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Implementation of innovative process control techniques to minimize variations, improve quality and increase production in paper industry


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Abstract: *Paper manufacturing is one of the most complex industrial processes in the world today. It is, of course impossible to manually control all the settings of a modern paper manufacturing process. Nowadays, paper maker relies upon many sources of information and measurement tools to assist in producing a product that meets or exceeds these demands. Although, there are many and varied online sensors, these are not enough to present a total and clear picture of the paper manufacturing performance. If appropriate pulp quality properties are measured continuously in the process, it is easy to see correlations with other things happening in the process and this enables taking correct actions and strategies based on measured facts. Early detection of deviations in quality makes early corrective actions possible. In the era of Industry 4.0 revolution and upcoming Industry 5.0, the manufacturing technology has to change. So, as to keep pace with changes, manufacturing industries are switching towards predictive controls rather than preventive controls. It is the uncertainty demanding adoption big data, data analytics, IoT, IIoT, optimization and reliability in both process and quality measurement. In fact an increasing amount of testing systems has taken place for directly online measurement during the production process, thus offering the possibilities for efficient process and product quality control. The ultimate need is establishing reliable methods to promote uniformity in procedures of testing and analysis. It achieved only by using rapid analytical methods (e.g., FT-IR, FT-NIR, XRD, XRF, UV analyzer, SEM, GC/MS, and ICP-MS, TGA etc.) and data analytics algorithm to improve the manufacturing performance. Systems are in line to collect all the data online through advanced and updated technologies to ensure and forecast the required quality at customer end.*

Keywords: *On-line analysis, Sensor, Bigdata, Cloud computing, Algorithm, IIoT*

1. Introduction

India is a country with over 1.358 billion population (~17.74% of World) and has per capita consumption of 13.9 kg paper per person per year (Global per capita of 57 kg). India has a paper industry with a turnover of INR 55,000 crores / year, and with an employment of ~ 2 million people (direct employment ~ 0.5 millions). Indian paper industry with about 4% of world's production has a demand growing at 5.5-6% annually. Fragmented industry, wide variations in raw material use, production processes, product range coupled with raw material and energy shortages, the industry today is at cross roads. Competitiveness, environmental challenges, economy, excellence of quality with sustainability issues are the challenges confronting the industry. India has 859 mills (499 working) with a total installed capacity of 25.55 MMT (operating capacity 20.16 MMT). The production is 16.91 MMT (~80% capacity utilization) in 2017-18. Wood based units (19 units) produce 19% of total production, while agro-based units (40

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units), produce 10% of total production. The contribution of recycled fibre units (440 Nos) is 71% of production. While wood and agro-based units contribute 3.27 and 1.161 million tonnes of paper and board, RCF mills produce ~ 12.03 million tonnes annually.

From 17 mills in 1952 with a capacity of 0.14 MMT, Indian industry has grown to the present size. India has a long way to go in achieving global efficiencies. While chemical consumption in chemical pulping averages around 25-29 kg equivalent caustic soda /T unbleached pulp, it is 11-12 kg in good global mills. Similarly specific lime consumption in Indian mills is around 80-90 kg /T of chemical pulp, while the global best figure are around 5 kg/ T pulp. Extended delignification and Oxygen delignification have been adopted by many large Indian mills, while many agro-mills have adopted continuous digesters in India.

Many Indian mills have adopted improved bleaching technologies, replacing elemental chlorine partly or fully with ECF bleaching. TCF bleaching is just entering Indian mills. In spite of this, elemental chlorine consumption continues to be high and is around 50-60 kg equivalent Cl_2 / T pulp.

The industry is very energy intensive. Specific primary energy consumption is around 45 GJ/T product in integrated mills in India. The figure is much lower in secondary fibre based mills. European pulp and paper mills consume around 10 GJ /T product of secondary energy (equivalent primary energy of ~22GJ/T), almost half of Indian mills.

Similarly Indian mills consume a large amount of coal around 1.3 T/T. In fact, in large mills sector, coal meets almost 50% of total energy needs. Seen another way, the % of energy used by mills from renewable sources, internally generated biomass and other bio-fuels in large mills sector is around 40-45%.Specific water consumption in large integrated mills averages 30-40 kl/T with the best figures ~48 kl/T. The waste water discharge ranges from 45-55 kl/T with the best figures around 20-25 kl/T product in integrated mills. Similarly the specific BOD, COD and TSS loads in integrated mills range 1.1, 10, 2 kg/T product. The figures for BOD and COD for European mills average 0.89 and 6.2 kg/T respectively. The specific GHG emissions in large integrated mills averages 2.6 T/T product with particulate emissions of 1.4 kg/T. The GHG emissions on in European mills average 0. 24 kg/T. Similarly the SO_x and NO_x releases from large integrated mills in India are around 1.94 and 0.32 kg/T respectively. All the figures indicate that India has to cover a lot of distance to be comparable to global best and be sustainable. The heartening developments in the industry relating to raw material sourcing, efforts to improve operations to reduce specific energy consumptions, chemical consumption, and water consumption are laudable. There is increased environmental consciousness. The Indian pulp and paper industry is known to be 'Capital Intensive', 'Raw Material Intensive', 'Energy Intensive', 'Water Intensive', 'Manpower Intensive', and 'Pollution Intensive' . However adoption of new technology has to see a quantum jump for Indian mills to match global bench marks.

2 Digital transformation

Digital transformation, and in general the adoption of technology is based on three things: people, process, and technology. This new wave of Industry 4.0 is not entirely new because the Pulp and Paper (P&P) industry has been working on it to scale and speed of changes coming at the workforce. The transformation happening at different levels of the digital mill is a function of the variety of technologies available, the rate of adoption, and people as the key differentiator for success. Analytics can be organized in a continuum by increasing the degree of complexity as described by Gartner in Figure 1. They start descriptive, then diagnostic, then retrospective and predictive, finishing in prescriptive analytics [1].

Figure 1 – Gartner Analytics Ascendancy Model

3. Laboratory Information Management System

Laboratory information management systems (as shown in Figure 2) belong to the class of application software intended for storage and management of information obtained in the course of the work of the laboratory.

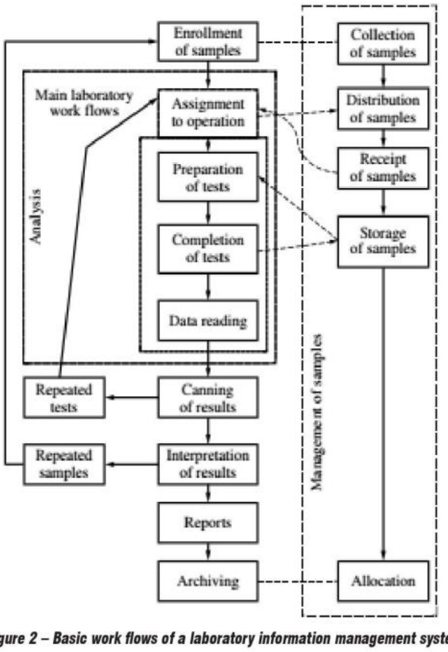

Figure 2 – Basic work flows of a laboratory information management systems

The systems are used to control and manage samples, standards, test results, reports, laboratory staff, instruments, and work flow automation. Integration of laboratory information management systems with the enterprise's information systems will make it possible to promptly transmit required data to the laboratory and the enterprise administration[2].

4. Sensor Correlation

Dynamic sensor correlation is drastically needed at every paper mill site to ensure that the online sensor measurements match their quality laboratory results. There are a lot of challenges in the field while dealing with sensor correlation. In this process usually means comparing online sensor measurements with offline measurements made in a quality control laboratory. The usual method of correlation analysis is to perform a two-variable regression. This is similar to the concept of independent and dependent variables. The lab value was assigned to the x-axis and the sensor value was assigned to the y-axis. The online sensor measurements are adjusted to match the lab measurements. Figure 3 shows an example of a moisture sensor correlation between the lab and the online sensor. Note that raw sensor data (standard) was used to perform the linear regression. The deviation between the online sensor and the lab mainly comes from the following three areas: sensor accuracy, process variations and lab test accuracy. All of the three areas should be accounted for in order to quantify the proper deviation.

Sensor data	Laboratory data
7.91	7.21
7.8	7.21
8.26	7.21
7.9	7.21
8.05	7.21
-0.24	0
0.35	0
-0.29	0
-0.34	0
11.65	11.24
12.83	11.24
13.06	11.24
11.91	11.24

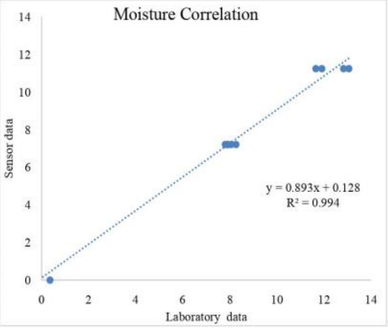

Figure 3 – Moisture Sensor Correlation Example

- **Sensor Accuracy:** Sensor accuracy should be provided by the sensor manufacturer's specifications

- **Process Variations During the Correlation Test:** Unless a static correlation is being conducted, during the correlation test, the paper property being correlated to is constantly changing while paper is being produced. It is not possible and practical to collect a sample from the exact spot the sensor is measuring.

- **Laboratory Test Method Accuracy:** Many factors can affect the precision and accuracy of lab test results. Laboratory influences can be contributed to factors such as instrument sensitivity, sampling error, instrument accuracy and sample condition error, etc.

$$DEV = \sqrt{S^2 + L^2 + P^2} + R \quad \text{-----------------(1)}$$

DEV=Expected 2-sigma variation
S=Sensory Accuracy
L= Lab influence
P= Process variation
R= Residual variation

The main thing for papermakers to remember is that it's important to setup proper expectations of the correlation results. This limit can be quantified objectively based on the sensor, process and lab variances.

5. SAP predictive maintenance

The assets of the companies should function properly to avoid downtime and improve production. Operational success will be when all the resources like the equipment, technical team and all others who are involved in the process are functioning together. Most of the companies still lack the visibility of the asset's lifecycle and performance.

Businesses today wish to predict the need for maintenance so that they can plan ahead of time. The inter-connectivity between machines through the Internet of Things has made it possible for companies to achieve predictive maintenance. Vast amounts of data availability have also helped companies implement analysis points within their structure. However, siloed data stored in various formats often slows down the time to extract insights. And, outdated methods of data processing have led to slow maintenance prediction- so much so that predictive failed as a possibility for many manufacturers.

With powerful capabilities in SAP/4HANA, companies can leverage the following core benefits of predictive maintenance as,

- Increase service profitability by enabling third-party service providers to deliver high-margin services by increasing visibility into field assets.
- Reduce maintenance expenses by planning maintenance schedules to improve resource utilization and reduce downtime.
- Improve asset availability by enabling asset operators to leverage data and analytics to predict the need for maintenance and take corrective measures quickly.

SAP/4HANA with its predictive maintenance capabilities can help your organization manage maintenance activities to optimize resource utilization and plan for anomalies down the road. By following the proactive strategies, like preventive and predictive maintenance, can improve the asset's utilization, uptime and reduced spending.

6. Proximate analysis by TGA

It is based on thermogravimetric analysis (as shown in Figure 4), deconvolution of the DTG signal and empirical correlations for characterizing biomass fuels for boilers and combustors. This methodology allows determining accurately and in a short time the main parameters required for industrial operation, as are the higher heating value (HHV), the contents of moisture, volatile matter, fixed carbon, ashes, carbon, hydrogen and oxygen, and the kinetic parameters of the thermal decomposition of the biomass. At the present time, these parameters are obtained by using specific equipment that are much more sophisticated and expensive than the methodology proposed[3].

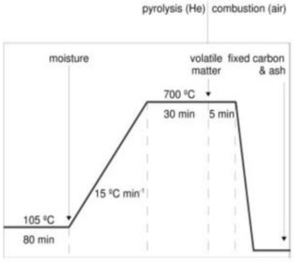

Figure 4 – Methodology developed for TGA.

7. Automated Paper Testing System

The automated paper testing systems (Figure 5) can perform almost all quality testing, prepare reports and archive data, communicate with other devices that monitor process parameters and all with little or no operator involvement. Furthermore, most of the measurement methods conform to well established industry standards, thus maintaining the continuity of information obtained from previous testing instruments.

New and innovative features now include:

- Faster testing – complete CD profile strip in 10 minutes or less (depending upon tests selected and frequency of measurement)
- New and more sophisticated test measurements
- Automatic sample feeding system
- Testing of CD profiles, MD strips, sheet samples (A3, A4, and letter sized)
- Can be operated by anyone – no paper testing knowledge is required

Figure 5 – Automated board and paper testing system

8. Free Lime estimation through Zeta Potential

The presence of unreacted lime (free lime) in the lime mud can cause many problems in the chemical recovery operation of kraft pulp mills. There are currently no standards for free lime determination. Conventional methods used in mill laboratories require extensive preparations and give inconsistent and sometime erroneous results. Zeta potential, a dispersion characteristic of the lime mud and liquor slurry, can be used to indirectly indicate the amount of free lime in the lime mud. This unique characteristic enables a rapid detection of free lime and helps mills take appropriate actions to avoid problems associated with over liming in the recovery process[4].

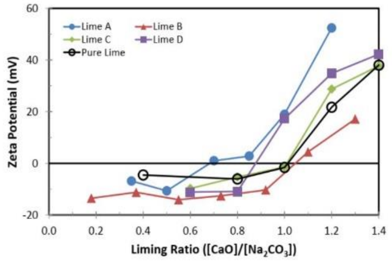

Figure 6 – Effect of liming ratio on zeta potential

9. FT-NIR Liquor Analyzer

FT-NIR spectrometers provide superior throughput (25x more energy) and wavelength accuracy and are essential for more demanding applications, such as those for pulp and paper applications. The use of a large optical path length (8mm – 20mm) enables greater sensitivity (A = molar absorptivity *path length* concentration) while minimizing possibility of cell plugging. In addition, inherent with the higher spectral resolution, calibration model transferability is enhanced; allowing models developed to be used from mill to mill[5].

Table 1 – FT-NIR liquor measurements

Liquor type	Component measured
White & green liquors	EA, AA, TTA, Na_2CO_3, Na_2S, Na_2SO_4, $Na_2S_2O_3$, %RE, %CE
Black liquor	EA, organic, inorganic & total solids
Weak wash	TTA, NaOH, Na_2SO_4, $Na_2S_2O_3$
ClO2 generator	Acid (H_2SO4), chlorate ($NaClO_3$), solids content
EA = Effective Alkali (NaOH + 1/2Na_2S) AA = Active Alkali (NaOH + Na_2S)	
TTA = Total Titratable Alkali (NaOH + Na_2S + Na_2CO3)	
%RE = % Reduction Efficiency	
%CE = % Causticizing Efficiency	

Table 1 shows a list of liquor streams and corresponding compositions that are available. Measurement accuracy as determined against manual titrations is summarized in Table 2.

Table 2 – Accuracy of FT-NIR measurements

Component	Accuracy
EA	± 0.5 g/L as Na_2O
AA & Na_2CO_3	± 0.8 g/L as Na_2O
TTA	± 1.0 g/L as Na_2O
Na_2SO_4 & $Na_2S_2O_3$	± 0.50 g/L as Na_2O
Organic & inorganic solids	± 0.5 %
Total solids & lignin	± 1.0 %
H_2SO_4	± 2.0 g/L
$NaClO_3$	± 3.0 g/L

A single spectrometer (shown in Figure 7) connected to four different sample stations with their own flow cells, with each sample station being able to accommodate multiple sample streams; one at the digester with 5 sample streams, one at the ClO_2 generator with a single sample stream, and two at the recausticizing plant with multiple sample streams, all working concurrently. This integrated platform system allows for flexibility with the analyzer. The FT-NIR system was installed at the mill to measure a single

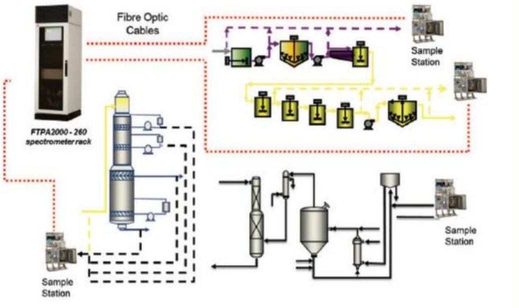

Figure 7 – Integrated platform FT-NIR system using one spectrometer with four sample stations at different unit operations.

stream, CGL liquor, for TTA trim control as well as feed forward slaker and Causticizing Efficiency (CE) control, while the feedback control relied on the slower manual testing. Over a six months period, the average CE was raised from 75% to 81% while using the FT-NIR based control strategy. Table 3 summarizes the economic benefits when one compares six months before and after control implementation.

10. Disruptive Measures in Wastewater Treatment

Moving from standard microscopic methods to tools like DNA and ATP provide methods to focus on the biological system and not just the physical/chemical plant. Using advances in DNA sequencing to identify unique microbial species and to quantify populations provides operators with knowledge needed to monitor and troubleshoot treatment plant (Figure 8) problems.

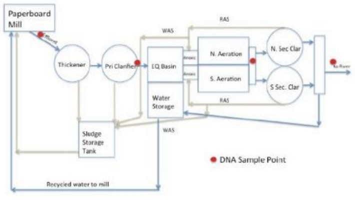

Figure 8 – Paperboard mill bio-stimulate DNA analysis

Though respirometry and microscopy add significant information on the health and types of microbial life in an aerobic wastewater system, they are not effective in anaerobic digesters, facultative lagoons, or polishing ponds found in pulp and paper mills. For these processes, ATP (adenosine triphosphate) and DNA (deoxyribonucleic acid) technologies can be utilized to evaluate these systems[6]. They can also be utilized on aerobic treatment processes. With these tools we can now determine exactly what microbes are present in the system and whether they are viable and working.

11. Mathematical modeling of black liquor rheological data

The non-linear regression method was based on the Levenberg–Marquardt (LM) algorithm, which is most widely used algorithm in nonlinear least square fitting. The Levenberg–Marquardt algorithm, starting with some initial parameter values, minimizes RSS by performing a series of iterations on the parameter values and computing RSS at each stage.

For engineering aspects, it is important to get a simplified expression/formula which will describe combined effect of solid content and temperature for the viscosity of black liquor. The multiple regression analysis on viscosity, temperature and solid content data showed the equation (2) may be proposed to evaluate the viscosity value of black liquor for various temperatures and solids content as,

$$\eta = 7.825 \times 10^{-9} \exp\left(0.159 \times C + \frac{3672.4}{T}\right) \text{---------} \quad (2)$$

Table 3 – Economic benefits

S.No.	Performance Variables	Pre analyzer	Post analyzer
1	CE estimate at causticizer (%)	74.4	78.9
2	Av. WLPF pressure (psi)	8	8.1
3	Av. hot lime screw speed (%)	46.6	47.7
4	Av. purchased lime screw speed (%)	3.1	0.3
5	Av. GL flow to slaker (USGPM)	698	679.5
6	Av. lime addition rate (lb./USG of GL)	0.312	0.398
7	Total hot lime added (tons/day)	142.32	145.68
8	Total purchased lime added (tons/day)	5.27	0.51
9	Total lime added (tons/day)	147.58	146.19
10	% of purchased lime in total lime added (%)	3.57	0.35
11	Total lime added for same GL flow rate (tons/ day)	138.54	146.19
12	Adjusted quantity of purchased lime for same GL flow (tons/day)	4.94	0.51
13	Av. lime quality number	Not measured	1.2
14	Av. digester production rate (ADMT/day)	781	783
15	Av. steam flow to evaporators for same digester production (klb/h) (k=1000)	176	169

Table 4 – Analysis of variance (ANOVA)

Source	Sum of Squares	Degree of freedom	Mean Square	F-Ratio	P-Value
Regression	19.8	2	9.9	842.14	<0.001
Residual	0.2	17	0.012		
Total	20	19	1.053		

$\eta_{experimental}$ (Pas)	$\eta_{predicted}$ (Pas)
0.128	0.145003
0.0932	0.105084
0.0769	0.077615
0.0601	0.058251
0.0516	0.044423
0.378	0.375311
0.262	0.271987
0.206	0.20089
0.162	0.15077
0.148	0.11498
0.911	0.828615

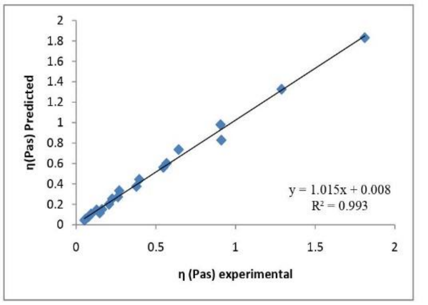

Figure 9 – Comparison of predicted viscosity value for black liquor by model equation (2) with the experimental viscosity value

The correlation coefficient (R^2) indicates that the model fits 99.01% of the variability in η with 1/T. The adjusted R^2 statistic, which is more suitable for comparing models with solids content (C) and temperature (T) as independent variables, is 98.88%. The standard error of the estimate (SEE) shows the standard deviation of the residuals to 0.108. The mean absolute error (MAE) of 0.077 is the average value of the residuals. Since, the p-value in the ANOVA Table 4 is less than 0.05; there is a statistically significant relationship between solids content (C) and temperature (T) with 95.0% confidence level. A comparison of predicted viscosity value for black liquor by model Equation (2) with the experimental viscosity value is shown in Figure 9.

12. Rheology of pulp suspensions using Ultrasonic Doppler Velocimetry

The Ultrasound Doppler Velocimetry (UDV) is an in-line method (shown in Figure 10) to determine the velocity in fluid flows. Velocity profile measurements through the use of an Ultrasonic Doppler technique on the other hand, uniquely identify the real velocity distribution and yielding radius in the gap. This technique measures the actual bulk shear rate imposed on the fluid and calculates the shear stress using the basic momentum balance equations, thus eliminating wall slip effects. Data obtained by using conventional rheometry techniques (macroscopic measurements) suffer from wall artefacts despite the use of a vane in large cup geometry that is known to minimize wall slippage. UDV technique gives an accurate determination of the flow curves of fiber/pulp suspensions (complex fluid). The main advantages are the ability to investigate flows of complex fluid and deliver real-time velocity profiles[7].

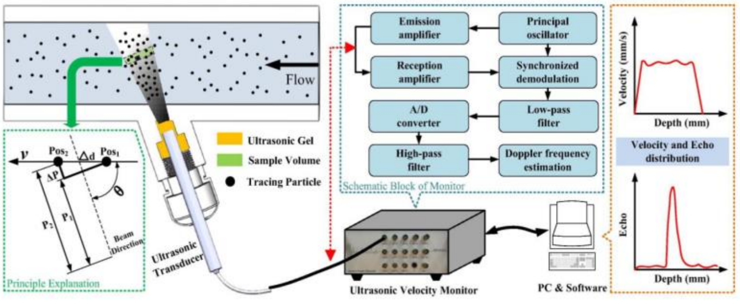

Figure 10 – Measurement system of UDV[8].

13. Total Organic Carbon (TOC)

Total organic carbon (TOC) is a general technique that measures the overall organic carbon load in a water stream. TOC analysis may be used as an alternative or comparative technique for COD and DCM analysis. TOC is used to ensure that the organic load being discharged in the wastewater stream is not too high. In some areas TOC can be used in place of Chemical Oxygen Demand (COD), once the TOC results are shown to be comparable with the COD results. The Figure 11 shows an example where TOC and COD results compare well, and the TOC replaced the COD analysis. A correction factor was applied to the TOC results to match the COD values. An on-line TOC can report results every 5-6 minutes, where a COD analysis can take 2 or more hours, and may use problematic reagents. A UV-persulfate TOC uses phosphoric acid and sodium persulfate, plus UV light, for the analysis, much easier chemicals to dispose of. If the carbon source is consistent then the COD technique can be replaced by TOC, where allowed[9].

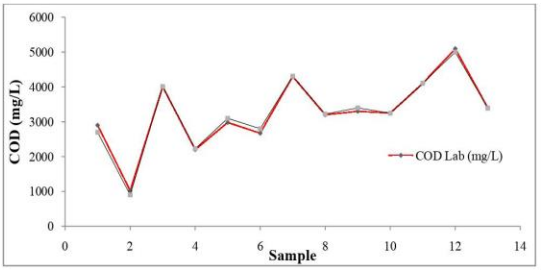

Figure 11 – COD and TOC comparison chart

TOC has potential for online effective measurement of micro-organic accumulation (EMMA) and was validated under mill scale for packaging, newsprint and tissue paper grades by IPST. The conventional method of micro-organics determination based on DCM extraction method is very time consuming (6 hrs./ sample) hence can be replaced with new method. Measurement of EMMA potential based on TOC technique has been found to be an effective tool in quick assessment (5 min./ sample) of runnability issues due to presence of micro organics concentration in mills. The method is equally applicable to wood based mills for micro pitch accumulation.

14. Conclusion

The aforementioned emerging techniques for pulp and paper industry would help to identify new R&D projects and potential technologies for market transformation activities. It could also offer new insights into technology development and energy efficiency potentials. However, aggressive R&D is still needed to address issues and barriers confronting the emerging technologies. The major barriers prevent new technology adoption and penetration is high initial capital investment, long payback period, and low cost effectiveness. Further research is required to improve and optimize these technologies in order to minimize wastes. Additionally, for some technologies, little information was available other than that provided by the developers of the technology developers. Independent studies and validation of the fundamentals and operation of these emerging techniques would be helpful to the private and public sectors as well as academia.

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