PREDICTION OF SELECTED PROPERTIES OF COTTON TYPE ROTOR YARNS

J. Militký
D. Křemenáková
G.Krupincová
S. Ibrahim
Technical University of Liberec
Liberec, Czech Republic

Abstract

Yarn mechanical and geometrical properties are dependent on the cotton fibers quality and technology of yarn production. The main aim of this paper is description of the influence of cotton fiber properties characterizing their quality on rotor yarn selected properties. There are several factors influencing quality of cotton fibers and variability of parameters is relatively high in terms of cotton cultivars. There are many inter dependencies between cotton parameters leading to the strong multicollinearities. Therefore the complex quality criterion is used together with fiber parameters in investigation of their influence on the yarn properties. The degree of cotton fibres quality is determined by using complex criterion (utility value). The basic construction parameters of yarns are yarn count "*Jem*" and yarn twist characterized e.g. by Phrix twist coefficient "*alf*". From these parameters the structural characteristics as packing density, orientation and mean surface helix angle can be computed. Total numbers of 180 cotton rotor yarns were prepared from seventeen kinds of cottons in five levels of yarn count and two levels of Phrix twist coefficient. For prediction of the yarn strength and mass unevenness from fiber quality and yarn structural parameters the dimension reduction approach combined with linear regression is used. The prediction ability is characterized by cross validation techniques.

Introduction

Generally are cotton yarn mechanical and geometrical properties dependent on the parameters of fiber, parameters of yarn formation (yarn fineness, twist etc.) and spinning technology. The theoretical predictive models are based on the mechanisms of yarn formation. Models of this type are not based directly on measured properties and the degree of fit is usually low in comparison with classical regression type models. On the other hand these models have better prediction ability and are based on the logical arrangements of variables.

Classical approach to prediction cotton yarn properties is based on the regression approach. By using of standard or powerful statistical methods the linear or nonlinear regression models were created as studied by Moghazy et al. (1989). This approach has some serious limitations:

- Regression models are additive (sum of possibly nonlinear contributions from selected fiber properties and yarn construction parameters denoted as factors.
- Some factors are mutually connected (i.e. yarn twist and fineness) but in the models are separated.
- There is a logical nonsense in linear combination of properties responsible for mechanical and geometric characteristics of yarns.

The pure statistical approach without creation of model in explicit forms is represented by neural network regression. The only advantage of neural network in comparison with classical regression models is automatic construction of nonlinear model.

Some experimental data sets allow creating models having some important factor as a constant. Typical example is investigation of cotton fiber influence on cotton yarn strength where are yarn formation parameters and yarn geometry constant. In this case it is not possible to create yarn model based on the theoretical assumption.
The suitable model can be selected from the set of provisional models or adaptively created based on the special graphical aids (partial regression graphs) as described by Meloun et al. (1994). The construction of predictive models has the two main kinds of problems:

a) Selection of the regression model form (linear, nonlinear, interaction),
b) Specification of the criterion for selection of the best predictive model.

In this contribution is shown that for solving of the problems a) the model based on the reduction of fibre strength by the multiplicative factors combined with linear regression is attractive. As a criterion for selection of predictive regression model the prediction correlation coefficient PR is used.

This paper focuses in the influence of cotton fibre properties and process parameters on rotor yarn strength, mass unevenness and hairiness.

Cotton Fiber Quality

There are several factors influencing quality of cotton fibres and variability of parameters is relatively high in terms of cotton cultivars. There are many inter dependencies between cotton parameters leading to the strong multicollinearities. Therefore the complex quality criterion can be used for prediction of yarn strength. The degree of cotton fibres quality can be determined by using cotton standards, complex criterion mentioned by several authors or by using of the utility value as explained by Militky et al. (2007). Korickij (1983) proposed the *IGa* criterion based on cotton length in terms of upper half mean length, uniformity index of staple length, short fibre content and micronaire also supported by Pan (1993). The main problem with Korickij approach is dependence on the cotton properties used for empirical function evaluation and no inclusion of individual fibre properties importance. More general concept based on the complex utility value was introduced by Militky (2007). Suppose we have K utility properties $R_1, ..., R_K$ (cotton fibre properties measured e. g. by HVI). Based on the direct or indirect measurements it is possible to obtain some quality characteristics $x_1, ..., x_K$ (mean value, variance, quantiles etc.). These characteristics represent utility properties. Generally it is possible to specify basic cotton fiber utility properties having potential influence to the cotton yarn strength given by Rasked (2002).

Fiber length (expressed as upper half mean ***UHM*** [mm],
Fiber length uniformity (expressed as uniformity index ***UI*** [%]),
Fiber strength (as bundle strength ***STR*** [cN/tex]),
Fiber elongation at break (***EL*** [%])
Fiber fineness and maturity (expressed by micronaire reading (***MIC*** [-]),
Short fiber content (***SF*** [%]),
Thrash content ***TR*** [%].

The importance of these properties is generally dependent on the spinning technology. The relative weight b of above listed properties (as importance percentages divided by 100 and then standardized i.e. sum of weights should be one) are given in the Table 1.

Table 1. Contribution of Cotton Properties to the Yarn Strength

Property/ Weight	Rotor Yarn	Ring Yarn
UI [%]	0.20	0.22
MIC [-]	0.16	0.17
UHM [mm]	0.14	0.24
STR [g/tex]	0.28	0.22
EL [%]	0.09	0.06
SF [%]	0.06	0.06
TR [%]	0.07	0.03

The values in the Table 1 were derived from pie graphs presented in the work by Rasked (2002). The main problem with utilization of above-mentioned properties for quality characterization is necessity of transformation to the utility scale.

Functional transformation of quality characteristics (based often on the psycho-physical laws) lead to partial utility functions given by Militky (2007).

$$u_i = f(x_i,\ L,\ H) \tag{1}$$

where L is value of characteristic for just non acceptable cotton ($u_i = 0.01$) and H is value of characteristic for just fully acceptable product ($u_i = 1$). For expressing quality of cotton fibers it is sufficient to replace standardization and nonlinear transformation to the partial utility function by the piecewise linear transformation.

For one side bounded properties quality is monotone increasing or decreasing function of quality characteristic *x* and therefore the piecewise linear transformation has form shown on the Fig. 1. For the case of LB (lower is better) properties were limits selected according to the known ranges published e.g. by Rasked (2002).

Thrash content *TR [%]*	*L = 6*	*H = 2*
Short fibre content *SF [%]*	*L = 18*	*H = 6*

For the case UB (upper is better) properties were limits selected according to the known ranges published by Rasked (2002).

Strength HVI *STR [g/tex]*	*L = 23*	*H = 31*
Length *UHM [mm]*	*L = 25*	*H = 32*
Uniformity index *UI [%]*	*L =77*	*H = 85*
Elongation *EL [%]*	*L = 5*	*H = 7.7*

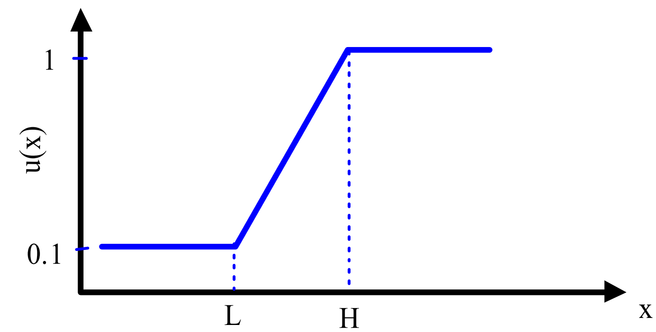


Figure 1. Transformation for One Side Bounded Cotton Properties
(*L* is Lower Limit and *H* is Upper Limit)

For two side bounded properties quality is monotone decreasing function of property value *x* on both sides from optimal (constant) region and therefore has the piecewise linear transformation form shown on the Fig. 2

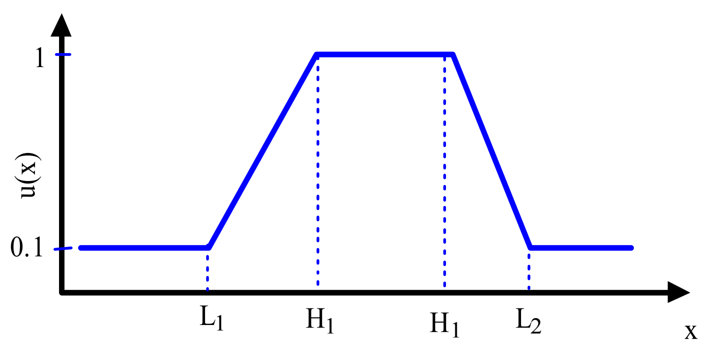


Figure 2. Transformation for Two Side Bounded Cotton Properties
(L_1, L_2 are Lower Limits and H_1, H_2 are Upper Limits)

For this case were limits selected according to the known ranges published by Rasked (2002).

Micronaire *MIC [-]*	*L1 = 3.4, H1 = 3.7*	*L2 = 5, H2 = 4.2*

The weighted geometrical average *QI* characterizing cotton fibers quality i.e. **Cotton Quality Index** is simply calculated as weighted geometric average of u_i with weights b_i.

$$QI = \exp\left(\sum_{j=1}^{m} b_j \ \ln(u_j)\right) \tag{2}$$

When forming the aggregating function *QI* from experimentally determined values of cotton fibers properties, the statistical character of the x_j quantities should be considered and the corresponding variance *D(U)* should be also determined.

Cotton Yarn Characteristics

Yarn structure can be described by some characteristics derived from models of yarn formation and basic technological parameters as yarn fineness T_p *[tex]*, and yarn twist Z *[m^{-1}]*. The twist coefficient T_y $\left[\mathrm{cm}^{-1}\mathrm{tex}^{1/2}\right]$ is natural combination of T_p and Z described by relation as described by Neckar (1990).

$$T_y = 10^{-2} Z \sqrt{T} \tag{3}$$

Fiber volume fraction V_f is then computed from equation

$$V_f = 0,7(1-0,78\exp(-0,195T_y)) \tag{4}$$

The random distribution of helical angles of fibers is used for computation of orientation factor n_β. Migration of fibers is negligible. Orientation factor η_β is function of helix angle β_D and yarn Poisson ratio η [9].

$$\eta_\beta = \frac{2\beta_D(1-\eta)+(1+\eta)\sin 2\beta_D}{4\beta_D} \tag{5}$$

Helix angle β_D is defined as below suggested by Pan (1992,1993).

$$\beta_D = arctg\left(10^{-1}T_y\sqrt{\frac{4\pi}{\rho V_f}}\right) = arctg\left(\alpha\sqrt{\frac{4\pi}{\rho V_f}}/\sqrt{10^3}\right) \tag{6}$$

where α is twist coefficient in [m^{-1}ktex$^{1/2}$] and ρ is fiber density in [kgm^{-3}]. Poisson ratio η has the form given below.

$$\eta = \frac{\sin^5\beta_D}{2\left(1-\cos^3\beta_D\right)\left(\frac{1}{2}\beta_D - \frac{1}{4}\sin 2\beta_D\right)} \tag{7}$$

Packing density $\mu\in[0,1]$ expresses in fact the fiber compactness in yarn. Packing density is defined as the ratio of fibers volume to the total volume of yarn. Prediction of yarn packing density is computed from the following model of Neckar (1990).

$$\frac{\left(\frac{\mu}{\mu_m}\right)^{5/2}}{\left[1-\left(\frac{\mu}{\mu_m}\right)^3\right]^3} = \frac{M\sqrt{\pi}}{2\mu_m^{5/2}\sqrt{\rho}}\left(Z\,T_P^{1/4}\right)^2 \tag{8}$$

where M [m] is the material characteristics and μ_m [-] is the limit packing density. For cotton is limit packing density μ_m = 0.8 and for rotor yarns is parameter M = 0.0027 m. These characteristics are used for deeper characterization of yarn structure.

Cotton Yarn Strength

Yarn strength is one of the most important yarn parameters, which is used for yarn quality control and design of fabrics. It is usually characterized by the relative strength **YS** [N/tex]. Yarn strength has great influence on the weaving process and mechanical parameters of textile products. The theoretical predictive models are based on the mechanisms of yarn formation or concept of strength utilization factors (i.e. lowering of fiber strength due to bundle utilization, orientation , number of fibers bearing load and limit arrangement of fibers in yarns. One simple model of this category is described by Pan (1992, 1993). His model for yarn strength is based on the reduction of fibrous bundle strength by multiplying it by utilization factors connected with bundle orientation (due twist) and bundle packing density in limit configuration.

Relative yarn strength σ_y is often expressed as product of relative fiber strength σ_f and correction factor ϕ_{fy} expressing utilization of fibers strength in yarn.

$$\sigma_y = \sigma_f \phi_{fy} = \sigma_b \phi_{by} = \sigma_f \phi_{fb} \phi_{by} \tag{9}$$

Utilization of fibers strength in yarn is product of fiber strength utilization in bundle ϕ_{fb} and utilization of bundle strength in yarn $\phi_{by.}$ The σ_b denotes bundle strength and is approximately equal to *STR*. For this case is $\phi_{fb} = 1$. These factors are computed according to the various relations. One of simplest empiric relation for relative yarn strength σ_y was derived by Solovev (see Neckar (1990).

$$\phi_{fy} = f_n f_l f_\alpha \psi \tag{10}$$

Factor f_n expresses influence of fiber number, f_l is factor of fiber length influence, f_α is factor of yarn twist influence and ψ is factor of technology influence. Neckar proposed another products form. Utilization of bundle strength in yarn was derived by Pan (1995).

$$\phi_{by} = V_f \eta_\beta \tag{11}$$

It is visible that the leading role on orientation factor has Poisson ratio especially for low and moderate twist coefficients used in this work.

<u>Yarn Unevenness</u>

A traditional approach to the yarn unevenness characterization is based on the so-called *CV* as mass variation between short portions of yarn measured on the Uster apparatus. Modern USTER devices have possibility to give raw data about whole mass variation curve (MVC).The unevenness (strictly speaking quadratic mass unevenness) is in fact the variation coefficient *CV* of mass or mass linear density. The total <u>quadratic irregularity</u> CV_T^2 can be decomposed into two parts [see Bona (1998)]

$$CV_T^2 = CV_B^2(L) + CV_V^2(L) \tag{12}$$

The symbol $CV_B^2(L)$ denotes external standardized variance between lengths L within total length H and $CV_V^2(L)$ is internal standardized variance between smallest lengths within "cut" length L. Standard output from Uster Tester *CV* is in fact external quadratic unevenness *CVB(L)* where L is length of measuring electrodes (for yarn is $L = 0.8$ cm) The value of total inspection length H is about 400 m. Generally, higher length L leads to smaller $CV_B^2(L)$ and higher $CV_V^2(L)$. For $L\to\infty$ is $CV_B^2(\infty) = 0$ and $CV_V^2(\infty) = CV^2$. For $L\to 0$ is $CV_B^2(0) = CV^2$.

Direct utilization of *CV* for evaluation of yarn quality has some disadvantages:

1. Unevenness *CV* is dependent on the number of fibers in yarn cross section N_f which is roughly equal to ratio of the yarn fineness T_P and the fiber fineness T_V

$$N_f = \frac{T_P}{T_V} \tag{13}$$

2. Value of *CV* is dependent on the yarn forming process and can be decomposed into two parts

$$CV^2 = V_I^2 + V_S^2 \tag{14}$$

where V_I is limit unevenness (dependent on type of the spinning process) and V_S is machine dependent unevenness (dependent on type of the spinning machinery).

Limit unevenness can be computed from Martindale relation (Poisson distribution of right fiber ends)

$$V_I = \frac{100}{\sqrt{N_f}} \tag{15}$$

In the case, when fibers are replaced by fibrous bundles the Bornett relation (Poisson distribution of fiber bundles) is more realistic ((see Bona [10]))

$$V_I = \frac{50}{\sqrt[3]{N_f}} \tag{16}$$

The behavior of *CV* will be therefore dependent on the both yarn and fiber fineness.

Experimental Part

The 180 rotor yarns were prepared under comparable conditions. Seventeen kinds of cottons commonly used in Czech Republic were selected. The 100% cotton yarns (composed from pure cotton lots) were produced in five levels of yarn count *Jem* (16,5tex, 20tex, 27tex, 37tex, and 50tex) and ten Phrix twist coefficient *alf* (two levels for each yarn count). The HVI system was used for determining fibre parameters. Fibre length parameters *UHM*, *UI*, *SF*, fibre bundle strength *STR*, elongation *EL*, micronaire *MIC* and trash content *TR* were measured. From MIC values the fibre fineness T_V were computed according to the empirical relation given by Montalvo et al. (2005)

$$T_V = 0.037175\ Mic - 0.023145 \tag{17}$$

The yarn unevenness *CV* was measured on the Uster Tester IV machine under standard conditions.

The yarn strength was measured on the Tensorapid tensile testing machine standard conditions. The yarn strength *YS* is mean value from 50 measurements.

Results and Discussion

The presence of possible outlying cotton lots was checked by the Mahalanobis distance plot [see Meloun et al. (1994)]. This plot for all fibre characteristics and *alf*, *Jem* is shown on the fig 3.

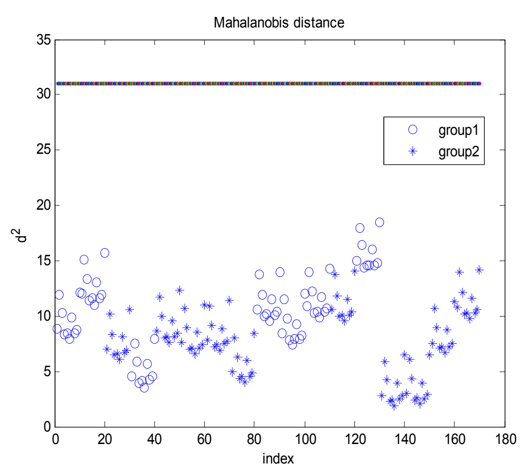


Figure 3. Mahalanobis Distance Plot

It is visible that no point is over the limit for outlying points. From cotton fiber characteristics the cotton quality index *QI* (see eqn.(2)) were computed. Mean orientation factor of fibers in the yarn η_β (denoted as ORI) was computed from eqn. (5). The helix angle β_D (denoted as BETA) was computed from eqn. (6) and packing density μ (denoted as *MI*) was computed from eqn. (8). Expected number of fibers in the yarn N_f was computed from eqn.(13). The Martindale limit unevenness (denoted as $CV_{lim\ M}$) was computed from eqn.(15) and Bornett limit unevenness (denoted as $CV_{lim\ B}$) was computed from eqn.(16).The standard linear regression method was used for prediction of yarn strength *YS* and yarn unevenness *CV* and estimation of influence of various factors on these characteristics [Meloun et al. (1994)]. Prediction ability in linear regression model is characterized by mean quadratic error of prediction (MEP) defined generally by relation

$$MEP = \sum_{i=1}^{n} \left(y_i - x_i^T b_{(i)} \right)^2 / n \tag{18}$$

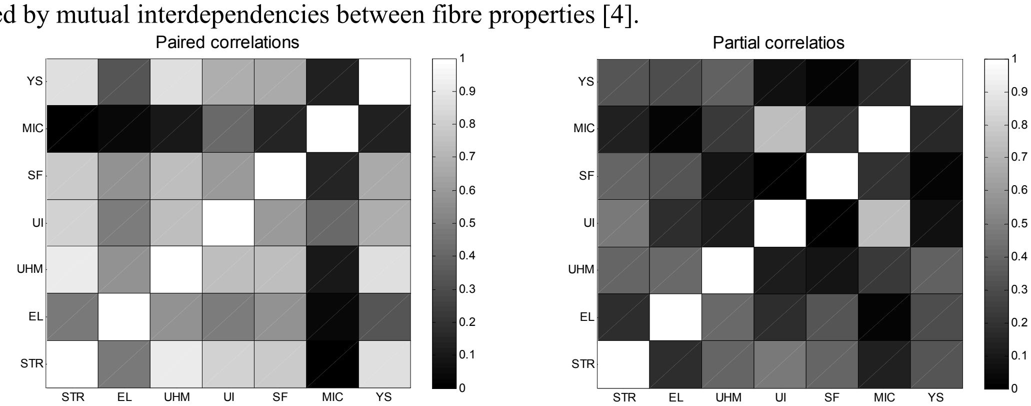
where $\boldsymbol{b}_{(i)}$ is the estimate of regression model parameters when all points except the i-th (i-th row $\mathbf{x}_i$ of matrix $\mathbf{X}$) are used. The statistics MEP uses a prediction $y_{pi} = \mathbf{x}_i^T \mathbf{b}_{(i)}$ which was constructed without information about the i-th point. Optimal model has minimal value of MEP. The MEP can be used for definition of the predicted multiple correlation coefficient PR

$$PR = \sqrt{1 - n * MEP / \sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{19}$$

The PR was used as criterion of predictive performance. Values of PR for all kind of tested dependencies are given in the table II. Response variable is equal to y and explanatory variable is equal to x in regression line model $y = a+b*x$.

Yarn Strength

For estimation of mutual dependencies between cotton fibre parameters and yarn strength *YS* the correlation maps of paired correlation coefficients and partial correlation coefficients were computed [Meloun et al. (1994)]. Correlation map for paired correlation coefficients is on the fig 4a) and for partial correlation on the fig. 4b). All fibre parameters excluding *MIC* have significant paired correlations with yarn strength. These correlations are negatively influenced by mutual interdependencies between fibre properties [4].



(a) (b)

Figure 4.(a) Correlation Map for Paired Correlation Coefficients,
(b) Correlation Map for Partial Correlation Coefficients

The significant partial correlations between *STR*, *EL*, *UHM*, *MIC* and yarn strength were found. The predictive performance of selected variables for prediction of YS (simple regression line) is shown in the Table 2.

Table 2. Predictive Performance of Line Regression Models

Response	Explanatory	PR
YS	*QI*	0.754
YS	*STR*	0.870
YS	*Ym*	0.760
Yload	*Fload*	0.981

The influence of *QI* on the *YS* is shown on the fig 5a). Dependence between *YS* and *STR* is shown on the fig. 5b).
The very good prediction ability of *STR* supports the empiric evidence of importance of fibre strength in rotor spinning (see table I). The slope *0.44* is equal to the fibre utilization factor in the yarn. The predicted yarn strength *Ym* was computed from the modified eqn (9)

$$Ym = STR\ \phi_{by} \tag{20}$$

where ϕ_b was computed from eqn (11). The dependence between measured yarn strength *YS* and predicted yarn strength *Ym* is shown on the fig. 6a). The prediction ability of this model is lower in comparison with prediction ability of *STR* only.

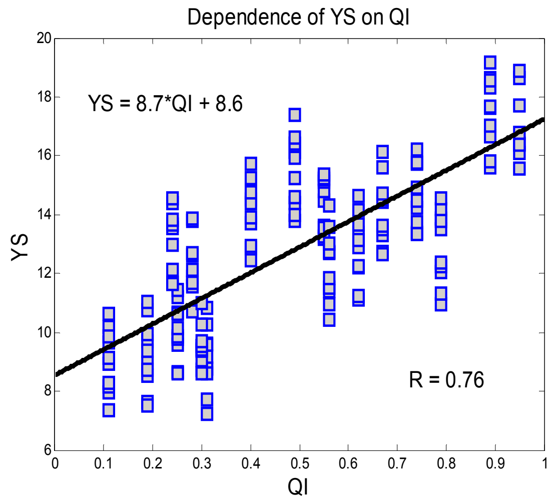


Figure 5.(a) Regression Line for Dependence of *YS* on *QI* ,

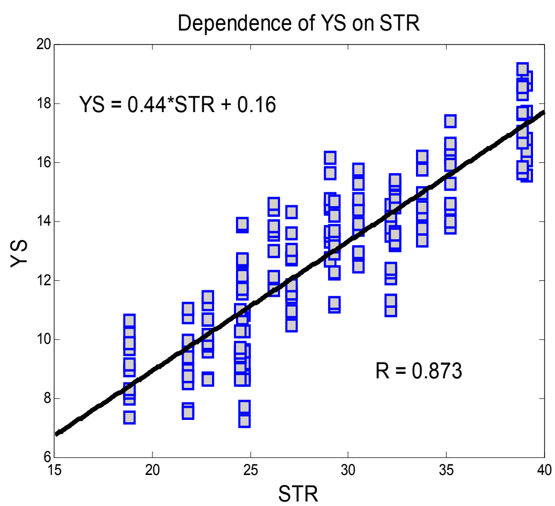


Figure 5.(b) Regression Line for Dependence of *YS* on *STR*.

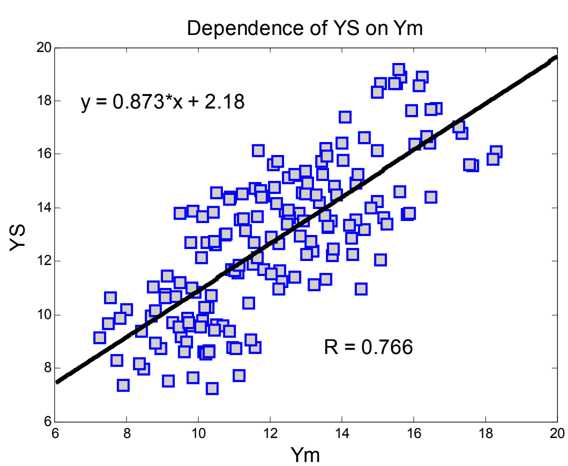


Figure 6.(a) Regression Line for Dependence of *YS* on *Ym* ,

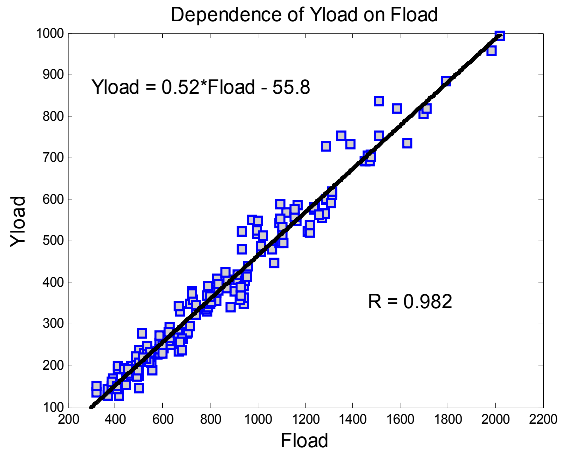


Figure 6.(b) Regression Line for Dependence of *Yload* on *Fload*

Relative yarn strength is in fact maximum load *Yload* = *YS*Jem* bearing by yarn divided by yarn fineness *Jem.* This value can be related to the load beared by all fibers *Fload*. After simple rearrangements we can compute this quantity as *Fload* = *STR*Jem* (it is maximum load of mean fiber in bundle divided by number of fibers in yarn cross section). Dependence of *Yload* on *Fload* is shown on the fig. 6b. It is visible that this model has very excellent prediction ability.

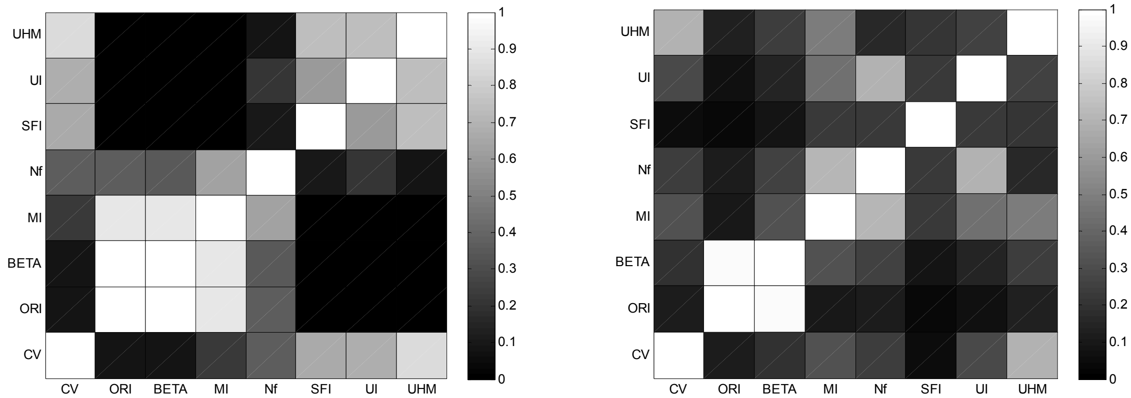
It is evident that this approach is very simple and has relatively good prediction capability. Important is that all models are clearly interpretable and are basically dimensionally homogeneous.

These results are limited due to practical range of technological parameters of yarn creation (yarn count, yarn twist). The complex criterion of cotton fibres *QI* correlates with yarn strength *YS* but correlation with *STR* alone is slightly higher.

The model shown on the fig. 6b) is probably one of the best from point of view of simplicity and content of important fiber and technology factors. For practical prediction of *YS* is the best model shown on the fig. 5b) (explanatory is STR only). The slope is here equal to the fiber utilization factor.

<u>Yarn Unevenness</u>

For estimation of mutual dependencies between cotton lots fiber parameters, yarn structural characteristics and *CV* the correlation map of paired correlation coefficients and partial correlation coefficients were computed [4]. Correlation map for paired correlation coefficients is on the fig 7a) and for partial correlation on the fig. 7b). All selected fiber parameters (*UHM*, *UI*, *SF*, N_f and *M*I have significant paired correlations with *CV*. These correlations are negatively influenced by mutual interdependencies between fiber properties as well [Meloun et al. (1994)].



(a) (b)

Figure 7.(a) Correlation Map for Paired Correlation Coefficients ,(b) For Partial Correlation Coefficients

The significant partial correlations between *BETA, MI, N_f, UI*, *UHM* and yarn *CV* were found.
Values of predictive performance *PR* for all kind of tested paired dependencies are given in the Table 3. Response variable is equal to *y* and explanatory variable is equal to *x* in regression line model
$y = a+b*x$.

Table 3. Predictive Performance of Line Regression Models

Response	Explanatory	PR
CV^2	$CV^2_{\ lim\ M}$	0.298
CV^2	$CV^2_{\ lim\ B}$	0.310
CV	*QI*	0.754

The influence of *QI* on the *CV* is shown in the fig 8a). The relatively good prediction ability of *CV* supports the empiric evidence of importance of fiber quality parameters in rotor spinning Poor correlations between CV^2 and Martindale or Bornett limit unevenness indicates non constancy of machine dependent unevenness V_S and roughness of *Tv* computation from eqn. (17).

Multiple regression models for yarn *CV* prediction, from yarn structural parameters (*BETA, MI*), number of fibers in yarn N_f and fiber geometrical parameters (*UI* and *UHM*) was created. The summarization of prediction models quality and the estimates of regression coefficients for individual variables are shown in the Table 4.

Table 4. Summarization of Prediction Model Results

PR	Estimate *BETA*	Estimate *MI*	Estimate for N_f	Estimate *UI*	Estimate *UHM*	Estimate *abs*
0.935	35.4	-41.7	0.00424	0.213	0.477	9.69

All estimates are significant on the probability level 0.05. The relation between predicted and measured yarn unevenness *CV* is shown in the fig. 8.(b).

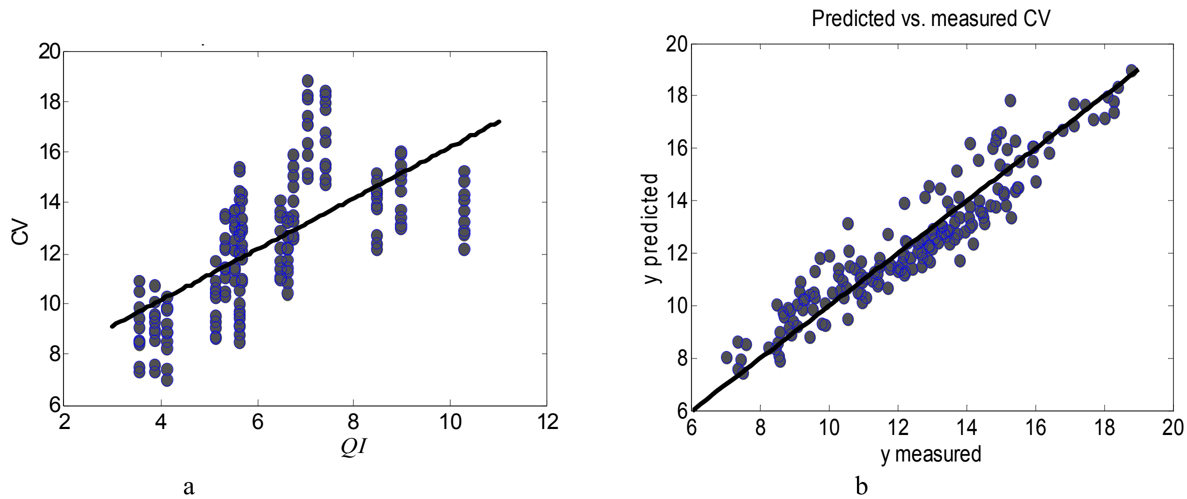


Figure 8. a) Regression Line for Dependence of *CV* on *QI*,
b) Relation Between Predicted and Measured *CV*.

Conclusion

It was found that:

- Yarn strength is critically dependent on the fibre strength. The simple models for yarn strength *YS* prediction is based on the reduction of fibre strength by the multiplicative factors from orientation, Poisson ratio and volume fraction combined with linear regression is useful as well. The influence of process parameters are hidden in yarn fineness and are not as important as fibre strength *STR*.
- Yarn *CV* is critically dependent on the yarn packing density *MI*, fiber helix angle *BETA* in yarn, number of fibers in yarn N_f and fiber length parameters *UI, UHM*. The complex criterion of cotton fibers quality *U* correlates significantly with yarn *CV*. Coarser yarns with lower packing density have higher *CV*.

These results are limited due to practical range of technological parameters of yarn creation (yarn count, yarn twist) and are valid for rotor yarns only.

Acknowledgements

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