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Plant-Wide Optimization using Process Digital Twin for Pulp Mills

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Abstract: *The global pulp and paper industry is undergoing a fundamental transition from conventional process automation toward intelligent, model-based, and data-driven autonomous operations. This shift is driven by mounting pressure to improve sustainability, reduce energy and chemical consumption, enhance operational productivity, and consistently maintain product quality across increasingly complex and integrated mill environments. Meeting these demands requires a step change in how mills plan, monitor, and optimize their operations — moving beyond isolated process unit-level optimization toward holistic, plantwide optimization.*

Traditional mill operations relying on manual planning, spreadsheet scheduling, and post-event reviews; lack the real-time visibility and analytical capability to manage the tightly coupled interactions between pulping, washing, bleaching, chemical recovery, utilities, and paper machine operations. These limitations lead to hidden performance losses such as quality deviations, chemical overdosing, excess energy consumption, and unstable inventories.

This paper addresses these challenges by presenting a digital-twin based framework for plantwide optimization of pulp mills. The proposed approach integrates a physics-based process model with real-time DCS data, laboratory measurements, and production scheduling inputs to deliver dynamic, mill-wide setpoint recommendations. Key capabilities include economic optimization, production planning, systematic bottleneck identification, and enhanced operational resilience, allowing operators to respond proactively rather than reactively to process disturbances. A structured implementation roadmap covering process model deployment for Kraft pulping processes includes the process flowsheet integration across the full mill scope simulation and real-time optimization.

Keywords: *Digital twin, fundamentals-based modelling, process simulation, pulp and paper, mill-wide optimization.*

Introduction

The global pulp and paper industry operates under sustained pressure to produce more output from existing assets while keeping operating costs low. Energy costs account for 15–40% of total production cost in a typical Kraft mill, with steam generation, evaporation, and lime kiln reburning being the primary consumers [1]. Chemical costs such as active alkali for cooking, oxygen for delignification, and chlorine dioxide, peroxide, and caustic for bleaching, add a further 10–20% of operating expenditure [2]. Even modest reductions of 3–5% in energy or 4–8% in chemicals translate into several million dollars of annual savings at mill scale, making these two cost centers the primary targets for optimization. Alongside cost pressure, regulatory requirements are steadily raising the performance bar. European Best Available Techniques (BAT) reference documents set binding benchmarks for specific energy and chemical consumption that mills must meet as part of their operating permits [3]. Similar frameworks are being adopted across North America and Asia, making compliance with energy intensity targets a legal and commercial necessity rather than a voluntary commitment.

Meeting both goals simultaneously, more throughput and less energy and chemical usage per ton of pulp production, cannot be achieved by improving individual process units in isolation. It requires a system-level optimization approach that treats the entire mill as a single interconnected system. Plantwide optimization (PWO) addresses this by simultaneously optimizing all process sections from a single model-based optimizer with a multi-hour look-ahead horizon, translating production targets into coordinated throughput rates while accounting for current inventory levels, planned maintenance windows, and equipment constraints. Mercangoz and Doyle [4] demonstrated that a coordinated mill-level optimizer achieves significantly better economic performance than unit-level controllers operating independently, confirming that proactive, system-level coordination is the core principle underlying the optimizer developed and demonstrated in this paper [5].

Section 2 reviews the current state and limitations of traditional mill operations. Section 3 introduces the digital twin concept and its specific application to pulp mills. Section 4 describes the Kraft pulping process. Section 5 represents the implementation and results for a few use cases. Section 6 describes the ABB Ability™ Plant Optimizer features. Section 7 concludes with future directions.

Current State of Pulp Mill Operations and Key Challenges

Process Interactions and Cross-section Coupling

The integrated Kraft mill consists of two tightly coupled material circuits: the fiber line, which runs sequentially through cooking, washing, oxygen delignification, bleaching, and finally the paper machine, and the chemical recovery loop, which passes through evaporation, the recovery boiler, and causticizing before returning regenerated white liquor back to the cooking stage. Disturbances propagate readily across both circuits i.e., a digester kappa deviation alters bleaching chemical demand, while an evaporator fouling event lowers black liquor solids, reduces recovery boiler steam output, and ultimately constrains cooking steam availability. Castro and Doyle [6] formally demonstrated this cross-section coupling through a detailed plantwide model of the fiber line, showing that interactions between digesters, washers, bleach towers, and storage tanks create dynamics that cannot be managed effectively by unit-level controllers alone, consistently identifying the gap between local unit control and system-level coordination as the primary source of unrealized mill performance potential.

Operational Losses Under Manual Coordination

Despite this tight interdependence, most mills manage production through daily shift meetings, spreadsheet-based scheduling, and accumulated operator experience. Zakharov and Jämsä-Jounela [7] analyzed the behavior of economically significant variables in pulp mill operations and found that uncoordinated decision-making across sections systematically leaves recoverable economic efficiency on the table. This approach generates five recurring and quantifiable operational losses:

- Product quality variability [7][8]: Without upstream-to-downstream visibility, bleaching chemical charges cannot be adjusted in anticipation of incoming kappa number variations from the digester. The result is brightness deviation, off-specification production, and grade transition waste. Fairbank [8] reports that kappa variability at the digester outlet is the single largest driver of bleaching chemical overconsumption and off-spec pulp production in Kraft mills, with advanced process control delivering measurable reductions in both.
- Excess steam and energy consumption [1]: Evaporators and recovery boilers routinely operate at sub-optimal loads because production rates across sections are uncoordinated. Steam is vented or throttled rather than utilized productively, adding 3–7% to specific energy cost per ton of pulp. Laurijssen et al. [1] confirm through cross-mill benchmarking that the gap between best-practice and average specific energy consumption in Kraft mills is largely explained by poor coordination between the fiber line and recovery loop, a gap that coordinated optimization can close.
- Chemical overdosing [2][9]: Operators routinely apply a 5–10% safety margin on active alkali charges and bleaching chemical doses to compensate for planning uncertainty. Tran and Vakkilainen [9] document this systematic overdosing in the context of the Kraft chemical recovery process, noting that uncertainty in white liquor availability and incoming kappa number are the primary reasons operators maintain excessive chemical buffers, resulting in unnecessary cost and increased effluent load.
- Inventory instability and near-limit operation [10]: Intermediate storage tanks such as bleached pulp towers, black liquor tanks, and white liquor storage drift toward their high or low operating limits when adjacent section production rates are mismatched. Near-limit tank levels eliminate buffer capacity and increase the risk of forced production curtailments. Dahlquist [10] identifies unmanaged inventory dynamics as a key contributor to unplanned production stops in biomass and chemical process facilities, a finding directly applicable to integrated Kraft mill operations.
- Slow and reactive disturbance handling [11]: Operators respond to equipment faults and quality deviations after they occur, not before. The combination of long process dead times, large thermal inertia, and slow chemical dynamics means that recovery is slow and often triggers secondary oscillations. Funkquist [11] demonstrated that uncompensated dead times in the digester chip level control loop are a primary driver of production variability in continuous cooking systems, underscoring the need for predictive, forward-looking coordination rather than reactive correction.

Limitations of Unit-level Advanced Process Control

Unit-level model predictive control (MPC) has been widely adopted in the pulp and paper industry to reduce process variability at individual sections such as the digester, bleach plant, and evaporator [12]. While MPC delivers measurable within-section improvements, including tighter kappa number control, reduced chemical variance, and more stable throughput, it cannot account for the downstream consequences of its decisions because it has no visibility beyond its own boundary. This is not a deficiency of MPC itself but a structural limitation: optimizing each unit independently does not produce optimal performance at the mill level. Mercangoz and Doyle [4] illustrated this clearly through a plantwide optimization study of the pulp mill benchmark problem, demonstrating that a coordinated mill-level optimizer, accounting for all major process sections simultaneously, achieves significantly better economic performance than unit-level controllers operating independently. The performance gap is therefore a structural coordination problem, not a control tuning problem, and one that requires a dedicated optimization layer above the individual unit controllers to resolve.

The Digital Twin Paradigm For Pulp Mills

Definition and Conceptual Framework

A digital twin, in the context of industrial process systems, is a continuously updated computational representation of a physical plant that integrates physics-based process models with real-time operational data. Unlike static simulation models used for design, simulation and operator training purposes; a process digital twin is a living, dynamic entity that reflects the actual state of the plant at each point in time and can be used to simulate future process behavior under proposed operating conditions. The mathematical foundation rests on solving a system of differential-algebraic equations (DAEs) representing mass balances, energy balances, reaction kinetics, and phase equilibria across all process units.

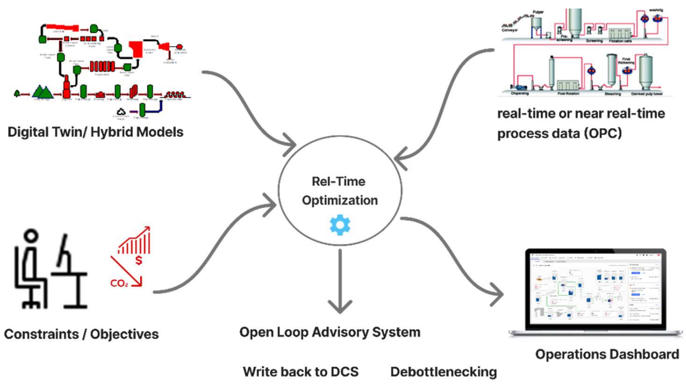

Figure 1: Schematic of the digital twin usage in real-time optimization

Three essential characteristics distinguish an effective process digital twin from a conventional simulation model as shown in Figure 1. They are (i) physics fidelity: the model must capture the fundamental mass, energy, and reaction kinetics governing each process, (ii) data integration: the model must be reconciled against real-time DCS data, and (iii) decision connectivity: the model's outputs must be actionable, driving setpoint recommendations that are communicated to operators or directly to the APC/DCS layer.

Levels of Model Fidelity in Pulp Mill Digital Twins

Not all process models in a mill digital twin need to operate at the same level of rigor. A pragmatic, fit-for-purpose modelling architecture applies three levels of model fidelity based on the criticality and dynamics of each process area:

- First-principles mechanistic models for the core reaction and separation processes such as digester H-factor kinetics, oxygen delignification Kappa reduction, and ClO2 consumption in ECF bleaching, where accuracy directly determines the quality of setpoint recommendations.
- Steady-state mass and energy balance models for high-inventory, slower-dynamics areas such as the recovery cycle, chemical preparation, and evaporation plant.
- Data-driven empirical models and soft sensors, validated against laboratory measurements, for properties that are difficult to model mechanistically which include paper strength development in the refiner and wet-end chemistry effects in the paper machine.

This hybrid modelling strategy, combining physics-based and data-driven elements, ensures both the interpretability and accuracy required for operational decision support in a production environment.

Real-Time Data Integration Architecture

The effectiveness of a mill digital twin is directly proportional to the quality and breadth of its data integration layer. A complete data integration architecture for a pulp mill digital twin includes five data streams:

- Process historian data providing real-time DCS tag values at high frequency (1–60 second resolution) for flows, levels, temperatures, pressures, and motor loads.
- Laboratory Information Management System (LIMS) data providing periodic measurements of pulp quality parameters such as kappa number, viscosity, brightness, shive content, ISO tear/tensile strength with latencies of 1–4 hours depending on sample frequency.
- On-line quality sensor data from installed instrumentation such as near-infrared (NIR) sensors for chip moisture and wood density, in-line kappa analyzers, automated brightness meters, refractometers for black liquor dry solids, where available, providing near-real-time quality feedback.
- Production and grade schedule data from the Manufacturing Execution System (MES), defining production targets, grade transitions, maintenance windows, and contractual constraints.
- Utility cost data such as steam pressure/tariff, power pricing, chemical prices which are enabling economic objective function formulation in the optimizer.

Data reconciliation and state estimation algorithms including Extended Kalman Filtering (EKF) and Moving Horizon Estimation (MHE), are applied to fuse multi-source data of varying quality and latency into a consistent, physically coherent representation of the mill state. This reconciled state becomes the initial condition for the optimizer's forward simulation.

Kraft Process Overview

The Kraft (sulfate) pulping process accounts for approximately 80% of global chemical pulp production and consists of two tightly integrated material circuits: a fiber line and a chemical recovery loop [13]. Typical integrated Kraft pulp mill flowsheet is given in Figure 2. Wood chips are cooked with an alkaline white liquor solution (sodium hydroxide and sodium sulfide) at 160–170°C to selectively dissolve lignin while preserving cellulose fibers. Following cooking, the fiber line proceeds through washing (which recovers dissolved organics as weak black liquor), oxygen delignification (reducing kappa by 40–50%), and multi-stage ECF bleaching (raising brightness to 88–92% ISO) before delivery to the paper machine. The distinguishing feature of the Kraft process is its closed chemical recovery loop: spent cooking liquor (black liquor) is concentrated in multi-effect evaporators to 65–75% dry solids, combusted in the recovery boiler at temperatures above 1000°C to generate high-pressure steam for mill energy, and chemically regenerated through causticizing and lime kiln operations back into fresh white liquor for cooking. This integration makes the mill largely self-sufficient in cooking chemicals and a net energy exporter but creates tight cross-sectional coupling: disturbances in any one section (e.g., kappa number deviation, evaporator fouling) immediately propagate through both circuits and constrain downstream sections.

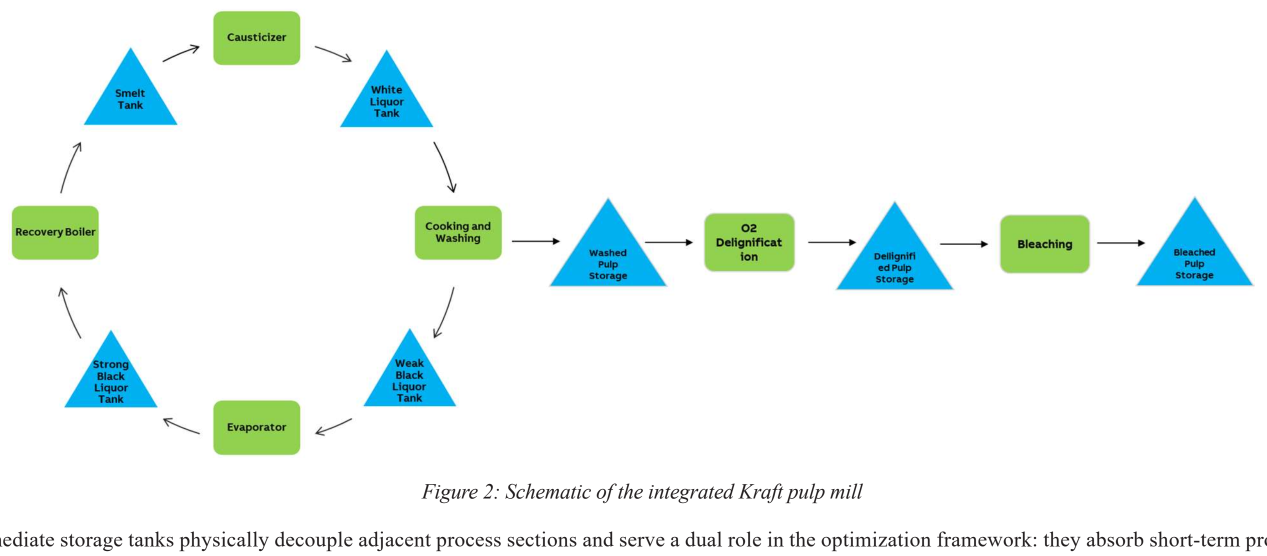

Figure 2: Schematic of the integrated Kraft pulp mill

Intermediate storage tanks physically decouple adjacent process sections and serve a dual role in the optimization framework: they absorb short-term production rate mismatches without forcing immediate process stoppage, and they provide the optimizer with inventory degrees of freedom i.e., the ability to pre-build or pre-deplete buffers in anticipation of known disturbances such as maintenance outages [13]. The tightly coupled nature of this system, combined with significant energy and chemical costs distributed across both circuits, creates both the necessity and the opportunity for systematic plantwide optimization that coordinates production rates across all seven sections simultaneously while managing these inventory buffers proactively.

Implmentation And Results

Process Modeling

The study utilizes a typical integrated Kraft pulp mill configuration as illustrated in Figure 2, encompassing both the fiber line and the chemical recovery loop. First-principles models were developed for each of the major process sections: cooking and washing, oxygen delignification, bleaching, evaporation, recovery boiler, and causticizing. Each sectional model is based on fundamental material and component balances that capture the essential process dynamics. The models were then integrated into a unified flowsheet representation that reflects the interconnected nature of the mill's operations, allowing for the propagation of state variables and constraints across all sections simultaneously.

To maintain computational tractability within the real-time optimization framework, the first-principles models were intentionally developed as low-fidelity representations rather than high-detailed mechanistic or data-driven alternatives. This design choice balances accuracy against the computational burden imposed by the nonlinear optimization solver. The low-fidelity approach ensures that the digital twin can simulate reasonable planning horizon with acceptable precision while remaining responsive to real-time decision-making requirements. Each model captures the key mass balance relationships, chemical conversions, and inventory dynamics required for the optimizer to predict feasible operating trajectories, without including secondary phenomena or micro-scale details that would add computational overhead without material benefit to the optimization decisions.

The validated digital twin model serves as the forward-simulation engine for all downstream optimization and decision-support functions. By representing the mill's integrated structure and the material flows between sections, the model enables the optimizer to anticipate the consequences of production rate changes across the entire system before they are executed in the physical plant. This capability is essential for the proactive strategies demonstrated in the use cases such as pre-buildup of inventory ahead of known disturbances which would not be possible with reactive, spreadsheet-based planning approaches.

Optimization

The integrated process model is embedded within a real-time optimizer formulated as a constrained quadratic program (QP) that executes on a rolling 48-hour prediction horizon with 4-hour decision intervals. The primary objective of the optimizer is to minimize production rate changes across all six controlled sections (cooking, oxygen delignification, bleaching, evaporation, recovery boiler, and causticizing) at each decision step. This minimum-change objective directly promotes smooth, stable mill operation and is operationally meaningful: excessive rate changes introduce quality disturbances (particularly in the digester and bleaching stages due to their long residence times), upset the mill's steam balance, destabilize combustion in the recovery boiler, and require lengthy re-establishment periods for temperature-sensitive unit operations such as the lime kiln. By penalizing rate variability, the optimizer naturally minimizes off-specification production and grade transitions while simultaneously addressing the dynamic demand signal from the paper machine.

The optimizer respects two categories of constraints that define the feasible operating region. Process capacity constraints enforce upper and lower production rate limits on each section, reflecting equipment design and operational safety margins; during planned maintenance windows, the affected section rate is constrained to zero. Equally important are inventory constraints that maintain all intermediate storage tanks within their safe operating band (20–80% of working volume) at every time step. The 20% lower bound prevents pump cavitation, while the 80% upper bound provides headroom for upstream surge flows. The combination of capacity and inventory constraints creates a tightly coupled feasibility region: for example, if the weak black liquor tank approaches its 80% upper bound during an evaporator outage, the optimizer must automatically reduce the cooking rate to prevent overflow, demonstrating the system-level nature of the optimization problem.

The 48-hour prediction horizon was chosen as a compromise between two competing requirements: sufficient look-ahead time to enable proactive prepositioning of inventory buffers ahead of known disturbances (such as planned maintenance windows). At each 4-hour decision interval, the optimizer resolves the full QP problem using current plant state data (production rates, tank levels) and current constraints (maintenance schedules, paper machine demand, equipment status), enabling adaptive re-planning as real-time conditions evolve. This rolling-horizon structure allows the system to correct prediction errors or unexpected disturbances while maintaining a continuous forward-looking optimization strategy.

Results Discussion

Use Case 1: Variable Paper Machine Demand with Planned Maintenance

The first use case addresses a realistic operational scenario in which the paper machine undergoes a planned maintenance outage. The paper machine demand remains constant at 150 m³/h until t = 28 hours, drops to zero during the maintenance window from t = 28 to t = 44 hours (a 16-hour outage), and then returns to the nominal constant flow rate of 150 m³/h after the maintenance is completed.

This variable demand profile represents a significant perturbation to the integrated mill system: with no downstream demand, the entire fiber line must be coordinated to avoid inventory overflow in the bleached pulp tower and all upstream tanks, while simultaneously maintaining the chemical recovery loop in a stable state to enable rapid ramp-up upon restart. The optimizer's task is to compute a sequence of production rate adjustments across all sections such that (i) all tank inventories remain within the safe 20–80% band throughout the entire 48-hour horizon, (ii) production rate changes are minimized to avoid quality disturbances, and (iii) the system is positioned to resume full operation smoothly once the paper machine maintenance is complete.

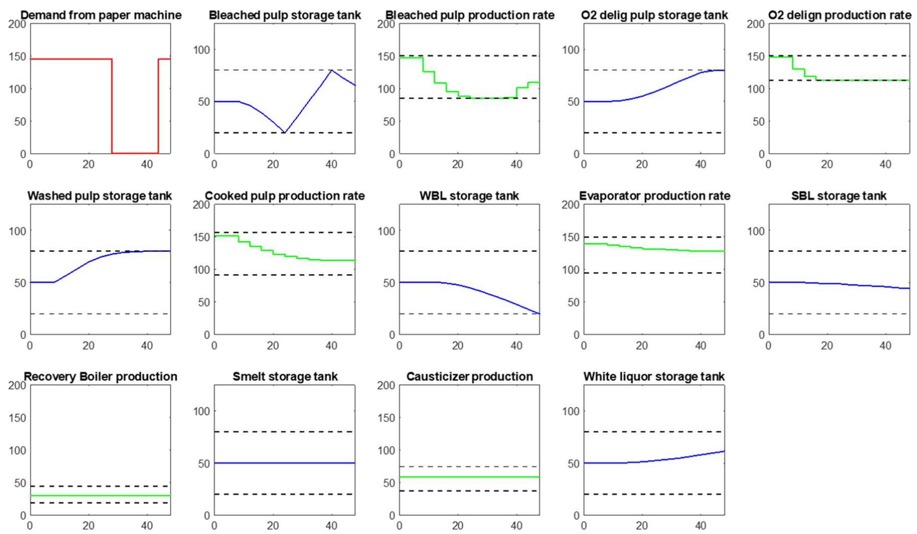

Figure 3: Optimal profiles and inventory levels calculated by the plantwide optimization solution – Use case 1

The optimizer executes a coordinated cascade of production rate reductions that propagates upstream from the paper machine through the fiber line and couples to the chemical recovery loop as shown in Figure 3 . As the paper machine demand approaches zero at 28 hours, the bleached pulp tower inventory begins to rise because pulp output to the paper machine exceeds the incoming flow from bleaching. The optimizer responds proactively i.e., several hours before the actual demand drops by reducing the bleaching production rate. This reduction in bleach plant output causes the oxygen delignification pulp storage tank to accumulate inventory, triggering a corresponding reduction in the oxygen delignification section production rate. As oxygen delignification throughput decreases, the washed pulp storage tank level rises, prompting the optimizer to reduce the cooking section production rate. Importantly, these reductions are not executed instantaneously at the moment of demand change; rather, they are initiated in advance of the demand transition to account for the substantial process residence times and material transport delays in each section. The digester, in particular, exhibits around 4 hour residence time, so a rate reduction at t = 25 hours takes effect (reaches the downstream bleaching section) only several hours later, precisely when the demand drop begins to manifest.

The reduction in cooking rate automatically decreases the weak black liquor production from the washing section, causing the weak black liquor tank inventory to decrease and the evaporator production rate to reduce proportionally. The proactive nature of optimization, i.e., initiating upstream rate reductions several hours before the constraint violation would occur, is the critical distinguishing feature from reactive manual shift planning. As Figure 3 illustrates, all tank inventories remain well within the safe limits despite the severe demand perturbation; the bleached pulp tower reaches approximately the high inventory limit but does not violate it. Once the paper machine maintenance is complete at t = 44 hours and demand returns to 150 m³/h, the optimizer immediately begins the coordinated ramp-up of all sections leveraging the buffer inventory that was pre-positioned during the maintenance window to ensure rapid restoration of full production without overshoot or constraint violations.

Use Case 2: Planned Digester Maintenance with Constant Paper Machine Demand

The second use case (Figure 4) considers a planned maintenance window on the cooking/digester section from t = 28 hours to t = 36 hours (an 8-hour outage), during which the digester production rate is reduced from its nominal 151 m³/h to zero and then ramped back to normal operation. The paper machine demand remains constant at 150 m³/h throughout the entire 48-hour horizon i.e., full production supply continuity must be guaranteed even while the primary fiber line bottleneck is completely offline.

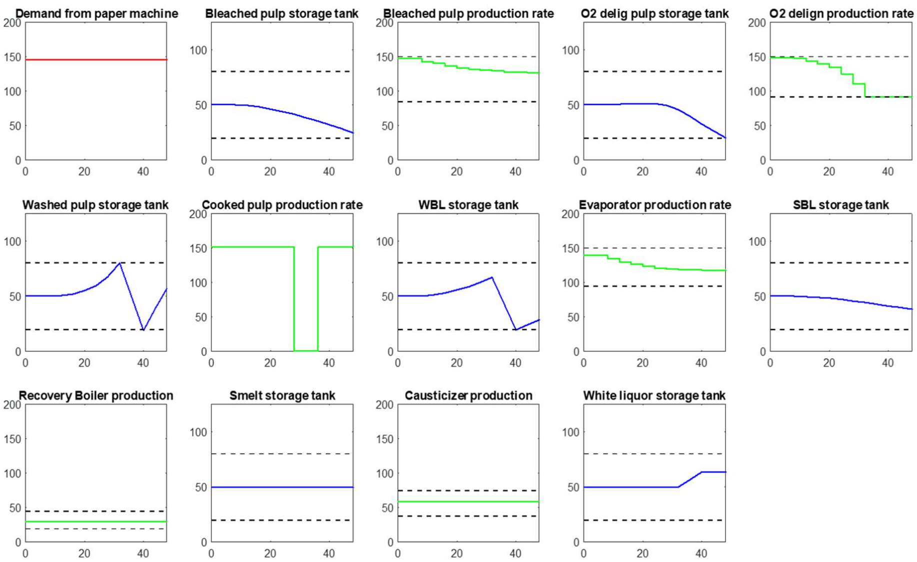

Figure 4: Optimal profiles and inventory levels calculated by the plantwide optimization solution – Use case 2

Recognizing the planned outage in advance, the optimizer proactively increases the washed pulp storage tank inventory toward its upper safe limit of 80% before t= 28 hours. This pre-positioning strategy is the critical enabling action: the accumulated washed pulp inventory acts as the primary buffer that sustains the upstream fiber line i.e., oxygen delignification, bleaching, and ultimately the paper machine throughout the 8-hour digester outage without interruption. Simultaneously, the optimizer reduces oxygen delignification and bleaching production rates in a coordinated and gradual manner during the outage period to control the rate of drawdown from the washed pulp tank, ensuring that its level does not fall below the 20% lower limit before the digester restarts at t = 36 hours.

On the chemical recovery side, the optimizer responds differently, reflecting the distinct dynamics of each recovery section. With the digester offline, no new weak black liquor is generated from the washing section, causing the weak black liquor tank level to gradually deplete as the evaporator continues to process its contents. The optimizer reduces the evaporator production rate proportionally to keep the weak black liquor tank level within its safe operating band and prevent pump cavitation at the lower limit. In contrast, the recovery boiler and causticizer production rates are held largely unchanged throughout the outage, as the strong black liquor tank and smelt dissolving tank inventories are not significantly affected by the short 8-hour digester downtime as their larger buffer capacities and slower dynamics provide natural insulation from this disturbance. An additional consequence of the digester being offline is that white liquor is not consumed for cooking during the outage window, causing the white liquor storage tank level to rise moderately, though it remains comfortably within the 20–80% safe band. Upon digester restart at t = 36 hours, the optimizer initiates a smooth, ramp-constrained increase in cooking rate to restore nominal production. Throughout the entire scenario, the paper machine receives uninterrupted supply at 150 m³/h, validating the optimizer's ability to handle a hard single-section outage through proactive, system-level inventory coordination.

Use Case 3: Planned Evaporator Maintenance with Constant Paper Machine Demand

The third use case (Figure 5) examines a planned evaporator maintenance outage from t = 24 hours to t = 30 hours, during which the evaporator production rate drops from its nominal 139 m³/h to zero before returning to normal, while the paper machine demand is held constant at 145 m³/h throughout the entire 48-hour horizon.

With the evaporator offline, weak black liquor from the washing section can no longer be processed, causing the weak black liquor tank level to rise and risk overflowing its 80% upper limit. To counter this, the optimizer proactively reduces cooking, oxygen delignification, and bleaching production rates well in advance of the shutdown, accounting for process delays and residence times in each section, thereby controlling the rate of weak black liquor generation at

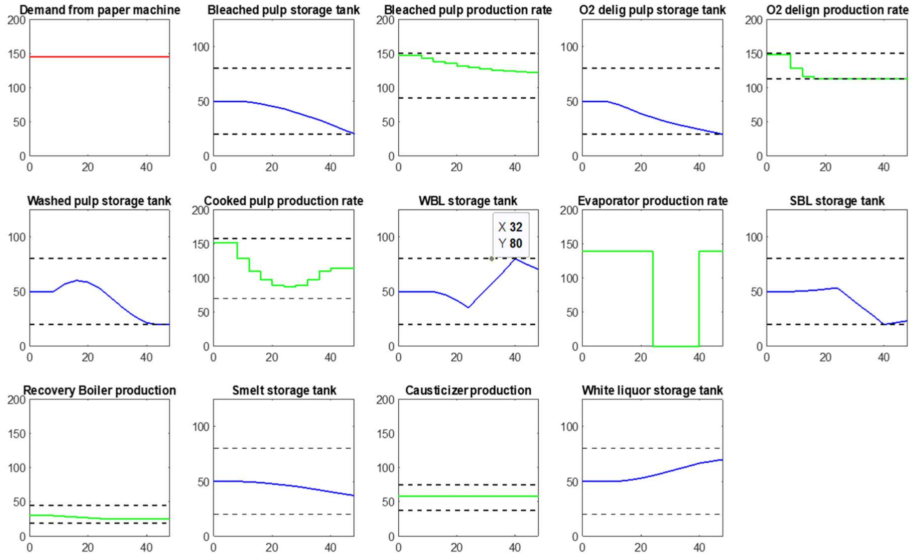

Figure 5: Optimal profiles and inventory levels calculated by the plantwide optimization solution – Use case 3

its source while the fiber line continues to meet the constant paper machine demand within all inventory bounds. Simultaneously on the recovery side, the interrupted supply of strong black liquor to the recovery boiler causes its storage tank inventory to deplete toward the 20% lower limit, and the optimizer responds by proportionally reducing the recovery boiler production rate ahead of the constraint violation, again driven by look-ahead rather than reactive correction. The smelt dissolving tank and white liquor storage levels show only marginal variation and remain safely within bounds throughout the outage, so the optimizer correctly maintains the causticizer production rate unchanged, avoiding unnecessary perturbations to the lime kiln and chemical regeneration cycle. Upon evaporator restart at t = 30 hours, all production rates are ramped back to nominal in a coordinated upstream-to-downstream sequence, and the paper machine receives uninterrupted supply at 145 m³/h throughout. It confirms that a recovery loop outage can be fully absorbed without any fiber line supply disruption when the optimizer acts with sufficient foresight across the entire integrated mill system.

Abb Ability™ Plant Optimizer

Solution Overview

The Plant Optimizer for Pulp Mills (Figure 6), a dynamic online optimization software solution that brings production planning and real-time mill operations into alignment. Its design philosophy is encapsulated in the tagline: "One mill. One strategy. One step closer to autonomy."

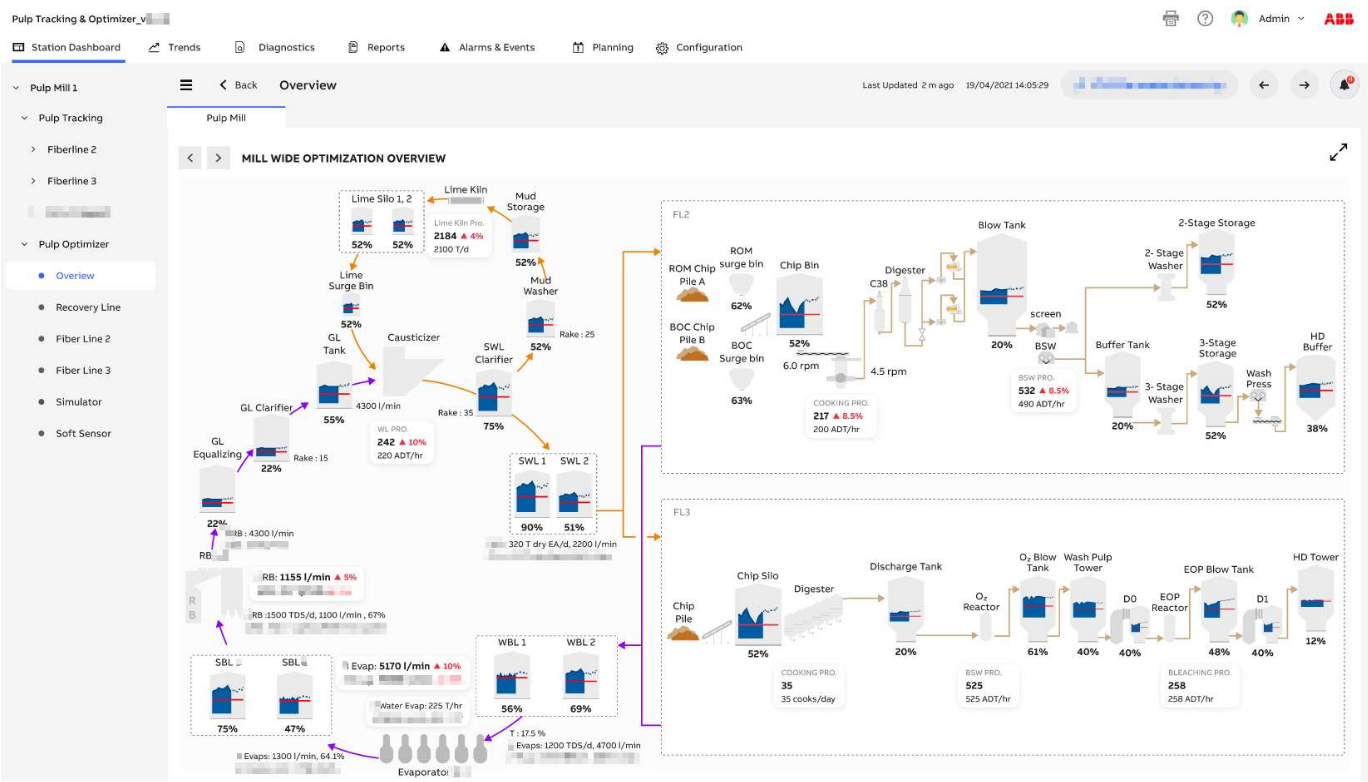

Figure 6: Schematic of the Plant Optimizer – Process Flow Sheet

The solution is structured around two primary modules: Pulp Tracker and Pulp Optimizer, that can be deployed independently or in combination depending on the mill's digital maturity and transformation roadmap.

Pulp Tracker: Mill-Wide Traceability Module

The Pulp Tracker module delivers end-to-end material and quality traceability across the full mill flowsheet. Its primary function is to provide operators and process engineers with real-time visibility of material movements and quality-critical properties at every stage of the production process, a capability that is fundamentally absent in mills relying on DCS-only monitoring.

Key functional capabilities of the Pulp Tracker module include:

- Real-time KPI dashboards: Tracks mill performance against production targets, quality specifications, and chemical consumption budgets.
- Quality deviation tracing: Automated root-cause linking of off-spec events at the paper machine or pulp bale to upstream process upsets, reducing investigation time from days to minutes.
- Grade change automation: Recipe-driven sequencing of setpoint transitions across the mill when changing between product grades, replacing manual, error-prone operator procedures.
- Alarm-based diagnostics with context-aware guidance: Presenting operators with pre-identified corrective action recommendations linked to the specific failure mode detected.

Pulp Optimizer: Economic Optimization Module

The Pulp Optimizer module is the real-time economic optimization engine of the Plant Optimizer platform. Its fundamental purpose is to continuously compute the operating setpoints and production rates across all process areas that maximize mill throughput and minimize production cost, subject to quality, safety, environmental, and equipment constraints, while respecting the higher-level production targets established by the MES planning layer.

Key functional capabilities of the Pulp Optimizer module include:

- Dynamic mass balance prediction: Real-time computation of expected flow rates, inventories, and quality trajectories across all process areas over the optimization horizon.
- Bottleneck identification: Continuous identification of the current throughput-limiting constraint across the mill, updated as operating conditions change.
- Scenario simulation: "What-if" analysis capability allows engineers to evaluate the mill-wide impact of proposed schedule changes, maintenance shutdowns, or grade transitions before committing to execution.
- Production Planning: Periodic (or continuous) calculation of recommended optimal production targets for multiple process units in fiber line and recovery line, which are communicated to the APC layer or presented to operators for implementation.

Integration Architecture with MES, APC, and DCS

The Plant Optimizer occupies the Real-Time Optimization (RTO) layer in the hierarchical automation pyramid, specifically positioned above the APC/MPC layer and below the MES production scheduling layer. This positioning is deliberate and architecturally significant: the optimizer translates long-term MES production targets into short-term optimal operating trajectories, which are then executed by the APC layer through regulatory setpoint control.

The integration architecture operates through three principal data interfaces: (i) a connection to the MES that receives weekly/daily production targets, grade specifications, maintenance schedules, and inventory constraints; (ii) a connection to the DCS historian and APC system through which the optimizer reads real-time process state and writes recommended setpoints; and (iii) a LIMS interface through which laboratory quality measurements are ingested for model reconciliation. This three-tier integration creates a coordinated, closed-loop control hierarchy where the MES defines what to produce, the Plant Optimizer determines how to produce it optimally, and the APC/DCS layer executes the operating strategy in real time, thereby achieving a structure that is architecturally consistent with the ISA-95 enterprise-control integration standard.

Conclusion

Plantwide optimization based on a validated digital twin is a practical approach to closing the performance gap between current manual mill coordination and theoretical mill potential in integrated Kraft pulp operations. The root cause of this gap is structural: the tight coupling between the fiber line and chemical recovery loop, combined with significant process delays, creates a coordination problem that cannot be solved by unit-level MPC controllers or reactive spreadsheet-based planning. The digital twin: a continuously updated physics-based representation integrating real-time DCS, laboratory, and production data enables proactive optimization by anticipating future inventory constraints and positioning buffers in advance rather than reacting after supply interruption. Across three industrial use cases, the optimizer maintained 100% paper machine supply continuity, satisfied all inventory constraints within safe 20–80% bands, and executed smooth production rate changes that minimize quality disturbances and energy variability.

The Plant Optimizer, comprising the Pulp Tracker (traceability) and Pulp Optimizer (economic optimization) modules, provides a complete, industrially validated platform for mill-wide optimization. As Kraft mills face intensifying demands for higher output and lower energy intensity from existing assets, the shift from reactive coordination to proactive, system-level digital optimization represents a fundamental change in how integrated pulp mill operations are managed and offers a clear path to competitive and regulatory advantage.

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