Systematic Equipment Performance Analysis of Canadian Kraft Mill Through New and Adapted Key Performance Indicators

Doctoral Consortium Contributions

Radia Ammara, Louis Fradette and Jean Paris

Department of Chemical Engineering, École Polytechnique de Montreal, Montréal, Canada

1 RESEARCH PROBLEM

Lower paper prices and demand, external competition and high energy and chemical costs have caused economic problems for the Canadian pulp and paper industry. As a result to this precarious situation, significant efforts are being undertaken to transform the pulp and paper industry into an efficient a profit-oriented industry. A pioneer solution to address this issue is the retrofitting of biorefineries into existing mills. This alternative helps P&P mills diversify their product portfolio and generate new revenues. However, this implementation requires additional supply of energy. Thus, a key step to be undertaken before implementation of a biorefinery option is the optimization of a mill with respect to energy and material. Several process integration (PI) techniques such as pinch analysis or mathematical optimization showed interesting results when applied in methodological way to a P&P mill (Kermani et al., 2014). However, these integration or optimization techniques implicitly assume that the unit operations and equipments in place operate efficiently and as intended to (Moshkelani et al., 2013), which is often not the case in a real Kraft mill. On the other hand, there is no incentive in seeking to optimize a process, when it does not fairly represent the real system. The results of the optimisation technique are in this case biased and not trustworthy. Equipment performance analysis is a necessary prerequisite step to be undertaken prior to any optimization or enhancement measure. The assessment of equipment performance applied in a strategic and methodological way using adapted key indicators can help identify areas with poor efficiency, diagnose the causes of inefficiencies and propose improvement projects with low investment cost and that can significantly reduce the operating cost of the mill (Keshtkar, 2013); (Mateos-Espejel et al., 2010a); (Mateos-Espejel et al., 2010b); (Mateos-Espejel et al., 2011a); (Mateos-Espejel et al., 2011c).

2 OUTLINE OF OBJECTIVES

The main objective of this research study is to develop a strategic methodology to evaluate the performance of unit operations using new and adapted key performance indicators. The systematic approach allows to:

- Systematically identify areas and equipments with poor performance from the perspective of energy, water and raw materials utilization, through the use of new and adapted key performance indicators.
- Diagnose effectively the causes of inefficiency. More than one KPI will be used to characterize the unit operation and thus allowing a better understanding of performance.
- Propose improvement projects to address the found inefficiencies.

At the end o this research study, a practical step by step guideline will be provided to the mills managers to help them characterize their unit operations, analyse their energy efficiency, examine their utilization of material and resources and diagnose the performance of key unit operations with more than one KPI for the purpose of overall performance monitoring, control and enhancement.

3 STATE OF THE ART

Pulp and Paper industry ranks fourth in terms of energy consumption among industries worldwide. Globally, in 2007, the P&P industry accounted for approximately 5% of total world industrial final energy consumption. The pulp and paper industry produces various types of pulp from virgin materials (wood and non-wood) and recycled materials (waste paper) that are subsequently processed into paper produced in either integrated or non-integrated mill.

The Kraft process is the prevalent pulping

Ammara R., Fradette L. and Paris J..
Systematic Equipment Performance Analysis of Canadian Kraft Mill Through New and Adapted Key Performance Indicators - Doctoral Consortium Contributions.

process in North America because of its closed loop recovery of pulping chemical and its strong and bright produce. A simplified schematic of the Kraft process is shown in figure (1).

Kraft process consists of two main parts: a paper line and a chemical recovery line. The paper line is composed of four departments: digesting where the woodchips are cooked, washing, bleaching and chemical preparation where the remaining lignin is removed from the fibers, and finally the paper machine.

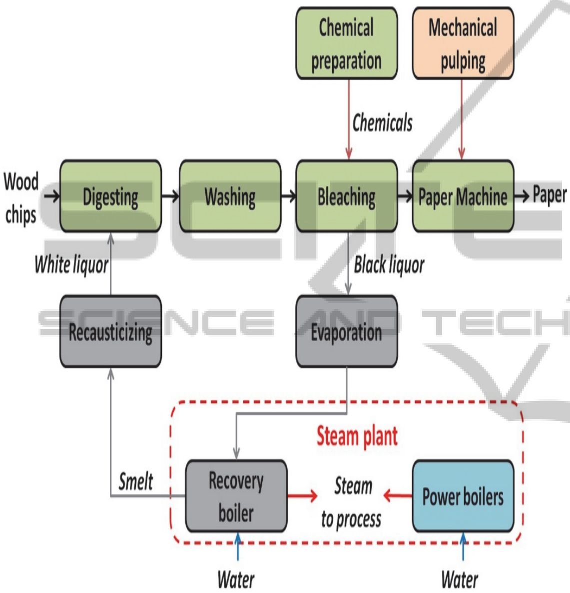

Figure 1: Simplified diagram of the mill Kraft process.

The core of the Kraft process is the chemical digester (also called cooking vessel) in which the individual cellulosic fibers are separated from lignin to form pulp. A series of counter-current washers is used to separate the black liquor from the fibers in the washing department. The purpose of bleaching is to remove the leftover lignin and brighten the fibers. Modern bleaching is achieved through a continuous sequence of process stages using different chemicals and conditions in sequence. The bleached pulp is then sent to paper machine. The chemicals used on site are prepared in the chemical preparation department. On the other hand, the chemical recovery line consists of three main departments: evaporation, recovery boiler, and chemical recovery. The weak black liquor (spent cooking liquor coming out of the digester) is concentrated in multi-effect evaporators and then concentrated before being burnt the recovery boiler to produce steam for the process and recover the spent chemicals. The latter is sent to the chemical recovery plant where a series of reactions take place and the white liquor is regenerated and sent back to the digester.

Process integration (PI) is an efficient approach that allows industries to increase their profitability through reduction of energy, water and raw material consumption and thus reducing their operating costs. PI embodies several conventional methods such as pinch analysis, mathematical optimization or hybrid techniques combining both the thermodynamics of pinch and the numerical computations of the mathematical optimization.

The problem of these process integration techniques implicitly assume that unit operations and equipments in place operate efficiently or as intended to (Moshkelani et al., 2013). In reality, this is often not the case. Equipment performance analysis is a necessary prerequisite step prior to undertake any integration measure. However, this prerequisite step of evaluation of the process is either simple or nonexistent in the actually available and published Kraft or integrated biorefineries performance enhancement/optimization methodologies. There are no clear guidelines on how to define a base case and how to evaluate a process for complete performance efficiency in terms of energy and resources utilization. There is no systematic or strategic methodology for a complete equipment performance analysis. Also, the key performance indicators available and used are not well suited to efficiently identify and diagnose the causes of inefficiencies in the mill, in terms of process performance or energy and material utilization (Villarreal, 2011); (Mateos-Espejel, 2009).

On the other hand, pulp and paper mills have several recycle streams that increase process interactions, which makes conventional pinch analysis or process integration techniques ill-suited. These techniques are applied to tackle energy efficiency without regards to the interactions of the complete process systems. Thus, fail to address the problems or the entire process with its interactions. An equipment performance analysis when strategically developed and applied may consider both specific operating conditions of a unit operation and its interactions with other sections of the process. Many key performance indicators have been developed and applied; however, they evaluate the efficiency of a process or a unit operation by comparing it to other mills and not to their own theoretical maximum efficiencies. These KPIs may be applied as a pre-benchmarking study helping mills managers situate their energy consumption performance comparing to that of other mills. However, the available KPIs do not take into account operating conditions and design parameters. This makes them not very suited for a good performance analysis.

Dimensional analysis is a mathematical system using conversion factor to move one unit of measurement to a different unit of measurement (Langhaar, 1951). The basic idea of dimensional analysis is that physical laws do not depend on the arbitraries in the choice of units of physical quantities. Every physical equation or relation between variables and/or dimensioned constants should be dimensionally consistent. In other words, each term of the equation or relation should have the same dimensions. Dimensional consistency imposes a certain number of constraints that are functional relations between the variables. This constitutes the main principle for dimensional analysis. Manipulating variables to create dimensionless groups or numbers to describe the physical phenomenon has widely been used in the chemical engineering or fluid mechanics field such as Reynolds number (Re) to describe the type of flows in all types of fluid problems, Froude number (Fr), for modeling flow with a free surface, or Nusselt (Nu), Biot (Bi), Peclet (Pe) for heat transfers or Carnot (η) for energy efficiency. Hence, it is a pertinent idea to create performance indicators based on dimensional analysis.

Pulp and paper industries are driven by steam, water and chemicals which makes them suitable for exergy studies. Exergy analysis is a valuable tool to evaluate the efficiency of a process. However, it has not evolved into a systematic method, such as Pinch Analysis or Water Pinch and has not been applied on a real Canadian Kraft mill, in combination with other tools for equipment performance analysis. Moreover, traditional energy studies only consider thermal energy. Exergy analysis considers all forms of energy and also the internal energy of the matter called chemical exergy.

Most published studies on performance evaluation analysis or energy improvement methods are based on computer simulation models. A recurrent problem of process simulation is the lack of explanation or information of how the data, used for all analyses, were gathered or treated. The simulation models are often not based on real reconciled mill data. There is no incentive in seeking to optimize a model, when it does not match the actual behavior of the real plant. A representative model based on reconciled data is a prerequisite step to any optimization or evaluation measure. However, lack of data redundancy in real Kraft mills has made data reconciliation complicated or unfeasible. No data reconciliation of a complete operating Canadian Kraft mill has been published. There have been studies on data reconciliation on Canadian newsprint mills, but never on a real Kraft mill (Bellec et al., 2007); (Jacob and Paris, 2003).

4 METHODOLOGY

To perform a complete equipment performance evaluation, the overall unified methodology shown in figure 8 is developed and applied. It consists of 6 main steps. The first step is to obtain a coherent model simulation that represents a steady-state of the process. To do so, real mill data collection, gross error detection and data reconciliation have been performed. Mill measurements data are collected for a chosen period of time. Since measurements inherently contain random errors due to sensors noise, the mass and balance around unit operations often do not balance. Data reconciliation is an optimization problem that aims to minimize the weighted sum of squared differences between the measured and the reconciled values under constraints that correspond to mass and heat balance (Bagajewicz, 2000); (Leibman et al., 1992); (Maquin et al., 2000); (Maquin et al., 1989). On the other hand, while DR is meant to correct random errors, gross errors due to a sensor failure should be detected first (Maronas and Arcas, 2009). This is done by verifying that all measurements remain within acceptable data range. Many statistical tests have been developed. However, they have never been applied on a real operating mill (Dewulf et al., 2008); (Gong and Wall, 1997); (Gong and Wall, 2001); (Regulagadda et al., 2010); (Sato, 2004). The results of the GED and DR show largely adjusted areas. This helps identify possible process leaks or biases present in the system (Krishnan-Dumitrescu, 2008). DR allows getting a coherent process model that represents a steady-state of the studied mill and also identifies a preliminary list of suspected problematic unit operations. Largely adjusted areas are highlighted for further analysis.

From the coherent steady-state of the process, exergy analysis of individual unit operations and of entire departments of the process has been performed. Exergy is a measure of both quality and quantity of the energy involved in transformations within and across the boundaries of a system. Unlike energy, exergy can be destroyed or lost, and thus unavailable for future transformation with the process system. Hence exergy analysis allows identifying poor energy performance areas and gives insight on how well exergy is used onsite.

Data reconciliation and exergy analysis help target problematic areas. A list of suspect poor performance efficiency equipments is established.

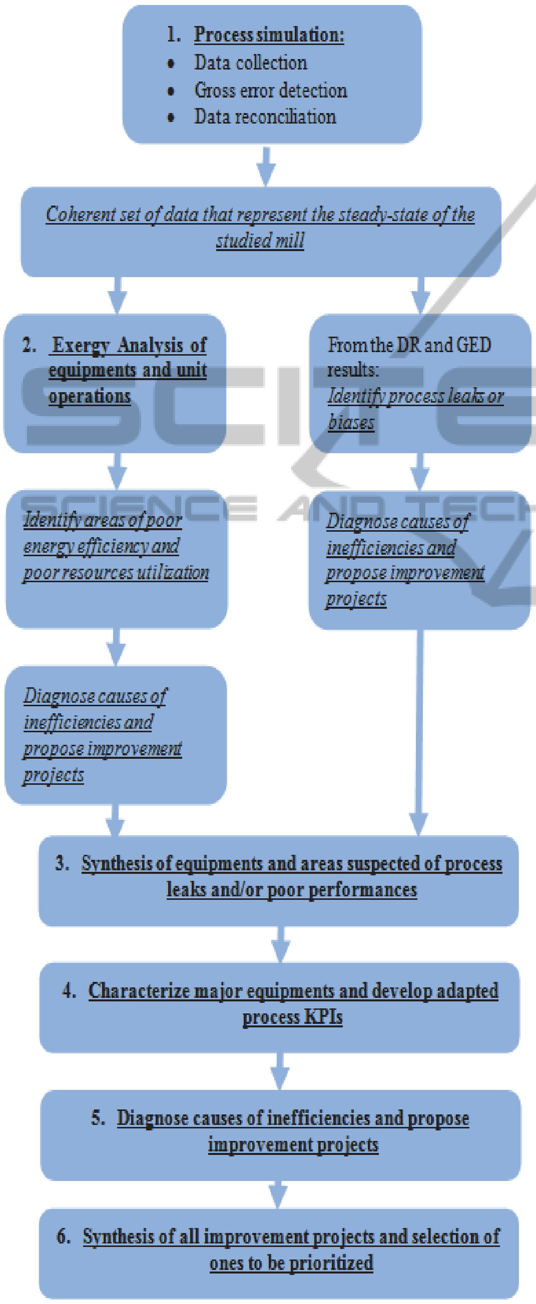

Figure 2: Overall methodology.

Adapted key performance indicators are developed to characterize and describe the process efficiency of the listed suspect equipments. A synthesis of improvement projects is then performed.

A list of priority improvement projects are proposed and recommended to the mills, in order to improve their overall efficiency.

Key performance indicators are developed by doing a dimensional analysis study around each unit operation. More than one KPI is used to describe the performance of the phenomena that takes place in a unit operation.

Figure 1 schematically displays the proposed overall methodology of the PhD study.

5 EXPECTED OUTCOME

Figures 3 and 4 display the results from the three first steps of the methodology. Figure 2 displays the largely adjusted variables in the process after data reconciliation. 53 measured variables have been considered to be able to obtain an observable representative system, suitable for reconciliation. The variables being largely adjusted are gathered around specific unit operations suspected of poor performance efficiency or process leak or biase. Data reconciliation and gross error detection identified the washing and digester departments and more precisely the steaming vessel (in the digester) and the 2 brown stock washers to be inefficient.

DR and GED fail to identify or locate the error without any doubt. It should be combined with other tools to effectively locate the error and diagnose the cause of inefficiency.

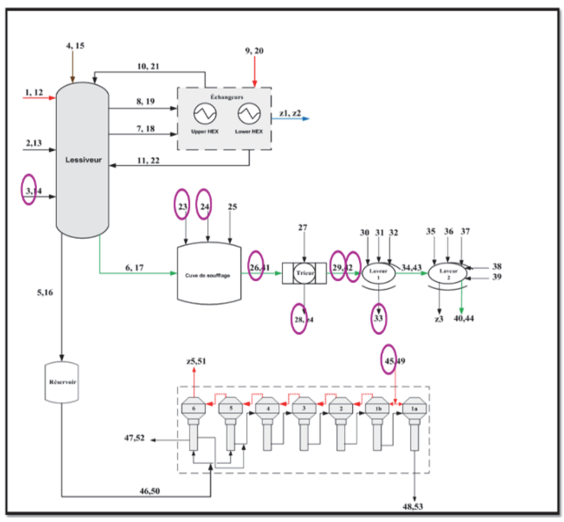

Figure 3: Largely adjusted areas after data reconciliation.

Figure 3 displays the results of the exergy analysis performed around all unit operations and sections of the case-study process. Chemical, electrical and thermal exergies have been considered. Kinetic and potential exergies have been neglected. Exergy efficiency has been defined as the ratio of the exergy of useful output product over the useful exergy input. This definition is very appropriate from engineering and practical point of view as the lost or unavailable exergy is not used within a system and the transiting exergy does not contribute in any exergy transformation and thus should not be considered in the calculation of the efficiency. The digester, washing, recausticizing, bleaching and steam plant departments are areas where energy savings are possible. Exergy destruction could be reduced in the digester and the recovery and power boilers. Exergy lost from the washing and steam plant could be reduced by recovery of the heat content of the effluents and stack gases. This is possible either by PI techniques and/or by combination with the installation of heat upgrading systems.

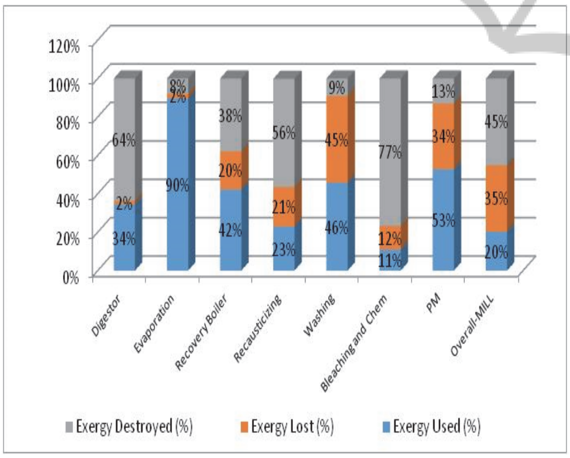

Figure 4: Exergy efficiency per department (%).

The steaming vessel, the brown stock washers 1 and 2, the D_0EOPD_1 bleaching towers, the recovery boiler and 4 power boilers and the clarifiers should be further investigated using more specific and adapted KPIs to diagnose the cause of inefficiencies. This is done in steps 4, 5 and 6 of the methodology.

Dimensional analysis of key equipments gave rise to a number of nondimensional groups with significant physical meaning and that describe the phenomena that takes place in the unit operation. The main characteristics of these non-dimensional groups are that they describe the phenomena looking into account operating conditions and design parameters which makes them suitable for KPIs developments.

At the end of this PhD thesis, practical and adapted KPIs will be developed for all key equipments of the Kraft process. A practical stepwise guideline will be provided for mills engineers to assist them in their equipment performance evaluation.

REFERENCES

Maziar Kermani, Z.P.-L., Marzouk Benali, Luciana Savulescu, Francois Maréchal. *An Improved Linear Programming Approach for Simultaneous Optimization of Water and Energy*. in *24th European Symposium on Computer Aided Process Engineering*. 2014. Budapest, Hungary: Elsevier.

Moshkelani, M., et al., *The forest biorefinery and its implementation in the pulp and paper industry: Energy overview.* Applied Thermal Engineering, 2013. 50(2): p. 1427-1436.

Keshtkar, M.J., *Steam and Water Combined Analysis Integration and Efficiency Ehancement in Kraft Pulping Mills*, in *Chemical Engineering Department*2013, Ecole Polytechnique de Montreal.

Mateos-Espejel, E., et al., *Simulation of a Kraft pulp mill for the integration of biorefinery technologies and energy analysis.* Pulp & Paper Canada, 2010a. 111(3): p. 19-23.

Mateos-Espejel, E., et al., *Systems interactions analysis for the energy efficiency improvement of a Kraft process.* Energy, 2010b. 35(12): p. 5132-5142.

Mateos-Espejel, E., L. Savulescu, and J. Paris, *Base case process development for energy efficiency improvement, application to a Kraft pulping mill. Part I: Definition and characterization.* Chemical Engineering Research and Design, 2011a. 89(6): p. 742-752.

Mateos-Espejel, E.S., L., Marechal, F., Paris, J., *Unified Methodology for thermal energy efficiency improvement: Application to Kraft process.* Chemical Engineering Science 2011c. 66: p. 135-151.

Garza Villarreal, H., *Assessment and Enhancement of the Performance of the Pulp Washing Operation in Kraft Mills*, 2011, École Polytechnique de Montréal.

Mateos-Espejel, E., *Development of a Stratergy for Energy Efficiency Improvement in Kraft Process Based on Systems Interactions Analysis*, P. Montreal, Editor 2009.

Langhaar, H.L., *Dimensional analysis and theory of models*. Vol. 2. 1951: Wiley New York.

Bellec, S., et al., *On-line processing and steady-state reconciliation of pulp and paper mill process data.* PULP AND PAPER CANADA-ONTARIO-, 2007. 108(6): p. 36.

Jacob, J. and J. Paris, *Data sampling and reconciliation: application to pulp and paper mills. Part: I*

methodology and implementation. Appita journal, 2003. 56(1): p. 25-29.
Bagajewicz, M., *A brief review of recent developments in data reconciliation and gross error detection/estimation.* Latin American Applied Research, 2000. 30: p. 335-342.
Leibman, M.J., T.F. Edgar, and L.S. Lasdon, *Efficient data reconciliation and estimation for dynamic processes using nonlinear programming techniques.* Computers & chemical engineering, 1992. 16(10–11): p. 963-986.
Maquin, D., O. Adrot, and J. Ragot, *Data reconciliation with uncertain models.* ISA transactions, 2000. 39(1): p. 35-45.
Maquin, D., M. Darouach, and J. Ragot, *Observability and data validation of bilinear systems.* Advanced Information Processing in Automatic Control, AIPAC'89, 1989: p. 113-118.
Maronna, R. and J. Arcas, *Data reconciliation and gross error diagnosis based on regression.* Computers & chemical engineering, 2009. 33(1): p. 65-71.
Dewulf, J., et al., *Exergy: its potential and limitations in environmental science and technology.* Environmental Science & Technology, 2008. 42(7): p. 2221-2232.
Gong, M. and G. Wall, *On exergetics, economics and optimization of technical processes to meet environmental conditions.* Work, 1997. 1: p. 5.
Gong, M. and G. Wall, *On exergy and sustainable development—Part 2: Indicators and methods.* Exergy, An International Journal, 2001. 1(4): p. 217-233.
Regulagadda, P., I. Dincer, and G.F. Naterer, *Exergy analysis of a thermal power plant with measured boiler and turbine losses.* Applied Thermal Engineering, 2010. 30(8–9): p. 970-976.
Sato, N., *Chemical Energy and Exergy*. Chemical, Petrochemical & Process2004: Elsevier Science Ltd. 1-160.
Lucia krishnan-Dumitrescu, W.e.o.a.c.L., *Data reconciliation for Industrial Processes*, in *18th European Symposium on Computer Aided Engineering*2008, Elsevier.