



Enhancing Bagasse-Based Packaging Board Performance through Integrated Fiber and Wet-End Control: An AI-Driven Approach



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Abstract: *The pulp and paper industry is increasingly adopting renewable bioresources such as sugarcane bagasse, wheat straw and other agricultural residues to meet sustainability mandates, reduce reliance on wood pulp, and leverage locally available raw materials. While bagasse and wheat straw offer environmental and economic benefits, its shorter fibers, higher fines content, and sensitivity to refining and wet-end conditions introduce variability that can compromise board quality such as ply bond strength.*

Real-time fiber optimization and water quality intelligence now enable proactive monitoring, predictive decision-making and process stabilization. This paper explores how fiber morphology analyzer combined with predictive process optimization can improve board properties by optimizing fiber fines, fibrillation, and retention while maintaining stable wet-end conditions. Integrated control of fiber and water systems enhances ply bond consistency, supports higher bagasse, wheat straw utilization, and reduces energy-intensive over-refining.

The study demonstrates that data-driven fiber and water management improves sustainability and mechanical performance, delivering consistent, high-quality bagasse-based packaging boards. As renewable fiber adoption increases, such integrated approaches provide a scalable pathway for environmentally responsible, high-performance packaging solutions.

Keywords: *Bagasse, Fiber Morphology, Wet-end, Artificial Intelligence*

Introduction

The pulp and paper industry is undergoing a structural transition driven by sustainability targets, raw material diversification, and increasing performance expectations for packaging boards. Rising pressure to reduce dependence on wood-based fibers, coupled with regional availability of agricultural residues, has accelerated the adoption of renewable bioresources in board production. Among these, sugarcane bagasse has emerged as a strategically important raw material due to its wide availability in agro-industrial regions, lower carbon footprint, and alignment with circular economy objectives. [1]

While bagasse and other renewable fibers offer clear environmental advantages, they also introduce significantly higher variability into the papermaking system. Compared to conventional wood fibers, bagasse fibers are shorter, thinner-walled, and contain a higher proportion of non-fibrous components, resulting in inherently higher and more variable fines content. [1,2] This variability is further amplified during stock preparation, where bagasse exhibits a high sensitivity to refining. Small changes in refining intensity can lead to disproportionate increases in fines generation, fiber cutting, and external fibrillation, creating a narrow operational window between optimal fiber development and excessive fiber damage.

In modern packaging board machines operating at high speeds and tight quality tolerances, such variability has a magnified impact on process stability and product performance. Fines content plays a dual role in bagasse-based systems: while an adequate level of fines supports fiber bonding and internal strength development, uncontrolled or unstable fines levels adversely affect drainage, retention, bulk, and formation. [3] In board structures, uneven fines distribution across plies further influences inter-layer adhesion and Z-direction strength, increasing the risk of quality inconsistency and delamination.

These fiber-related challenges are closely coupled with process water chemistry. Elevated and fluctuating fines loads increase the concentration of dissolved and colloidal substances in the white water system, destabilizing wet-end chemistry and reducing retention efficiency. Variations in white water stability can interfere with fiber-fiber bonding, alter chemical performance, and amplify the effects of raw material and refining variability. In bagasse-based furnishes, where extractives and non-cellulosic components are more prevalent, these interactions become even more complex and dynamic.

Traditional quality control approaches, largely based on periodic laboratory testing and operator-driven adjustments, provide delayed and fragmented insights into these rapidly changing fiber–water interactions. As a result, mills often rely on conservative compensatory strategies such as over-refining or excessive chemical dosing to maintain board strength and runnability. While these actions may temporarily stabilize quality, they increase energy consumption, chemical usage, and long-term process variability, undermining both sustainability and operational efficiency.

Solution

To address this challenge, a data-driven fibre–water optimization framework was implemented, treating fiber development and process water chemistry as interdependent system variables rather than isolated control points. The objective of this framework was to stabilize bonding-active fines and fibrillated fibers, particularly in the middle ply of board while maintaining wet-end conditions that support their effective retention and distribution. The proposed framework was validated through a 90-day study conducted on a packaging board machine producing duplex board grade with a significant proportion of sugarcane bagasse. The machine operated at speeds of 500 m/min with a production capacity of approximately 300 - 450 TPD. The extended study duration was selected to capture normal operational variability, including fluctuations in bagasse lot quality, refining intensity and wet-end stability rather than short, steady-state conditions.

The primary performance objective during the study was not only to achieve target strength levels, but to reduce variability in ply bond strength, a critical quality parameter sensitive to fines availability, fibrillation and retention at the ply interfaces. Continuous data streams collected during the 90 days formed the basis for correlating fiber development, water system behavior, and final board performance.

Haber Approach:

Fibre Quality Control as a System Variable

Within the framework, fiber development was controlled based on continuous visibility into parameters directly linked to bonding performance, including fines content, degree of fibrillation, fiber length distribution, and fiber conformability indicators such as curl. Rather than targeting fixed refining energy or freeness values, control actions focused on maintaining stable and sufficient levels of bonding-active material, recognizing that bagasse already provides a fines-rich furnish when properly preserved.

This was enabled by Haber’s in-house, AI-driven Fiber Morphology Analyzer, which delivers continuous, actionable visibility into fiber development by automatically measuring fines content, fiber length and length distribution, fibrillation intensity, and shape/conformability indicators such as curl (and related morphology cues that correlate strongly with bonding potential). Designed for day-to-day mill use, the fiber morphology analyzer pairs robust hardware with intelligent analytics to produce consistent results across grades with minimal on-site upkeep, reducing manual lab dependence, shortening feedback loops for operators, and keeping total cost of ownership low. Positioned strategically upstream of the mixing chest, the fiber analyzer captured detailed data on the pulp slurry and other process conditions immediately prior to sheet formation. The measurements included key fiber morphology parameters such as fiber length, coarseness, fines content, and fiber flexibility, all of which play a critical role in influencing ply bond strength and the uniformity of the final paper.

The fines to fibrillation ratio play a critical role in determining the ply bond strength and overall stiffness of the board. Fines, being the smallest fiber fragments, help fill voids at the ply interfaces, increasing the contact area between layers, while fibrillated fibers provide mechanical interlocking (Fig. 1) that strengthens the bonds across plies. [4–6] Maintaining a balanced fines-to-fibrillation ratio ensures stronger and more uniform ply bonds, minimizing weak spots and reducing variability in board performance. This balance ultimately enhances the board’s stiffness, enabling it to better resist delamination, bending, and mechanical stress, and is therefore key to achieving high-performance, durable boards with consistent quality.

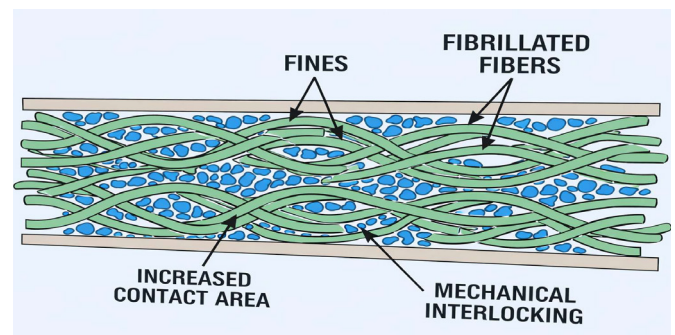


Fig 1: Microstructural view of fines-assisted fiber interlocking

Stabilizing Wet-End Conditions for Effective Bonding

Fiber development alone is insufficient to ensure consistent strength if wet-end conditions fluctuate. Variations in white water consistency, pH, conductivity, and dissolved and colloidal substances directly affect fines retention, floc stability, and inter-fiber bonding efficiency. In bagasse-based systems, these effects are amplified due to the higher fines load and greater sensitivity to chemical imbalance.

To maintain this stability, Haber deployed its AI-driven TSS (Total Suspended Solids) sensor to provide continuous visibility into white-water and approach-flow consistency, capturing fast shifts in suspended solids that typically precede fines carryover, retention swings, and wet-end instability. The sensor converts high-frequency measurement into actionable signals, helping operators and control logic detect disturbances early (e.g., dilution upsets, poor retention chemistry response, deposit release events etc.) and correct them before they impact sheet structure. In effect, it acts as an early-warning layer that keeps the wet end “in control,” so fiber and fines behavior remains predictable across changing operating conditions.

Continuous monitoring of wet-end water behavior enabled early detection of disturbances that could have lead to fines losses or uneven distribution across plies. By stabilizing water chemistry and system cleanliness, the framework ensured that bonding-active fines generated through controlled refining were effectively retained and uniformly distributed at the ply interfaces.

Program Design

This program is designed to enable automated monitoring and control of critical process parameters using Haber’s proprietary platform as the central control and visualization platform. A key focus of the program is the controlled blending of fines and fibrillated fibers to achieve the required furnish and product performance targets. In addition to fiber blending, the program optimizes retention and drainage to ensure effective capture of fines and fibrillated fibers during sheet formation. Key water properties, including pH and conductivity, are continuously monitored and controlled to maintain stable wet-end conditions and consistent product performance.

This real-time data related to fines content, fibrillated fiber proportion, flow rates, and consistency is extracted from field instruments, sensors, and control systems and integrated through structured data pipelines. This extracted data is validated and analyzed to determine the optimal blending ratio based on predefined requirements such as strength, drainage, formation, and retention performance.

Haber applies defined control logic to continuously adjust the blending of fines and fibrillated fibers, ensuring the ratio remains within the specified target range. Based on live process feedback, the system either recommends corrective actions or automatically executes control adjustments to maintain consistent blending and process stability.

Data Extraction

Data collection is a crucial aspect of the AI-based optimization framework in the papermaking process. Over a six-month period, data was gathered for 100+ process parameters using a combination of real-time sensors placed

at critical sections in the production line and the in-house AI-enabled fiber analyzer set up before the headbox.

To improve retention and drainage performance, real-time water chemistry data from Haber's eLIXA platform was integrated with fiber and machine parameters. Critical variables such as pH, conductivity, and ionic balance were continuously monitored, as they directly affect fines capture, fiber charge interactions, and the efficiency of retention and drainage aids especially in bagasse-based furnishes with high fines content. Incorporating these chemistry parameters allowed the model to account for wet-end variability, enabling optimized retention efficiency, improved drainage behavior, and more stable sheet formation.

Data Cleaning

Once the data was collected, a thorough cleaning process was performed to ensure accuracy and reliability. Inconsistencies and errors were identified and removed, including duplicate entries, missing values, and sensor measurement errors. Outliers that could skew model predictions were carefully evaluated and eliminated where necessary.

Multivariate Analysis and Model Building

With the cleaned data in place, a comprehensive multivariate analysis was conducted to identify the key variables influencing paper strength. The analysis began with 100+ variables covering all aspects of the papermaking process, from fiber morphology and water chemistry to machine settings. The goal was to identify the critical factors that had the most significant impact on strength properties, particularly ply bond strength, which are key performance indicators for packaging manufacturers. Through multivariate analysis, the list of variables was narrowed down to the top 12 -18 variables that showed the highest correlation with the target strength properties.

Given the production of multiple paper grades with varying specifications, the data was divided into grade groups based on similarities in properties and production conditions. Grades with similar basis weights, fiber compositions, and machine operating windows were grouped together. Some grades have limited runtime, making it challenging to collect sufficient data for standalone models. By grouping these grades, models could be developed using shared

data, enabling reliable predictions and process optimization even for less frequently produced grades. In total, four grade groups were created from eighteen different grades. This grouping ensured that the models were sufficiently generalized to capture common trends while remaining specific enough to maintain prediction accuracy.

Feature engineering was performed to transform raw data into meaningful features suitable for model development. For example, fiber fibrillation index and fines content were combined into composite features representing overall fiber bonding potential in the middle layer. Collinearity among variables was identified and addressed to prevent redundant information from influencing the model. Highly correlated parameters, such as fiber coarseness and fines content, were carefully evaluated to retain only the most relevant contributors.

The dataset was then split into training and testing subsets to ensure robust model development and reliable validation of prediction accuracy and performance.

The objective of the model was to predict strength properties, particularly ply bond strength, based on furnish composition, blending ratios, water chemistry conditions, and other critical process variables. Using historical data, the model predicted expected ply bond strength for a given operating condition and recommended the optimal furnish composition and process settings to achieve the target strength. When integrated into Haber's proprietary software Mt Fuji, the model enabled real-time control of key parameters, including fiber mix and wet-end chemistry, helping achieve the target ply bond strength consistently while minimizing variability across grades.

Results

The strength of the solution lies in the integration of fiber development and water system intelligence. By correlating real-time fiber indicators with wet-end stability metrics, the framework enabled proactive adjustment of fibre blending ratio and wet-end parameters. This system-level optimization replaced reactive corrective actions with predictive control of the underlying mechanisms governing sheet structure and strength development.

The changes in fiber and water parameters, as summarized in the tables 1 and 2, demonstrate measurable improvements.

Table 1: Change in fiber parameters

Parameter	Before Optimization	After Optimization
Fibrillation index	0.42 ± 0.07	0.45 ± 0.02
Average fiber length (mm)	0.85 ± 0.12	0.84 ± 0.05
Curl index	0.12 ± 0.03	0.11 ± 0.01

Table 2: Change in water parameters

Parameter	Before Optimization	After Optimization
White water consistency (%)	0.025	0.02
pH	6 - 7	6.5 -7
Conductivity (µS/Cm)	1540 - 1950	1650 - 1800

These upstream improvements translated into tangible enhancements in board performance, as captured in the metrics table 3.

Table 3: Tangible enhancement in board performance

Metric	Before Optimization	After Optimization
Ply bond in Z-direction strength (J/m ²)	170 - 190	180-190
Strength variability (J/m ²)	±8-10	±2-3
Refining energy (kW/MT)	460 - 470	440 - 450
First pass retention (%)	76	81

Key observations:

- Ply bond strength variability was reduced by ~72%, decreasing from ± 9 J/m² before optimization to ± 2.5 J/m² after optimization
- Stable achievement of the target ~ 180 J/m² ply bond strength (Fig. 2)
- 15% reduction in over-refining, leading to lower specific energy consumption

Ply bond strength was measured using the Z-direction tensile method in accordance with TAPPI Standard T 220 [7], and drainage and refining performance were evaluated with reference to Canadian Standard Freeness methods (TAPPI T 236) [8].

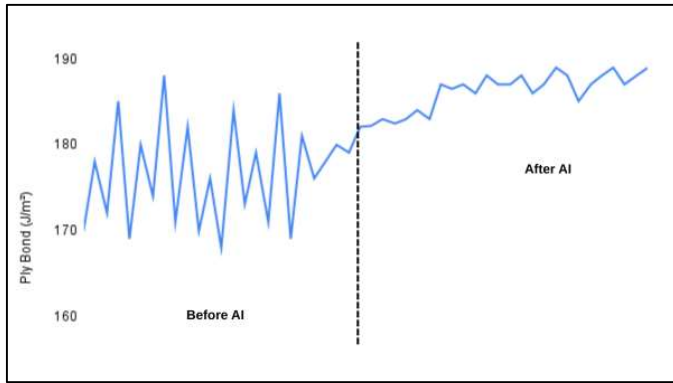


Figure 2: Ply bond strength before and after AI

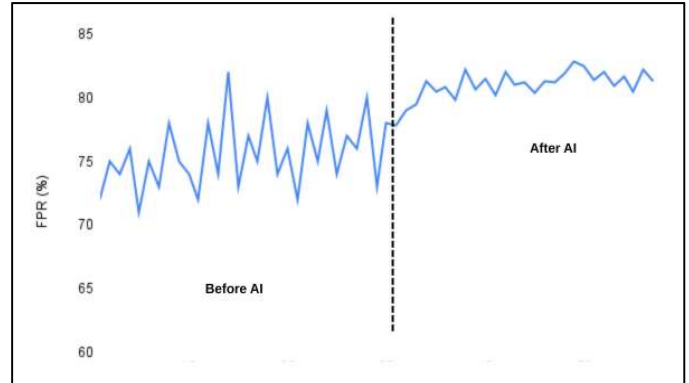


Figure 3: FPR % before and after AI

Variability on the first pass retention also decreased to a great extent (Fig. 3).

These results demonstrate that the integrated management of fiber morphology and wet-end conditions effectively enhances sheet strength, uniformity, and process efficiency, establishing a direct link between parameter optimization and improved performance in bagasse-based packaging boards.

Conclusion

The transition toward renewable bioresources in the pulp and paper industry requires advanced process intelligence to manage variability without compromising performance. This study demonstrates that the integration of fiber morphology analysis and continuous water quality intelligence provides a robust framework for system-level optimization in packaging board production. By shifting from reactive adjustments to data-driven control, mills can improve quality stability, reduce energy usage, and increase the effective utilization of renewable raw materials such as bagasse [1,9].

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