materials affects the quality of cotton yarn; the level of significance depends on characteristic, which is used for yarn hairiness definition.
- Increase in fibre length (especially *UHM*, *ML* and *UI*) causes decrease in yarn hairiness mainly in case of S_3 because of potential higher number of belt fibres.
- Increase in *SFC* or *SFI* and *TRC* or *TRA* leads to accumulation of fibre and impurities in spinning rotor. This leads to break the spinning process and production of low quality yarn. Worse arrangement of fibres in the yarn together with higher number of belt fibre on its surface causes less yarn unevenness, higher hairiness in terms of short fibre ends number and less mechanical yarn characteristics.
- Higher complex fibre quality indicator (*SCI*, *IG* and *U*) leads to better spinability of material only.

Matrices of paired correlation coefficients (R_{12}) and partial correlation coefficients ($R_{1i\,(1,2,3,...k)}$) were computed for estimation of mutual dependencies[12]. The importance of these coefficients was evaluated by so called *p* values (*1-p* is computed confidence level)[12]. The correlation map for $R_{1i\,(1,2,3,...k)}$ is given on Fig. 1. The partial correlation among the *H* and *MIC, UHM, UI, SFI, p, f, STR, +b*, R_d, *IG, U, SCI, T, Z, CV*, thin-50%, thick+50% and *F* is confirmed. Similarly, it can be concluded that there exists correlation among S_{12}, S_3, *S, t, p, SCI* and thick+50%.

The correlation analysis shows that there exists strong fibre-fibre and fibre-yarn parameters multicolinearities. It is also visible that fibre arrangement in yarn influences yarn unevenness, number of faults, yarn hairiness and yarn mechanical parameters. It is proved that the quality of fibre in terms of HVI parameters affects the quality of yarn. The question is, what parameters of yarns and fibres should be used for quality assessment and why. In other case, there are a big group of characteristics, which should be measured and evaluated. The principal component analysis was used to reduce the number of variables and orthogonal transformation converts a set of observations of possibly correlated variables into a set of linearly uncorrelated new quantities – components[12]. These components summarize the information on original variables at the cost of minimal information loss. These components are mutually independent and are arranged according to their contribution to explaining the total dispersion of observed variables. The number of principal components is less than or equal to the number of original variables. The basic characteristic of each principal component is its level of variability – in other words dispersion. Principal components are arranged according to their importance, so according to decreasing dispersion. The most of the information on the variability of original data concentrates in the first component, while the least is in the last component. PCA is the simplest of the true eigenvector-based multivariate analyses and can be used as a tool in explanatory data analysis and for making predictive models[12].

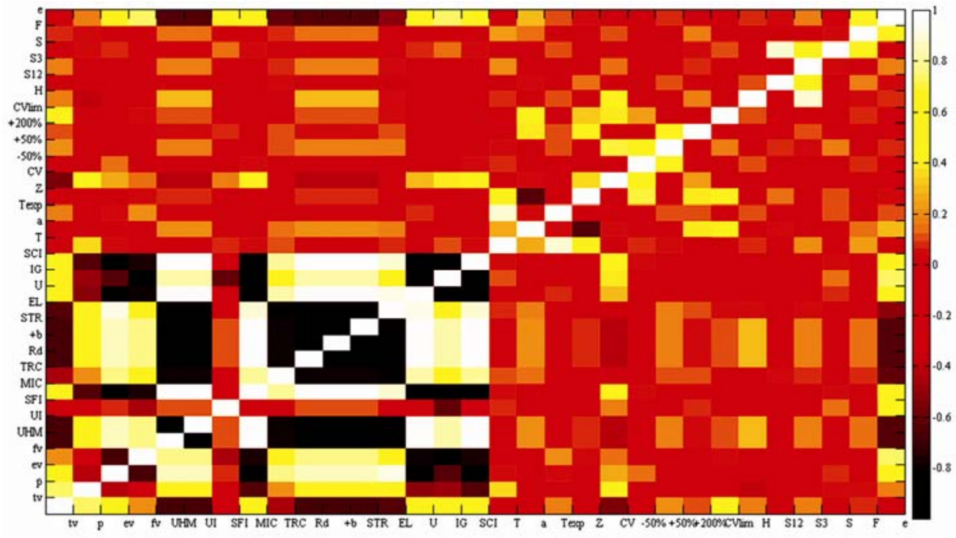

Fig. 1— Correlation map for partial correlation coefficient $R_{1i\,(1,2,3,...k)}$.

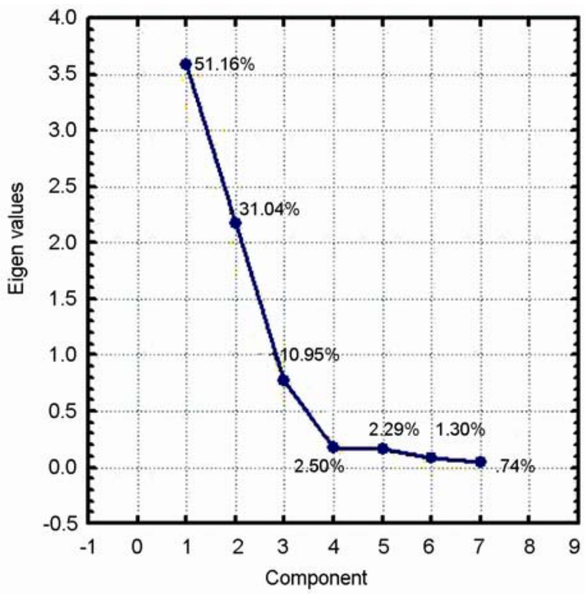

Fig. 2 — Eigen value scree plot

Properties of fibre and yarns are chosen according to previous experiences and the variability of the original data, which we describe. Selection of the most significant components number is realized by Scree plot of Eigen value (Fig. 2). The first three components describe the 93.15% of original variables. It is enough for PCA analysis and building PCA model (Fig. 2 and Table 1). The structured nature of data from the point of view of variables and observation is visible from corresponding PCA plots (Fig. 3). The importance of individual variables to principal components can be studed from Fig. 3(a).

Table 1— Contribution of individual variables to the principal components models

Property	Component		
	1	2	3
IG	0.2024	0.0776	0.0478
T, tex	0.0493	0.3614	0.0034
CV, %	0.1572	0.1564	0.0099
H [-]	0.0299	0.3875	0.0072
S_{12} [-]	0.0827	0.0136	0.8744
F , $cNtex^{-1}$	0.2459	0.0034	0.0009
ε , %	0.2326	0.0001	0.0564

New latent variables – components have the centre in center of gravity of data. The vector length of original characteristic in projection is proportional to the importance of characteristics from its dispersion point of view. The unit circle, which is marked by green color in Fig. 3(a), helps in assessment of results (less significant characteristics are close to centre). The angle between vectors is proportional to the correlation coefficient (strong positive correlation – angle 0°, strong negative correlation - angle 180° and no linear correlation - angle 90°). The reduction in variables was done in respect to PCA leading plot [Fig. 3(a)]. T selected variable is marked by blue color in [Fig. 3(a)] and shown in Table 1.

There are points representing the yarns in scatter component weights plot in projection plane 12, which are clearly separated in to five groups in respect to *T* and *CV*. When the subgroups are analyzed, it is

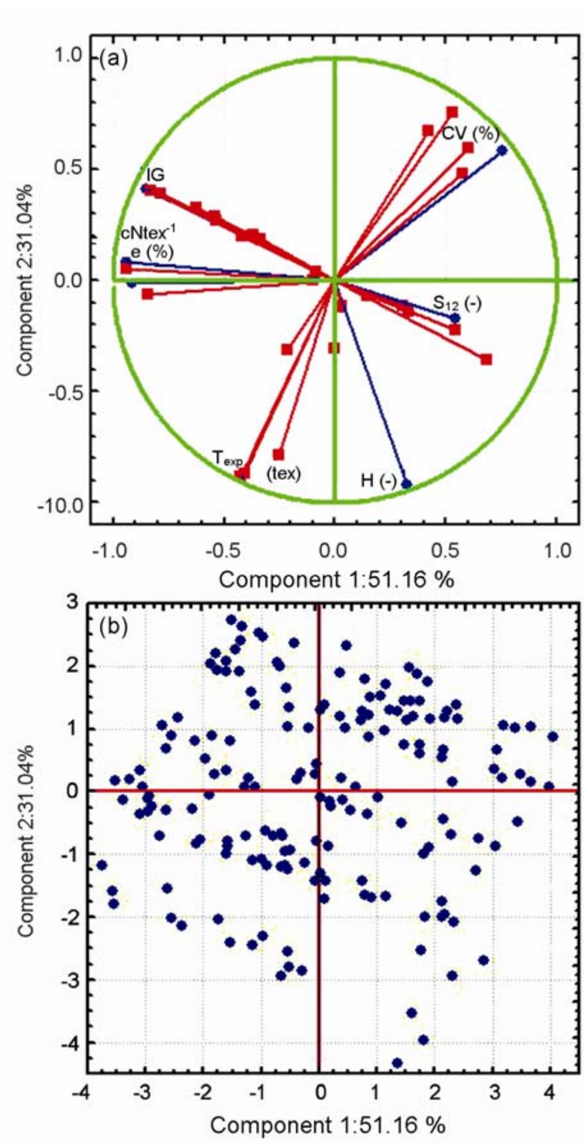

Fig. 3— Principal component analysis plots [(a) projection of variables to the plane 12 and (b) projection of observations to the plane 12]

clearly visible that the points representing the yarn are arranged according to their Z, level of hairiness defined by *H*, S_{12}, quality of cotton fibres given by *IG* and mechanical parameters of yarn *F* and *e*. The contribution of individual original variables to the first three component of PCA is shown in Table 1. This simple multivariate analysis leads to conclusion that the influence of fibre quality and yarn characteristics is significant. The PCA model based on first three components can be used for reduction of variables and yarn quality verification.

3.2 Regression Model Building

Typically *H* is predicted by the regression model, neural network or fuzzy logic. These models are based usually on *T* and selected fibre or technological parameters [13-15]. The simple and general model is implemented in Uster Statistic[15]. *H* is, in this case, based only on *T* and the level of power *q* is given for various fibre materials or blending ratio of selected fibre components, as shown below:

$$H = T^{q} \qquad \ldots(9)$$

The standard of powerful regression methods can be used for precision of *H* prediction. This approach is limited due to mutual correlation between variables (multicolinearity) and limited range of technological yarn parameters (*T* and *Z*). The selection of important variables to be included in a regression model was realized by all possible subsets regression. Explanatory variables are fibre characteristics and fibre complex criteria together with yarn characteristics. Step-wise results of all techniques used for *H* are given below:

$$H = f\left(UHM, UI, STR, MIC, R_d, +b, T_{\exp}\right) \qquad \ldots(10)$$

$$H = f\,(UHM\ ,\ MIC\ ,\ T_{\exp}), \qquad \ldots(11)$$

$$H = f\left(\frac{1}{UHM}, MIC, T^{1/2}_{\exp}\right), \qquad \ldots(12)$$

$$H = f\left(\frac{1}{UHM}, MIC, T^{2/3}_{\exp}\right), \qquad \ldots(13)$$

Regression triplet was also tested. The Fisher-Snedecor test was used for the model verification. Mutual correlation among variables was assessed using the Scott's multicollinearity criterion. Cook-Weisberg test was used for verifying heteroscedasticity and Jarque-Berr test for normality. The quality of build regression model was assessed using F-statistic (*FIS*), Akaike's information criterion (*AIC*) and mean squared error of prediction (*MEP*). The three regression models based on *UHM*, *MIC* and *T* are defined by Eqs (11) - (13). The estimation of regression parameters together with their confidence intervals is given in Table 2, where b_4 is the intercept. The quality of model fit was verified due to *MEP* criterion, coefficient of determination (R^2) and multiple prediction correlation coefficient (R_p). The relationship between predicted and measured *H* is shown in Fig. 4.

Table 2 —Regression model parameters and criteria of their quality

Model	R	R^2	R_p	MEP	AIC	b_1	b_2	b_3	b_4
Eq. (11)	0.927	0.859	0.726	0.045	-519	-0.091 (-0.099; -0.082)*	0.210 (0.152; 0.267)*	0.034 (0.031; 0.037)*	5.220 (4.882; 5.558)*
Eq. (12)	0.930	0.865	0.734	0.052	-505	79.419 (71.971; 86.866)*	0.166 (0.104; 0.227)*	0.340 (0.366; 0.434)*	-1.156 (-1.516; -0.796)*
Eq. (13)	0.932	0.867	0.738	0.051	-508	79.418 (72.038; 86.798)*	0.165 (0.104; 0.227)*	0.171 (0.156; 0.185)*	-0.628 (-0.964;-0.291)*

* Confidence interval of estimated regression parameters.

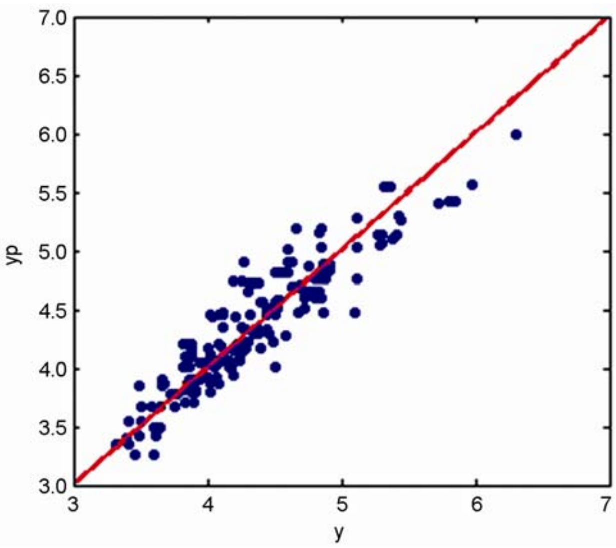

Fig. 4— Comparison of measured y and predicted yp cumulative hairiness index H for (7c)

The partial regression graph for selected characteristics included in regression model, defined by Eq. (11), is not linear but can be simply linearized by power transformation of exogenous variables. It is found that the variable *UHM* can be replaced by 1/*UHM*. Similarly, *T* can be replaced by the power one half $T^{1/2}$ or two third $T^{2/3}$ transformation. All three models are simple and have good predictive power. The model defined by Eq. (12) shows the best qualitative criteria (Table 2). On the other hand, the variability of regression parameters (b_1, b_2, b_3 and b_4) is the highest. The model defined by Eq. (11) is the best from the point of view of estimation regression parameters (b_1, b_2, b_3 and b_4) variability but its qualitative criteria is lower (Table 2). In the light of these results it can be concluded that the simple equation for estimation of *H* implemented in Uster Statistic is sufficient for its rough estimation. Models defined by Eqs (11) - (13) are relevant and can be used for more precise assessment of *H* in respect to the quality of cotton fibres.

4 Conclusion

The correlation analysis confirms that the influence of majority of fibre parameters is not so important. Only the cotton fibre length characteristics change the spinability of fibre material and influence yarn quality and mainly its hairiness significantly. Yarn hairiness increases when the yarn count increases. The influence of twist is not so high but in agreement with empirical findings, such as the higher twist leads to the lower hairiness. Realized experiment enables verification of earlier experiences for open-end spun yarns.

The correlation analysis also confirms that fibre parameters (mainly the lenght characteristics) influence not only yarn hairiness but also the other yarn characteristics. Reduction in variables and orthogonal transformation using PCA analysis enables building the PCA model, which is based on first three components. It is developed in respect to *IG* and selected yarn qualitative characteristics in terms of *T*, *CV*, *H*, S_{12}, S_3 and *F*. Thanks to PCA projection of observation to plane 12 [Fig. 3(b)] to make it possible to find five separated groups of yarn with the typical behavior given by the technological parameters of yarn and quality of fibres. PCA confirms that not only yarn unevenness and mechanical parameters but also yarn hairiness should be included in yarn quality criteria.

The regression analysis was used for building precise prediction model. The regression models for *H* models are simple and have good predictive power. *H* was estimated because of frequent use during output and acceptance yarn quality inspection. The same approach was used for summation criteria prediction model building. Results weren't from the point of view of statistic correct and the reason is hidden in presence of higher number of outliers and gold points, which influence not only the character of model but also its predictive power.

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