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AI-Driven Intelligent Process Optimization and Operator Assistance for Smart Paper Manufacturing

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Abstract: *Paper mills are progressively integrating advanced technologies to improve process stability, product quality, and operational efficiency. Yet, many mills continue to grapple with persistent challenges such as process variability, intermittent product losses, and the retirement of experienced operators along with the erosion of process knowledge. This paper introduces an AI-driven platform designed for intelligent process optimization and operator assistance in paper manufacturing applications. The platform combines real-time process monitoring, advanced analytics, remote expert support, and Advanced Process Control (APC) applications to support continuous process improvement. The integrated system includes tools for control loop analysis, alarm management, sheet break analysis, grade change optimization, and online process monitoring. An Artificial Intelligence (AI)-based Operator Assistant integrated with Distributed Control Systems (DCS), Quality Control Systems (QCS), alarm systems, operating manuals, and historical process data provides real-time troubleshooting and operational guidance. A pilot case study conducted on a high-speed paper machine demonstrated an 80% reduction in paper rejects, a 63% reduction in sheet breaks, and significant improvements in quality stability and grade change performance. Thus, an integrated approach can improve operational stability, reduce production losses, and support data-driven paper manufacturing operations.*

Keywords: *Intelligent Process Optimization, Artificial Intelligence in Paper Manufacturing, Paper Machine Process Optimization, Real-Time Process Analytics, Smart Manufacturing.*

1. Introduction

The pulp and paper industry is rapidly advancing toward smart manufacturing through digital technologies, AI, APC, and real-time analytics. Paper mills are already gathering and storing vast operational data from DCS, QCS, drives, lab & alarms data in historians. Yet, basic technical issues such as poorly tuned process loops, signal loss and equipment failures are often overlooked, generating significant product variability in Machine Direction Long-Term Variation (MDL), Machine Direction Short-Term Variation (MDS) & Cross Direction (CD) resulting product rejects and production losses.

Among all process areas, wet-end mixing stability remains one of the largest contributors affecting the paper machine performance, influencing process variability, product quality, retention efficiency, machine stability, and operational profitability. The hidden contributor to these variations is:

Mixing dynamics: Fiber and water mixing as indicated by consistency is critical to paper machine performance, strongly influencing basis weight and moisture. Broke and water are recycled to stock preparation for cleaning and fiber recovery, with some diverted to wastewater. These interconnected flows mean an upset in one area can trigger secondary upsets elsewhere, sometimes reinforcing into sustained oscillations.

Furnish mixing and fiber interaction: Furnish is a complex blend of virgin fibers, secondary fibers, broke, and recovered fiber from the Save-all. Each stream varies in composition, treatment, and additives, with properties that constantly change, leading to process upsets. A significant portion does not form paper on the first pass, requiring broke and white-water recycling, which adds variability.

Thin and thick stock mixing: At the Hydro Mix, thick stock from the machine chest combines with silo white water. The cleaner pump draws large volumes of white water, diluting thick stock to thin stock (<1% consistency). Consistency swings here directly impact MD basis weight stability.

Chemical mixing and retention dynamics: Effective chemical performance depends on proper balance of addition points, hydrodynamic shear, and wet-end properties. Misalignment causes poor flocculation, uneven sheet formation, and excessive chemical waste.

Process knowledge gap and decision support: Operators frequently lack information or analytical tools to transform large volumes of data into actionable insights. Compounding this is a growing knowledge gap driven by workforce changes, retirement of experienced operators, and increasing process complexity.

Traditional DCS and QCS systems alone are often insufficient to identify these complex interactions in real time, creating the need for intelligent monitoring, contextual analytics, and AI-assisted operational support.

This paper introduces an integrated AI-based platform for intelligent process optimization and operator support in paper manufacturing. By combining process analytics, machine learning, and conversational AI, the platform enables advanced monitoring, optimization, and decision-making. Its objective is to improve process stability, reduce variability, minimize losses, enhance quality, and provide continuous operational support through remote expert services and AI-driven analysis tools.

2. Literature Review

Modern pulp and paper manufacturing processes generate large amounts of operational data through DCS, QCS, drives systems, and field instrumentation. However, many mills still face challenges in converting this process data into actionable operational knowledge for improving machine performance, process stability, and product quality [1].

Traditionally, process troubleshooting and optimization activities in paper mills have relied heavily on operator experience, manual observation, and offline analysis methods. Although these approaches provide practical operational understanding, they are often insufficient for handling complex and highly dynamic process interactions occurring in modern high-speed paper machines [2]. In many cases, operators are required to analyse hundreds of process variables simultaneously during process disturbances, making real-time decision making difficult and highly dependent on individual expertise.

The complexity of paper manufacturing processes is further increased by strong interactions between process variables such as stock flow, refining energy, retention chemistry, moisture profile, steam and condensate systems, machine draws, vacuum systems, and environmental conditions. Variations in raw material properties, fibre quality, furnish composition, and operating conditions also contribute significantly to process instability and quality deviations [3].

In recent years, Industry 4.0 technologies such as AI, Machine Learning (ML), Industrial Internet of Things (IIoT), and APC have gained significant attention in process industries for improving operational efficiency and predictive decision making [4]. AI and ML techniques have shown strong potential in predictive maintenance, anomaly detection, process optimization, and quality prediction applications across several industrial sectors.

Several machine learning techniques such as neural networks, random forest algorithms, support vector machines, and deep learning models are increasingly being used to identify hidden patterns and correlations within large process datasets [5]. These technologies enable early identification of abnormal operating conditions and help operators take preventive actions before process disturbances lead to production losses.

Within the pulp and paper industry, AI-based applications are being explored for sheet break prediction, control loop monitoring, grade change optimization, quality forecasting, and energy management [6]. Real-time process analytics platforms can continuously monitor process behaviour, detect abnormal conditions, and generate operational recommendations based on historical and live process data.

At the same time, APC technologies have demonstrated measurable improvements in process stability, product quality, chemical consumption, and energy efficiency. APC applications such as retention control, freeness optimization, blending ratio control, and recovery process optimization help reduce process variability and minimize operator dependency [7].

Despite these advancements, many paper mills still face challenges related to fragmented data systems, limited use of AI tools in daily operations, and loss of process knowledge due to workforce changes and retirement of experienced personnel. Existing systems are often isolated and focused only on individual applications without providing integrated operational intelligence across the mill.

Therefore, there is an increasing need for intelligent digital platforms that combine process analytics, AI-based monitoring, APC technologies, remote expert support, and operator assistance into a unified solution for smarter paper manufacturing operations.

3. Architecture / Platform Overview

An integrated platform was developed to meet the operational needs of reduced quality variations and optimized production in paper mills. An overview of the architecture of this platform is given in Figure 1. The AI tool consists of modules designed to support continuous monitoring, diagnostics, optimization, and operational decision-making in paper mill processes. It integrates process data from DCS, QCS, drives systems, historians, laboratory systems, and field instrumentation to provide real-time operational visibility and performance analysis across the paper machine and supporting process areas.

The platform includes quality report analysis tools for identifying quality variations, process deviations, and long-term performance trends. Control loop performance analysis modules continuously monitor regulatory control loops to detect oscillations, poor controller tuning, valve stiction, actuator problems, and instrumentation-related issues that can negatively affect machine stability and product quality. Online loop tuning and process identification tools support controller optimization and improve dynamic process response.

In addition, the platform includes intelligent alarm analysis functions for identifying nuisance alarms, alarm flooding conditions, and abnormal operating situations to improve operator response and plant safety. Sheet break analysis tools provide detailed event diagnostics and root cause analysis to help reduce production losses and improve machine runnability. Grade change analysis modules evaluate transition performance, identify process bottlenecks, and reduce off-spec production during product changes.

The system also provides online mass, water, and energy balance monitoring for identify process inefficiencies, reduce utility consumption, and improve overall resource utilization. Together, these analytical and optimization tools help mills identify hidden process problems, improve operational visibility, reduce process variability, and support continuous process improvement initiatives.

The unique strength of the platform lies in its integration of process analytics, AI-based diagnostics, APC, and remote expert support within a unified digital environment.

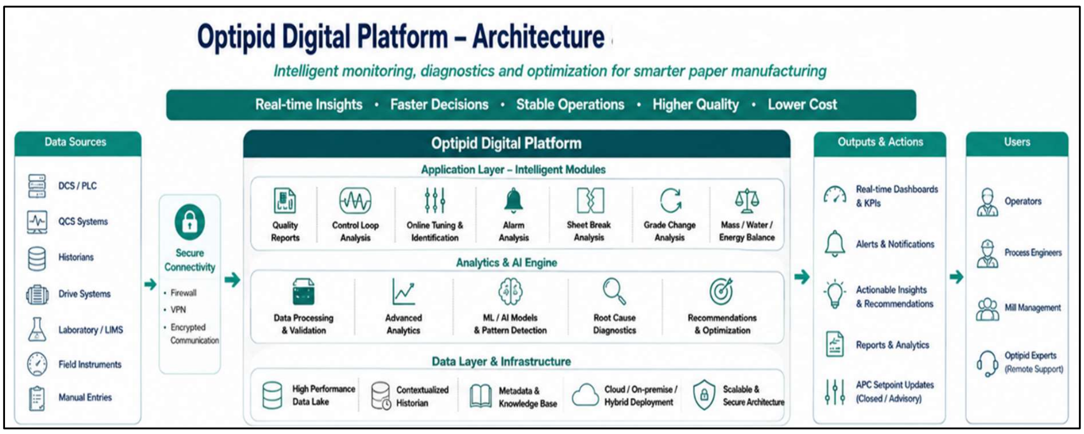

Figure 1: Architecture of Optipid digital platform

The platform combines data collection, analytics, diagnostics, APC monitoring, and operator support into a centralized digital intelligence environment.

4. Features

Quality report analysis

Sheet quality variations are typically represented as two-dimensional profiles across the MD and CD. The quality report analysis module focuses on detailed evaluation of MDL with Root Cause Analysis (RCA) module, MDS, and CD (with Profile Capability Module) variability to identify instability, recurring quality deviations, and abnormal operating behaviour affecting product performance as shown in Figure 2.

Figure 2: Quality analysis and root cause

The system further applies advanced statistical techniques such as Power Spectrum Analysis (PSA) and Principal Component Analysis (PCA) to detect hidden patterns, cyclic disturbances, and dominant sources of variability within the process data. These analytical methods help identify potential root causes related to mechanical issues, control loop interactions, process disturbances, or operational changes contributing to sheet quality variation.

Process health analysis

The process analysis module as shown in Figure 3, monitors regulatory control loops to detect oscillations, poor tuning, valve stiction, actuator problems, and instrumentation issues. The analysis helps improve loop performance, process stability, and overall machine controllability through continuous diagnostics and optimization recommendations. Also, automatic tuning tool calculates the right tuning numbers.

Figure 3: Process health check

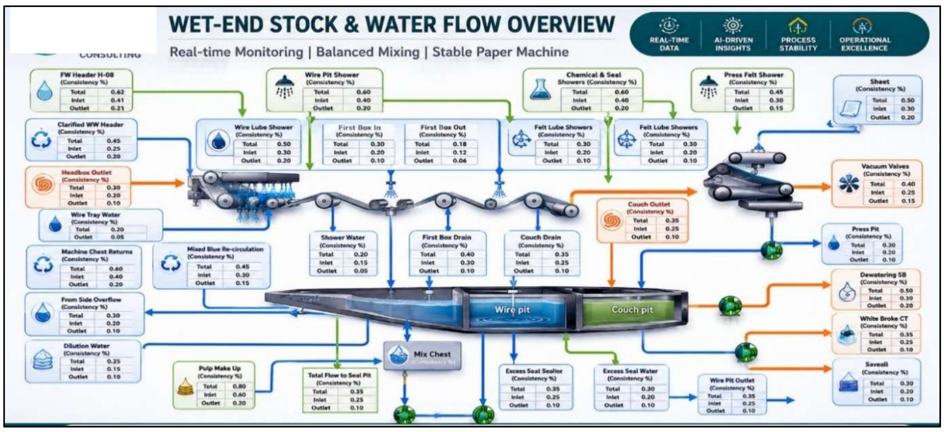

Figure 4: Mass and water balance check

Mass-water-energy balance analysis

The Mass-water-energy balance Analysis module as shown in Figure 4, provides online monitoring of process flows, water usage, steam consumption, and energy distribution across the mill. The system helps identify process inefficiencies, abnormal losses, and optimization opportunities for improving resource utilization and reducing operating costs.

Root cause analysis

Problems with MD and CD variation are big reasons for unstable paper quality, sheet breaks, rejects, and production losses.

- MD variation usually comes from things like changes in stock consistency, unstable flow control, mixing issues at the wet end, steam fluctuations, or poorly tuned control loops.
- CD variation often happens because of head-box flow imbalance, dilution control problems, uneven fiber spread, or mechanical alignment issues.

MD root cause analysis: MD variations indicate time-dependent process disturbances such as stock flow instability, consistency fluctuation, machine speed variation, steam/condensate imbalance, or control loop tuning issues affecting sheet uniformity along the machine direction.

CD root cause analysis: CD variations indicate cross-machine profile non-uniformity caused by slice lip deformation, actuator tuning mismatch, thermal/moisture imbalance, head-box flow distribution issues, or localized equipment disturbances across the paper width.

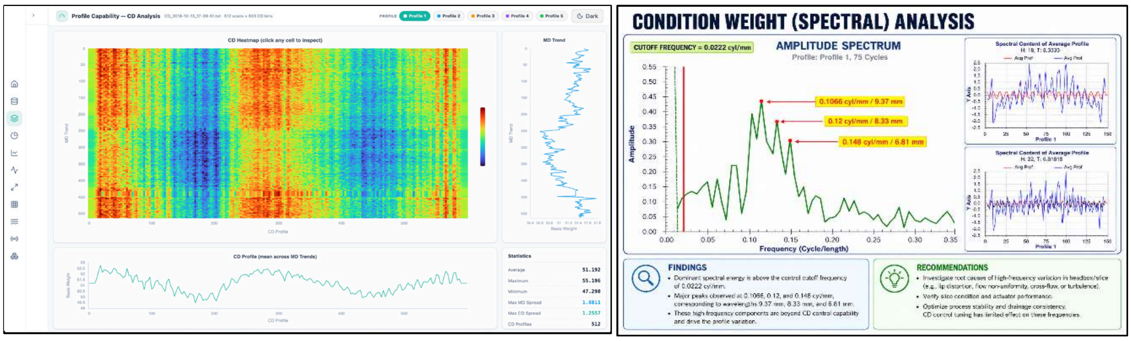

Figure 5: Root cause analysis

Traditional DCS and QCS systems often struggle to catch the complex links between process, control, and mechanical factors in real time. The new AI-based platform constantly reviews process data, quality trends, alarms, and process behaviour as shown in Figure 5. By doing this, it can uncover hidden root causes behind Machine MD and CD variation. The result is better process stability, less variability, and stronger overall paper machine performance.

Grade change analysis

The Grade Change Analysis module as shown in Figure 6, monitors grade transition sequences and evaluates process stabilization performance during product changes. The system helps to identify potential problems related to level-1 & level-2 and reduce transition time, minimize off-spec production, and improve machine efficiency through optimized grade change strategies.

The grade change analysis tool evaluates process response, transition stability, settling time, overshoot, and production loss during recipe or basis weight changes to identify operational inefficiencies and control performance gaps. The intelligent recommendation engine provides optimized tuning parameters, ramp strategies, operator guidance, and disturbance mitigation actions to minimize grade change time, reduce off-spec production, and improve machine stability.

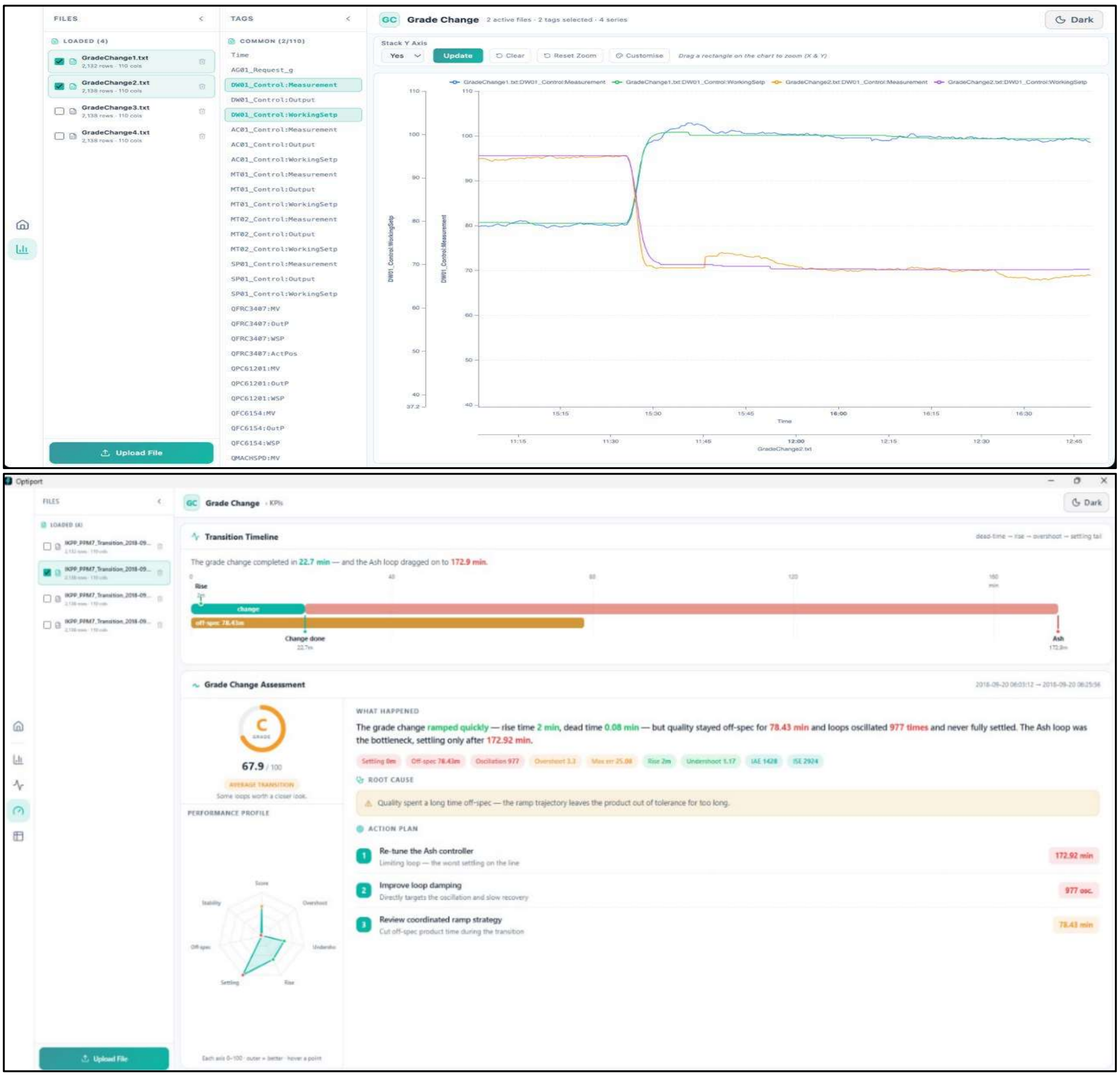

Figure 6: Grade change analysis

Sheet break analysis

The Sheet Break Analysis module as shown in Figure 7, monitors abnormality in the paper machine and performs advanced AI-driven analysis of sheet break events using process trends, machine conditions, control performance, and historical operating data. The system applies golden batch comparison, 2-sigma deviation monitoring, drift detection, pattern recognition, good-vs.-bad run classification (RF – Random Forest Algorithm) and z-score analysis to identify abnormal operating behaviour leading to sheet breaks.

The tool enables early detection of process instability, recurring disturbance patterns, and hidden operational deviations across stock preparation, wet end, press, dryer, and reel sections. The analysis helps reduce unplanned downtime, minimize production losses, improve machine runnability, and support intelligent operator decision-making for stable and optimized paper machine operation.

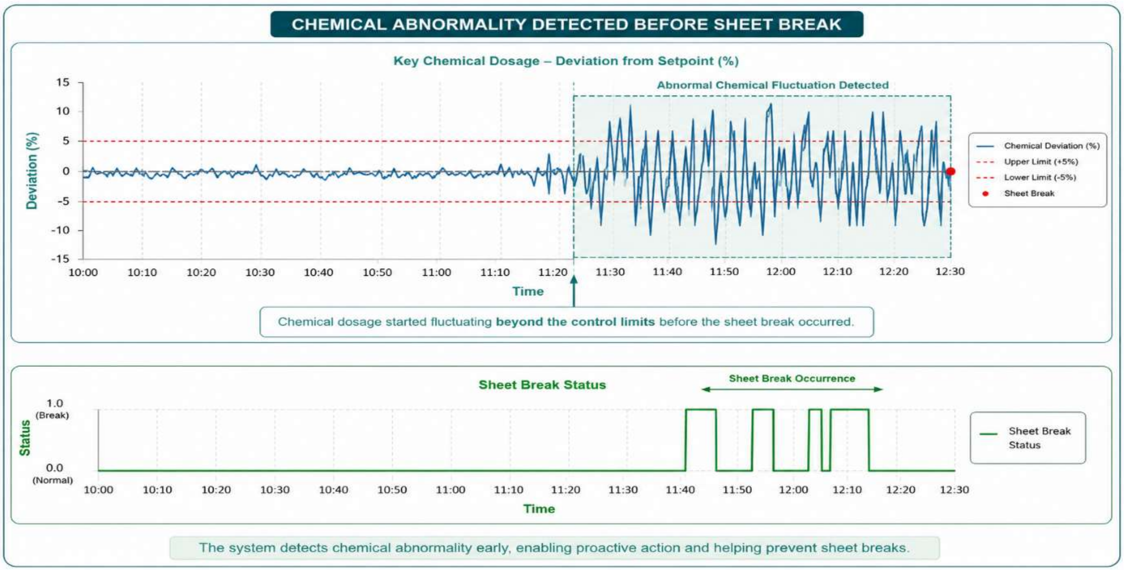

Figure 7: Sheet Break analysis

AI operator assistant

A major innovation of the platform is the AI Operator Assistant. This is an industrial AI chatbot designed specifically for pulp and paper applications. The assistant can interact with operators and engineers using natural language and provide immediate operational guidance. The AI assistant is integrated with

- DCS systems
- QCS systems
- Drives systems
- Alarm databases
- Operating manuals
- P&ID documents
- Historical process data

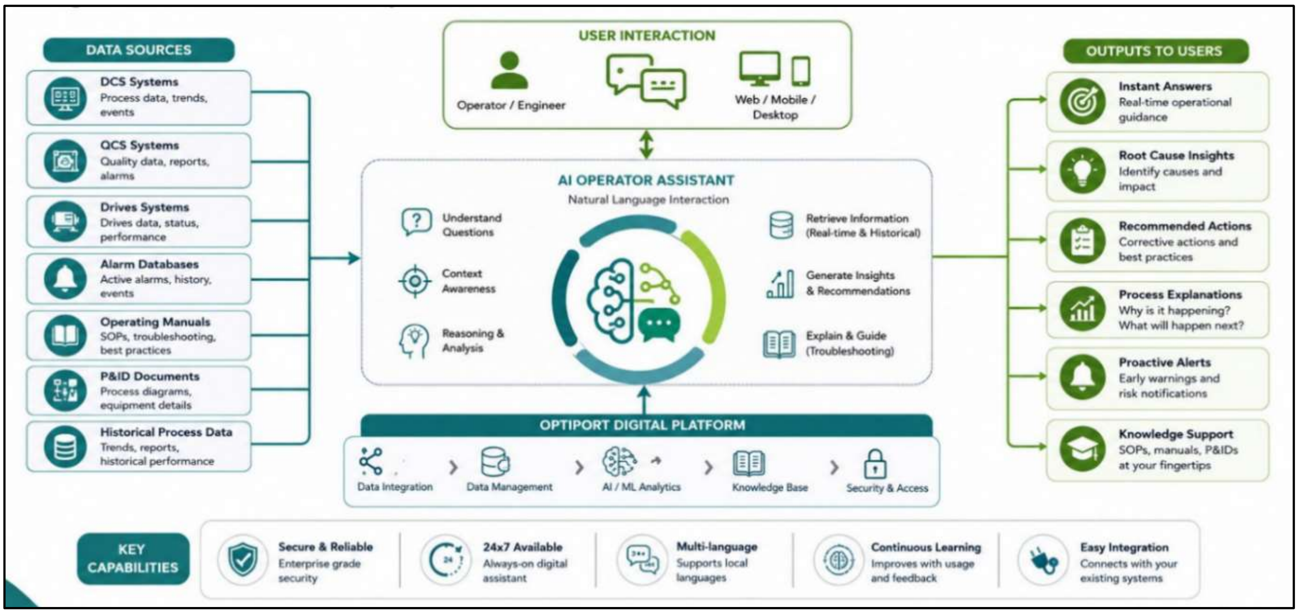

Figure 8: AI operator assistant – work flow

Using this information, the assistant can support troubleshooting, explain process conditions, recommend corrective actions, and answer operational questions in real time (Figure 9). This helps reduce dependency on individual expert knowledge and improves knowledge sharing across the organization.

For example, operators can ask questions such as ‘Prior to first start-up of Centricleaner what are all the points to be checked?’ or ‘Why did basis weight control become unstable?

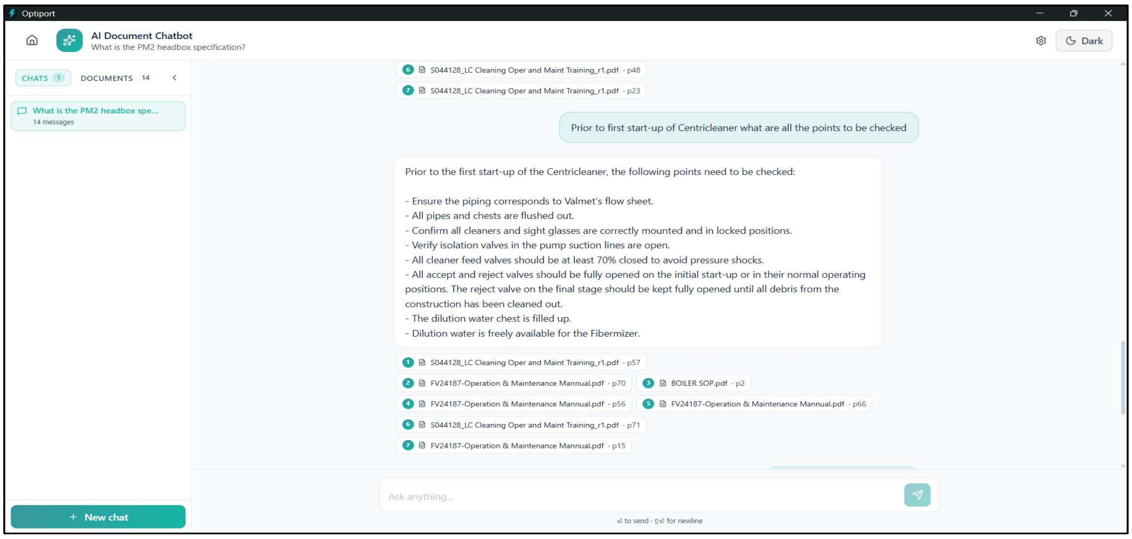

Figure 9: AI operator assistant – work flow (Centricleaner)

5. Case Study: AI-Driven Optimization of a Fine Paper Machine

A pilot implementation of the intelligent optimization platform was carried out in a high-speed paper machine producing packaging grades in South Africa. The objective was to evaluate the effectiveness of AI-assisted process monitoring, control loop optimization, and operator support functions under actual operating conditions.

5.1 Machine and Process Overview

The study was performed on a paper machine equipped with a DCS, QCS, and extensive process instrumentation. The machine experienced significant challenges as shown below. A total of 228 control loops associated with stock preparation, wet-end mixing, basis weight control, moisture control, steam and condensate systems, vacuum systems, and chemical dosing were monitored and optimized using the proposed platform.

5.2 Operational Challenges

Prior to implementation, the paper machine experienced the following operational challenges,

- Paper rejects exceeding 500 tons per month.
- High MD basis weight and moisture variability.
- Frequent sheet breaks and long recovery periods following process disturbances.
- Slow quality stabilization during grade changes, resulting in excessive off-grade production.
- Poor wet-end stability and inconsistent quality control system response.
- High operator workload and dependence on manual interventions.

5.3 Results

Following implementation, significant improvements were achieved across multiple performance indicators, as summarized in Table 1.

Table 1: Result Table

KPI	Before	After	Improvement
Paper Rejects	~500 tons/month	<100 tons/month	80% reduction
Sheet break duration	Baseline	Reduced by 63%	63% reduction
MD basis weight variation	Baseline	Reduced by 46%	46% reduction
MD moisture variation	Baseline	Reduced by 39%	39% reduction
Grade change recovery time	~30–40 min	12–18 min	>50% reduction

The results demonstrate that the integrated application of AI-based diagnostics, advanced process analytics, and control loop optimization can substantially improve machine stability, product quality consistency, and operational efficiency.

Wet-end variability was identified as the primary contributor to process instability and quality deviations. Targeted optimization of wet-end controls, together with enhanced QCS performance and grade change tuning, significantly improved process robustness and reduced production losses.

The machine also achieved improved quality stability with basis weight MD variation reduced by 46% and moisture variation reduced by 39%. Grade change recovery time was improved to approximately 12–18 minutes as shown in Figure 10.

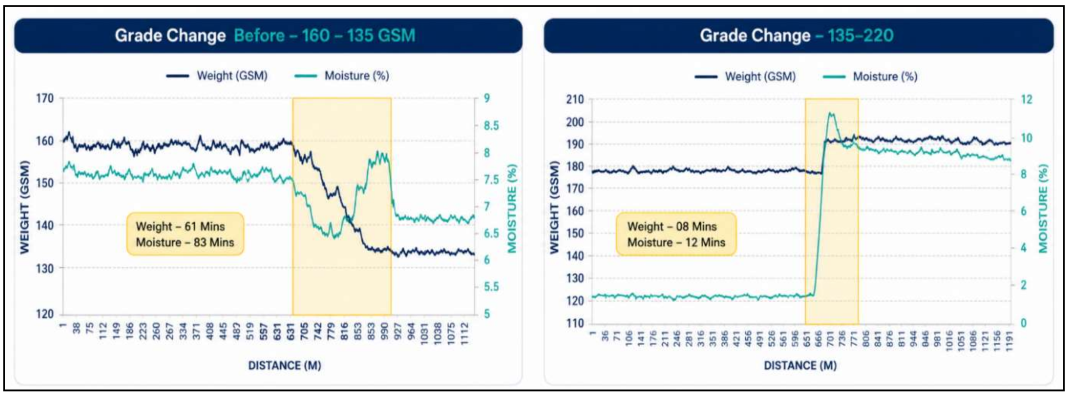

Figure 10: Grade change time reduction

Paper rejects were reduced from approximately 500 tons/month to below 100 tons/month as shown in Figure 11 while sheet breaks were reduced by approximately 63% as shown in Figure 12.

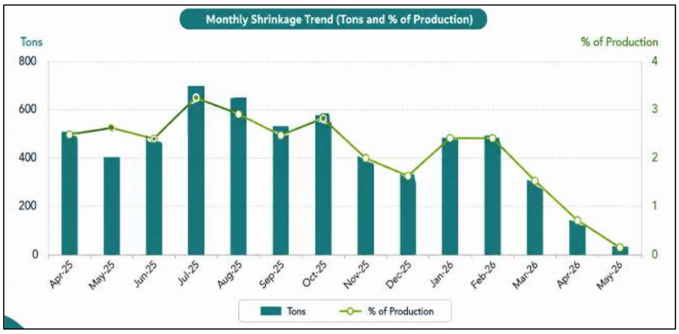

Figure 11: Reduction in monthly paper rejects

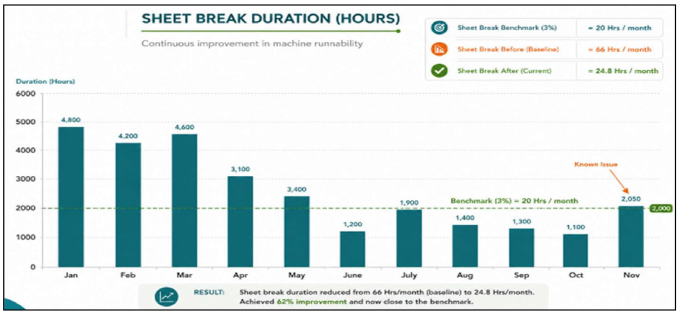

Figure 12: Reduction in monthly sheet break duration

The proposed solution helps mills achieve better process stability, improved operational efficiency, reduced variability, and stronger process knowledge management. This paper provides practical insights into the implementation of AI and paper machine optimization in paper manufacturing and highlights the future potential of intelligent operator assistance systems for smarter and more sustainable mill operations.

6. Conclusion

The proposed digital platform integrates AI, real-time analytics, and intelligent operator support to improve machine stability, reduce process variability, and minimize production losses in paper manufacturing.

Pilot implementation demonstrated significant reductions in paper rejects and sheet breaks, improved quality performance, and faster grade change recovery. The platform also supports knowledge continuity through real-time troubleshooting and data-driven decision support.

By reducing off-grade production, fiber losses, and resource consumption, the platform contributes to sustainability objectives related to circular economy initiatives, decarbonization, and energy efficiency. The convergence of AI, process expertise, and digital technologies offers a practical pathway toward more resilient, efficient, and sustainable paper manufacturing operations.

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