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Automation to Intelligence: Moving from control based towards data driven adaptive systems

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Abstract: *The ongoing digital transformation in the pulp and paper industry is driving the adoption of advanced process automation, data analytics, and simulation technologies to achieve smart manufacturing. This paper examines the evolution of control systems from tradition control systems towards modern mill wide control architecture and further progress towards a semi-autonomous mill and finally, autonomous operations for smart manufacturing.*

Autonomous operations imply the need for an integrated approach of manufacturing process, rather than traditional decoupled processes. A few examples have been presented in this paper, demonstrating the benefits of unified integrated approach. A holistic optimization approach across the pulp-to-paper value chain is presented to improve yield, reduce losses, and enhance energy efficiency by the use of digitization, APC and AI.

Use of AI and soft sensors for predicting final quality is demonstrated through a case study in this paper. The other typical benefits are also demonstrated.

Additionally, the study addresses innovations in Virtual modelling tools like process simulators and digital twins that can be used to reduce the start-up time of a new project, help in remote commissioning. One case example has been included in this paper to explain the benefits of virtual modelling tools.

The paper concludes that the convergence of control systems, optimization tools, and digital solutions is critical for enabling next-generation smart manufacturing in the pulp and paper sector.

Keywords: *Distributive control systems, APC, AI, Analytical models, simulators, Digital twins, waste water.*

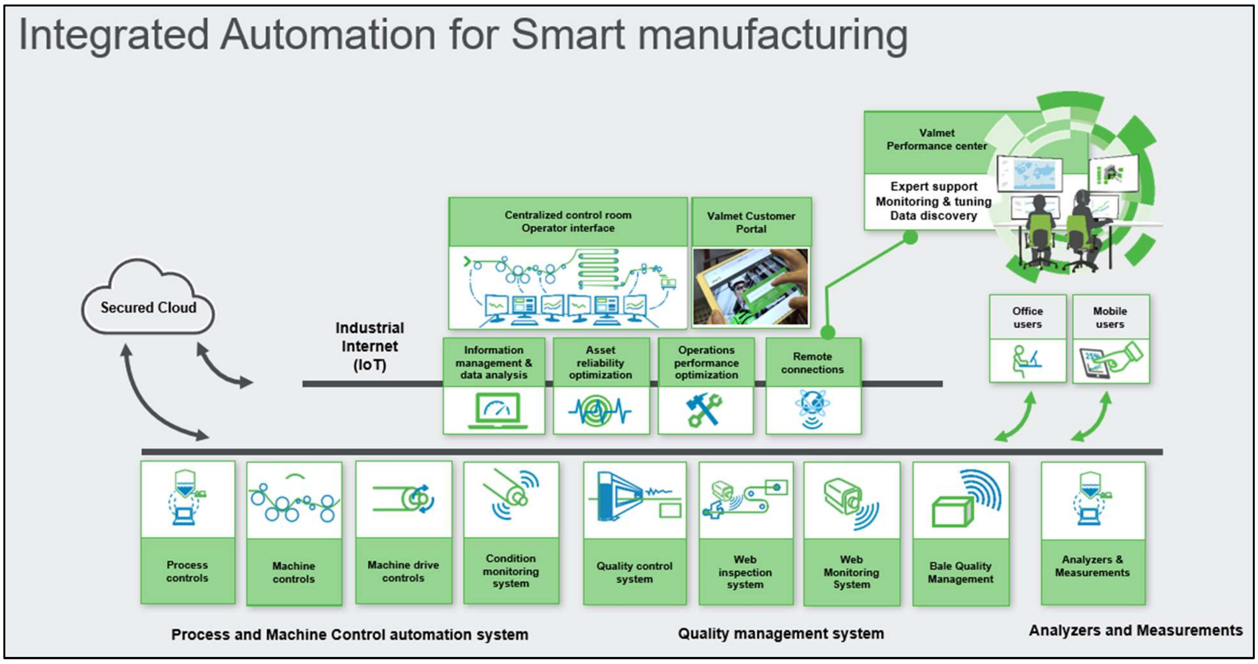
Introduction

The global pulp and paper industry is undergoing a critical paradigm shift. Faced with rising resource costs, fluctuating raw material qualities, stringent environmental mandates, and the pressure to maximize throughput, modern mills are transitioning away from localized, reactive control methodologies. Historically, mills operated via siloed systems where process control, machine diagnostics, quality management, and environmental monitoring were treated as separate domains.

To survive and thrive in this shifting landscape, the sector is increasingly embracing digitalization and automation to transition from conventional process control to fully integrated smart manufacturing systems. This evolutionary leap unifies the physical plant operations with advanced data-centric algorithms, transforming massive flows of historical and real-time plant data into actionable intelligence. This paper establishes a comprehensive framework for smart manufacturing by exploring modern unified control architectures, data analytics, simulation technologies, and plant-wide environmental optimization.

Modern Control System Architecture for Smart manufacturing

Achieving operational excellence begins with establishing a unified, resilient, and future-proof automation foundation across the entire mill. Modern distributed control system architectures have evolved beyond traditional, rigid boundaries to integrate process controls, machine controls, drive controls, and quality control systems (QCS) into a single, cohesive operating framework (Figure 1).



(Figure 1- Integrated Automation Architecture)

Advanced Process Control (APC) → Steppingstone towards mill wide optimization

While the mill wide control architecture forms the base for manufacturing, the next step forward is the Advance Process controls which takes the manufacturing from basic controls (that involves considerable human intervention) to semi-autonomous mill (1). The below figure 2 illustrates aspirations of each stakeholder in the mill. APC helps to meet these targets to quite extent and can be implemented in a phased manner.

(Figure 2- APC, the step towards semi-autonomous mill operations)

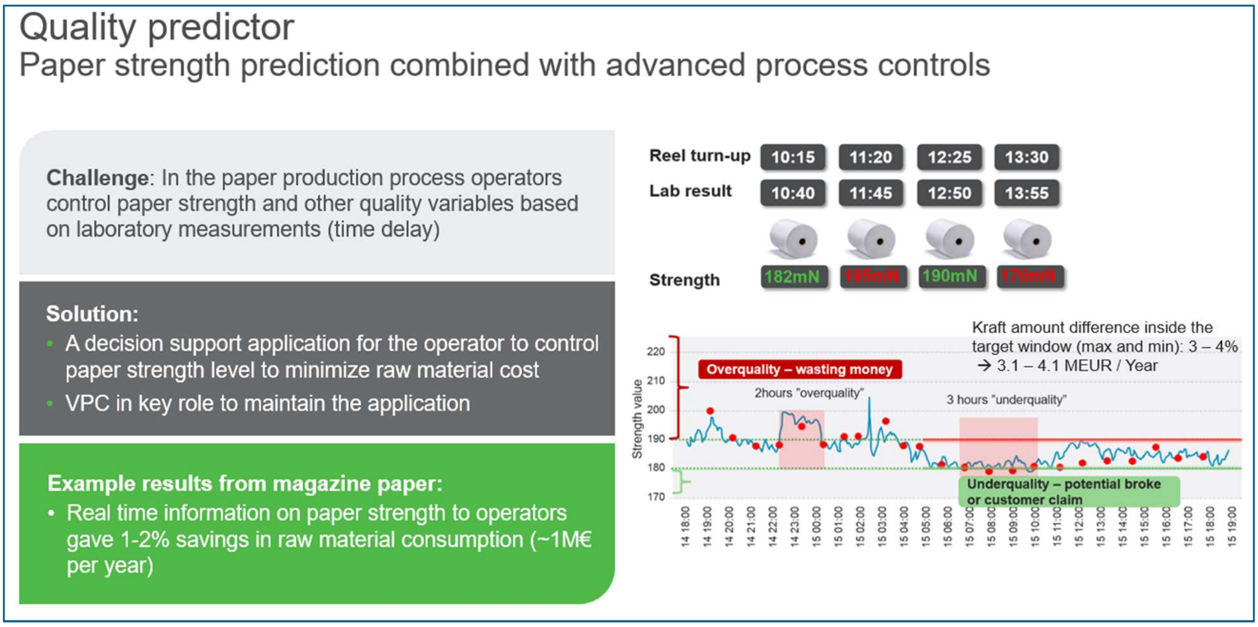
Artificial Intelligence and Predictive Analytics

Once the manufacturing process has reached the semi-autonomous level, the integration of Artificial Intelligence (AI) and Machine Learning (ML) technologies strengthen the operational efficiency by shifting mill operations from a reactive posture to a proactive, predictive model.

Many critical parameters in pulp and paper production (such as kappa number, brightness, chemical residuals, paper strength properties, formation etc) traditionally require time-consuming laboratory analysis or manual sampling.

- **Data-driven Models** act as "soft sensors" by ingesting real-time upstream data and predicting final product characteristics instantly.
- **Quality Consistency** is achieved by anticipating deviations before they manifest physically, the control system initiates closed-loop corrections, stabilizing quality and drastically reducing the volume of off-spec or broke paper.

A case example from a mill is demonstrated below which shows considerable positive impact on raw material consumption along with quality forecast. (Figure 3).



(Figure3: Case study: Quality prediction with soft sensors and AI)

Mill-Wide Value Chain Optimization with APC and AI

The final step towards Autonomous mill (1) and smart manufacturing would be integrating all the mill areas and making them act as a single entity with all required synergies.

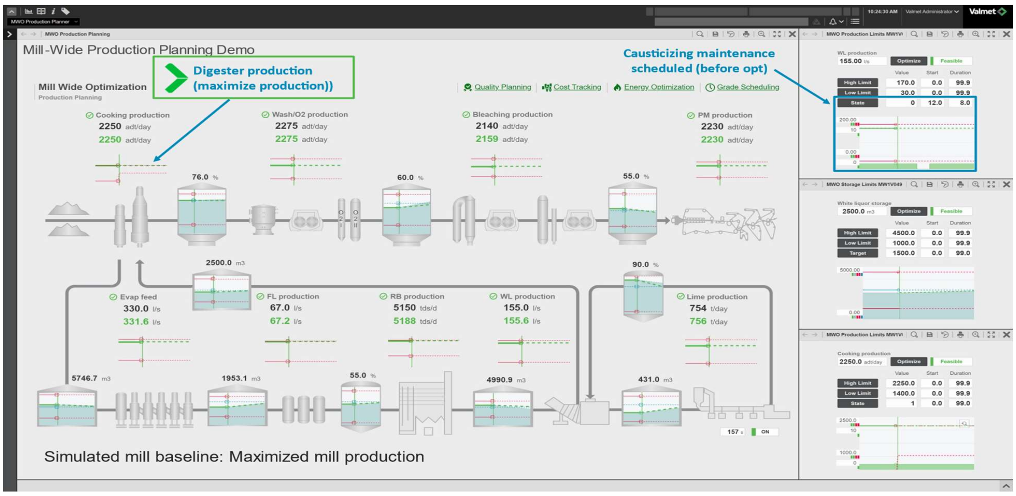
Implementing APC & AI applications across key process areas creates a unified control layer that can account for cross-process interactions and upstream/downstream dependencies. When these controllers are designed with consistent models, objectives, and constraints, they naturally create synergies that support mill-wide optimization. This approach improves overall process stability, reduces variability propagation, and enables coordinated economic optimization rather than local optimization of individual units with fragmented approach of multi-model/multi-vendor approach.

(Figure 4) illustrates focus parameters and expected outcomes for each area in a Pulp & Paper mill. When all areas/units are working as a single entity (MWO) rather than in isolation, the overall performance is optimized.

Process Area	Focus Optimization Parameters	Expected Outcomes
Fiber Processing	Chemical dosage, Energy consumption, Target brightness and fiber morphology.	Maximized fiber yield, reduced electrical consumption, optimized Fiber properties, consistent production.
Chemical Recovery Systems	Liquor solids maximization, combustion air balance, lime kiln efficiency.	Increased chemical recovery rate, maximized green liquor quality, reduced environmental footprint.
Mill-Wide Production Balance	Buffer tank level management, steam/power network load-balancing, synchronized mill schedule.	Minimization of product losses, optimized energy efficiency, smooth fiber transition.

(Figure 4: Typical expectations and impacts of MWO)

This synchronized, mill-wide decision-making approach treats the entire plant as a unified optimization unit (2). It prevents local optimizations from causing upstream or downstream bottlenecks, balancing fiber, chemical, and energy flows perfectly across the site. A case study (figure 5) illustrates how causticizing maintenance schedule can be planned to keep the digester production to the maximum possible level.



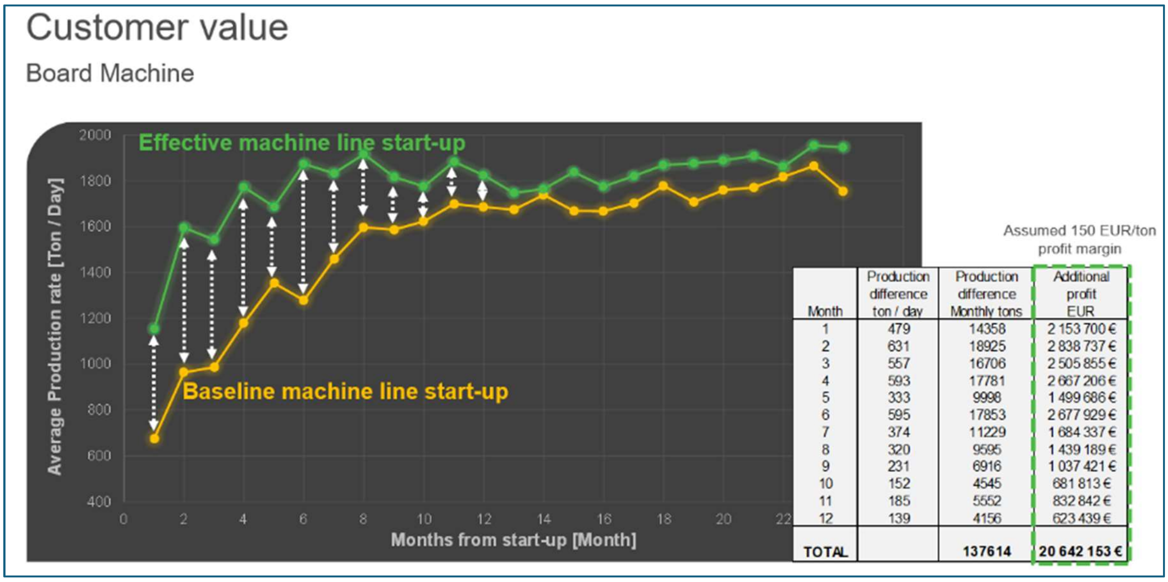
(Figure 5)

Plant Process Simulators and Digital Twins

Having talked about APC, AI and MWO, there are also available smart Virtual modeling tools that can contribute significantly to smart manufacturing. These tools have transitioned from isolated engineering design applications into vital, real-time operational components. Plant process simulators and digital twins play a critical role in this transformation by enabling highly accurate, dynamic modeling of full mill operations.

Simulators create a highly realistic clone of the plant control room. Operators can train for rare process upsets, startup sequences, and grade changes in a safe environment, establishing high situational competence without risking physical assets.

Similarly, before implementing a new control strategy or upgrading physical equipment, the changes can be thoroughly tested on the digital twin. Virtual commissioning (figure 6) reduces physical startup times and significantly mitigates operational risks.



Month	Production difference ton / day	Production difference Monthly tons	Additional profit EUR
1	479	14358	2 153 700 €
2	631	18925	2 838 737 €
3	557	16706	2 505 855 €
4	593	17781	2 667 206 €
5	333	9998	1 499 686 €
6	595	17853	2 677 929 €
7	374	11229	1 684 337 €
8	320	9595	1 439 189 €
9	231	6916	1 037 421 €
10	152	4545	681 813 €
11	185	5552	832 842 €
12	139	4156	623 439 €
TOTAL		**137614**	**20 642 153 €**

(Figure 6: Case study- Virtual commissioning)

While we have discussed all the important aspects of smart manufacturing, but it is incomplete without implementing sustainability initiatives to use scarce resources optimally and reduce the footprint on the environmental health by decreasing effluents (chemicals, sludge etc). It has to be considered as an integral part of smart manufacturing.

Modern environmental regulations demand that mills strictly limit freshwater intake and ensure that all discharged effluents meet rigorous water quality criteria. Achieving these mandates requires deploying advanced inline measurement technologies combined with specialized analytics.

Conclusion

The convergence of unified distributed control systems, multivariable advanced process controls, predictive AI analytics, and dynamic simulation tools represents the definitive path forward for next-generation smart manufacturing in the pulp and paper industry. By constructing an interconnected, data-centric framework, mills can break down historic operational silos.

The technical findings validated across modern applications prove that a comprehensive, data-driven framework significantly enhances productivity, reduces process variability, and ensures sustainable resource utilization. Ultimately, integrating these smart technologies changes automation from a tactical tool for process stability into an enterprise-wide strategy for profitability, resource efficiency, and environmental compliance.

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