A new procedure for the routine assessment of paper diagonal curl

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ABSTRACT: Diagonal curl can lead to severe problems for end users, such as frequent jams during copy or printing. We reviewed the key factors underlying paper curl and diagonal curl and presented a new measurement method for assessing diagonal curl. The methodology overcomes most of the limitations of current methods that have prevented them from being adopted for routine testing purposes. The methodology is already being implemented in a paper mill and is providing new elements for data analysis and adding previously unavailable information to process/quality databases. In runnability tests, diagonal curl measurements were found to correlate well with the occurrence of paper jams.

Application: Paper producers can now monitor diagonal curl as part of their quality assessment routines, using minimal equipment and sample handling and processing.

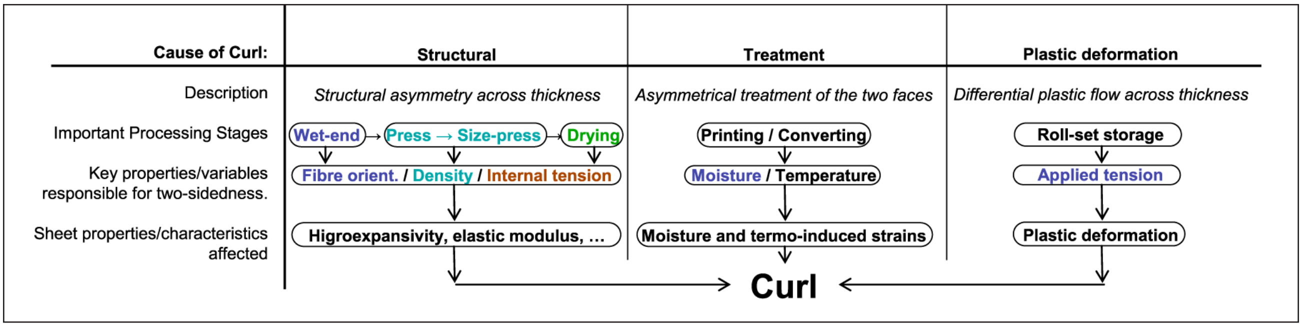
Curl of paper and paperboard, defined as the deviation from a flat surface, constitutes an important quality problem for paper and paperboard producers, as it can seriously affect converting and printing operations, where a flat and dimensional stable material is required in order to achieve the desired high production rates and quality.

Since the pioneering work of Smith [1], curl problems have been studied using experimental [2–6], theoretical [7–11], and industrial approaches [12–15] and the three main types [16] of conceptual causes are reasonably well understood. Those types can either appear isolated or simultaneously.

The first cause is ***asymmetrical treatment of the two faces of paper during its use***. Because of its composition, paper is a reactive material that changes with the relative humidity of the surrounding medium and, to a lesser extent, temperature variations. Wood fiber is composed of substances that show high affinity to water (e.g., cellulose, hemicellulose). Therefore, an increase in the environment's relative humidity induces the adsorption of water in fibers, which leads to swelling. Once an individual dimensional variation is communicated to its neighboring fibers and then to the interconnected network of fibers, the result is a change in the geometric dimensions of the paper sheet. Fiber swelling occurs preferentially in the radial direction (because of the helicoidal rolling of cellulose fibrils in the fiber walls). Therefore, paper tends to expand more along the cross-machine direction (CD) because fibers are more aligned in the machine direction (MD). When the two faces of paper are exposed to different moisture variations, they will show different dimensional responses, and the interplay of stresses developed across the paper thickness results in a final curvature, i.e. curl. The direct consequence is that there will always be paper curl, as long as asymmetrical treatment is applied to paper. In practice, asymmetrical treatment is more the rule than the exception (e.g., electrophotographic and offset printers), so paper curl is a phenomenon that paper producers have learned to live with but continually strive to mitigate. One way to do this is to lower paper's hygroreactivity, i.e., paper hygroexpansivity, by tensioning fibers while the web is still humid and freezing them in such an internal stress condition during drying so that they have less freedom to move upon moisture intake [5, 9, 17–21].

However, even if both faces of paper are exposed to the same processing conditions, it can still develop a curvature. This happens when there is a ***structural asymmetry across the thickness of paper*** that induces different dimensional responses to the same external stimulus. Fiber orientation is a primary source of structural unevenness in the thickness direction, especially in the Fourdrinier type of paper machines or even in the so-called hybrid machines (machines with the same type of formation section as the Fourdrinier paper machine, but equipped with a top former to improve treatment symmetry on both faces of paper). Different levels of fiber orientation in the bottom (usually more aligned) and the top generate different levels of anisotropy in the mechanical properties of paper (e.g., elastic modulus) and, most importantly, in its hygroexpansion coefficients (that characterize dimensional responses to humidity changes, along the MD and CD directions). When both sides are exposed to the same moisture variation, their differential dimensional response will produce a curvature. The curvature axis will typically be perpendicular to the direction where the hygroexpansion coefficient is higher (which is usually the CD direction, leading to an MD curl axis) and its face will be away from the one that expanded the most or contracted the least. Even though fiber orientation constitutes an important contribution to structural asymmetry in the thickness direction, differences in internal (or drying) tension, density, and pulp composition can also play a role in curl development.

Finally, the last cause for paper curl is the result of impos-



I. Causes of curl, along with the process stages where they develop, key properties or variables involved, and the sheet parameters or characteristics affected that lead to the final and observed paper deformation.

ing a ***differential plastic flow along the thickness of paper***. After being subjected to tension for some time, paper can only recover a part of its original dimensions due to the existence of plastic flow. By imposing different plastic deformations in the two faces, a curvature will result, as in the roll-sets near the core of papers kept a long time in storage facilities. However, this curvature can be easily eliminated, by passing the paper over small-diameter rollers or bars so it is bended away from the direction of curvature. **Table I** presents the systematizing approach for classifying curl, according to the nature of its root cause.

One curl manifestation that is particularly problematic and a matter of great concern to paper producers is the occurrence of curl modes with a diagonal curvature axis, i.e., not aligned either with the MD or CD axes. In fact, it is believed that such type of deformation tends to be even more detrimental to the runnability of printing operations than the other manifestations of curl, leading to higher rates of paper jams. Therefore, it is crucial for paper producers to have methods available for promptly monitoring the current state of paper produced to assess its potential to develop such kinds of undesirable deformations at later stages. Furthermore, there is a need for paper producers to develop a deep knowledge base about the potential root causes underlying such phenomena as well as acquire all the necessary technical means and methodological procedures to perform the required screening laboratorial work defined in a paper curl root-cause searching protocol. That protocol can also serve as an out-of-control-action-plan (OCAP), if diagonal curl is under statistical process control (SPC) surveillance, for which it is necessary to have a quick and reliable measurement method.

This paper addresses the issue of developing a measurement methodology for diagonal curl and illustrates its application potential, which is already being partially explored at a specific paper company. This methodology has features that make it quite attractive for routine use in mill practice, something that is confirmed by the experience acquired so far from its real-world implementation. We also discovered, for a particular copy test, an interesting result regarding a good correlation of diagonal curl measurements with the observed copying runnability performance of paper.

CURL MEASUREMENT

Routine procedures for curl assessment, as they are carried out in most paper producing mills, usually begin by analyzing paper before any processing. Any curling tendency toward one of the two faces, during the ream opening stage, is properly noted and registered (ISO 14968:1999, "Paper and board—Cut-size office paper—Measurement of curl in a pack of sheets"). Then, a well-defined number of paper sheets is submitted to a copy process, where a standardized image is printed on one of its two faces (simplex mode) or on both faces, one right after the other (duplex mode). The face on which the paper receives the test image is always known, as such information is important for the posterior analysis of curl measurement results that provide clues for inferring anisotropy across the thickness direction. After copying, paper curl is then characterized according to its three fundamental aspects: face (the side toward which paper curls), direction (the axis of the curvature), and magnitude (an assessment of how far the sample under analysis is from a flat surface).

For assessing curl magnitude in the MD and CD directions, ISO 14968:1999 adopts a procedure based on the comparison of paper curvatures at the edges of the samples with a curl gauge where curvatures (arcs of circumferences) are indexed to a magnitude scale (reciprocal radius). This standard does not indicate any procedure for the quantification of an existing diagonal curl component, other than its adequate annotation in the test report. Nevertheless, several procedures for measuring diagonal curl were already proposed in the literature. Niskanen [4] and Nordström, Carlsson and Hägglund [22], proposed two such methodologies that begin by measuring the vertical displacements of a paper sample with a particular format (90-mm diam. circles or 10-cm squares, respectively) relative to a flat surface, through noncontact, optical distance measuring instrumentation over a grid of points. Afterwards, off-line processing of such measurements culminates with the estimation of a second-order polynomial surface, from which it is possible to quantify the magnitude of curl components directly from the estimated parameters. For such a surface, Eq. 1 follows:

$$w(x,y)=\frac{K_x}{2}x^2+\frac{K_y}{2}y^2+\frac{K_{xy}}{2}xy+a+bx+cy \qquad (1)$$

where w is the vertical displacement over a flat surface, x and y the orthogonal position coordinates, K_y and K_x are the curvatures along the MD and CD axes, respectively, and K_{xy} is the twist curl component.

Although they allow for complete and consistent characterization of curl, this class of methodologies has some drawbacks. Apart from requiring expensive equipment, the need to cut samples in squares or circles introduces some extra variability and moves further from an evaluation of the dimensional behaviour of paper with standard commercial dimensions. The complexity of the corresponding measurement protocols is also not attractive for routine quality control in everyday mill practice.

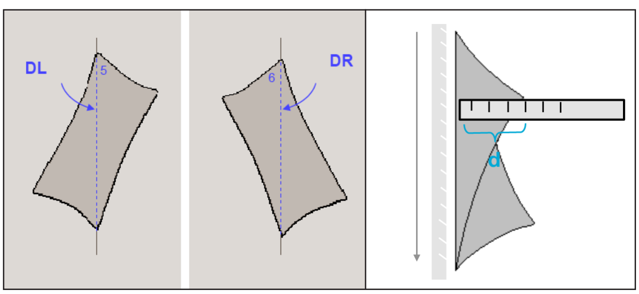
Another alternative, proposed in the ISO 11556 standard ("Paper and board— Determination of curl using a single vertically suspended test piece"), consists of using a specially modified Vernier caliper to measure several features of deformation in a suspended circular sample, along with measurement of the angle between curl axis and the MD direction. However, such a measurement protocol is too much complex for routine use, requiring samples with nonstandard shapes and the use of specially designed tools.

Given such limitations, we conceived and tested a methodology for assessing the magnitude of paper diagonal curl. The methodology has the desirable features of being simple, fast, reliable, and able to explore synergies with current practice and uses handy instrumentation and a simple experimental protocol.

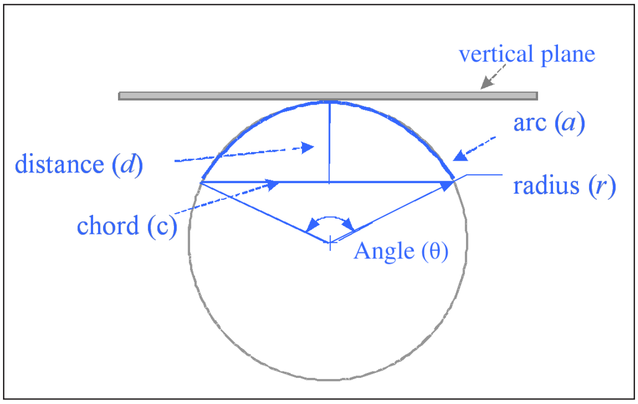
METHODOLOGY

Our proposed methodology was designed to be well aligned with ISO 14968:1999, given its wide acceptance in the paper-producing sector, in particular as a routine testing procedure for characterizing copy paper curl tendencies. However, we extended the corresponding experimental protocol to be able to cope with the quantification of diagonal curl magnitude, whenever present.

The procedure for assessing diagonal curl magnitude consists of suspending a sample with a well-defined number of sheets from each of its corners so that the curl axis is perfectly aligned with the vertical dimension (**Fig. 1**). Then, in this position, an operator measures the maximum distance



1. Proposed methodology for assessing the magnitude of diagonal curl: (left) suspended sample with the diagonal axis aligned in the vertical direction and (right) the measurement of distance d.



2. Components involved in the computation of curl magnitude (C) from distance, d.

d from the sheet corner to the flat vertical surface and registers this value.

Distance d must now be related to the diagonal curl magnitude (C), which in the above referred standard is quantified as the inverse of a circle's radius given by the arc that best matches the observed curvature. In order to clarify how this can be accomplished, we analyse first the relationship between such a distance and curl magnitude, in the simpler situation where no diagonal component exists, i.e., where only MD or CD curl is present. **Figure 2** depicts the relevant geometrical quantities in this situation, namely: distance d (measured by the operator according to the procedure mentioned above), arc a (length of paper in the CD direction when measuring MD curl, and vice-versa, when measuring CD curl) and angle θ (in rad), as shown in Fig. 2. Under these conditions, we have Eq. 2:

$$\theta r = a \tag{2}$$

To incorporate distance d in the analysis, it must be related to these quantities. Using algebraic and trigonometric considerations, it can be proven that the relationship in Eq. 3 holds:

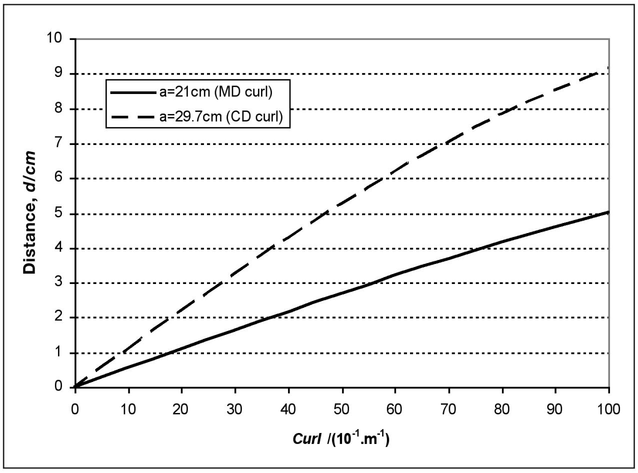
$$d = 2r\sin^2\left(\frac{\theta}{4}\right) \tag{3}$$

Introducing Eq. 2, as well as the definition of curl magnitude, $C = 1/r$, in Eq. 3, yields the following expression relating C, d, and a in Eq. 4:

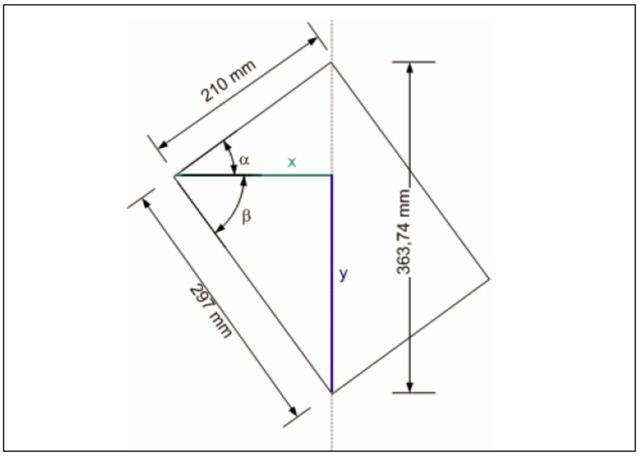
$$d = \frac{2}{C}\sin^2\left(\frac{a \times C}{4}\right) \tag{4}$$

Figure 3 illustrates the application of Eq. 4 for an A4 format paper sheet, with a one-to-one, nonlinear relationship between d and C, the two quantities whose relationship we want to define, in the range of values found in practice.

To extend this reasoning to diagonal curl, a sample should be hung so that the diagonal axis of curl will be well aligned with the vertical direction by the operator (**Fig. 4**). For the sake of clarity, we also addressed the case where such a di-



3. Relationship between distance d and curl magnitude (C), for the MD and CD directions.



4. Representation of a suspended sample (A4 format) with diagonal curl axis coinciding with the main diagonal.

agonal axis corresponds to the main diagonal of the paper sheet, a situation often met in practice. In this case, by comparing Fig. 4 and Fig. 2, it is evident that two times the distance *x*, shown in Fig. 4, plays the same role as arc *a* in Fig. 2.

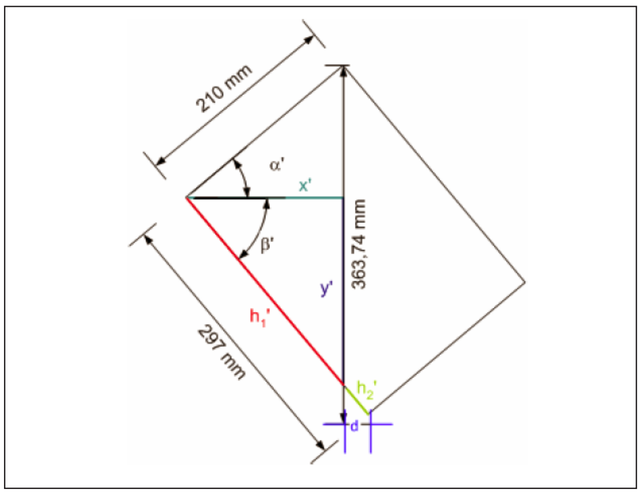
Distance *x* can be easily obtained from the geometric dimensions of the paper sheet (Fig. 4), solving the following Eq. 5:

$$\begin{cases} x = 210 \times \cos(\alpha) \\ x = 297 \cdot \cos(\beta) \\ \alpha + \beta = \dfrac{\pi}{2} \end{cases} \Leftrightarrow \begin{cases} x = 171.47\ mm \\ \alpha = 0.615\, rad \\ \beta = 0.955\, rad \end{cases} \quad (5)$$

Therefore, to relate curl magnitude with distance $a = 2x$ (measured at the corner of the sample, as illustrated in Fig. 1.), it is necessary to invert Eq. 4 to obtain the corresponding magnitude of *C*. **Table II** shows that the operation can be quickly accomplished using numerical, graphical, or tabular approaches. Table II also presents situations where the curl axis is not aligned with the paper sheet main diagonal. Even for reasonable displacements (e.g. 20 mm), corrections to the basic relationship are yet relatively small. **Figure 5** represents a suspended A4 sample with the diagonal curl axis not aligned with the main diagonal, presenting instead a non-zero displacement (*d*).

Curl/ ($10^{-1}m^{-1}$)	Displacement / mm					
	0	10	20	30	40	50
	Distance *d* / cm					
10,0	1,5	1,4	1,3	1,3	1,2	1,2
12,5	1,8	1,8	1,7	1,6	1,5	1,5
15,0	2,2	2,1	2,0	1,9	1,8	1,7
17,5	2,6	2,5	2,4	2,3	2,1	2,0
20,0	2,9	2,8	2,7	2,6	2,4	2,3
22,5	3,3	3,1	3,0	2,9	2,7	2,6
25,0	3,6	3,5	3,3	3,2	3,0	2,9
27,5	4,0	3,8	3,7	3,5	3,3	3,2
30,0	4,3	4,1	4,0	3,8	3,6	3,5
32,5	4,7	4,5	4,3	4,1	3,9	3,7
35,0	5,0	4,8	4,6	4,4	4,2	4,0
37,5	5,3	5,1	4,9	4,7	4,5	4,3
40,0	5,7	5,4	5,2	5,0	4,8	4,5
45,0	6,3	6,1	5,8	5,6	5,3	5,1
50,0	6,9	6,7	6,4	6,1	5,9	5,6
65,0	8,6	8,3	8,0	7,7	7,3	7,0
100,0	11,4	11,1	10,7	10,4	10,0	9,6

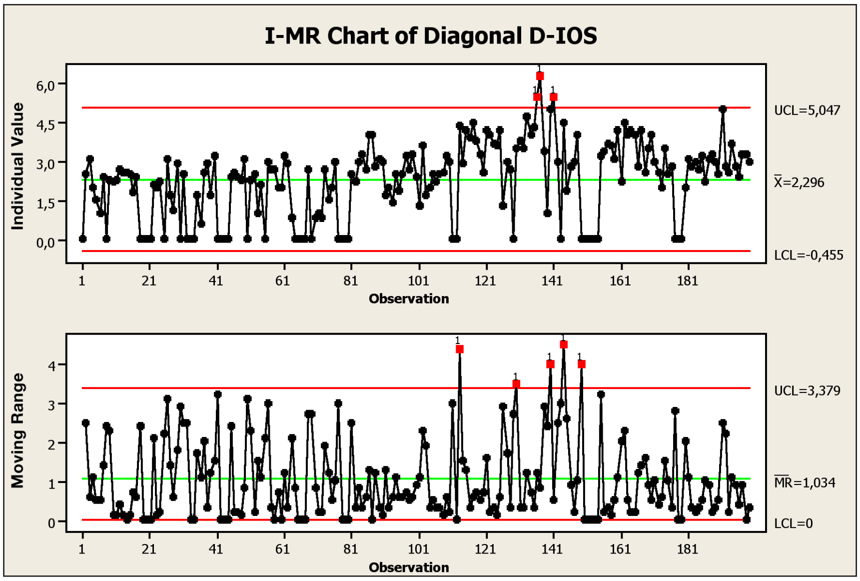
II. Relationship between curl magnitude and distance d, when the curl axis is well aligned with the main diagonal of the sheet (0 displacement), and when there is some non-zero displacement between them.



5. Representation of a suspended sample (A4 format) with the diagonal curl axis not aligned with the main diagonal, presenting instead a non-zero displacement (d).

The proposed methodology for quickly measuring diagonal curl magnitudes can also be consistently related to other available measurement techniques. In particular, as a coherency measure, all methodologies should provide the necessary parameter estimates for univocally defining the observed deformation, usually approximated by a second-order surface. As discussed earlier, some techniques address this issue by cutting samples with a special format (squares or circles) and use an experimental apparatus to measure deformation heights, after which parameters are fit through ordinary least squares [4, 11, 22]. The other methodology we reviewed (ISO 11556) estimates curvature in the direction of curl, characterised by angle θ with the MD direction. Such a curl curvature, evaluated in this same direction (also assuming a circular deformation, as in our method), can then be related to the parameters of the second-order surface, Eq. 1, as follows:

$$K_x = K_\theta \sin^2(\theta) \\ K_y = K_\theta \cos^2(\theta) \\ K_{xy} = 2K_\theta \cos(\theta)\sin(\theta) \tag{6}$$



6. Control charts for individual curl values and moving range (I-MR), for the statistical monitoring of the mean and process variability, respectively, of diagonal curl on a particular copy test.

In Eq. 6, θ is the angle between the axis of curl and the paper MD direction, viewed in the concave side (if MD is positioned in a clockwise direction from the axis of curl, the angle is positive, and negative otherwise). Therefore, it is possible to use such a set of equations to convert our curl measurements to the corresponding curl components. For instance, in the case where the curl axis is located along the main diagonal of a commercial paper sheet, θ, is given by Eq. 7, with values taken from Fig. 4 and Eq. 5:

$$\theta = -\left(\frac{\pi}{2} - \beta\right) = -\alpha = -0.615\ rad \tag{7}$$

Our method measures curl as a reciprocal radius, i.e., assuming circular deformations, so no further modification is required. However, an assumption that considers a circular deformation encompasses an approximation of the two definitions of curl: that based on a circular deformation, for which curl is measured by a reciprocal radius, and that based on a second-order surface, where curl in direction $i = \{x, y\}$ is defined by Eq. 8:

$$K_i = -\frac{\partial w^2}{\partial i^2} \tag{8}$$

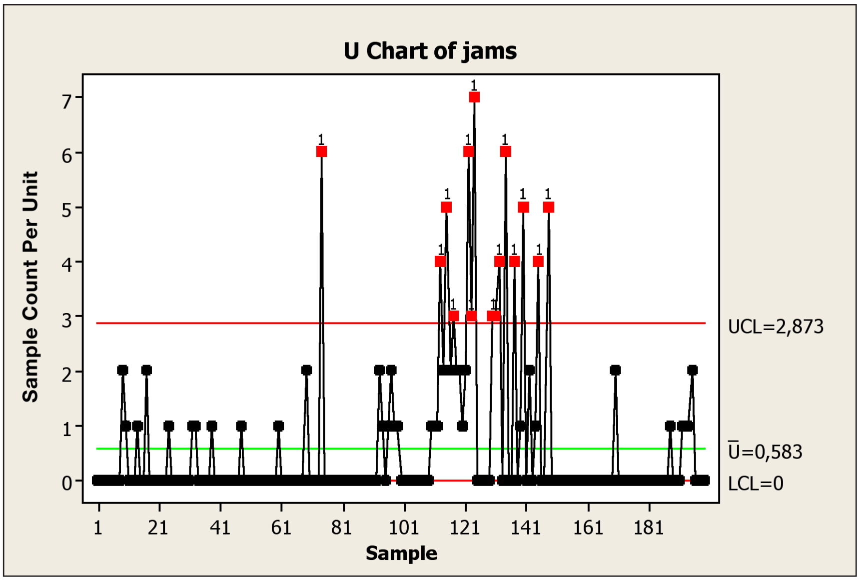
In Eq. 8, w is the distance from the flat reference surface. In other words, for a circle centered at the origin, $K_i = -\partial w^2/\partial i^2\big|_{i=0} = 1/R$, meaning that the two definitions match locally, in the neighbourhood of the origin (*i* = *O*) or for small displacements.

Our proposed measurement protocol is both simple and practical and therefore well suited for routine mill applications. It can also generate, if needed, all the information provided by alternative, more complex methods that either require samples with special shapes, expensive equipment, or use only one paper sample. By assessing it in the context of conventional procedures already implemented in the paper industry, our method contributes to the enrichment of process/quality databases by providing information about diagonal deformation modes in copy tests. This opens new analytical perspectives for relating quality problems, such as jams during printing tests, with more fundamental paper features.

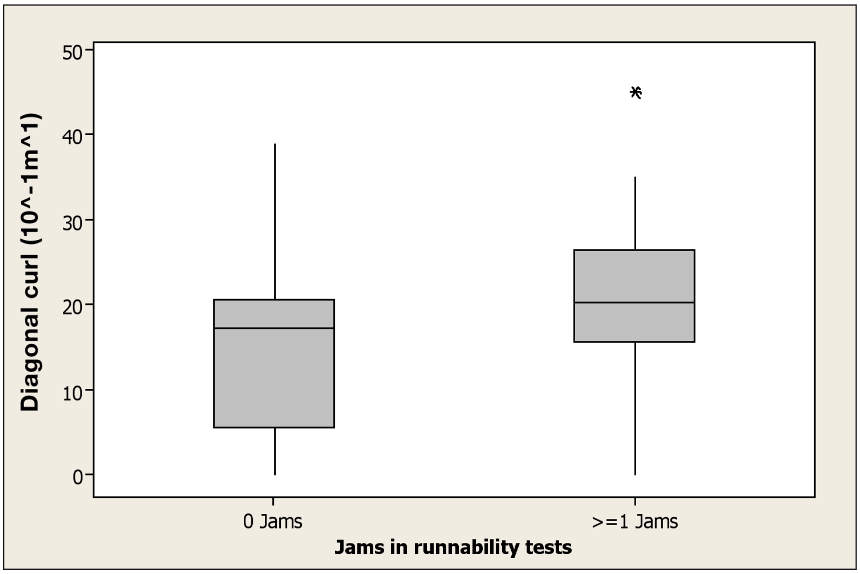
INDUSTRIAL IMPLEMENTATION

To illustrate the added value of having at our disposal data collected from such an additional quantitative measurement technique implemented routinely, we use an example of a possible data analysis task, based upon available historical data collected from a paper plant where our proposed curl measurement methodology has been implemented. **Figure 6** contains statistical process control charts [23] for monitoring the variability of diagonal curl measurements for a particular printing test. These charts show that with some localized exceptions, the quality characteristics are under a state of statistical control (i.e., without abnormal sources of variation) for both the mean and dispersion. With further analysis of what happens to other important quality variables when problems are detected in the curl tests, it is possible to determine that there is also a significant occurrence of paper jams (**Fig. 7**) in the runnability test. Therefore, it can be inferred that the curl values obtained with our procedure are good predictors of the quality of paper regarding its runnability performance.

We analyzed the diagonal curl values obtained when no paper jams were recorded and compared them with those



7. Control chart for attributes (U-chart) regarding the statistical monitoring of the number of paper jams registered during each test run.



8. Box plots of diagonal curl measurements, when no jams were detected and when some jams did occur.

where some paper jam occurred (**Fig. 8**). We obtained a significant difference in the mean values (p-value of 0.001, with 95% confidence interval for the difference in means [-8.53, -2.27]), indicating that such diagonal curl testing, based on the proposed methodology, is significantly correlated with the occurrence of paper jams. Because our study was based on observational data (as are most of the studies involving the exploitation of information contained in industrial databases), causality generally cannot be strongly attributed on the basis of the correlations detected, no matter how significant they are. However, for this particular case there is a clear cause-effect rational for the correlation, namely that abnormal paper deformation patterns naturally lead to paper jams. That sheds some light on what may be causing such significant correlation and should be investigated more fully.

In summary, the availability of quantitative diagonal curl measurements allows for the monitoring of an important paper quality feature and brings additional informative content to product/process quality databases. Such information is not conveyed by other existent variables, although that may be of high value in the analysis of paper quality problems. In fact, there is a lack of measurement approaches in routine printing tests that are sensitive to misalignments in fibre preferential orientation. Diagonal curl measurements, being quite often a result of such a misalignment between fibre orientations across paper thickness, have the capability of signalling abnormal situations that manifest in the final use of paper.

CONCLUSIONS

We discussed the main issues regarding paper curl and, in particular, the appearance of deformation modes not aligned with the paper's symmetry axis, i.e., diagonal curl. Our new methodology, which overcomes some limitations of other currently available methods, has the following key features:

1. It uses the same samples as for evaluating MD and CD curl, and therefore is easily integrated with current routine curl tests;
2. It uses samples with standard commercial paper dimensions (A4), thus avoiding time- consuming intermediate stages for sample cutting to the required size;
3. It uses samples consisting of 10–15 sheets of paper that are vertically suspended, as opposed to other methods that are based on a single sheet; and
4. It adopts the same magnitude scale as the well known ISO 14968 standard ("Paper and board—Cut-size office paper—Measurement of curl in a pack of sheets"), thus facilitating the interpretation of results and implementation by operators.

The proposed measurement methodology brings new elements and information to support paper data analysis, enriching process/quality databases with additional potential knowledge. We illustrated its utility with an example in which diagonal curl measurements, for a particular copy test, correlated well with the occurrence of jams in paper runnability tests. **TJ**

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INSIGHTS FROM THE AUTHORS

We have addressed diagonal paper curl from both the theoretical (modelling and simulation) and conceptual (knowledge organization, development of a conceptual cause-effect model) point of view, as well as from the experimental and industrial perspectives. The main motivation for our work is the inherent complexity of the phenomenon, as it depends on a large variety of factors that interact in nontrivial ways, and has high economic importance for paper producers.

Our main challenge was the development of a simple, accurate, and robust protocol that paper producers could use in practice. We studied the current state-of-the-art methods in the field, diagnosed their limitations, and proposed creative solutions to circumvent them. We selected, optimized, and validated the final procedure in a real-world environment.

This research underlines the importance of involving the operational managers and personnel from the early stages of problem definition, to set the project on track for future use in industrial practice. With the proposed methodology, mills will have available a simple and effective way to quantify paper diagonal curl that is easily integrated with the implementation of other measurement standards already in use and does not require new equipment or complex samples processing.

In future work, we will develop a similar methodology for paperboard.

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