USING MILL-WIDE OPTIMIZATION TO MAXIMIZE PULP PRODUCTION AND STABILIZE OPERATIONS

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SUMMARY

This paper presents the findings of a trial project for a mill-wide production planning advisory solution, which was implemented for an industrial-scale market kraft pulp mill using a recently launched mill-wide optimization platform. While the pulp and paper industry has been optimizing individual process areas for several decades, a mill-wide optimization layer to steer all process areas towards high-level objectives has largely been missing. In the mill-wide production planning solution, a process flowsheet model is periodically optimized online to evaluate the current and future production targets for all individual process areas, as well as the bottlenecks of the mill. The solution is used for maximizing production towards mill limits, balancing inventories, scheduling discrete process events, and visualizing the overall state of the mill. The results of the trial pulp mill project demonstrate significant improvements in production efficiency, and the solution enables more proactive decision-making at the mill. Use cases for improving and forecasting day-to-day operations are presented in this paper. Results from a "re-optimize the past" offline analysis conducted during the project baseline period are reviewed. Challenges encountered during the commissioning phase are addressed, and the impact on total mill production is discussed.

Keywords: autonomous mills, kraft mill optimization, mill-wide optimization, process flowsheet optimization, production planning.

INTRODUCTION

Mill-wide production optimization and its application to the pulp and paper industry are examined in this paper. Like other industries, pulp and paper makers are currently facing challenges and opportunities in terms of profitability and environmental goals [1-2]. These include high energy and capital intensity, the need to reduce emissions, the availability of raw materials, and changing consumer trends. Aside from development of new process technology, these trends call for improved productivity through digital development [3], which rests on the ability to maximize on-spec production with respect to demand, and minimize lost production due to process downtime, operational bottlenecks, and insufficient quality. At the same time, overall production should be more flexible, providing more opportunities to run the mill in different ways based on product, raw material, and energy prices.

To achieve these goals, mills have increasingly started to aim at autonomous operations in the long term [4]. This development is not restricted to automatic control, but rather comprises mills with optimized process areas and an optimized overall production, where the system is able to monitor its own performance and adapt to changing process conditions. The pulp and paper industry has been implementing advanced process control to optimize individual process areas for over three decades [5]. This long-term development has resulted in measurable and sustainable benefits in terms of production rates, quality, and energy. However, the optimization of individual process areas often fails to account for process area interactions, such as the limiting effect of the chemical recovery line on the fibre line production rate in a kraft pulp mill, for example. These interactions generate mill-level bottlenecks that limit the overall production rate and quality [1-2]. Indeed, what has been missing in pulp and paper production, to avoid suboptimal outcomes at the mill level, is a mill-wide optimization layer to steer individual processes towards higher-level objectives and avoid the formation of mill-level bottlenecks.

There are several technical requirements for implementing a mill-level optimizing solution. The solution needs to be dynamic, accounting for relevant production trajectories and their associated economic impacts. The solution needs to track the current and future process states, as well as effectively implement equipment stop and grade change related discrete states. To have practical relevance, the solution needs to run in real time with connectivity to mill data. Furthermore, model parameters need to be adapted continuously to changing process conditions, so that simulated process trajectories correspond to the current mill operation, and calculated production targets have practical relevance. Mill-level solutions that are usually considered for industrial processes include hierarchical model predictive control (MPC) and real-time optimization (RTO) of mostly static process models [5-6].

This paper presents a mill-wide optimization (MWO) approach that has the capability to provide optimized production and quality targets for the whole mill in an online setting. The approach is based on dynamic flowsheet optimization, which accounts for relevant process interactions and provides effective simultaneous management of all process inventories. In the MWO, a mill flowsheet model is periodically optimized to calculate the current and future production targets for each process area in the fibre line and recovery cycle based on current and past mill data.

The MWO approach is employed in this paper as a mill-wide production planning solution, with a trial project at a market kraft pulp mill. Production planning was specifically chosen as the initial MWO application area, as accurate production rate forecasts form a foundation for a global optimization of the mill based on product prices, raw material and utilities costs, energy costs, and quality deviations, at a later stage. The implementation of a centralized online production planning solution for all mill departments in this paper is thus a crucial first step for an overall optimization of the whole pulp mill.

The MWO platform and the mill-wide production planning solution described in this paper represent novel developments in the pulp and paper industry, as advanced mill-level production optimization can readily be employed without the need of extensive user expertise, and as the platform can be configured for various pulp and paper production and quality planning problems. In academia, pulp mill production planning has been investigated for a longer time. Reviews on early work were provided by Leiviskä [5,7], who also modified the single-objective time delay algorithm of Tamura for pulp mill scheduling [7]. The approach was piloted for an integrated kraft pulp and paper mill setup, although without access to online measurement data [8]. Santos & Dourado [9], applied genetic algorithm multi-objective optimization to an integrated kraft mill model to minimize electricity use and the amount of production rate changes, while meeting the paper production target and closing inventory levels. Beyond the early literature, Sarimveis et al. reported results from mixed-integer flowsheet optimization for integrated mills, aiming at maximizing production revenue and reaching closing inventories [10]. Petterson et al. presented a model predictive production planning application for an industrial integrated mill, where a nonlinear program was solved to minimize a combined objective of production and quality variables, with a differential equation process model as a constraint [11]. Mercangöz & Doyle implemented a static linear programming-based RTO optimizer for production and quality setpoints in a pulp mill benchmark problem [2]. Recent research has focused on the mixed-integer lot-scheduling optimization of paper grades in integrated mills, considering only a highly simplified flowsheet for the pulp mill [1,12].

The proposed mill-wide optimization approach, the mill-wide production planning solution, the baseline analysis carried out prior to the online implementation, and the MWO project at the kraft pulp mill are described in the subsequent sections of this paper. Several use case categories are also defined, demonstrating how the production planning solution is utilized in day-to-day operation for improving production performance and forecasting mill behavior. The paper concludes by discussing the impact on total mill production and laying out potential next steps beyond production planning.

EXPERIMENTAL

The theoretical background of the mill-wide production planning and the experimental setup of the trial pulp mill project are presented in this section. The basics of process flowsheet optimization are elaborated on in the first subsection. The second subsection discusses the optimization platform features required for online implementation. The third subsection describes the concept of the “re-optimize the past” baseline analysis and its setup for the target pulp mill, while a fourth subsection is dedicated to the specific implementation of the online production planning solution at the target mill.

Process Flowsheet Optimization

In the mill-wide optimization approach, a process flowsheet model of the whole mill is optimized directly to maximize or minimize the specified production objectives, subject to defined process and event constraints. The mathematical optimization problem is configured, the mill is modelled, and the optimization is performed using a dedicated software platform, which has been specifically designed for process industries. It has built-in features to track stream properties and components, is open to embed customized models, and has advanced features for programming scheduling, planning, and data reconciliation problems. The platform can readily be used for different types of linear, non-linear, discrete, and dynamic optimization problems.

The flowsheet model (Fig. 1) consists of unit operation modules for process areas and inventories, as well as flowsheet boundary sources and sinks. Interactions between the unit operations are thus accounted for via the process flows and storage levels. Unit operation models are identified using historical data from the mill and describe the relevant input-output relationships for the optimization problem, mainly mass and volumetric flows in the case of mill-wide production planning.

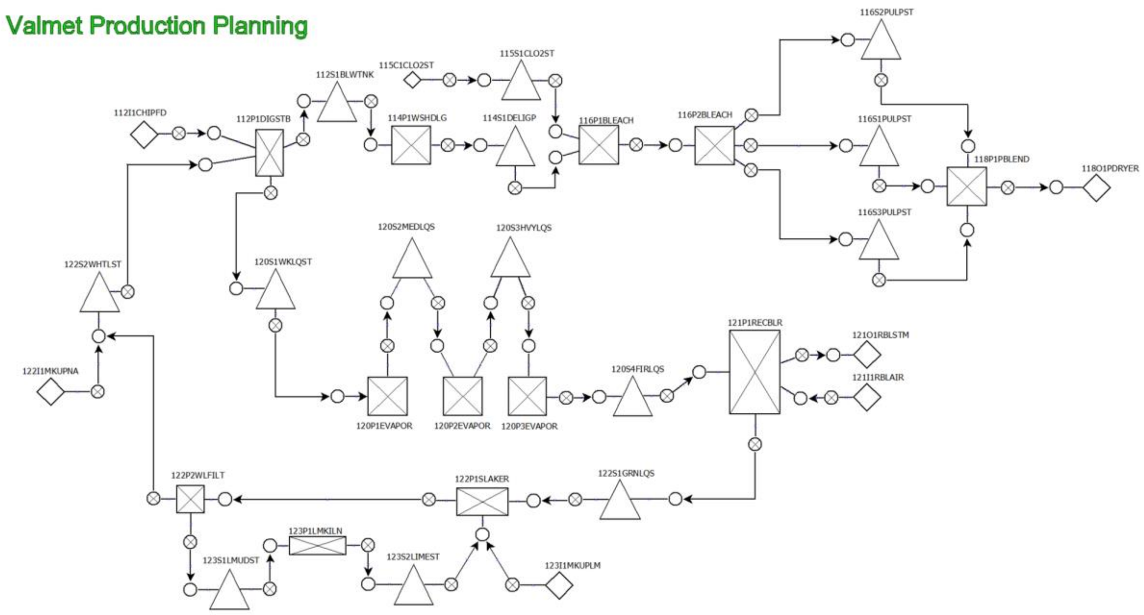

Figure 1. Process flowsheet model of the kraft pulp mill.

The flowsheet model is converted into a set of equations that are used for simulating and optimizing future process state trajectories. In the MWO approach, a weighted single-objective function consisting of profit terms that can be applied to any flowsheet variable (production amounts in this paper), performance terms related to variable target deviation (e.g., inventory levels) and smoothing, and optional penalty terms for soft variable limits, is maximized for the defined optimization time horizon by adjusting a mill-wide set of flowsheet variables (optimized inputs). The problem is constrained by the process model equations with given initial conditions, non-optimized inputs, process area and inventory bound and rate constraints, as well as defined department stops and grade changes. An equation-oriented optimization approach is used, meaning that the entire equation set of the flowsheet is exposed to the solver and solved simultaneously. There is no assumption of input/independent variables or output/dependent variables for unit operations when solving the problem. The flowsheet model methods are connected to the chosen optimization solver in the MWO platform, the feasibility of the solution is determined in a separate pre-solve stage, and the solver evaluates the nature of the discovered optimum.

Optimization Platform

The MWO platform enables a straightforward online implementation and modification of the flowsheet optimization problem described in the previous section. As such, it includes the necessary software infrastructure for periodically running one or more instances of the optimization problem based on defined starting values and user settings. Naturally, the platform needs to perform several functions in addition to the actual optimization. The platform includes software for data collection and distribution of scalar and vector data types. Vectors are used to store future targets, limits, process states, grades, as well as the projected future optimization results. The platform has the capability to perform real-time pre-optimization and post-optimization calculations for both scalars and vectors; for unit conversion, model adaptation, time shifting of data, and calculation of initialization values.

The optimization platform has a configurable user interface with specialized components for visualizing and setting future process limits, targets, states, and product grades. This allows production and operating staff to manage and visualize the future state of the mill. To maintain the mill-wide perspective, the MWO main display provides a compact flowsheet view of the mill, showing the relevant optimized production trajectories. Each process area and inventory have their own operating displays for modifying future settings, and additional displays provide a detailed view of the optimization results.

"Re-optimize the Past" Offline Analysis

A "re-optimize the past" offline analysis was performed prior to the implementation of the online solution to estimate the potential benefits of mill-wide optimization, when comparing to historical production data. A team of automation and process experts conducted a comprehensive audit to perform interviews, gather information and collect historical process data, one year in total. The data was used to identify production, inventory, and process constraint models for each process area. The model equations were used to build the process flowsheet model in Fig. 1.

Using a specialized offline MWO application, the historical data was "re-optimized" 3 days at a time to evaluate the production increase potential, and to identify mill bottlenecks limiting the production increase. For each 3-day period, historical data and statistics were used to set the initial conditions of the process model, the process and inventory limits, and the unit operation stops and slowdowns to match the historical operation. Notably, the optimized pulp, liquor, and lime inventory targets were set to match the historical inventory at the end of the 3-day period to avoid increasing or drawing down inventories for production gain. The results for each 3-day period were automatically recorded and tabulated by the application.

Production Planning Solution

Following the benefits analysis, the process flowsheet optimization was put online using the described MWO platform. The resulting open-loop advisory solution provides the optimized current and future production targets for each unit operation in the pulp mill (optimized input variables) for the next 3 days (optimization horizon), including digesters, washing, bleaching, pulp dryers, evaporators, recovery boilers, causticizing, and lime kilns. The overall optimization objective is to maximize production (tonnes pulp produced) and smooth out production changes while balancing current and future pulp and liquor inventories (tank/chest levels).

The optimization is automatically performed every 30 minutes, but can also be performed on demand, for example after defining a future process unit stop. Mill overview displays show the recommended production targets, the optimized production and inventory trajectories, and the production bottlenecks. The production bottleneck graphics clearly indicate which production rates and process constraints will hit high or low limits during the 3-day horizon. This helps the mill understand the targets recommended by the advisory system and highlights which areas of the mill are most often limiting total production. Advanced displays are used to monitor and diagnose the optimization status, and the health of the process models.

The application includes automated calculations for the liquor and lime inventory targets based on the total balance and desired distribution of liquor and lime between the tanks. In addition, the "open-loop" future projection of tank and chest levels is shown, which is the trajectory of the given inventory if no production changes are made.

RESULTS AND DISCUSSION

The overall results of the mill-wide production planning trial project at the market kraft pulp mill are outlined here. The "re-optimize the past" baseline analysis results are summarized in the first subsection. The online application results are explored in the second subsection, containing the overall impact, MWO use case descriptions, as well as the progression and findings of the commissioning.

"Re-optimize the Past" Analysis Results

Table 1 shows the production increase potential from the MWO, and bottleneck frequency for each department as identified by the "Re-optimize the past" analysis. Causticizing was identified as the most common optimization bottleneck, followed by the evaporators. The average production increase potential for cooking and the pulp dryer was 4.5% according to the optimization results. It should be noted that that the production increase was slightly different between the departments due to differences in measurement accuracy.

Table 1. "Re-optimize the Past" production increase potential and bottleneck frequency.

	Production Increase	Bottleneck
Cooking	**4.5%**	4.1%
Washing	4.3%	1.5%
Bleaching	3.4%	6.8%
ClO2 Prod	3.5%	6.9%
Pulp Dryer	4.5%	0.6%
Evaps	4.4%	30.9%
Rec Boiler	4.6%	11.1%
Caust	4.9%	**42.2%**
Kiln	2.9%	2.4%

The production increase potential was validated with the mill personnel via use-case examples from the historical data analysis period. These examples demonstrated how the optimization was able to increase production and how the online system will be used to help push production.

Online Production Planning Results

Based on the improvement potential identified in the benefit analysis, the mill decided to proceed with the online solution. Following the tuning and commissioning phase of the project, the application was taken into use. At first, the optimization results were reviewed by the project team and shown daily to the mill, with encouragement to take the recommended actions. As time progressed, the mill started to review the recommendations more independently with frequent interaction with the project team to answer questions, fix problems, tune the system, and add new features. A robust support model has been kept in place to help the mill learn how to take full advantage of the system. In exchange the mill is providing invaluable feedback for application improvements.

The results from the first 8 months with the mill-wide production planning solution running have been very encouraging. The application has demonstrated to the mill that it is often possible to increase the pulp production, resulting in 2 record production months in the first 4 months after the application was put into use. Figure 2 is a histogram of the cooking production target for the year prior to the application being put into use and the 8 months since the application was put into use.

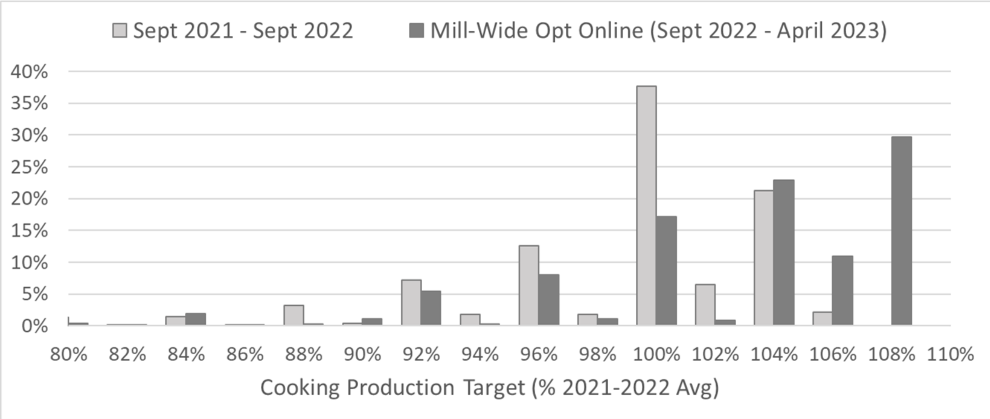

Figure 2. Cooking production target histogram.

Figure 2 shows how the cooking production target was increased to significantly higher levels, resulting in a 5.2% realized production increase on average. It should be noted that the increase is close to the 4.5% increase estimated by the "Re-optimize the Past" analysis. The production increase was validated using other production measurements in the fibre line; the O_2 delignification production increased by 6.6% on average and the pulp dryer production increased by 3.5% on average.

During the trial period, the production optimization was constrained by process area bottlenecks that varied over time, as shown in Table 2. The cooking production bottleneck was clearly the most frequent. However, the evaporators, recovery boiler, causticizing and the pulp dryer had all been the bottleneck for the overall production at different points in time. Causticizing was the second leading bottleneck compared to the "Re-optimize the Past" analysis, where it was the main bottleneck, although this observation was also impacted by adjustments that the mill made to process area bound constraints. Having a clear visualization of the bottlenecks helped the mill gain a better understanding of the process, improved interaction between production lines and departments, and helped in the prioritization of maintenance activities. It should be noted from Table 2 that the mill did not always increase production to the optimization bottlenecks, which indicates that production could have been increased further.

Table 2. Production optimization bottlenecks (% time at limit).

Process Area	Average	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23
Cooking	66.6%	63.7%	84.7%	92.3%	94.5%	60.9%	75.3%	48.4%	12.8%
Washing - O2 Delig	0.5%	0.2%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	3.1%
ClO2 Prod	0.9%	0.3%	2.5%	0.0%	1.0%	1.6%	0.3%	0.3%	1.0%
Bleaching	0.1%	0.0%	0.1%	0.0%	0.0%	0.0%	0.3%	0.0%	0.3%
Pulp Dryer	10.9%	0.0%	0.0%	0.7%	0.3%	0.0%	40.8%	28.6%	16.6%
Evap Set 1	12.4%	15.3%	12.2%	6.4%	5.5%	5.3%	0.5%	12.1%	42.4%
Evap Set 2	6.8%	37.1%	4.5%	0.1%	0.0%	0.0%	10.1%	1.9%	0.8%
Evap Set 3	5.7%	6.6%	15.6%	2.8%	0.8%	0.3%	2.6%	2.3%	14.4%
Rec Boiler Feed	19.0%	3.4%	17.6%	40.9%	17.6%	37.3%	22.2%	9.4%	3.9%
Rec Boiler Sec Air	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rec Boiler SH Steam	1.8%	13.8%	0.3%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%
Causticizing	27.0%	4.2%	1.4%	3.3%	4.7%	26.6%	49.0%	46.7%	80.1%
Lime Kiln	7.3%	20.4%	0.1%	5.5%	0.4%	7.7%	3.7%	3.2%	17.2%

In addition to improvements to overall production, specific production planning use cases were identified and grouped into three main categories. In the first category, "debottlenecking", the purpose of the MWO was to highlight which process areas actually limited the production increase, when the mill was running nominally. The mill production could thus be pushed against its limits by increasing the cooking production upper bound until a bottleneck was encountered. Shifting bottlenecks in the recovery cycle could also be monitored effectively through this practice.

The second category, “balancing”, was arguably the most crucial, as the recovery line needs to constantly react to the fibre line production changes to avoid limitations resulting from liquor inventories. A typical case example was the coordination between the evaporator inlet feed and the cooking, where the evaporator production rate needed to be increased sufficiently during cooking production rate increases to avoid increasing weak black liquor levels and avoid having to reduce cooking production back down to prevent weak black liquor overflow.

“Planning” of mill department maintenance stops and slowdowns was the third category. What-if scenario simulations were carried out for different maintenance schedules within the 3-day optimization horizon to identify the optimal timing and maximum duration for a planned maintenance operation. In addition to planned actions, the operators found it useful to evaluate the feasibility of unplanned maintenance actions; for example, how much an immediate four-hour maintenance of the white liquor filter would affect the recovery boiler throughput. The use of the MWO production planning application for full mill shutdown and start-up preparation remains to be fully explored and optimized, although initial observations indicated that the application will provide significant value in these situations.

Implementation of the online solution presented several challenges and opportunities to improve functionality during the testing and commissioning phase of the project. One of the main technical challenges was avoiding optimization mathematical infeasibilities, which are normally associated with keeping the pulp and liquor levels within the low and high limits. New features were added to help reduce the frequency of infeasibilities to the point where they are currently very rare. Another challenge was to improve the robustness of the model adaptation to account for unit stops, and sudden unexplained shifts in process signals (e.g. manual signal calibration). Balancing of the recovery cycle liquor inventory levels, and the lime cycle inventory levels, via calculated level targets, was also improved during the course of the project, to better adapt for changes in process behaviour.

Another point of focus during implementation was the user experience and way of working with the MWO application. Several workshops were held with the mill to help them better understand the functionality of the application and get their feedback on how to visualize and interact with it. There were multiple outcomes of this work. The main production planning display was redesigned to be a compact flowsheet view of the mill similar to the demo application display shown in Fig. 3. In addition, procedures for how to utilize the MWO application most effectively and corresponding definitions of user roles and responsibilities were jointly developed with the mill.

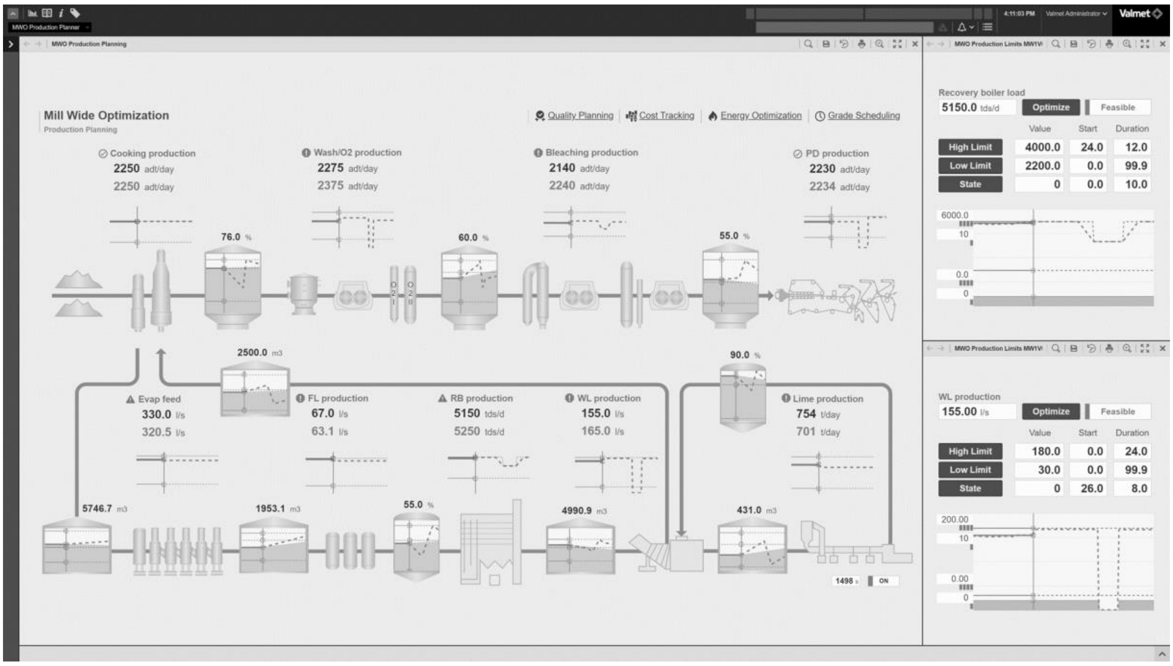

Figure 3. Production planning main display.

CONCLUSIONS

The results of the mill-wide production planning trial project clearly demonstrate that optimizing and coordinating mill departments through flowsheet optimization can be used for evaluating and realizing improved production efficiency. In addition to helping the mill increase production, specific use case categories were identified which helped the mill improve performance in different ways. Providing a clear visualization of the optimized future state of the mill from a high level, including current and future bottlenecks, helped the mill to make decisions about how to run individual departments to better account for future needs. In general, mill-level coordination increased the interaction and cooperation between mill departments and helped increase the understanding of the overall production and its limiting factors.

It is the authors' belief that mill production planning will serve as the foundation for other mill-wide optimization solutions, such as quality planning, energy planning, and grade scheduling, which will help mills realize additional benefits and obtain globally optimized operations. Ultimately, these systems will be converted from open-loop advisory solutions to closed-loop autonomous solutions that will self-repair and adapt based on changing raw material quality and availability, process operating conditions, and economic conditions.

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