Strategies for increasing availability and milling performance at Colombian mills

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Abstract Continuous operation of the sugar-energy industry in Colombia (322 days average for 2015) presents demanding technical challenges. CENICAÑA has an ongoing project on diagnosis for maintenance management for Colombian mills, looking for improvement opportunities. Cane reception and milling were confirmed as the most critical areas, using availability and maintainability indices. Equipment, including cane conveyors and preparation machines, were identified as critical in the reception area. In the crushing station, intermediate carriers and roller surface wear were the major determinants in the global performance index (OEE). Additionally, a monthly follow-up to the main performance indicators in a milling tandem showed how roller shell wear impacts negatively on pol losses in bagasse. Following a proactive approach (FMECA), intermediate carriers and preparation machines were redesigned. In order to increase roller shell mean time before failure (MTBF) and reduce tooth fractures, welding procedures were studied and heat transfer during solidification of welding deposits has been modeled using FEA. Experimental procedures have been used to validate results. This paper reports advances in the entire research project.

Key words RCM, maintenance, asset management, mill, OEE

INTRODUCTION

Field productivity (116 t/ha average in 2015) and crushing days/year (322 average for 2015) are strengths of the Colombian sugarcane industry in a competitive local and global market. Maintenance must guarantee reliability and availability, reducing lost time (average of 5.6% for 2015). As an example, a typical trend in maintenance at Colombian sugar mills is:

- Scheduled crushing days: 330.
- Scheduled short stoppage (4 hour) for heavy duty shredder maintenance and minor repairs, approximately each 15 days in dry weather and about 8 days during rainy weather.
- Two main 7-10 day maintenance stoppages for maintenance of crushing units (in the more rainy months, May and November). Crushing rate planned to be reduced almost 27% in rainy months.
- Evaporator cleaning while crushing using switching valves with redundant vessels, always with 5-effect configuration.
- 2015 lost time: 7% Harvest + Factory.

Reliability Centered Maintenance (RCM) has been adopted by several international sugar factories, who reported successful results. Buker (2010) presented the experience of USSC (United States Sugar Corporation) in adopting ‘Reliability Excellence’ as a new approach. They reported an increase of OEE (Overall Equipment Effectiveness) from 74% for 2007 to 93% for 2010. Letizia and Brown (2010) presented results of new software to capture and analyze data and to reduce down-time. Root Cause Analysis (RCA) methodology was applied at four Mackay Sugar factories and availability was increased from 89.1% for 2004 to 91.1% for 2009.

Since 2012, CENICAÑA has been working on a project to drive adoption of new management maintenance approaches such as RCM by the Colombian sugarcane mills. Here, we report the first results in diagnosis and adoption of RCM strategies.
METHODOLOGY

Diagnosis

As a first step, the PAS055:2008 (ISO 55000: 2014) asset management standard was used as a guide to develop diagnosis tools. Eleven maintenance management topics were evaluated using a rule of five levels, where the highest one was classified as ‘World Class’. Three sugar mills were evaluated by the diagnosis tools developed. After that, an OEE (overall equipment effectiveness) determination methodology was proposed and compared with the traditional lost-time indicator. OEE is the product of three factors (Pistarelli 2010):

- Availability Factor: Effective Production Time / Scheduled Production Time
- Performance Factor: Net Production Time (NPT)/ Effective Production Time
- Quality Factor: Valuable Production Time (VPT) / Net Production Time.

An OEE above 85% (Baker 2010; Suzuki 1995) is classified as ‘World Class’.

For diagnosis purposes, the variables were taken as:

- NPT is a relationship between time of real production and time estimated for maximum rate production achieved during the period evaluated.
- VPT is the product of NPT and the difference between target overall recovery (OR) (estimated at 90.7%) and the achieved OR.

RCM strategies

General RCM strategies to be implemented were outlined and four topics were considered:

- Diagnostics: Apply a diagnostics tool from the asset management standard.
- Organizational: Adopt a maintenance management approach using RCM.
- Planning and control: Adopt RCM tools:
  - Proactive analysis tool: Failure Modes, Effects and Criticality Analysis (FMECA). Criticality matrix for factory equipment.
  - Tool for unexpected failure analysis: RCA (Root Cause Analysis).
  - Tool for monitoring of Key Performance Indicators (KPI) for maintenance planning and execution: MTBF (Mean Time between Failures), MTTR (Mean Time to Repair), OEE, ratio of maintenance cost to production cost, among others.
- Performance: One Point Lesson (OPL) was chosen as an effective tool to improve skills of maintenance personnel.

Technical issues

We targeted increases in roller shell life and OEE for the entire milling station in the project. One technical issue is the cast-iron shell hard-facing applied to increase life in a high extraneous matter environment. Some incorrect welding practices have been blamed for early fractures of roller teeth.

Modelling of heat transfer during shell hard facing was performed using FEA. This work involved:

- Development of a basic heat transfer model during welding of a roller tooth
- A heat input model from a moving source, proposed by D. Rosenthal (Kou 2003) was applied:

\[
\frac{2\pi(T - T_0)k}{Q} = \exp\left(\frac{V \cdot r}{2 \cdot a}\right) \cdot K_0 \cdot \frac{V \cdot r}{2 \cdot a} \quad \text{Equation 1}
\]

Where

- \( T \) = Temperature
- \( T_0 \) = Initial temperature of base metal
- \( k \) = Thermal conductivity of base metal
- \( g \) = Thickness
- \( Q \) = Heat flux from source to base metal
- \( V \) = Application velocity
- \( a \) = Thermal diffusivity of base metal
- \( K_0 \) = Modified Bessel function
- \( r \) = Radial distance from origin \((x^2 + y^2)^{1/2}\).

- Model results were validated whenever possible with infrared thermometry.
- Metallography analysis was performed on samples of hard faced teeth.
- FEA was used for static and rotodynamic performance of preparation machines.
RESULTS

Diagnosis

A diagnosis questionnaire was utilized in three sugar mills and results showed a Level 3 in maintenance management maturity (Fig. 1). Aspects with more room for improvement were:

- Maintenance management strategy well defined and adopted;
- Risk management;
- Performance review.

Aspects with acceptable performance were:

- Organization-administration;
- Learning and growing;
- Information management.

![Fig. 1. Diagnosis questionnaire results from one pilot mill.](image)

OEE

The OEE indicator was calculated for the entire Colombian industry for 2014 and 2015 (Fig. 2), with a minimum value of 74% and a maximum value of 87%, showing potential room for improvement with RCM adoption. OEE was correlated with the lost time indicator. A sugar mill that adopted RCM in 2010 on its own initiative, showed one of the highest OEEs (87%) and has reduced lost time (factory) from 3.9% to 2.5%.
Criticality matrix and KPIs for a pilot sugar mill

The Pareto analysis for the three sugar mills showed that cane reception and cane crushing were critical with higher lost time and frequency of failure events. Figure 3 shows the analysis for one of the mills.

Fig. 2. OEE and lost time for Colombian sugar mills.

Fig. 3. Pareto analysis for lost time and failure events frequency. Pilot mill #1 (2012, 2013, 2014).
In deeper analysis of the crushing station, we calculated MTBF and MTTR KPIs for one pilot mill. Intermediate carriers and Donnelly-type feed chutes were identified as critical with a MTBF of 70.5 h. The highest MTTR was for the shredder (1.6 h). Table 1 show availability (see Equation 2) calculated for each item of equipment. Table 2 confirms the shredder and intermediate carriers as critical equipment.

\[ Availability = \frac{MTBF}{MTBF + MTTR} \]  

**Table 1.** Equipment availability.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>MTBF</th>
<th>MTTR</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill intermediate carriers</td>
<td>70.47</td>
<td>30.81</td>
<td>69.5%</td>
</tr>
<tr>
<td>Mills</td>
<td>95.25</td>
<td>15.27</td>
<td>86.1%</td>
</tr>
<tr>
<td>Cane conveyor</td>
<td>158.80</td>
<td>22.55</td>
<td>87.5%</td>
</tr>
<tr>
<td>Turbines</td>
<td>163.93</td>
<td>13.13</td>
<td>92.5%</td>
</tr>
<tr>
<td>Cane feed table</td>
<td>218.66</td>
<td>12.00</td>
<td>94.8%</td>
</tr>
<tr>
<td>Others</td>
<td>327.73</td>
<td>33.75</td>
<td>90.6%</td>
</tr>
<tr>
<td>Cane knives</td>
<td>403.44</td>
<td>36.92</td>
<td>91.6%</td>
</tr>
<tr>
<td>Cane shredder</td>
<td>654.96</td>
<td>97.50</td>
<td>87.0%</td>
</tr>
<tr>
<td>Trommel</td>
<td>750.16</td>
<td>13.71</td>
<td>98.2%</td>
</tr>
<tr>
<td>Cane belt conveyor</td>
<td>874.41</td>
<td>62.00</td>
<td>93.3%</td>
</tr>
<tr>
<td>Cane leveller</td>
<td>937.19</td>
<td>47.14</td>
<td>95.2%</td>
</tr>
<tr>
<td>Steam pressure (low)</td>
<td>1050.18</td>
<td>21.60</td>
<td>97.9%</td>
</tr>
<tr>
<td>Bagasse carrier</td>
<td>1249.45</td>
<td>71.43</td>
<td>94.5%</td>
</tr>
<tr>
<td>Hilo crane</td>
<td>2386.95</td>
<td>38.18</td>
<td>98.4%</td>
</tr>
</tbody>
</table>

**Table 2.** Criticality level for cane-recieve and cane-crushing equipment.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Criticality level (0-5) MTBF</th>
<th>Criticality level (0-5) MTTR</th>
<th>Criticality matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill intermediate carriers</td>
<td>3</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Cane shredder</td>
<td>3</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Cane carrier</td>
<td>4</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Mills</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Bagasse carrier</td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Others</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Cane knives</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Turbines</td>
<td>4</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Cane feed table</td>
<td>4</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Cane belt conveyor</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Cane leveller</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Trommel</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Steam pressure (low)</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Hilo crane</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**FMECA for critical equipment at cane reception and crushing station**

From the analysis described above, different activities were developed following the FMECA approach in order to reduce critical equipment unexpected failures.
Cane preparation machinery redesign

Among the alternatives to improve the reliability of cane preparation machinery was to review the design, especially when the system is under increasing load and it is necessary to also increase available power. FMECA allowed identification of:

- Function: knifing machine (fixed knives preceding a medium duty shredder) with new electric drive 2350 HP (1750 kW) at 890 rpm.
- Failure modes identification. Effects and consequences of failures.
  - Shaft requires high reliability under torsional and flexural stresses and it needs to be safe (far from) under possible resonant frequencies. FEA was used for both assessments.
  - Possible failure modes:
    - Knives and bolts fracture under impacts with stones and tramp iron. Vibration due to imbalance after losing mass or parts under impact.
    - Crushing rate reduction because of wear of knives and/or high fiber.
    - High stresses in shaft and bearings.
  - Consequences of failures:
    - Process and personnel at risk because of fractures and eventual resonance.

Based on results of the different analysis, the mill moved to swing back knives instead of fixed knives with:

- Greater capacity of energy absorption from impacts with big stones and tramp iron arriving with hand-cut cane.
- Increase in the shaft diameter for better safety factors in fatigue and static loads. Also to get far away from fundamental critical speed.
- Use of a new lubrication recirculating system (oil) for better reliability of bearings.
- Rotor and knives geometry calculated with a method proposed by Crawford (1969) in order to obtain a reasonable swing-back angle.

The new rotor was commissioned in 2014. Figure 4 shows a reduction of 90% in the lost time for failures of knives because of impacts. That represented 20 crushing hours more in availability.

![Knifing machine lost time](image)

**Fig. 4.** Lost time in knifing machine before and after redesign.

Mill intercarriers

FMECA of intermediate carriers for another pilot mill allowed determination of its principal functions:

- Receive bagasse from preceding mill.
- Transport bagasse up to the next chute.
- Allow application of imbibition juice or water.
A allows arcing on delivery roll.
B allows bypassing to the next crushing unit so repair of the crushing unit is possible.
C during repairs allow simple detachment with low MTTR.
D achieve high MTBF.

The main failure modes were identified and classified as operational (jams) and mechanical (chains, bearings, shafts) using maintenance information. Afterwards, a reviewed design for intermediate carriers was proposed for the sugar mill. A shorter carrier able to swing during maintenance, without interfering with the crane, is under adoption to reduce MTTR.

Mill-roller performance analysis

OEE is a comprehensive indicator that considers three factors: availability, performance and quality. Pol % bagasse was measured (June to September) together with the accumulated cane crushed (Fig. 5). Points A were obtained during the first days after major repair, including new or refurbished rolls, bearings, scrapers and trash plate. Points B show a stable period and points C show an increasing trend for pol loss indicating roll wear as the main cause for performance reduction after approximately 340,000 t. Maintenance and operational practices need to be reviewed to mitigate the performance deterioration.

![Fig. 5. Pol% bagasse versus cane crushed.](image)

Modeling of heat transfer during hard facing

**Teeth model for roller shell**

A transient simulation was performed to determine the cooling curve for a single tooth with a heat flux applied during hard facing to one side. Table 3 shows the parameters used to determine the heat input. Figure 6 presents the cooling curve obtained. Finer modelling is under way.

| Voltage (V) | 24 |
| Current (A) | 250 |
| Welding speed (mm/s) | 300 |
| Efficiency | 80% |
| Heat flux (kW/m/s) | 16 |

**Table 3.** Model parameters for heat input to teeth.
Thin-plate model

In order to verify the heat transfer modelling during welding, experiments were performed using steel plates with thermography recordings from behind the arc. Figure 7 shows the comparison of the three methods to obtain the cooling curve for thin plates. More experiments with cast iron teeth and plates are required, considering all tooth depths in order to estimate microstructures in a TTT (Time, Temperature and Transformation) curve.
Metallographic analysis

Arcing while crushing is not a regular practice in Colombian sugar mills. The surface is maintained during short stoppages (shredder hammer change or reversing). New or refurbished shells are initially hardfaced manually or automatically with stick or wire consumables. Metallographic analyses were performed on cast iron hardfaced teeth samples (2.96% C; 1.8% Si; 0.81% Mn; 0.37% Cr; 0.086% P; 0.051% S). Results confirmed the presence of martensite in the transition between welding and parent material and HAZ (Heat Affected Zone). Perlite and bainite are in the HAZ (Fig. 8). The width of the HAZ showed that manual welding gives wider zones (0.61 ± 0.19 mm) than the automatic procedure (0.42 ± 0.03 mm).

CONCLUSIONS

Current maintenance approaches based on reliability (RCM) are desirable for the Colombian sugar industry to be sustainable. RCM is considered to be a set of processes including changes, assessments and action-plan formulation, execution and implementation that requires a proactive attitude towards information management, KPIs, follow up and control and elimination of unexpected failure events.

A complex industry such as sugar-energy mills requires the use and adoption of best practices in engineering such as FEA, CFD, condition-based maintenance and the best tools for root cause analysis.

ACKNOWLEDGEMENTS

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REFERENCES

Stratégies pour accroître la disponibilité et la performance des moulins colombiens


Mots-clés: RCM, entretien, gestion, moulin, OEE

Estrategias para incrementar la disponibilidad y desempeño de tándems de molienda en Colombia

Resumen. El funcionamiento continuo de la industria suco-energética en Colombia (322 días promedio para 2015) requiere de desafíos técnicos exigentes. CENICANAl tiene un proyecto en curso que busca de oportunidades de mejora en la gestión del mantenimiento en Ingenios de Colombia. La Recepción de la caña y la Molienda se confirmaron como las áreas más críticas, aplicando índices de disponibilidad y confiabilidad propios del mantenimiento. Equipos, tales como los conductores de caña y máquinas de preparación, fueron identificados como críticos en la zona de Recepción. En la estación de Molienda, los conductores intermedios y el desgaste de la superficie de trabajo en las mazas de los molinos fueron los principales determinantes en el índice de desempeño global (OEE). Además, un seguimiento mensual de los principales indicadores de rendimiento en un tándem de molienda mostró cómo el desgaste del casco de la maza tiene un impacto negativo sobre las pérdidas de pol en bagazo. Siguiendo un enfoque proactivo (FMECA), se rediseñaron los conductores intermedios y máquinas de preparación. Con el fin de aumentar el tiempo medio antes de la falla (MTBF) y reducir las fracturas de los dientes en el casco de la maza del molino, se estudiaron los procedimientos de soldadura y de transferencia de calor durante la solidificación de los depósitos de soldadura, siendo modelada mediante la técnica de FEA. Algunos procedimientos experimentales se han utilizado para validar los resultados. Este documento informa de los avances en la totalidad del proyecto de investigación.

Palabras clave: RCM, mantenimiento, gestión de activos, molino, OEE