Factor and Cluster Analyses of the Structure of Correlations between High Consistency Pulp Properties during Refining and Paper Strength Characteristics

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This article analyses high-consistency pulp refining using a disk refiner. During the experiment, the size of the gap between the rotor and stator cutters (0.5 to 1.5 mm), rotor speed (2,000 to 2,500 rpm), pulp consistency (10 to 20%), and freeness value (15 to 60 °SR) of the pulp were varied. The refining results were characterised by changes in 10 output parameters: morphological properties of cellulose fibres (average length, width, fibrillation index, water retention value, average kink angle, and coarseness) and the physical and mechanical characteristics of handsheets (breaking length, bursting strength, tearing resistance, and folding endurance). A total of 56 observations were made on the samples. Factor and cluster analysis methods were used to study the structure of correlations between the output parameters. More than 96% of the total dispersion of all output parameters was due to a change in two latent (hidden) factors: the first one was responsible for 79.6% of the dispersion and is presumably identified as the degree of external fibre fibrillation and the second one (16.6% of the dispersion) as fibre flexibility (including coarseness and average kink angle).

DOI: 10.15376/biores.18.4.8090-8103

Keywords: Pulp refining; Correlation factor analysis; Cluster analysis; Morphology of cellulose fibres; Physical and mechanical characteristics of handsheets

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INTRODUCTION

Pulp refining in disk refiners is an important operation in pulp and paper production on which the morphological properties of fibres and the strength characteristics of paper largely depend (Alashkevich *et al.* 2006, 2010; Chen *et al.* 2016).

There are usually correlations between these characteristics. This indicates the existence of a smaller number of more general, “deep” properties of cellulose fibres that change during refining, which, in turn, results in a change (variance) in the measured characteristics of pulp and paper (Lawley and Maxwell 1962; Pen 1972; Everitt *et al.* 2011; Almonti *et al.* 2019). Such properties are called hidden (latent) factors. They can be identified and analysed by multivariate mathematical statistics, in particular, by the factor and cluster analysis methods (Pen 1972; Kim and Mueller 1986; Strand 1987; Brown *et al.* 2004; Pulkkinen *et al.* 2010; Novoselskaya *et al.* 2019).

In this article, both these methods are used in the analysis of high-consistency pulp refining (from 5% and higher). This research is relevant because fibres during refining can experience various kinds of deformations and structural changes that, when compared to the refining of low-consistency fibrous suspensions, have some differences (Wathén 2006). These structural changes are characterised primarily by such important indicators as: external fibre fibrillation, which increases the outer surface characteristics of fibres and the number of interfibre bonds, as well as internal fibrillation, which is accompanied by an increase in interfibre bonding forces and flexibility and a decrease in fibre coarseness, without weakening the strength of the fibre itself (Matveev 1974; Bhardwaj *et al.* 2004; Hou *et al.* 2011; Chen *et al.* 2017). The listed properties of fibres are largely influenced by the consistency of the refined pulp. Increasing pulp consistency during refining ensures greater external and internal fibre fibrillation, thereby increasing the strength characteristics of the finished paper products (Kang and Paulapuro 2006; Lebedev *et al.* 2018; Przybysz *et al.* 2020; Penkin *et al.* 2022).

A number of studies have shown that a high-consistency pulp refining process is appropriate for obtaining highly-extensible paper, which is especially important in the manufacture of sack papers (Henderson *et al.* 1965; Gurnagul *et al.* 2005). It is also worth noting that high-consistency pulp refining ensures the preservation of the original fibre length due to high interfibre friction and a decrease in the cutting action from the cutting edges due to relatively large gaps between the grinding surfaces of the rotor disks and the refiner stator (Fernando *et al.* 2012; Kerekes 2015; Ushakov *et al.* 2020). This high interfibre friction during high-consistency refining, on the one hand, ensures better fibre processing, giving fibres a high water retention value and an external specific surface area, *i.e.*, indicators characterising changes in internal fibre fibrillation (Sundström *et al.* 1993; Fernando *et al.* 2007, 2011). On the other hand, an excessive increase in pulp consistency reduces fibre fibrillation, causing fibres to twist (Hartler 1995). This deformation is called “fibre latency” (Klark 1983; Gard 2002). When refining high-consistency pulp, fibre latency occurs due to mechanical effects in the refining zone of the disk refiner. This results in a large number of highly deformed (twisted, kinked, or crumpled) fibres in the pulp (Page *et al.* 1985; Pen and Karetnikova 2008).

The purpose of this study is to identify the number and physical nature of hidden factors that cause the dispersion of morphological and paper-forming properties during high-consistency pulp refining.

EXPERIMENTAL

Materials

Bleached LS -1 hardwood sulphate pulp (a semi-finished product from Ilim Group, Bratsk (Russia)) was selected for experimental studies. The degree of delignification (Kappa number) was 2.0 to 4.0. Before refining, the pulp was defibrated with water according to ISO 5263-3 (2004) standard. The refining was carried out in a laboratory disk refiner as presented in Fig. 1.

Pulp of the required consistency was placed into hopper 1 of the disk refiner. After that, screw feeder 2 was used to transfer the pulp from hopper 1 to working area 3 to refine it between the cutters of rotor 4 and stator 5. Next, the pulp was passed through outlet 6. The gap between the rotor and stator cutters was changed using mechanical adjusting device 9 by moving the stator along its axis. The rotational speed of the disk refiner rotor drive and the screw feeder was regulated using SMV frequency converters (AC Technology Corporation, Lenze AC Tech, Uxbridge, MA, USA).

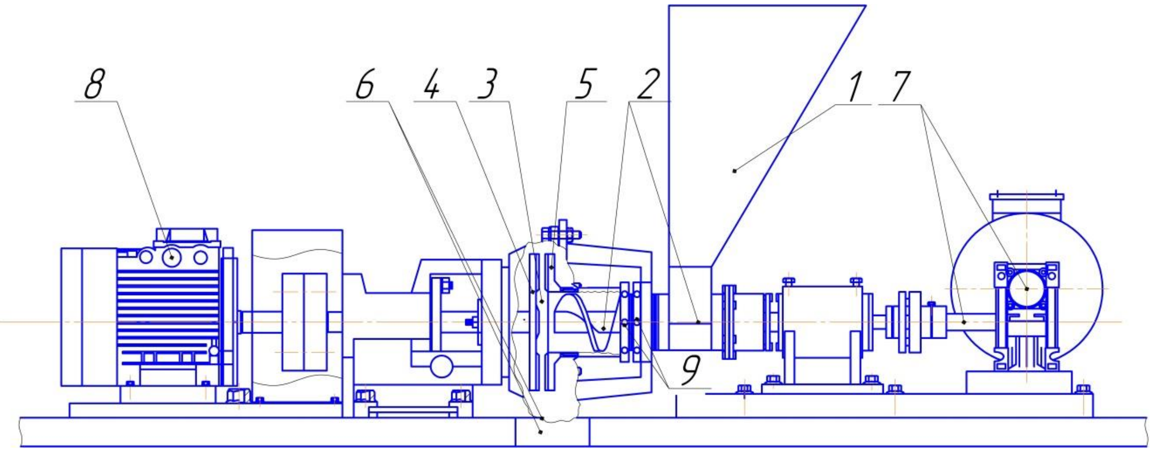

Fig. 1. Disk refiner (1 – pulp hopper; 2 – screw feeder; 3 – refining zone; 4 – rotor disk; 5 – stator disk; 6 – outlet; 7 – screw feeder worm gear; 8 – electric motor of disk refiner rotor drive; 9 – mechanical adjusting device)

To assess the variability of the pulp refining quality, an increase in the freeness value was determined according to the Shopper-Riegler method (°SR) using the SR-2 device (Manufacturer Metrotex, Moscow, Russia) as per ISO 5267-1 (2000). For analyses, pulp samples were taken with a freeness value of 15, 30, 45, and 60 °SR. According to ISO 16065-2 (2019), the morphological properties of fibres were determined at least three times for each sample using the *MorFi Neo* fibre analyser (Manufacturer “TECHPAP”, Gieres, France). The studied morphological properties of fibres included such indicators as listed below.

Average fibre length $L_{avg.}$ (mm) was determined according to the Eq. 1,

$$L_{avg.} = \frac{\sum L_i}{N} \tag{1}$$

where L_i is the length of developed fibres. As shown in the calculation diagram of Fig. 2, L_i is determined by the fibre analyser as the sum of segments of rectilinear sections of fibres along their axis; N is the number of recognised fibres.

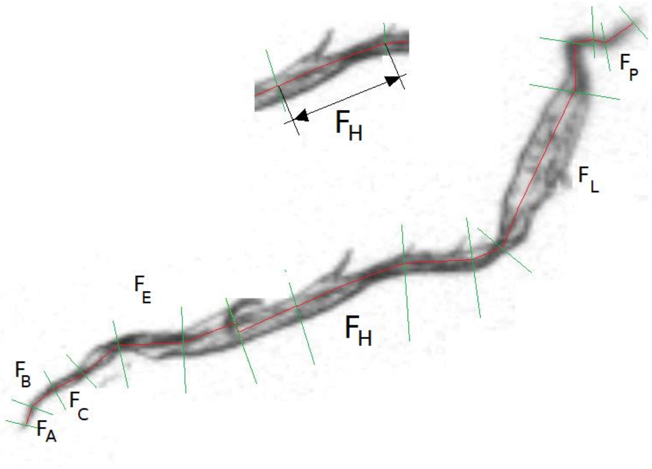

Fig. 2. Fibre length recognition by fibre analyser
($L_i = F_A + F_B + F_C + …. + F_H + … + F_P$)

The fibrillation index *Fib* (%) was calculated as the ratio of the sum of the lengths of all fibrils to that of the lengths of all recognised fibres and can be expressed through the Eq. 2,

$$Fib = \frac{\sum_{i=1}^{N} F_i}{\sum_{i=1}^{N} L_i} \times 100\% \tag{2}$$

where *Fi* is the -sum of all fibrils per fibre, and L_i is the length of developed fibres.

Fibre coarseness *k* (mg/m) is calculated as the ratio of the mass of all fibres (recognised by the fibre analyser) to their total length. Average fibre width *Z* (µm), as well as average fibre length, is summarily calculated using the device for each fibre segment. Average kink angle *A* (°), is determined as the points of abrupt change in the direction of the fibres where they can break.

In addition to the listed morphological properties of the fibres, the water retention value (WRV) was evaluated as an indicator characterising the fibre swelling degree according to ISO 23714 (2014). The WRV of the pulp indicates the moisture remaining in it after centrifugation under certain conditions. Pulp centrifugation was completed using the MPW – 310 device (MPW Instruments, Warsaw, Poland). The moisture content of the pulp after centrifugation was determined by the difference in the mass of the sample before and after drying (%), and can be expressed using the Eq. 3,

$$WRV = \frac{W_{wet} - W_{dry}}{B_{wet}} \times 100\% \tag{3}$$

where W_{wet} is the mass of wet fibres after centrifugation (g), and W_{dry} is the -mass of dry fibres (g).

To determine the physical and mechanical characteristics, a sheet machine (Werkstoffprufmaschinen, Leipzig, Germany) was used to form handsheets. Before testing the physical and mechanical characteristics, the handsheets were conditioned under standard conditions. The physical and mechanical characteristics of the handsheets were evaluated according to the following indicators:

− Breaking length in accordance with ISO 1924-2 (2008), using a RMB 30M tensile testing machine (Experimental Production Workshop, Moscow, Russia);

− Bursting strength in accordance with ISO 2758 (2014), using an EC35 apparatus (TMI 13-6, Rotterdam, Holland);

− Tearing resistance in accordance with ISO 1974 (2012), using a RB-1 device (Experimental Production Workshop, Moscow, Russia);

− Folding endurance in accordance with ISO 5626 (1993), using the DRK111B Folding Tester (Shandong Drick Instruments Co., Ltd., Jinan, China)

Methods

Pulp refining and factor and cluster analyses

During the experiment, the size of the gap between the rotor and stator cutters (with a range of variation 0.5 to 1.5 mm), rotor speed (2,000 to 2,500 rpm), pulp consistency (10 to 20%), and freeness value (15 to 60 °SR) of the pulp were varied. Table 1 presents the input technological factors of the refining process and the output parameters of the morphological properties of the pulp and the physical and mechanical characteristics of the handsheets. A total of 56 observations (refining modes) were made on the samples. The observations and their statistical characteristics are given in the Appendix (Tables S1 and S2).

The results (statistical characteristics, correlation, factor, and cluster analyses) were mathematically processed using the Statgraphics Centurion XVI software product (free version).

Table 1. Factors of the Refining Process and Output Parameters

Factors of the Refining Process and Output Parameters	Designation	
	In formulas	In tables and figures
Factors of the refining process		
Rotor speed (rpm)	n	X_1
Gap size (mm)	s	X_2
Pulp consistence (%)	C	X_3
Freeness value (°SR)	Sh	X_4
Output parameters		
Average fibre length (mm)	$L_{avg.}$	Y_1
Fibrillation index (%)	Fib	Y_2
Fibre coarseness (mg/m)	k	Y_3
Average fibre width (µm)	Z	Y_4
Water retention value (%)	W	Y_5
Average kink angle (°)	A	Y_6
Folding endurance	U	Y_7
Breaking length (m)	L	Y_8
Bursting strength (kPa)	P_a	Y_9
Tearing resistance (mN)	E	Y_{10}

RESULTS AND DISCUSSION

The preliminary statistical analysis of the observations revealed correlations between most of the output parameters (Table 2). This is a consequence of a relatively small number of common properties – "hidden" (latent) factors (*common factor*, *latent factor*) f_j that exert a greater or lesser influence on the output parameters and determine the structure of the correlation matrix.

Table 2. Correlation

	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}
Y_1	1	–	–	–0.743	–0.749	0.334	–0.436	–0.703	–0.698	–0.698
Y_2	-0.681	0.681	0.217	0.813	0.705	-0.574	0.834	0.851	0.909	0.868
Y_3	-0.217	1	0.059	0.307	0.595	0.383	0.011	0.431	0.375	0.327
Y_4	-0.743	0.059	1	1	0.844	-0.308	0.659	0.914	0.877	0.820
Y_5	-0.749	0.813	0.307	0.844	1	-0.176	0.473	0.913	0.888	0.873
Y_6	0.334	0.705	0.595	-0.381	-0.176	1	-0.431	-0.317	-0.329	-0.408
Y_7	-0.436	-0.574	0.383	0.659	0.473	-0.431	1	0.657	0.731	0.641
Y_8	-0.703	0.834	0.011	0.874	0.913	-0.317	0.657	1	0.972	0.927
Y_9	-0.697	0.851	0.431	0.877	0.888	-0.329	0.731	0.972	1	0.943
Y_{10}	-0.698	0.909	0.375	0.821	0.837	-0.408	0.641	0.927	0.943	1
		0.868	0.327							

This study used *factor analysis* and *cluster analysis* to identify the number and nature of hidden factors [1 through 5].

Factor analysis was used to derive a regression equation based on a matrix of correlations between output parameters. Linear regression is written as Eq. 4,

$$Y_i = l_{i1} f_1 + l_{i2} f_2 + \ldots + l_{it} f_t + \varepsilon_i \text{, } i = 1, \ldots, m; m > t, \tag{4}$$

where f_j is the hidden factor *"common (latent) factor"*; t is the number of latent factors; m is the number of output parameters (in the studied case, $m = 10$); l_{it} is the loading of the j^{th} latent factor on the i^{th} output parameter; ε_i represents the residuals representing the sources of deviations affecting only Y_i. Equation 4 expresses the basic hypothesis of factor analysis: the set of correlated variables Y_i $(i = 1, 2, ..., m)$ can be represented as a linear function of a smaller number of latent factors f_j $(j = 1, 2, ..., t)$ and a set of independent residuals ε_i.

Factor analysis of the results given in Table S1 was performed by the Minres method. The *Varimax Rotation* criterion was used for orthogonal transformation of factor loadings. Statistical significance with a confidence of at least 95% was established for two latent factors responsible for 96.19% of the total dispersion of all 10 output parameters, including 79.56% of the dispersion for the first factor and 16.62% for the second one (Table 3).

Table 3. Factor Loading Matrix after the Varimax Rotation

Variable	Factor Loading		Estimated Commonality
	Factor 1	Factor 2	
Y_1	-0.744	0.024	0.555
Y_2	0.918	-0.380	0.987
Y_3	0.369	0.801	0.777
Y_4	0.908	-0.032	0.825
Y_5	0.922	0.328	0.958
Y_6	-0.383	0.619	0.529
Y_7	0.693	-0.332	0.591
Y_8	0.972	0.086	0.953
Y_9	0.984	0.012	0.969
Y_{10}	0.942	-0.027	0.888
Contribution from total variance (%)	79.56	16.62	96.19

Figure 3 shows a two-dimensional factor space with the output parameters under observation. The coordinates of the points are *factor loadings* (see Table 3).

In addition to factor analysis, cluster analysis of the output parameters was performed using the *Ward's, Distance Metric Squared Euclidean* method (Fig. 4).

The classification procedures used are based on different data grouping methods. The object of factor analysis is the matrix of paired linear correlations between the output parameters. In cluster analysis, the basis for grouping is the geometric distances between the normalised values of the output parameters. Nevertheless, the results of the groupings turned out to be identical. This is confirmed by a visual comparison of Figs. 3 and 4.

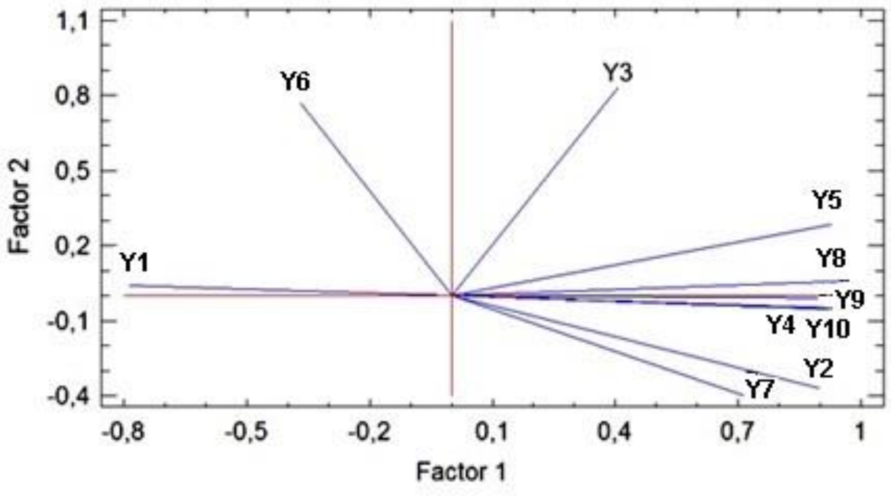

Fig. 3. Plot of the factor loading

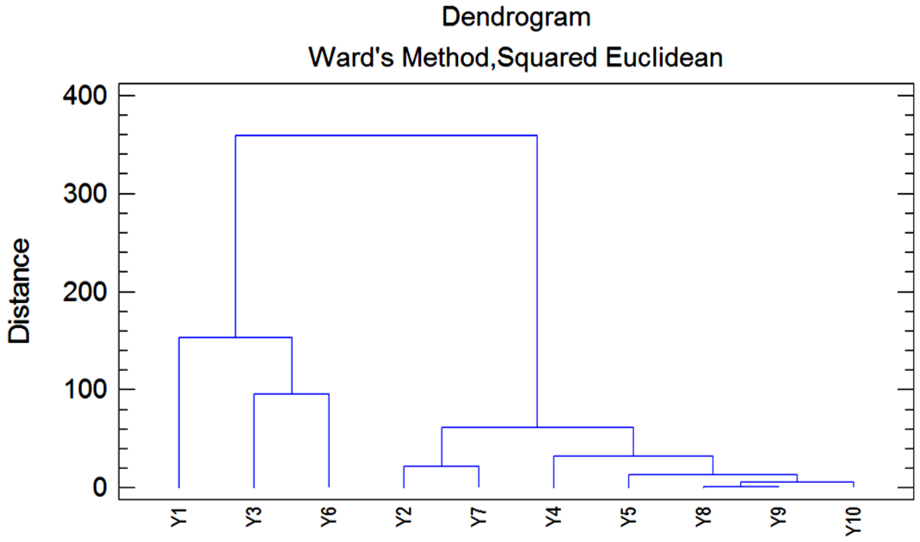

Fig. 4. Results of clustering by fibre properties

The main part of the output parameters (Y2, Y4-, Y5, Y7, Y10) was grouped into a relatively dense cluster on the positive part of the coordinate axis of the first latent factor (Fig. 3). The nature of this factor can be identified with the external fibre fibrillation degree: the positive correlation of this property with the water retention value of the pulp, the fibrillation index, and the strength characteristics of the handsheets did not contradict the generally accepted prior information.

The negative correlation between the average fibre length Y_1 and other characteristics in the studied cluster was unexpected. A possible reason is because of a decrease in the length of the fibres during refining with a simultaneous increase in the external fibrillation degree. Figure 5 shows the relationship between these properties for one of the refining modes. Similar dependences are revealed in other refining modes within the pulp consistency range of 10 to 20%.

The second latent factor affects the coarseness of the fibres Y_3 and their average kink angle Y_6. Presumably, the nature of this factor is associated with internal fibrillation.

High-consistency pulp refining is accompanied by an increase in internal fibrillation, resulting in increased flexibility and plasticity. The increased flexibility is accompanied by an increase in the number of kinked fibres and a decrease in their coarseness, as shown in Fig. 6.

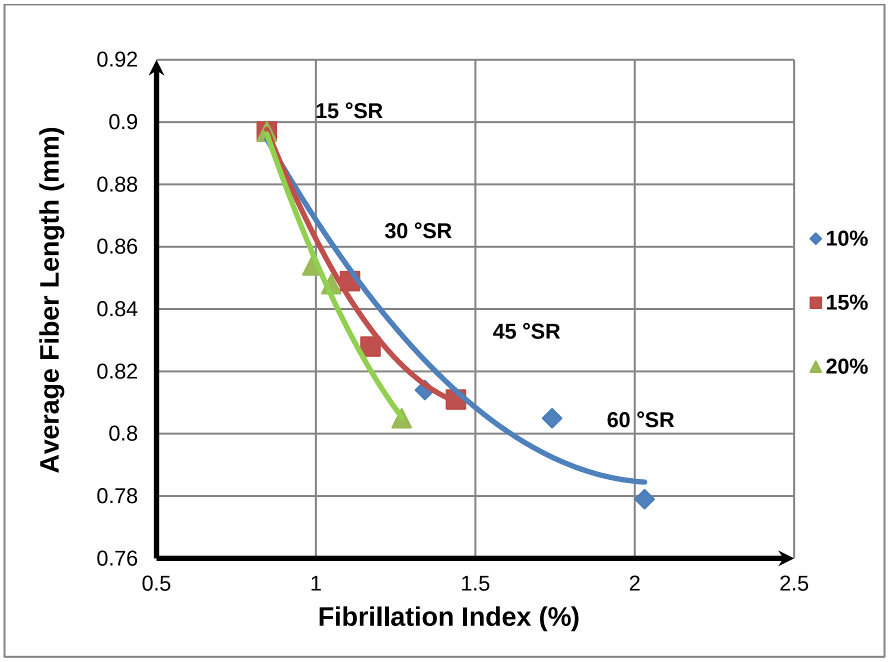

Fig. 5. The relationship between average fibre length on the fibrillation index (refining mode: rotor speed 2,000 rpm; gap between the rotor and stator cutters 1.5 mm; pulp consistency 10, 15, and 20%)

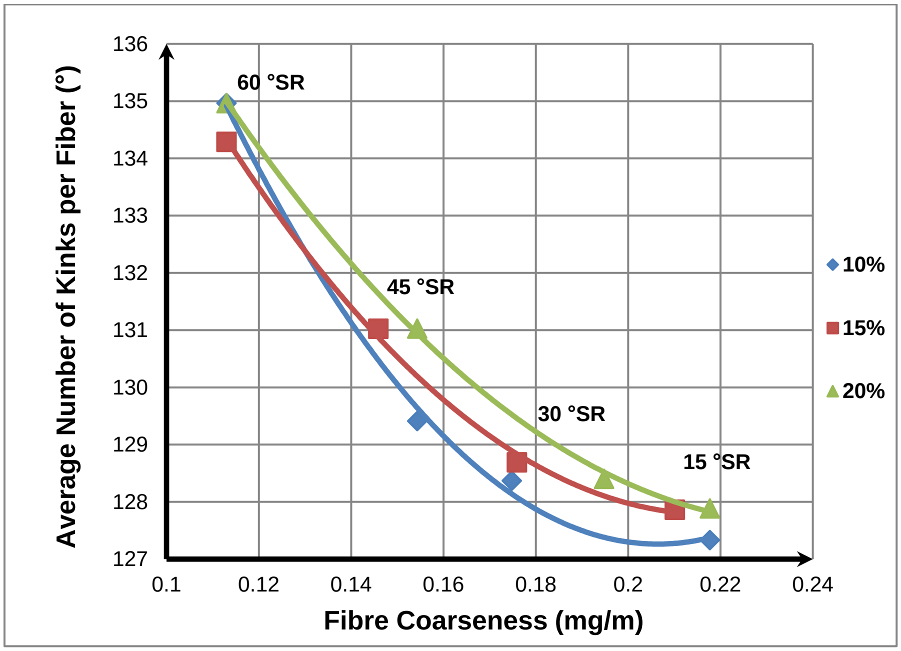

Fig. 6. The relationship between average kinked angle of fibres on their coarseness (refining mode: rotor speed 2,000 rpm; gap between the rotor and stator cutters 1.5 mm; pulp consistency 10, 15, and 20%)

CONCLUSIONS

1. The study conducted between the morphological properties of the fibers and the strength characteristics of the paper by the methods of factor and cluster analysis showed that the share of the total dispersion of the studied parameters of the refining process is determined by two hidden factors. One of the factors is related to the degree of fibrillation of the fibers, and the other to their flexibility. The total share of the total variance of all observed indicators, due to the influence of two hidden factors, is 96.2% of their total variance. The first of the identified factors determines 79.6% of the variance of the variance in the observed indicators, the second 16.6%.
2. The effectiveness of "information extraction" by multivariate mathematical statistics (correlation, factor, and cluster analysis methods) was demonstrated using the example of studying experimental data on the pulp refining process, which is one of the most important production processes in paper technology. It was established that the external fibrillation of cellulose fibres makes a major contribution to the variability of the physical and mechanical properties of paper sheets during high-consistency pulp refining.

ACKNOWLEDGMENTS

This work was carried out under the State Assignment issued by the Ministry of Education and Science of Russia for the project: “Technology and Equipment for the Plant Biomass Chemical Processing” by the Plant Material Deep Conversion Laboratory (Subject No. FEFE-2020-0016).

This work was performed using equipment of the Centre for Collective Use of the Krasnoyarsk Research Centre of the Siberian Branch of the Russian Academy of Sciences. We express gratitude to the staff of this centre for their assistance in our research.

REFERENCES CITED

Alashkevich, Yu. D., Kovalev, V. I., and Nabieva, A. A. (2010). *Influence of the Headset Pattern in the Process of Grinding Fibrous Semi-finished Products: Monograph in Two Volumes. Volume 1,* Siberian State Technological University, Krasnoyarsk, Russia.

Alashkevich, Yu. D., Reshetova, N. S., and Gudovskiy, V. P. (2006). *Theory and Design of Machines and Equipment of the Industry: Tutorial in Two Parts. Part 2,* Siberian State Technological University, Krasnoyarsk, Russia.

Almonti, D., Baiocco, G., Tagliaferri, V., and Ucciardello, N. (2019). “Artificial neural network in fibres length prediction for high precision control of cellulose refining,” *Materials* 12(22), article 3730. 1-13. DOI: 10.3390/ma12223730

Bhardwaj, N. K., Duong, T. D., and Nguyen, K. L. (2004). “Pulp charge determination by different methods: Effect of beating/refining,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 236(1), 39-44. DOI: 10.1016/j.colsurfa.2004.01.024

Brown, T., Miles, K., McDonald, D., and Wood, J. (2004). “Multivariate analysis of seasonal pulp quality variations in a TMP mill,” *Pulp & Paper Canada* 105(10), 230-234.

Chen, T., Xie, Y., Wei, Q., Wang, X., Hagman, O., Karlsson, O., and Liu, J. (2016). “Effect of refining on physical properties and paper strength of *Pinus massoniana* and China fir cellulose fibers,” *BioResources* 11(3), 7839-7848. DOI: 10.15376/biores.11.3.7839-7848

Chen, T., Wu, Z., Wei, W., Xie, Y., Wei, Q., Wang, X., Hagman, O., and Karlsson, O. (2017). “Optimizing refining conditions of *Pinus massoniana* cellulose fibers for improving the mechanical properties of ultra-low density plant fiber composite (ULD_PFC),” *BioResources* 12(1), 8-18. DOI: 10.15376/biores.12.1.8-18

Everitt, B. S., Landau, S., Leese, M., and Stahl, D. (2011). *Cluster Analysis 5th Edition*, Wiley, King’s College, London, UK.

Fernando, D. (2007). *Ultrastructural Characterization (Morphological and Topochemical) of Wood Pulp Fibres; Effects of Mechanical and Kraft Processes*, Doctoral Thesis No. 2007:39, Swedish University of Agricultural Sciences (SLU), Department of Forest Products/Wood Science, Uppsala, Sweden.

Fernando, D., Muhic, D., Engstrand, P., and Daniel, G. (2011). “Fundamental understanding of pulp property development during different TMP refining conditions using the application of new Simons’ stain method and fibre surface ultrastructure,” *Holzforschung* 65(6), 777-786. DOI: 10.1515/HF.2011.076

Fernando, D., Muhic, D., Engstrand, P., and Daniel, G. (2012). “Surface and internal micro/ultrastructure of TMP fibres produced during high-intensity refining elucidate the development of pulp and paper properties,” *Holzforschung* 66(4), 467-475. DOI: 10.1515/hf.2011.175

Gard, J. (2002). *The Influence of Fibre Curl on Shrikage and Strength Properties of Paper*, Master’s Thesis, Lulea University of Technology, Lulea, Sweden.

Gurnagul, N., Merng, Ju. S., and Shallhorn, P. (2005). “Optimizing high-consistency refining conditions for good sack paper quality,” in: *Appita Annual Conference*, Melbourne, Australia, pp. 379-386.

Hartler, N. (1995). “Aspects on curled and microcompressed fibers,” *Nordic Pulp & Paper Research Journal* 10(1995), 4-7. DOI: 10.3183/npprj-1995-10-01-p004-007

Henderson, J. T., Barton, J. S., and Erfurt, H. (1965). “Effects of high consistency refining on the properties of the consolidated web,” in: *Consolidation of the Paper Web*, F. Bolam (Ed.), Transactions of the Cambridge Symposium, Vol. 2, Pira, UK, pp. 875-895. DOI: 10.15376/frc.1965.2.875

Hou, Q., Yang, B., Liu, W., Liu, H., Hong, Y., and Zhang, R. (2011). “Co-refining of wheat straw pulp and hardwood kraft pulp,” *Carbohydrate Polymers* 86(1), 255-259. DOI: 10.1016/j.carbpol.2011.04.040

ISO 1924-2 (2008). “Paper and board — Determination of tensile properties — Part 2: Constant rate of elongation method (20 mm/min),” International Organization for Standardization, Geneva, Switzerland.

ISO 1974 (2012). “Paper — Determination of tearing resistance — Elmendorf method),” International Organization for Standardization, Geneva, Switzerland.

ISO 16065-2 (2019). “Pulps — Determination of fibre length by automated optical analysis — Part 2: Unpolarized light method,” International Organization for Standardization, Geneva, Switzerland.

ISO 23714 (2014). "Pulps — Determination of water retention value (WRW)," International Organization for Standardization, Geneva, Switzerland.

ISO 2758 (2014). "Paper — Determination of bursting strength," International Organization for Standardization, Geneva, Switzerland.

ISO 5263-3 (2004). "Pulps - Laboratory wet disintegration," International Organization for Standardization, Geneva, Switzerland.

ISO 5267-1 (2000). "Pulps - Determination of drainability — Part 1: Schopper-Riegler method," International Organization for Standardization, Geneva, Switzerland.

ISO 5626 (1993). "Paper — Determination of folding endurance," International Organization for Standardization, Geneva, Switzerland.

Kang, T., and Paulapuro, H. (2006). "Effect of external fibrillation on paper strength," *Pulp & Paper Canada* 107(7/8), 51-54.

Kerekes, R. J. (2015). "Perspectives on high and low consistency refining in mechanical pulp," *BioResources* 10(4), 8795-8811. DOI: 10.15376/biores.10.4.8795-8811

Kim, J. O., and Mueller, C. W. (1986). *Factor Analysis: Statistical Methods and Practical Issues*, Sage University Paper Series on Quantitative Applications in the Social Sciences, Series № 07-014, pp. 1-88.

Klark, J. (1983). *Pulp Technology (Science of Pulp and Paper, Pulp Preparation, Paper Processing, Test Methods)*, Lesnaya Promyshlennost, Moscow, Russia.

Matveev, B. P. (1974). *Study of the Main Factors of the Process of Refining Sulphate Unbleached Pulp in a Disc Mill at High Consistency*, Ph.D. Dissertation, Leningrad Technological Institute of Pulp and Paper Industry, Leningrad, USSR.

Lawley, D. N., and Maxwell, A. E. (1962). "Factor analysis as a statistical method," *Journal of the Royal Statistical Society. Series D (The Statistician)* 12(3), 209-229. DOI: 10.2307/2986915

Lebedev, I., Kazakov, Y., Chukhchin, D., and Romanenko, K. (2018). "The role of fibers surface in development of papermaking properties of technical pulp in the refining process," *Khimiya Rastitel'nogo Syr'ya* 2018(2), 207-216. DOI: 10.14258/jcprm.2018022248

Novoselskaya, O. A., Kolesnikov, V. L., Penkin, A. A., Solov'eva, T. V., Kashin, A. N., Nagornova, I. V., and Varepo, L. G. (2019). "Management the paper printing properties by methods of factor analysis," *Journal of Physics: Conference Series* 1260, article ID 032031. DOI: 10.1088/1742-6596/1260/3/032031

Page, D. H., Seth, R. S., Jordan, B. D., and Barbe, M. C. (1985). "Curl, crimps, kinks and microcompressions in pulp fibres – their origin, measurement and significance," in: *Paper Making Raw Materials, Transactions of the 8th Fundamental Research Symposium*, Oxford, England, pp. 183-227. DOI: 10.15376/frc.1985.1.183.

Pen, R. Z. (1972). "Factor analysis of the results of the active experiment," *Zavodskaja Laboratorija (Journal Plant Laboratory)* 1, 70-73.

Pen, R. Z., and Karetnikova, N. V. (2008). *Wood and Waste Pulp Technology, Manual*, Siberian State Technological University, Krasnoyarsk, Russia.

Penkin, A., and Kazakov, Y. (2022). "Changes in the morphological characteristics of secondary fiber obtained from wet-strength paper during gentle refining of recycled pulp. Part 1. Fiber characteristics," *Russian Forestry Journal* 2022(5), 157-172. DOI: 10.37482/0536-1036-2022-5-157-172

Przybysz, P., Dubowik, M., Malachowska, E., Kucner, M., Gajadhur, M., and Przybysz, K. (2020). "The effect of the refining intensity on the progress of internal fibrillation and shortening of cellulose fibers," *BioResources* 15(1), 1482-1499. DOI: 10.15376/biores.15.1.1482-1499

Pulkkinen, I., Fiskari, J., and Alopaeus, V. (2010). "New model for predicting tensile strength and density of eucalyptus handsheets based on an activation parameter calculated from fiber distribution characteristics," *Holzforschung* 64(2), 201-209. DOI: 10.1515/HF.2010.030

Strand, B. C. (1987). "Factor analysis as applied to the characterization of high-yield pulps," in: *TAPPI Pulping Conference*, Washington, D.C., USA, pp. 61-66.

Sundström, L., Brolin, A., and Hartler, N. (1993). "Fibrillation and its importance for the properties of mechanical pulp fiber sheets," *Nordic Pulp & Paper Research Journal* 8(4), 379-383. DOI: 10.3183/npprj-1993-08-04-p379-383

Ushakov, A. V., Alashkevich, Yu. D., Kozhukhov, V. A., and Kovalev, V. I. (2020). "Current state and prospects for improving the process of milling fibrous semifinished high concentration processes (review)," *Khimiya Rastitel'nogo Syr'ya* 2020(4), 315-329. (in Russ.). DOI: 10.14258/jcprm.2020048251

Wathén, R. (2006). *Studies on Fiber Strength and its Effect on Paper Properties*, Ph.D. Dissertation, Doctor of Science in Technology, Helsinki University of Technology, Espoo, Finland.

Article submitted: July 8, 2023; Peer review completed: July 29, 2023; Revised version received: October 3, 2023; Published: October 12, 2023.
DOI: 10.15376/biores.18.4.8090-8103

SUPPLEMENTARY

APPENDIX

Table S1. Observations

№	X1	X2	X3	X4	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
1	2500	1.5	20	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
2	2500	1.5	20	32	0.837	1.209	0.139	20.8	272	130.74	6	2592	112	340
3	2500	1.5	20	47	0.837	1.264	0.187	21	302	133.00	18	3950	155	471
4	2500	1.5	20	62	0.819	1.431	0.171	21.1	325	134.08	47	5102	212	549
5	2000	1.5	20	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
6	2000	1.5	29	27	0.854	0.918	0.194	20.6	262	133.03	7	2921	102	262
7	2000	1.5	20	48	0.848	1.048	0.195	20.9	316	134.40	28	4526	151	471
8	2000	1.5	20	62	0.805	1.369	0.218	21.3	326	134.89	31	5184	184	523
9	2500	0.5	20	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
10	2500	0.5	20	30	0.824	1.029	0.151	21.1	274	131.98	12	3620	115	314
11	2500	0.5	20	42	0.821	1.230	0.151	21.4	318	132.82	24	4446	154	471
12	2500	0.5	20	62	0.810	1.374	0.207	21.2	355	134.94	88	5678	200	601
13	2000	0.5	20	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
14	2000	0.5	29	31	0.813	1.314	0.087	21.2	250	125.38	13	3573	138	497
15	2000	0.5	20	40	0.801	1.672	0.092	21.3	299	125.03	70	6172	209	601
16	2000	0.5	20	61	0.798	1.822	0.092	21.5	311	124.32	150	6460	210	627
17	2500	1.5	10	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
18	2500	1.5	10	28	0.849	1.005	0.113	20.9	275	135.34	5	2386	108	313
19	2500	1.5	10	43	0.847	1.027	0.227	20.7	295	135.04	16	3248	133	392
20	2500	1.5	10	60	0.832	1.313	0.191	21.3	320	136.34	41	4567	208	601
21	2000	1.5	10	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
22	2000	1.5	10	31	0.814	1.342	0.131	20.5	252	128.41	16	4037	140	497
23	2000	1.5	10	48	0.805	1.741	0.117	21.4	308	128.37	95	5225	221	523
24	2000	1.5	10	62	0.779	2.031	0.129	22.1	313	128.73	262	7036	277	601
25	2500	0.5	10	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
26	2500	0.5	10	29	0.844	0.940	0.145	20.8	262	135.14	7	3085	112	392
27	2500	0.5	10	45	0.85	1.113	0.146	20.8	294	136.48	18	3785	154	418
28	2500	0.5	10	58	0.826	1.342	0.179	20.9	315	135.82	41	5555	187	470
29	2000	0.5	10	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
30	2000	0.5	10	33	0.837	1.242	0.083	20.6	227	129.20	18	3538	143	523
31	2000	0.5	10	46	0.801	1.544	0.112	20.8	336	131.40	98	4372	192	575
32	2000	0.5	10	60	0.792	1.952	0.126	21.6	330	129.05	286	5925	242	627
33	2500	1.0	15	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
34	2500	1.0	15	30	0.904	1.028	0.152	20.8	282	133.15	8	3086	118	392
35	2500	1.0	15	45	0.844	1.114	0.182	21.2	302	135.31	18	4372	163	496
36	2500	1.0	15	63	0.816	1.307	0.253	21.1	371	136.06	65	6501	214	471
37	2000	1.0	15	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
38	2000	1.0	15	29	0.863	1.005	0.155	21	293	132.29	21	3538	121	366
39	2000	1.0	15	43	0.852	1.105	0.166	21.1	297	134.10	51	5061	160	471
40	2000	1.0	15	61	0.833	1.178	0.174	21.3	313	135.41	98	5678	197	497
41	2250	1.5	15	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
42	2250	1.5	15	30	0.849	0.964	0.179	20.8	293	132.85	10	3703	122	471
43	2250	1.5	15	46	0.828	1.171	0.167	20.9	323	134.07	35	4773	161	497
44	2250	1.5	15	57	0.811	1.339	0.174	21.1	332	133.86	65	5802	201	523
45	2250	0.5	15	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
46	2250	0.5	15	27	0.861	0.952	0.141	21	248	132.95	8	3332	124	366
47	2250	0.5	15	43	0.83	1.200	0.154	21.1	312	135.15	19	5020	161	471
48	2250	0.5	15	63	0.839	1.454	0.140	21	315	135.37	96	5473	203	602
49	2250	1.0	20	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
50	2250	1.0	20	30	0.727	1.059	0.119	21.1	274	133.27	9	3332	122	313
51	2250	1.0	20	45	0.698	1.26	0.143	21.2	315	134.25	22	3950	138	471
52	2250	1.0	20	57	0.694	1,36	0.164	21.4	374	134.76	41	5020	186	549
53	2250	1.0	10	15	0.897	0.846	0.113	20.3	147	134.96	4	998	55	216
54	2250	1.0	10	30	0.863	1.027	0.159	21.1	275	135.40	14	3456	117	392
55	2250	1.0	10	45	0.837	1.336	0.125	21.2	297	136.49	41	4899	170	418
56	2250	1.0	10	60	0.825	1.505	0.121	21.2	303	135.89	54	6131	218	523

Table S2. Statistical Characteristics Observations

Statistics	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Count	56	56	56	56	56	56	56	56	56	56
Average	0.840	1.16	0.14	20.88	262.77	133.46	38.0	3644.3	137.94	410.21
Standard Deviation	0.047	0.29	0.03	0.42	72.69	2.89	56.06	1843.48	60.54	138.13
Minimum	0.694	0.84	0.08	20.3	147.0	124.32	4.0	998.0	277.0	216.0
Maximum	0.904	2.01	0.25	22.1	374.0	136.48	286.0	7036.0	222.0	627.0
Coeff. of Var. (%)	5.66	25.5	26.0	2.04	27.66	2.16	147.5	50.58	43.89	33.91