A systems approach for process debottlenecking towards a sustainable pulp and paper industry

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ABSTRACT: Increasing the competitiveness of the pulp and paper industry requires an effective optimization of its existing assets in line with a long-term vision for process transformation, production upgrade, and product diversification. Currently, pulp production increase is one of the main sources of additional revenue for the kraft industry. Likewise, energy efficiency is often employed as a cost-effective approach to reduce operating costs, enhancing the possibilities to lower fossil fuel consumption and contributing to a low-carbon economy. On the other hand, reaching higher production targets and facilitating process transformation, such as biorefinery implementation, heavily depend on the status and performance of a mill's current infrastructure; therefore, a system analysis is needed to assess the new production requirements, the bottlenecks, and the interactions across departments.

In order to obtain practical improvement solutions, direct and indirect impacts on process performance and resource utilization should be considered. This work provides an overview of the key challenges that need to be addressed for production increase and energy efficiency improvement. The methodology starts by a scope analysis for debottlenecking and screening capacity limitations vs. mill targets, followed by their ranking (bottleneck ranking diagram). Benchmarking, gap analysis, and root-cause techniques are applied to diagnose system inefficiencies. This mill-wide debottlenecking assessment is then used to guide the selection of a long-term sustainable operation and design a portfolio of improvement projects by avoiding cross effects of the short-term projects on the long term. A case study of a kraft pulp mill is used to illustrate the proposed methodology.

Application: The systematic approach presented here helps provide insights into critical capacity-limiting mill departments. This knowledge can inform decision-making, enabling mills to develop well-planned debottlenecking strategies and to retrofit or revamp processes so they meet current requirements while remaining adaptable to future objectives.

The pulp and paper (P&P) industry is facing serious challenges because of severe market competition and stricter environmental regulations [1]. To keep their competitive position, P&P mills have to implement new processes and retrofit existing units, which require large amounts of capital. Mills are often short in capital, notably because of low operating margins; therefore, a cost-effective strategy for debottlenecking mills is highly desirable. Significant efforts have been taken to improve the competitiveness of the P&P industry while building a new business model in line with the current trends for product diversification [2], industry digitalization [3], and effective decarbonization [4]. The main revenue stream for this industry continues to rely on the production capacities and performance of the existing assets.

Pulp and paper plants are constantly changing their complex operating strategies to accommodate market demands for a diverse product range and specifications [5]. This context affects a mill's global performance [6,7]; therefore, it requires optimizing the key operating parameters and upgrading limiting departments to maximize profit. Moreover, as one of the high-energy and water-intensive sectors, the P&P industry could benefit from improving energy efficiency and lowering fuel consumption [8]; consequently, making decisions on the optimal operation and design changes depends on the site-wide trade-offs among process capacity, departmental efficiencies, steam and power generation, and energy utilization (including production and distribution of hot water).

Although several process system engineering methods for debottlenecking are available in the literature [9,10], approaches that explicitly address the complex problematics of P&P mill debottlenecking in transition to biorefinery and deep decarbonization are limited. This work aims to tackle these problematics while also overcoming the need for extended data sets. A reduced and targeted set of data to monitor and assess the performance of a mill's existing assets is selected. Several approaches for debottlenecking developed and applied in other industrial sectors have been reviewed, adapted, and combined with process knowledge. Furthermore, system integration, data analysis, and modeling and simulation tools have been considered to compensate for the gaps in addressing these problematics in the pulp and paper industry. The aim is to propose a practical and relatively simple approach for the industry.

This publication presents a systematic approach to identify and evaluate potential for increasing pulp production and to mitigate capacity limitations and impacts on resource utilization, while simultaneously keeping a global perspective and considering the local context and system interactions. The proposed methodology will focus more on process debottlenecking insights for optimizing the existing assets and less on the energy system optimization; however, the well-known energy efficiency methodologies and tools should be integrated and applied along the debottlenecking approach, especially when strong interactions occur between process operation and the energy network [11]. A data-driven analysis is proposed to capture the variability of process operations, and to identify historical capacity limitations. This specific approach is described and illustrated across a case study.

PROCESS DEBOTTLENECKING

Debottlenecking is the process of getting more production out of existing plants by improving operations and retrofitting processes. Most industrial plants have some inherent, though in most cases unknown, opportunities to increase their production capacities and efficiencies through debottlenecking.

Usually, the debottlenecking problem involves three main questions. First, which processes most limit the overall process operations and economics? Second, how much debottlenecking potential exists? Third, how do you remove these bottlenecks with acceptable capital costs and payback periods? Different researchers have tried to answer all or some of these questions in their research working on different industrial sectors. In the context of the P&P process, a few more questions need to be addressed, notably: Is the debottlenecking of the critical equipment sufficient to sustain a long-term process transformation and/or biorefinery integration? How many departments/sections of the process require debottlenecking for a production increase? What is the roadmap to optimize the existing process assets and upgrade targeted equipment?

The debottlenecking process is well understood and studied in the oil and gas industry. Zhang et al. presented a level-by-level debottlenecking approach in refinery operations by first addressing the process separation aspects, followed by the heat exchanger network and finally the utility system [12]. Their approach considers a mathematical model to identify processes that most constrain the refinery profit. The debottlenecking objective was to shift bottlenecks from an expensive process to a cheaper process by modifying networks such as the hydrogen network and the utility system. In the latest stage, the bottlenecks that cannot be handled by the network modifications are retrofitted by using detailed process models to achieve the required extra capacity.

The debottlenecking concept is also discussed by other researchers in the oil and gas industry [13-15]. Other sectors have also been investigated, including the pharmaceutical industry [16], the bio-process manufacturing industry [17], effluent treatment [18], batch chemical processes [19], cocoa manufacturing processes [20], and metallurgical plants [21].

Nandakumar et al. [9] discussed the emerging concept of lean manufacturing and the application of various techniques such as Define Measure Analyze Improve Control (DMAIC) and value stream mapping (VSM) methods for assessing manufacturing scenarios in food processing, focusing on the production and packaging processes. Their main objective was to identify and eliminate the bottlenecks in these processes by reducing variability, defects, and wastes while focusing on customer data-driven decisions. Although this method aimed to eliminate defects from the process, it clearly highlights the relevance of data analysis and the need to filter a complex problem to find the root cause of bottlenecks while distinguishing between uncontrolled and controlled variables.

In their paper, Adham and Buchholz highlighted the relevance of modeling and simulation tools for the debottlenecking of high temperature metallurgical plants [21]. Beside the heat and mass balances used to simulate the processing steps, their methodology uses the concept of the bottleneck ranking diagram, followed by process analysis to identify capacity increase options. They proposed the cost-capacity curves to determine the minimum cost points for expansion. The approach to estimate department capacities for the bottlenecking diagram is described as a data analysis based on capacity utilization, yield, and equipment nameplate specifications. More specifically, the data characterizing the best-demonstrated periods of operations are determined to establish the potential throughput vs. the new production targets. Their bottleneck ranking diagram concept has been adopted for the kraft pulping process and integrated into this work, as will be described later in the paper.

A novel bottleneck tree analysis (BOTA) to cope with the increasing capacities within industrial refineries had been presented by Teng et al. [13]. This is a heuristic graphical debottlenecking method proposed to pinpoint the process capacity bottlenecks. These researchers coupled the BOTA with other decision-making methods to improve operational performance while taking environmental conditions into consideration. This in-depth analysis method requires a significant volume of data, process detail, and capacity conditions.

Production line bottlenecks may shift in time, making it difficult to pinpoint their exact location. The problematics may be hands-on identified and addressed by managers using "go and see" practices together with mixed reality technologies that provide real-time key performance indicator (KPI) visualization (Lean and Industry 4.0 tools) for bottleneck identification in production lines [22]. This puts in perspective the relation between production KPIs and actual events occurring in the production line in real time. This approach provides a deeper understanding of critical production KPIs to production managers and operators; however, in the pulp and paper industry, the selection of the critical KPIs that influence the production bottlenecks is often difficult to define, especially due to the high system interaction and cross effects between multiple departments. Thus, the method proposed in this paper builds on the insights offered by these approaches and adds process knowledge in support of the identification of the relevant KPIs, putting in perspective the relevance of the actual bottlenecks vs. the apparent bottlenecks that could be inappropriately identified at first.

In the pulp and paper industry, maximizing profits heavily relies on pulp production capacity and on system interactions within the process and with the utility systems. In terms of bottlenecks, many kraft mills in North America have or perceive to have their main production bottleneck at the recovery boiler [23]. Up to one fourth of perceived recovery boiler bottlenecks may be of this nature, or associated with the way the recovery boiler is operated [24]. A new recovery boiler is expensive, and some mills upgrade/retrofit their existing recovery boiler for higher production. Mills that cannot further upgrade their recovery boilers can use lignin extraction from the black liquor to debottleneck their recovery boilers and diversify their product portfolio [2,25-28].

Mills can also be constrained by their digesters, pulp machine dryers, and/or recaustisizing processes, among others. Operating beyond the design capacity, as may occur in some departments (e.g., brownstock washing and bleaching stages), can result in operation instability, increased production costs (due to higher chemical and energy use), and overall process reliability issues. The equipment considered as the main bottleneck may be an apparent bottleneck, as its operation could be adversely affected by upstream equipment (e.g., recovery boiler bottleneck coming from lower product solids from the evaporator, which in turn can come from low brownstock washing efficiency); therefore, to debottleneck existing equipment, a global vision encompassing pulp production and utility systems is required. This will enable plants to achieve high capacity utilization and support the implementation of transformative technologies, while optimally managing resource utilization.

Chioua et al. proposed a top-down approach for a plant-wide root cause identification of faulty assets [29]. They considered the plant KPIs to identify the specific unit operation where the disturbance originates. A similar approach will be adopted in this study to deepen the analysis and effectively pinpoint the root cause of process bottlenecks.

ENERGY EFFICIENCY

Pulp and paper production is an energy-intensive process, and improving energy efficiency is one of the main means for reducing the sector's greenhouse gas emissions (GHG) and eliminating its fossil fuel consumption. The overall energy efficiency of a P&P mill is directly influenced by the operation and design of the process heat recovery system, water network, and heating and cooling utility systems. In this sense, numerous opportunities for saving steam through water use reduction, process improvements, and heat recovery have been identified and are already implemented in many mills [30]. Despite such efforts, untapped waste heat recovery potential remains in most sites. This potential could be valorized through new and underutilized existing heat exchangers, taking into account specific process constraints; quick short-term opportunities for steam savings should, however, be fitted within a long-term roadmap to avoid locking out future heat recovery projects [31].

Utility systems for steam and power generation play an important role in the competitiveness of the P&P industry [32]. As a key unit operation, the recovery boiler creates a strong interaction between process and utility operation. It is at the core of the chemical recovery cycle for the pulping process, and its operation influences the overall pulp production performance as well as the mill energy efficiency. In case the recovery boiler produces less steam, the load on power boilers would increase to meet the process steam demand and power generation targets. As a result, more biomass and/or fossil fuel would be used.

Several benchmarks, process integration, and optimization approaches are employed to evaluate the current state of energy efficiency, identify energy saving projects, and define the trade-off between power generation, fuel consumption, and process performance. An energy benchmarking review for the P&P industry was prepared by Rogers et al., summarizing the top-down and bottom-up approaches for assessing energy reduction potentials in industry [33]. Although high level top-down benchmarks are useful for measuring national energy consumption trends, energy benchmarking may only provide limited reference for individual plants, as each one is unique through its infrastructure, technology status, operation, and production specifics; therefore, understanding a plant operation based on specific data and developing data-based mill models is required to fully characterize specifics and effectively define improvement solutions.

Kong et al. listed 25 emerging technologies for the P&P industry to reduce its energy use and carbon dioxide (CO_2) emissions. They highlighted the potential energy savings, environmental benefits, costs, and commercialization status (technology readiness) for each technology [34]. Fleiter et al. assessed 17 process technologies to improve energy efficiency in the German P&P industry up to 2035 using a techno-economic approach [35]. The results showed a savings potential of about 21% for fuel and 16% for electricity demands.

Andersson and Thollander studied the level of implementation and operationalization of energy-related KPIs in the Swedish pulp and paper industry [36]. They showed the importance of developing relevant energy KPIs and procedures for monitoring energy performance in industry as an essential element of successful energy management.

FPInnovations (Pointe-Claire, QC, Canada) and CanmetENERGY, a Natural Resources Canada research center in Varennes, QC, Canada, have published an article about the promising results of their integrated energy optimization studies to maximize efficiency, increase green power sales, reduce GHG emissions, debottleneck production, and facilitate product diversification [37]. They report the results for 15 mills that have an estimated potential energy savings and additional power generation opportunities of CA$55 million. Their holistic approach is combining expert knowledge on P&P processes with data analytics tools and other proprietary software. More recently, in another report by the same authors, integrated energy optimization studies performed at six other mills were evaluated. They highlighted potential savings of CA$6.4 million/year for the identified energy optimization projects (corresponding in this case to an implementation rate of 52% of the total number of projects), equivalent to additional direct GHG emission reductions of 68.2 kt CO_2/year [38].

Many design methodologies have been developed for optimizing energy, water, and other resources in industrial processes [39]. Similarly, various methods for heat exchanger network synthesis and retrofit design exist, beside the well-known Pinch analysis for heat and mass integration [11,40]. Simultaneous optimization of energy and water has also been the topic of several studies, and numerous optimization methodologies have been developed to address this problematic [41]. Although most of these design methodologies combine thermodynamics, design heuristics, and mathematical programming techniques to improve the retrofit solution, insights on the efficiency of process unit operations and operation flexibilities are not systematically considered due to the challenges involved in obtaining rigorous models that incorporate process knowledge. However, capturing the complexity of process unit operations would enable the identification of cost-effective operational improvement projects and further improve the performance of energy systems design.

Given the complex system interactions within P&P mills, there is a high interdependence between the mill's existing assets' performance and bottleneck levels and the energy efficiency level; thus, process operation and design changes for mill debottlenecking should be analyzed taking into consideration their impacts on the energy and cogeneration system to ensure global performance is achieved. An effective utilization of P&P mills' existing assets often leads to energy efficiency improvements and environmental impact reduction; thus, through a system-wide debottlenecking, a reasonable reduction in the specific energy usage is accomplished at higher production levels from existing process assets.

METHODOLOGY

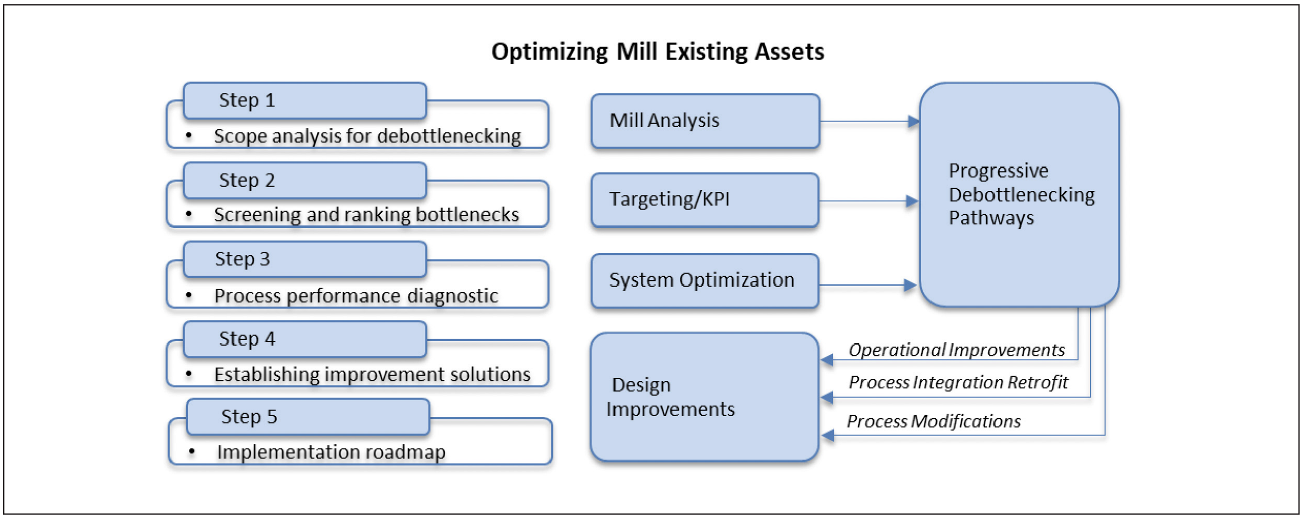
Identification of critical bottlenecks and their link with the actual causes is challenging, given the high complexity of system interactions within the industrial site and the dynamics of production grade rotation. The main process bottleneck often occurs within the chemical recovery loop while the fiber line operation may be limited in capacity at the digester and at the pulp dryer. About 60% of mills in Canada have been reporting capacity limitations at the recovery boiler and evaporation system levels [24]. Environmental regulations, turbine capacity, and power contract requirements could add additional constraints to the process. In most cases, higher pulp production means extra demand on the utility system, and this can also limit the production increase when the power boiler operates at its maximum steam capacity; thus, the assessment should go beyond the process boundaries and integrate the utility, effluent treatment, and even auxiliary support systems. Furthermore, developing future cost-effective improvement solutions and potentially expanding towards biorefinery could lead to upsets in the process and the energy balance. Therefore, optimization of the existing assets is critical for mill transformations.

In this work, a debottlenecking methodology is proposed to identify optimal strategies for improving mill performance by focusing on the main capacity-related issues and their root causes. The aim of this methodology is to define where and how low-cost improvements can be applied before significant changes or process transformations are required. Several analytical tools have been combined together with process knowledge to respond to the compounded debottlenecking challenges. **Figure 1** presents the main steps involved in the proposed methodology.

Step 1: Scope analysis for debottlenecking

In the first step, insights on mill-encountered bottlenecks (at the level of equipment, resources, and reliability) are established together with new production targets based on input from the mill's upper management, engineers, and operating personnel. Understanding the management's perspective and priorities is essential to clearly define the mill's problematic. Information about the ongoing and upcoming projects is also inquired at this step such that the assessment builds towards a unified global strategy solution. This should be done to avoid later complications if the mill strategic development is kept independent from debottlenecking efforts, while also taking the opportunity to reshape some mill projects to better accommodate the long-term vision.

A mill-wide questionnaire has been prepared and used to facilitate gathering information. Specifically, it investigates the mill's targeted production volume. The mill's feed-



1. Overall approach for optimizing existing mill assets (KPI: key performance indicator).

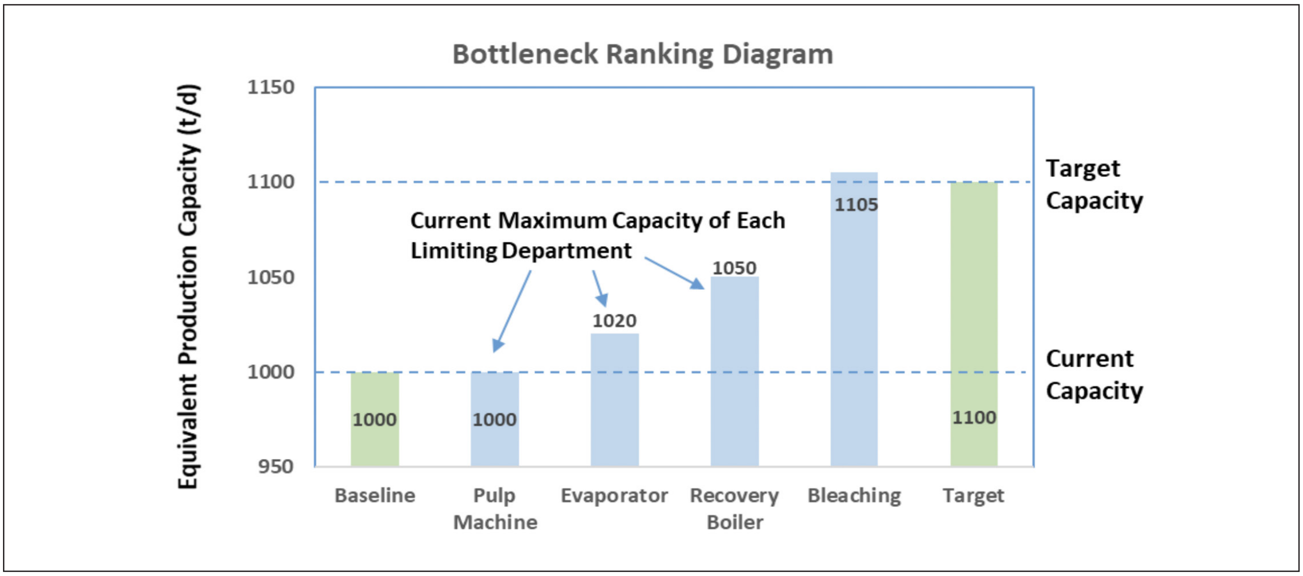
back on the capacity-limiting departments and on the equipment that most often causes unplanned shutdowns is gathered at this step. This information only provides a preliminary overview. A deeper investigation is required to fully understand the bottlenecks. The mill's plans for future process transformation and product diversification is also checked at this step. The utility system is assessed through a top-level analysis, i.e., via a study of marginal steam and power generation capacity and costs.

Step 2: Screening and ranking bottlenecks

A systematic screening approach has been used to identify and quantify process bottlenecks at the departmental and mill-wide levels. A bottleneck ranking diagram (BRD) is adopted to map each individual department's production capacity vs. the global target and to classify the departmental relevance for debottlenecking, as illustrated in **Fig. 2**.

In order to generate this diagram, the mill's historical data covering approximately one year of operating time is collected and analyzed to identify the best, stable (for at least few days) high-production operating periods. These periods are used to establish the maximum operating capacities of each mill department. The capacity of each department has to be expressed as equivalent metric tons of pulp produced at the machine to allow comparison between departments on the same basis.

Converting factors are defined for each department as a ratio between the key characteristic measure of each department and the pulp machine production. For example, the ratio of dry solids sent to the recovery boiler per metric ton of pulp produced at the machine has been used to define the recovery boiler's capacity. The ratio of weak black liquor flow sent to the evaporators per metric ton of pulp produced has been considered to represent the evaporators' capacity



2. Simplified bottleneck ranking diagram (BRD) (t/d: metric tons per day).

(as equivalent metric tons of pulp production). Converting factors are calculated based on average values for long operating time periods as a way to mitigate the variability (including pulp and black liquor inventory variability, process lags, and operating condition variability) of these factors due to process dynamics. Moreover, the capacity levels observed during the best-demonstrated period of operation are cross evaluated with the equipment design specifications to define the true maximum production capacity.

Once the capacity of each department is expressed as equivalent pulp production at the machine, they are presented in a bar chart as shown in Fig. 2. The visualization of the base line and the targeted production together with the maximum capacity of all the other mill departments provides a fast and global representation of the current status of the mill's existing assets and the scope for debottlenecking.

Figure 2 illustrates a simplified BRD with a 1000 metric tons per day (t/d) baseline production and 1100 t/d targeted production. In this example, the pulp machine appears to be the immediate constraint for pulp production increase, followed closely by the evaporator, with only 20 t/d extra capacity vs. the baseline, and the recovery boiler with 30 t/d extra capacity vs. the evaporator. The bleaching department seems to have enough production capacity to meet the targeted production. For simplification, the departments with higher production capacity are not represented in Fig. 2.

This graph effectively guides the next steps of the work by pointing out which departments need further diagnostics and assessment to identify the main limitation (the true cause of bottlenecks). In this case, debottlenecking priority needs to be given first to the pulp machine area and second to the evaporator and recovery boiler departments.

Energy system components (power boiler, cogeneration capacity) should also be part of the bottlenecking assessment, especially when a mill is exploring long-term strategies to diversify production while adding new process units/technologies on site.

Step 3: Process performance diagnostic

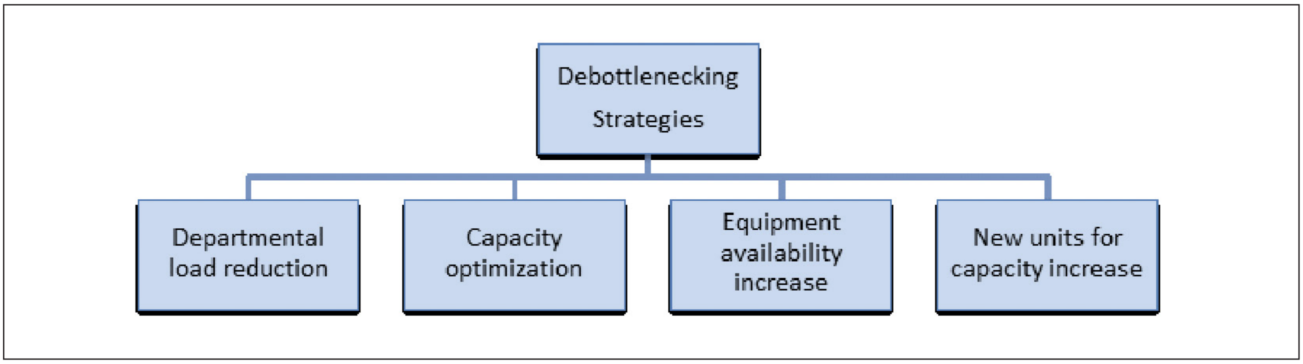
Focusing on the critical department(s), the process performance diagnostic is deepened via an analysis of plant data and KPIs. More precisely, by using a gap analysis and benchmarking, the main inefficiencies are pinpointed for further consideration and improvement. The KPIs and key operating data for critical departments are collected and compared to reference performance values towards scoping the potential for improvements as later illustrated in the case study. A multivariate data analysis is used to identify the optimal operating values for key operating parameters.

Operating parameters are selected and their historical data are collected and pre-processed (removal of noisy, non-representative, and misleading data). Further on, KPIs describing the process operation are defined and a principal component analysis is performed to identify the influential variables.

Generic root-cause diagrams are developed for each mill department. These diagnostic trees are used to navigate the process system interactions, from apparent inefficiencies or departmental bottlenecks to their relevant sources (which can be in other departments). This diagnostic analysis embeds process knowledge and data-driven analysis to effectively relate the specific bottlenecks with the actual limitations. The heat exchanger network diagnosis is also addressed at this step. An illustrative example of a root-cause tree is presented later in the case study.

Step 4: Establishing improvement solutions

Different debottlenecking strategies for each bottlenecked department have been analyzed, and specific project improvements have been identified to facilitate the application of the proposed approach. A decision tree is developed for each department, including opportunities for capacity increase and energy efficiency improvements (see case study for examples). The main strategies considered for overcoming production limitations are departmental load reduction, capacity optimization, equipment availability increase (reliability and maintainability), and capacity increase by adding new units (**Fig. 3**). Three levels of change are proposed for each debottlenecking strategy based on capital requirements: operational improvements at low cost, retrofit design changes for medium cost, and process modifications with large capital expenditure.



3. Debottlenecking strategies.

In regards to the utility system and the mill water-energy network, a simulation-optimization model is used to develop and examine energy efficient operating strategies for each successive process change. Each debottlenecking strategy embeds a review of energy system implications. Specific variations or changes to the thermal conditions of all the process streams as a result of debottlenecking are incorporated in the heat exchanger network optimization to mitigate any potential adverse effects on the steam consumption.

Step 5: Implementation roadmap

The selection and prioritization of the projects depend on the mill pulp production target, the potential of each opportunity for production capacity increase, contribution to the operating cost (consumption of energy, water, and chemicals), environmental impacts (water, GHG emissions), and capital costs. In order to characterize each opportunity for decision support, the cross effects among opportunities together with the impacts on process performance and resource utilization are addressed through process modeling and simulation.

Overall, this methodology aims to respond, in a practical way, to the main challenges of optimizing the mill's existing assets at the level of process operations (as low-cost projects) and process design for higher production capacity and enhanced energy efficiency.

Increasing energy efficiency in production processes is essential to reduce environmental impacts of pulp and paper mills. Debottlenecking production processes is a promising approach that allows the effective utilization of existing assets with a reduction of the specific energy utilization (GJ/t). In most cases, increasing production with existing assets allows a considerable decrease of specific energy usage.

A case study is used to illustrate the application of the proposed methodology in a kraft pulp mill, highlighting several opportunities for debottlenecking black liquor evaporator, pulp machine, and brownstock washing processes. This case study shows that a significant production increase could be achieved at low cost through an effective process debottlenecking.

CASE STUDY

A kraft mill in Canada producing about 950 t/d bleached pulp (with best operation reaching up to 1000 t/d) was used to illustrate the proposed debottlenecking methodology. In the first step, mill data and process operation conditions were collected to build the preliminary simulation model and characterize all mill departments. As an initial step, discussions with the mill's personnel were also conducted (based on a detailed audit questionnaire) to better understand the current situation and define the mill's debottlenecking scope. A 10% production increase target was set by the mill's management, with a request to focus on identifying low-cost debottlenecking opportunities.

Step 1: Scope analysis for debottlenecking

During this mill-wide scoping step, the mill reported recent modernization projects that were implemented to increase the digester production throughput; however, only a small production increase was achieved, as the pulp machine and the black liquor recovery system subsequently became the limiting departments. Other capacity issues were encountered at the utility and effluent treatment systems. The mill was also interested in cost reduction projects (chemical, energy, and water reduction), and it was open to the idea of product diversification if such an opportunity could be identified.

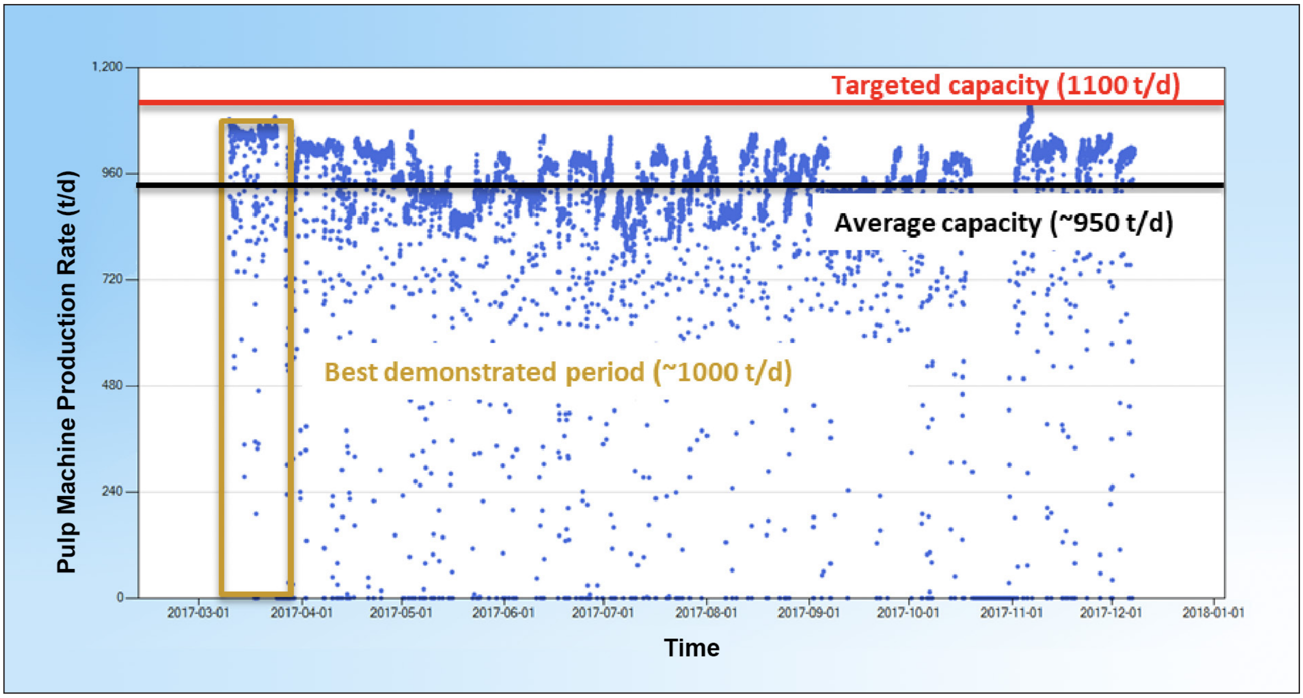
Step 2: Screening and ranking bottlenecks

In the second step of the study, each department capacity was assessed in further detail. The maximum operating capacity for each department was derived from an historical data analysis using the EXPLORE software [42]. For each department, the capacity levels observed during the best-demonstrated period of operation (at least three days of sustainable high-capacity operation) were identified and cross evaluated with the equipment design specifications to define the true maximum production capacity. **Figure 4** illustrates that the pulp machine's capacity is 1000 t/d during its best operating period. Maximum pulp production capacity for each department was set using a similar approach, while accounting for departmental converting factors as defined in the Methodology section (e.g., equivalent pulp production at the recovery boiler has been defined using the ratio between dry solids flow to the recovery boiler per metric ton of pulp produced at the machine).

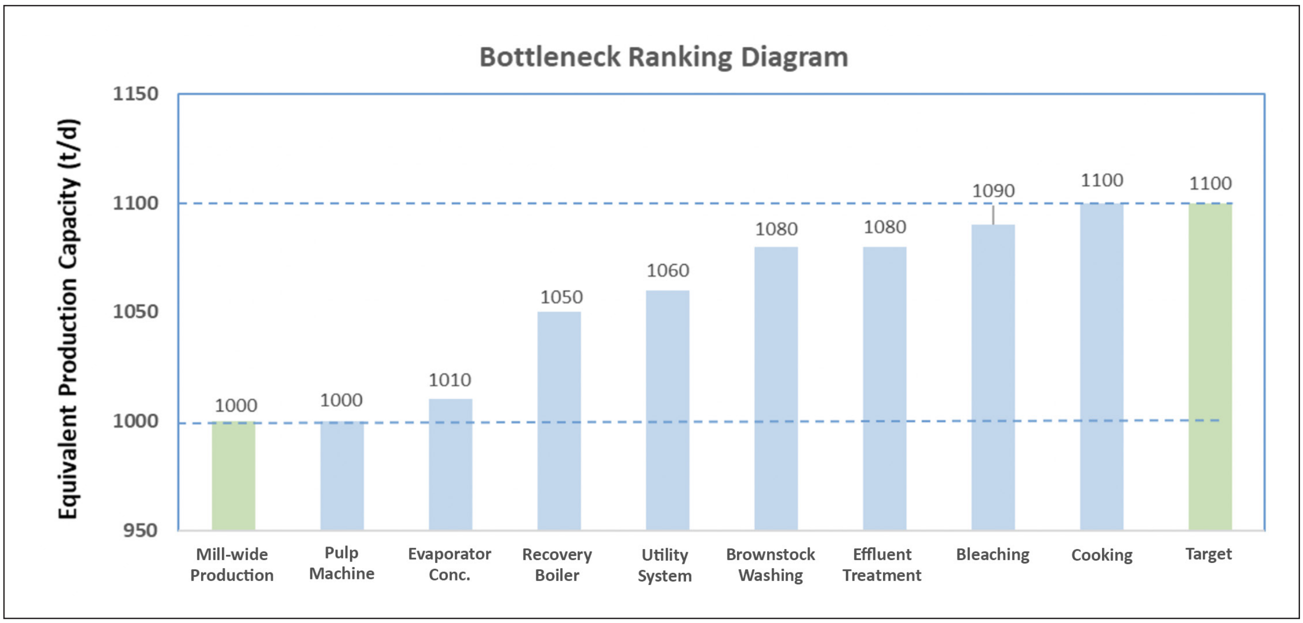
As presented in the Methodology section, the BRD (**Fig. 5**) is used to provide a global representation as well as classify and rank all the departments with deficit (mill bottlenecks) and surplus capacity in relation with the current and targeted mill production. The mill's BRD indicates that there are multiple bottlenecks in this mill. It confirms the mill's perception on the critical bottleneck at the pulp machine (PM), and also highlights a few other bottlenecks that need to be corrected. The evaporation capacity has to be addressed, followed by the recovery boiler. Small capacity limitations are observed at the brownstock washing and bleaching departments, but low-cost operational projects could be sufficient for debottlenecking these departments. Further on, the BRD illustrates a lack of capacity at the level of utility and effluent treatment systems (that would require energy and water saving projects for debottlenecking).

Step 3: Process performance diagnostic

An in-depth process knowledge is crucial at this step in order to identify and pinpoint the actual root causes of the process bottlenecks. The identification of the true root causes is required to distinguish between the apparent and



4. Best operating time — pulp machine illustration.



5. Bottleneck ranking diagram.

real process bottlenecks and to guide the debottlenecking efforts towards the real source of inefficiency/capacity limitation rather than trying to overcome the issues at the end-point/impacted department.

In accordance with the BRD (Fig. 5), the initial focus should be on the pulp machine. The pulp machine has a Fourdrinier forming section, a three-press section, and a Fläkt airborne dryer. A detailed gap analysis on the KPIs and key operating parameters for the pulp machine has been conducted to define the scope and improvement potential (see benchmark values in **Table I**).

A multivariate data analysis was performed for each section of the pulp machine using CanmetENERGY's EXPLORE software [42]. The analysis has led to the identification of the optimal value for some operating parameters (see reference values in Table I). More specifically, the analysis revealed that the steam pressure valves are fully open in the dryer, confirming that the pulp machine is dryer capacity limited. Therefore, projects that decrease dryer steam demand would contribute to higher

Key Performance Indicator	Current Value	Benchmarking Value
PM specific steam consumption, t_{steam}/t_{pulp}	1.08	0.85
Dryer steam demand, t_{steam}/t_{pulp}	0.95	0.75
PM specific water consumption, m^3/t_{pulp}	6.25	4.80
Availability	85%	90%
Couch roll consistency	23%	26%
Last press consistency	43%	45%
Key Operating Parameter	**Current Value**	**Reference Value**
Pulp consistency at headbox	1.45%	1.60%
Basis weight, g/m^2	920	950
Temperature at shower water, °C	70	65
Steam box specific flow, kg_{steam}/t_{pulp}	130	150
Vacuum level in the vacuum press (in Hg)	18.5	21
Vacuum level in the couch roll (in Hg)	17	19

I. Pulp machine (PM) gap assessment.

machine production capacity. This mill operates with higher steam and water consumption at the pulp machine, compared to benchmarking values for similar mills. The equipment availability can also be improved by reducing pulp web breaks and machine downtimes; furthermore, insufficient dewatering at the forming section of the machine has been observed, as the current operating consistency at the couch roll is below benchmark. In addition, sub-optimal conditions for several related operating parameters indicate a potential for a few other control improvements. The available extra capacity in the vacuum system has been considered for improving dewatering and contributing to the drying load reduction.

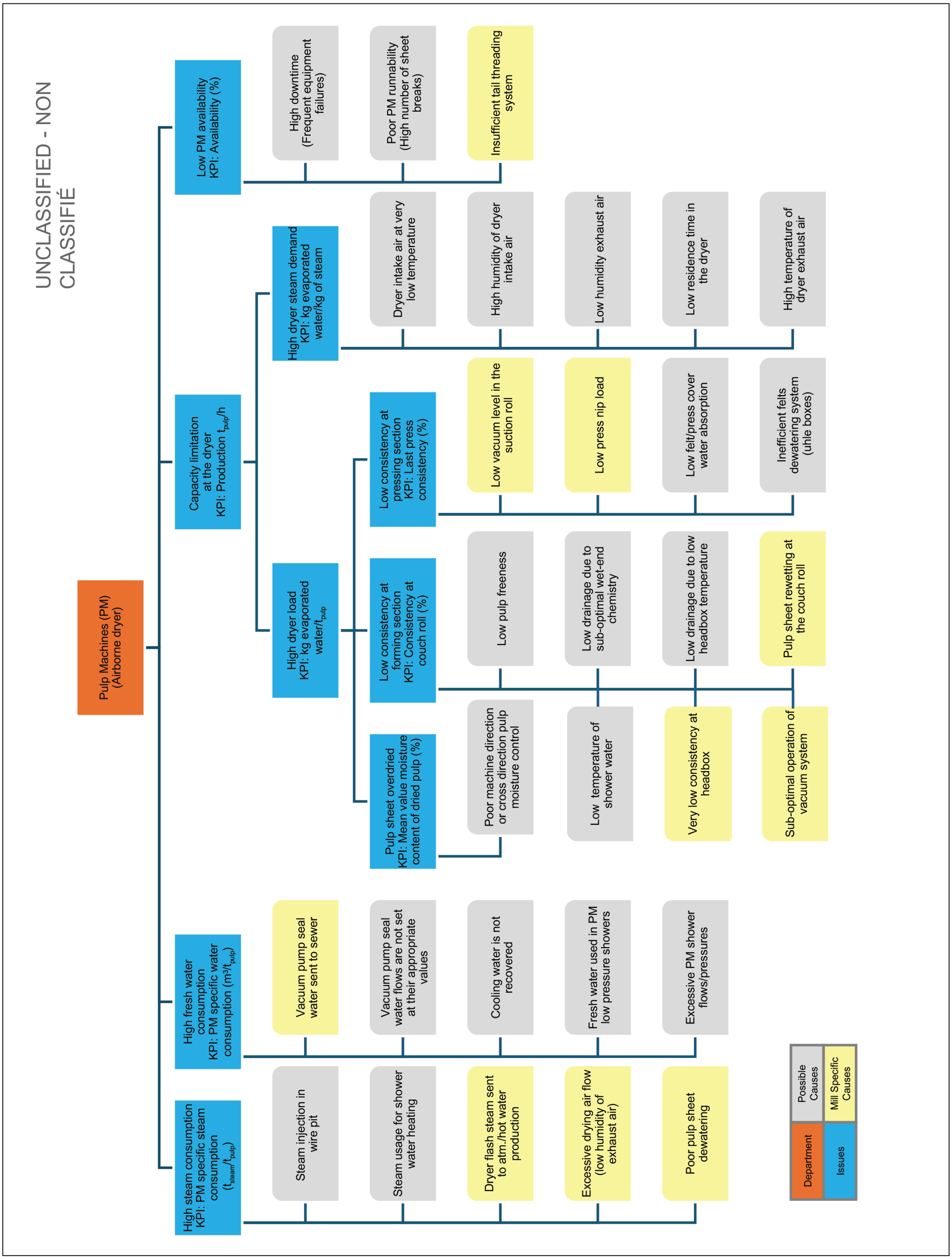
According to the pulp machine gap assessment presented in Table I, the main performance issues are high pulp machine steam and water consumption as well as higher dryer load and steam demand, increasing the steam requirements from the utility system. The following root causes were identified during the causality analysis: dryer flash steam lost to atmosphere; low air recirculation in the dryer due to many decommissioned fans; poor pulp sheet dewatering, which negatively affects the dryer steam consumption; unrecovered vacuum pump seal water leading to higher water consumption; too low headbox consistency; sub-optimal vacuum system operation; pulp sheet rewetting at the couch roll; low vacuum level at the suction roll; low pressure nip load; and an inefficient tail threading system. All of these root causes contribute to production time losses (**Fig. 6**).

Four main debottlenecking strategies have been considered for optimizing the pulp machine capacity: 1) dryer load reduction; 2) dryer capacity optimization; 3) equipment availability increase, and 4) dryer size increase. Knowing the main reasons that limit the machine capacity, specific projects have been developed for each strategy. As requested by the mill, priority has been given to operational improvements to keep the investment cost to a minimum; therefore, dryer load reduction including headbox consistency increase, vacuum system optimization, steam shower flow optimization, nip load maximization, and vacuum level increase (**Fig. 7**) have been selected as part of the low-cost improvement solutions. Vacuum pump seal water recovery has also been considered to lower the mill's water consumption. Energy savings can be achieved by enhancing the dryer condensate flash steam system and the recovery of flash steam for steam showers. The proposed debottlenecking projects decrease the dryer load by reducing pulp sheet moisture at the last press and optimizing dryer operations.

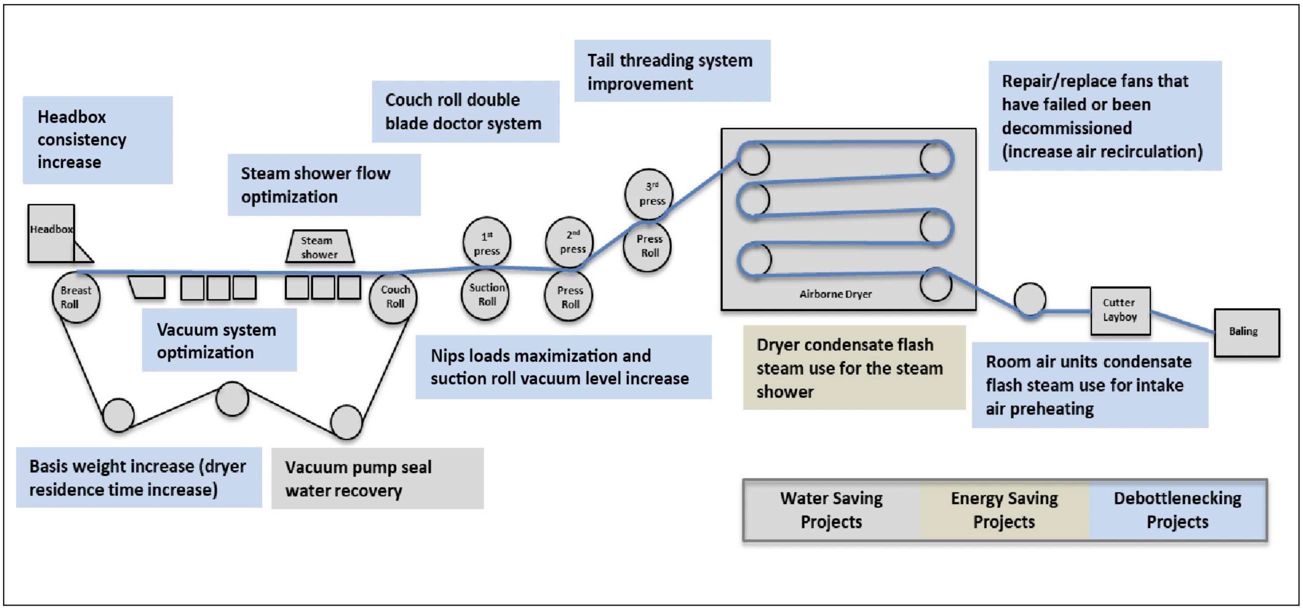
The preliminary impact analysis indicates a potential to increase production by up to 6.5% from operational improvements of the pulp machine, with additional benefits on water, energy, and GHG reductions (**Table II**). Additional retrofit and revamping projects, with medium to large investment costs, can be considered to reach a higher pulp machine capacity matching a production increase target of 10% (**Fig. 8**).

Step 4: Establishing improvement solutions

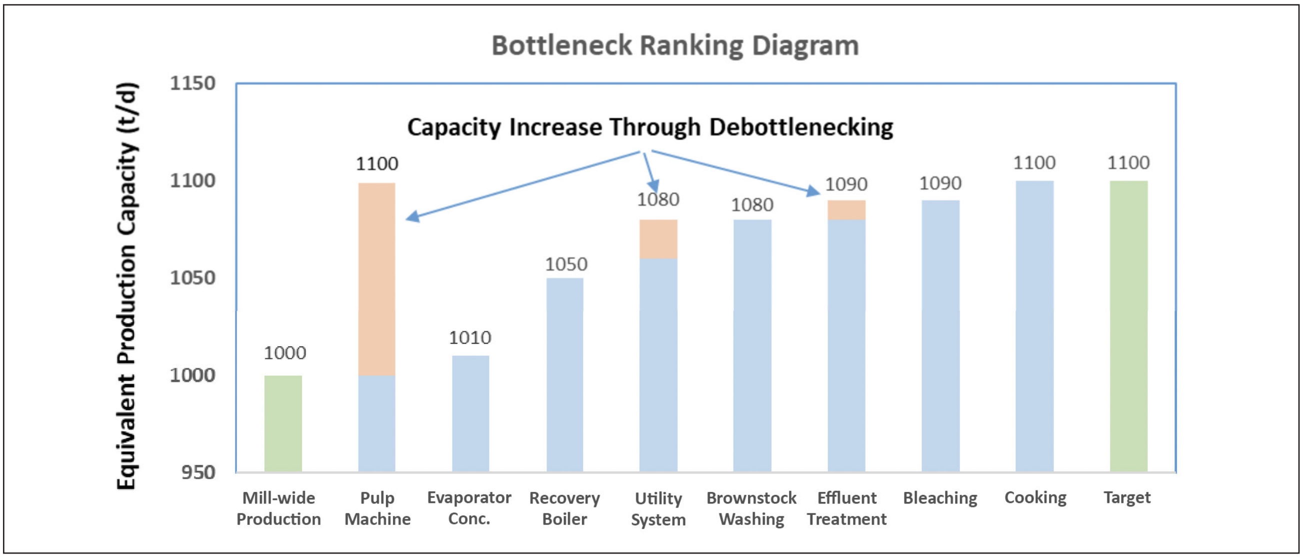
Data analysis, preliminary mass and energy balances, and results from mill trials were used to estimate the impacts



6. Root cause tree diagram for pulp machine (simplified).



7. Overview of pulp machine debottlenecking opportunities.



8. Bottleneck ranking diagram (BRD) after pulp machine improvements.

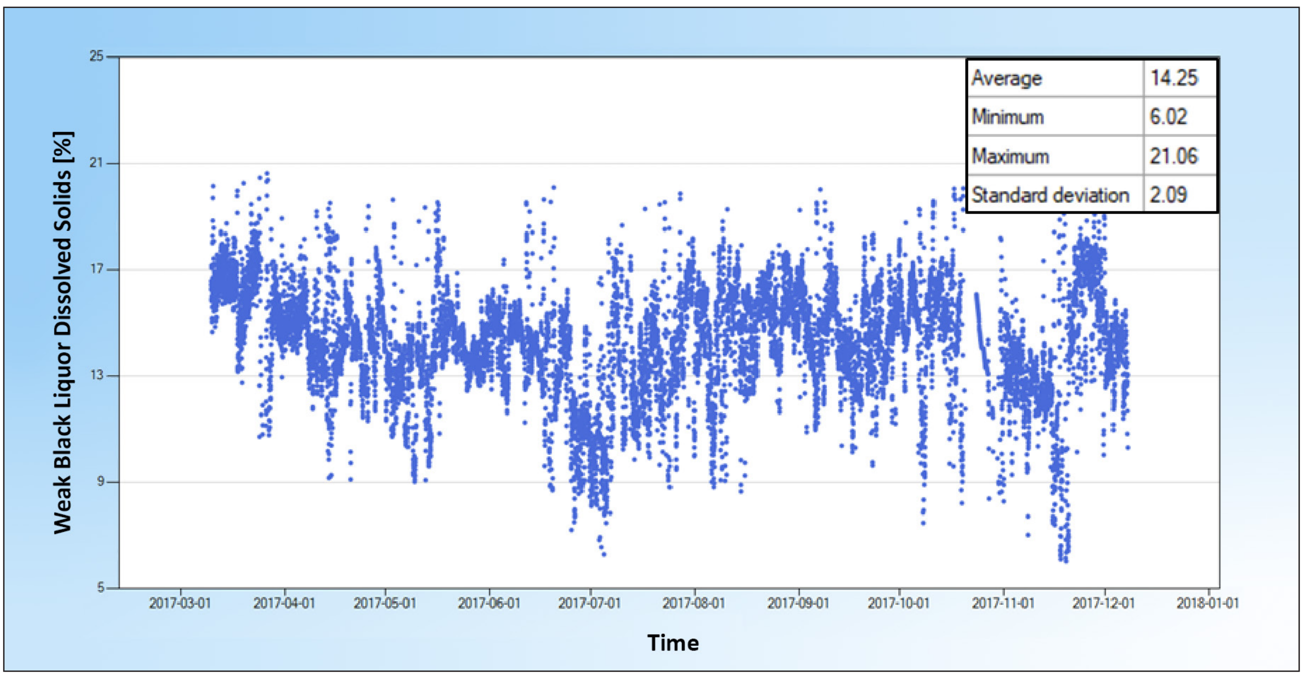
of the proposed projects. Further specific trials for operational projects and detailed engineering on key selected retrofit projects would have to be performed prior to implementation. Although many of these project ideas may be applicable to other mills, the final set of debottlenecking solutions is unique and mill specific, given the large variations and differences of equipment design and operation, product portfolio and resource availability, utilization, and costs.

In this case study, a significant 6.5% pulp machine debottlenecking could be achieved through low- or no-cost capital expenditure (CapEx) projects. Such cost-effective debottlenecking solutions would easily help overcome the economic challenges involved in the implementation of a project and accelerate its application. Once the pulp machine bottlenecks were analyzed and debottlenecking solutions identified, the same methodology was used for the evaporator and the recovery boiler as the next limiting departments.

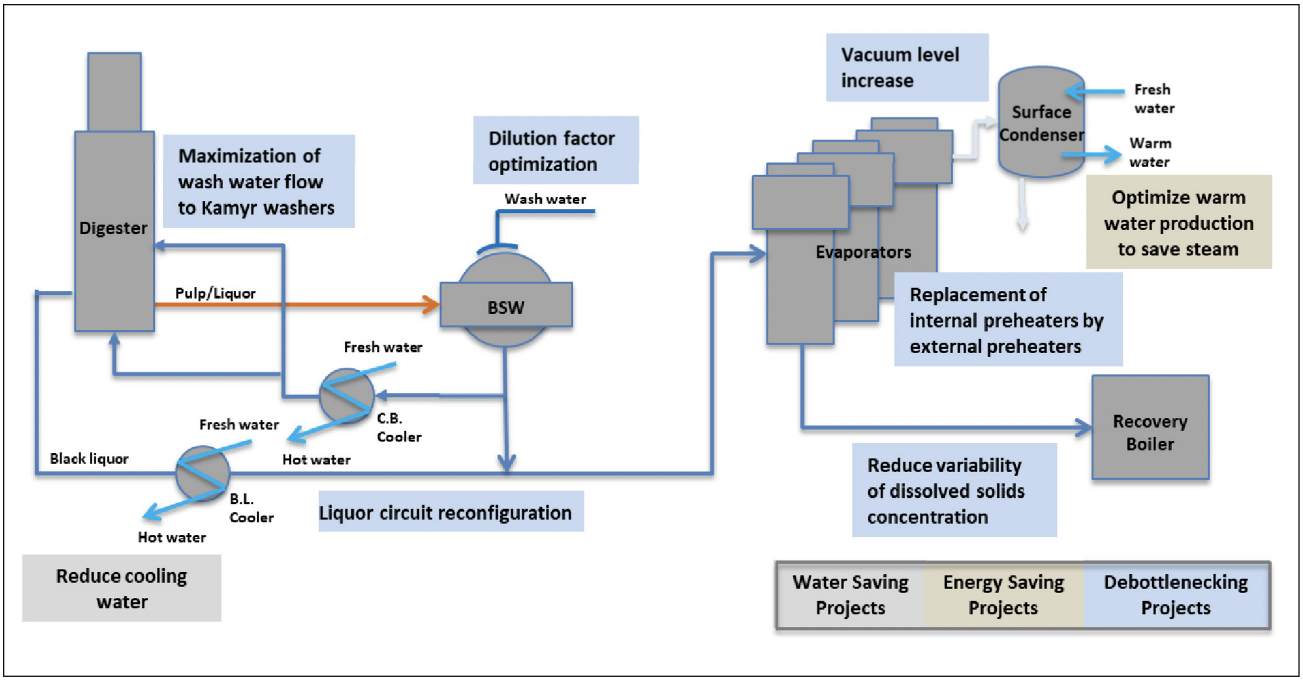
The evaporator capacity is not sufficient to process and concentrate all the weak black liquor to the desired solids level (70% or higher) if production is increased above 1010 t/d. At the diagnostic step, it was observed that the weak black liquor concentration was relatively low, with high variability, as shown in **Fig. 9**. A root cause analysis indicated that a sub-optimal operation of brownstock washing and the inefficient management of the weak black liquor/filtrates were the main causes of this issue. Brownstock

Proposed Project	Project Type	Expected Production Increase	Capital Investment	Energy Savings t_{steam}/t_{pulp}	Other Benefits
Headbox consistency increase	Operational	~ 0.5%	–	< 0.01	GHG reduction
Basis weight increase	Operational	< 0.5%	–	< 0.01	GHG reduction
Vacuum system optimization	Operational	~ 2%	–	~ 0.02	GHG reduction; improved PM runnability
Steam shower flow optimization	Operational	~ 0.5%	–	< 0.1	GHG reduction; improved PM runnability
Nip loads maximization and suction roll vacuum level increase	Operational	~ 3%	–	~ 0.03	GHG reduction
Couch roll double blade doctor system	Retrofit	~ 1.5%	Low	~ 0.015	GHG reduction; improved PM runnability
Tail threading system improvement	Retrofit	~ 2%	Moderate	–	GHG reduction; improved PM runnability
Failed or decommissioned fan replacement/repair	Retrofit	< 0.5%	Moderate	< 0.1	GHG reduction
Room air unit condensate flash steam use for intake air preheating	Retrofit	< 0.5%	High	~ 0.05	GHG reduction
Dryer condensate flash steam use for steam shower	Retrofit	–	Moderate	~ 0.10	GHG reduction
Vacuum pump seal water recovery	Retrofit	–	Moderate	–	1.45 m^3/t_{pulp} water savings

II. Debottlenecking project impact; preliminary estimates for pulp machine (PM) debottlenecking (GHG: greenhouse gas).



9. Weak black liquor concentration — high variability.



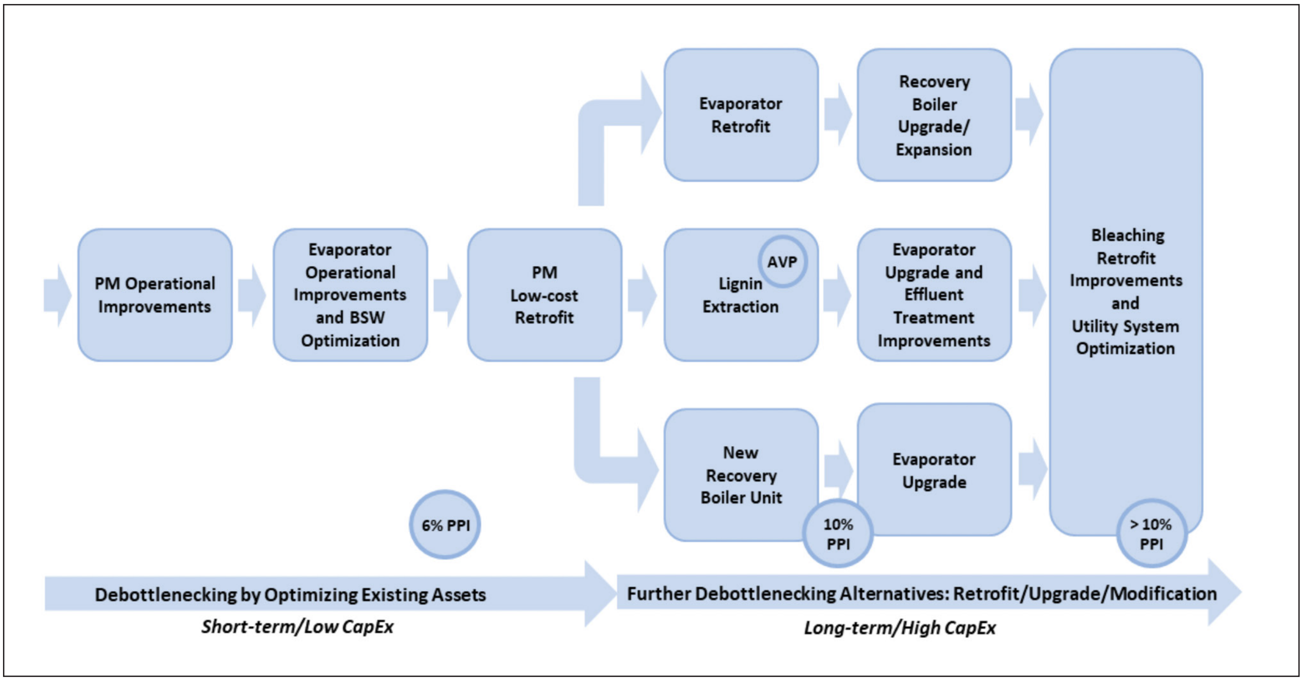
10. Brownstock washing (BSW) and evaporator projects.

washing is a complex process operation that highly influences other unit operations along the fiber line; likewise, brownstock washing performance affects the chemical recovery cycle by its design and operation efficiency. A multivariate data analysis confirmed that wash water flow was having a direct impact on black liquor evaporator energy consumption, while dissolved solids recovery efficiency affects the recovery boiler steam production and chemical consumption in several departments (bleaching, wastewater treatment, makeup chemical cooking).

An automatic dilution factor control system was proposed (**Fig. 10**) to reduce the weak black liquor concentration variability and increase its solids concentration, contributing to debottlenecking the evaporators. The evaporators' operation could be further improved by optimizing the evaporator surface condenser vacuum level. It was proposed to adjust the primary condenser cooling water temperature set point to reach a better trade-off between evaporator capacity and the final cooling water temperature. As the evaporator cooling water is one of the main sources of process warm water, its temperature can have a direct impact on the steam consumption for hot water production. Overall, the proposed approach allowed an increase in the evaporator capacity per metric ton of pulp, while transferring concentrated black liquor at a slightly higher dissolved solids concentration to the recovery boiler. A higher solids concentration in the firing liquor, combined with the optimization of the combustion air system, would increase the recovery boiler capacity. Installing advanced soot-blowing controls has also been recommended to reduce heat transfer surface fouling. Such improvements would extend the period between cleaning outages and increase the temperature of the steam leaving the superheater. These improvements also contribute to increasing the recovery boiler production capacity and also allow a small increase in power generation in the back-pressure turbines. The proposed measures would result in up to 5% increase in throughput at the evaporator and similar debottlenecking potential at the recovery boiler. This would be sufficient to reach the increased capacity that can be obtained at the pulp machine dryer through the proposed debottlenecking strategy (pulp production of 60 t/d, or 6% total).

Step 5: Implementation roadmap and major capital projects

The case study demonstrated that operational improvements combined with low-cost retrofit projects are highly effective in unlocking relevant capacity and improving asset utilization. Short-term solutions to increase the overall mill production by up to 6% through operational improvements were proposed and mostly implemented at the mill. However, as advanced control was implemented and process variability was minimized through the optimization of system interactions across departments, these projects were not sufficient to achieve the targeted debottleneck, and high CapEx additional investments were highlighted as required to achieve further capacity increase. Therefore, the remaining 4% gap to reach the targeted capacity would require additional evaporator capacity within the chemical recovery loop. Three main conceptual pathways, notably evaporator retrofit, lignin extraction, and new recovery boiler unit, were considered to increase capacity to 10% while creating opportunities for new added-value products



11. Potential roadmap (PM: pulp machine; BSW: brownstock washing; PPI: pulp production increase; CapEx: capital expenditure; AVP: added-value product).

(**Fig. 11**). These high CapEx pathways were, however, not detailed in this study. As a preliminary recommendation, the state of the current equipment (age, scaling, corrosion levels, and maintenance needs) and the related economics for improvement were selected as key factors highly influencing the pathway selection.

The lignin extraction pathway was considered the most effective way to debottleneck the recovery boilers and provides an opportunity for added-value products from lignin. This major capital project would open the opportunity to develop new lignin-based added-value products and diversify the mill's product portfolio; the capacity of the evaporators, however, would have to be increased beyond what can be achieved with operational improvement projects alone. Several other bottlenecks in the pulp line would also have to be addressed to obtain the maximum benefits of a lignin extraction project. Due to the large investment required, this project was not prioritized by the mill at this point but will be revisited in the future.

In addition to the debottlenecking solutions discussed previously, bleaching process and utility system improvements would be required if a higher pulp production increase is expected. However, this was not analyzed in this study.

CONCLUSIONS

Process debottlenecking and mill asset optimization should be seen as a strategic approach that goes beyond the throughput increase. Ideally, effective debottlenecking should enable a plant to achieve new production targets and simultaneously reduce its overall specific energy, water, and chemical consumption; moreover, the retrofitted or revamped process(es) should meet current regulations, as well as potentially more restrictive air emission and effluent regulations in the future. The project implementation sequence needs to meet short-term plant priorities while sustaining the long-term vision for retrofitting and upgrading.

This paper presents a site-wide system approach to assess the current process performance, identify inefficiencies, and propose projects to increase mill production and profitability in the pulp and paper industry. Process knowledge, data analytics and system interaction analysis are integrated together to identify the source of inefficiencies. This enhances the selection and sequencing of improvement projects in a cost-effective manner. To further improve the energy efficiency of the global solution, strategies for increasing waste heat recovery and optimizing utility systems are embedded in the methodology.

Understanding the mill-wide system interactions, operating conditions, constraints (flow and temperature limits), and maintenance issues is essential to identify the actual bottlenecks and their true root causes. Mill performance optimization and debottlenecking need to account for the overall process chemistry, starting with feedstock characterization (wood species composition, chip quality) and evaluating their implications and complex interdependencies, which ultimately influence downstream performance and process loading. This global debottlenecking approach, enriched with data-driven modeling and effective energy system optimization, is recommended for mills looking at increasing production and improving overall efficiency.

Data analysis (using the EXPLORE software in this case) is pivotal to the proposed methodology, notably to characterize maximal departmental capacities, to compare them against specific KPIs and to diagnose process variability around bottlenecked equipment for effective operational improvements.

The study proved that effective debottlenecking could provide significant value by leveraging the existing asset potential at low cost, before any high CapEx retrofits and debottlenecking upgrades are considered for long-term mill transformation strategies.

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About this journal

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This topic of research aligns with the mandate of our organization, which is dedicated to industrial systems optimization and decarbonization, energy efficiency, and natural resource optimization. The research presented here provides a systematic approach to identify and evaluate process bottlenecks and their related potential to increase pulp production, optimize existing assets, and recommend strategies for mitigating capacity limitations and impacts on resource utilization.

The most challenging aspect of this research was navigating the complex interconnections between each step of the production process and the cross-effects that affect the global production capacity. To address this, we conducted literature reviews, consulted with experts in the field, and employed advanced data analysis and modeling techniques to characterize the system interactions and define bottlenecking mitigation strategies.

One of the most interesting aspects of our findings was proof of the benefits of integrating the process knowledge, data analytics, and system interactions analysis to identify the sources of process inefficiencies and to guide the selection of debottlenecking and improvement projects.

Mills can benefit from the information presented here by gaining insights into critical capacity-limiting departments and the challenges associated with process debottlenecking. This knowledge can inform decision-making, enabling mills to develop well-planned debottlenecking strategies and to retrofit or revamp processes so they meet current requirements while remaining adaptable to future objectives.

Our ongoing research will focus on refining our approach, combining it with modeling techniques, and exploring additional avenues for the kraft mill of the future. This will involve developing new technology models, simulating their integration, and assessing their impact on improving the efficiency and sustainability of kraft mill systems. Additionally, economic aspects will be incorporated into the analysis to provide a comprehensive understanding of the potential benefits and implications of these advancements.

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