How can numerical models help decision makers and improve existing cane sugar factories?

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Abstract  Decisions in the sugar industry are complex when it comes choosing the best plant configuration for a new project or the best settings mix in an existing factory because of the complex interconnection between all flows and parameters. To find the optimal operating settings with a target of maximizing income, or to determine the best configuration to maximize ROIs for future investments, powerful and well-designed techno-economic models are need. Our approach is to support investors, factory management and technical staff in defining and updating their choices and optimal settings on a techno-economical basis. It combines on-site surveys over the entire factory and accurate simulations using numerical models in order to find the best combination of settings or the best investment strategies. We used an internally developed model CAMEIO™ that helps to model the current situation in the factory to find abnormal figures or bottlenecks and then to simulate the factory performance for different scenarios with new settings or equipment in order to choose the best ways to improve. Studies that have been completed successfully focus on everything the customer needs such as a new plant project, factory expansion and conversion (refinery, syrup plant, power selling, ethanol), energy saving, and optimized setting assistance during the crushing season. Results obtained are convincing and have allowed factories to reduce energy consumption and sugar losses, and to improve production. In a factory during the cane sugar harvest, without additional investment, economic gains can reach more than 2% of the initial revenues. The power of numerical models, combined with onsite surveys by expert teams, is a new way to determine the correct choice of settings and investments in order to run the plant at the optimal techno-economical point.

Key words  Sugar factory optimization, energy consumption, techno-economical study, investment scenarios, optimized settings

INTRODUCTION

Sugar factories are very complex entities due to the variety of industrial processes and products. From sugarcane, factories are able to produce different types of sugar, energy (steam, electricity) and ethanol. Most of the factories are running well but it is very difficult to know if they are running at their optimal economical operating points regarding equipment performance and optimized production mix. The variability of cane quality (pol and fibre) and other physical or economical external parameters such as sugar, ethanol and electricity prices make any techno-economical optimization very complex. Just because each individual part of the factory runs well, it does not mean that the plant generates the highest revenue. For example, sometimes factories have to extract less sugar from the cane to consume less electricity and steam in order to export more electricity to the grid if the price of electricity is high and that of sugar is low.

To illustrate how mills may be optimized we chose CAMEIO™, a numerical model recently developed internally. The model was created to solve such problems and to allow factory management to get the best performance from their plant and to make the correct investment choices.

CONTEXT, MATERIALS AND METHODS

Context

To have a complete view of factories and find the optimal techno-economical operating point is not easy and needs the support of models to help human experts. Sugar factory processes from the cane yard to the production of sugar, ethanol and electricity are well known and combine many physical disciplines such as mechanics, thermodynamics, electricity and chemistry. However the interconnections between each part of the factory add significant difficulties for whole-plant simulations.
In the past, it took significant time to calculate the impact of cane properties (pol and fibre) on the entire process because engineers had to calculate each part of the factory manually and individually. Numerical models are great tools to do this and, associated with human expertise, can expand opportunities for achieving good plant operation (Belotti 2014, 2015).

Although we focus on existing factories in this paper, another obvious use is in feasibility studies for greenfield projects. Indeed, the large number of different configurations needs the help of numerical models to determine which configuration will deliver the best return on investment (ROI).

Calculations are important in planning equipment size, anticipating any kind of variations, detecting bottlenecks and finding the best plant configurations, but it is very important to add an economical view to any optimization. A plant can physically run well with good production of sugar, electricity and ethanol without generating the maximum revenue and, hence, without running at its full economical potential. That is why it is very important to add an economical balance to the usual mass, thermal and electricity balances.

In this study, we only looked at revenues and not at operating costs such as the number of workers, etc.

Model chosen for this study

Models used for such type of study need to be robust and flexible and must cover the entire factory (sugar plant, distillery, power house, utilities). We chose CAMEIO™ (Cane Plant Model for Incomes and Energy Optimization) to study specific cases. This model was tested and calibrated on about 100 factories around the world.

Although the main interest is to have a global view of the plant, the calculations need to go deep into details to adjust each process, so data are needed to simulate different configurations and scenarios.

Software architecture

CAMEIO™ is built by blocks representing each part of the factory and interconnected together with feedback loops to be able to simulate the whole factory and have mass, thermal, electrical and economical balances for the entire plant with good precision. The main blocks are: front end, purification, concentration, crystallisation, refinery, distillery, power house, bagasse storage, utilities, financial block. In automatic mode, about 150 main parameters allow the user to design the architecture of the factory and its equipment settings. In manual mode, more than 1000 inputs are needed. The simulations are very quick (half a minute) and allow simulation of a large number of different cases.

General approach for real case studies

The general methodology used was:
- Model the plant and fit the current situation with the model.
- Analyse results, abnormal values and bottlenecks by comparisons between simulation results and reality.
- Define scenario options for improvement (could be new settings or new equipment).
- Simulate the scenarios with the software (CAMEIO™ in this study).
- Analyse results, sort scenarios and define the best techno-economical ways of improvement/investment.

REAL-CASE APPLICATIONS

Performance enhancement for existing factories

The process to reach the optimal operating point follows through research of the potential of the plant and the detection of abnormal performance and bottlenecks.
Context of case study

We consider here a real case studied in 2015. The sugar factory chosen ran at about 100 tonnes of cane per hour. The main architecture elements are:

- Front End: three sets of cane knives for the preparation and four classical mills (three rollers driven with steam turbines and two pressure points).
- Concentration: five effects only with rising film evaporators for a global area of 1.9 m²/t cane. There is no condensate system to recover thermal energy from flash vapours.
- Crystallisation: CBA scheme used.
- Back end refinery: Three strikes.
- Powerhouse: Two boilers and two turbo-alternators for electricity production. The factory is not connected to the grid, so electricity is not a source of income.
- There is no distillery.

Factory management wanted to increase the cane crushing capacity by 15% while maintaining good sugar recovery efficiency. This had to be done with lowest investment, in particular without any new boilers. Currently, the factory cannot crush more cane and produce more sugar because of steam consumption and boiler size.

To avoid the investment in a new boiler, the problem is almost equivalent to reducing the steam consumption.

Methodology and results

All the simulations were done for three types of cane called A1, A2 and A3 (Table 1) - A1 corresponds to a bad situation with low fibre and low pol; A2 represents the average cane properties of the previous harvest; and A3 corresponds to a cane with higher fibre and higher pol.

Table 1. Pol and fibre of cane used in the CAMEIO™ simulations.

<table>
<thead>
<tr>
<th>Cane</th>
<th>Pol</th>
<th>Fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>A2</td>
<td>13</td>
<td>16.5</td>
</tr>
<tr>
<td>A3</td>
<td>15</td>
<td>17</td>
</tr>
</tbody>
</table>

In some of the following tables, the symbol ‘+’ in A1+, A2+, A3+ corresponds to simulations done with a cane flow of 115 t/h (initial mass flow + 15%).

The study was divided into three steps:

STEP 1: Model the current situation and adjust the theoretical model to conform to reality:
- Site survey for technical expertise and plant data/equipment size collection.
- Numerical simulations for mass/thermal/electrical balances for the entire plant using data collected on site and through CAMEIO™.
- Simulation results analysis combined with on-site observations to fit the model to reality.

The main objective of this phase was to confirm the mass, thermal and electrical balances of the plant in order to define abnormal values. The steam consumption was about 550-600 kg/t cane (steam used during stops were taken into account), corresponding to the nominal size of the boilers (60 t/h).

As example, some results are available in Table 2. The worst case for the boilers is A3 because of the high pol (15) and so the steam consumption is high.
Table 2. Examples of results (CAMEIO™).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed juice flow (t/h)</td>
<td>94.5</td>
<td>96.4</td>
<td>98.5</td>
</tr>
<tr>
<td>Mixed juice brix (%)</td>
<td>12.2</td>
<td>14.0</td>
<td>15.7</td>
</tr>
<tr>
<td>Real extraction (%)</td>
<td>91.8</td>
<td>92.0</td>
<td>92.5</td>
</tr>
<tr>
<td>Clear juice flow (t/h)</td>
<td>96.7</td>
<td>98.7</td>
<td>100.8</td>
</tr>
<tr>
<td>Clear juice brix (t/h)</td>
<td>11.7</td>
<td>13.5</td>
<td>15.2</td>
</tr>
<tr>
<td>VE consumption without stops (kg/tc)</td>
<td>523</td>
<td>560</td>
<td>598</td>
</tr>
<tr>
<td>High pressure steam from boilers (t/h)</td>
<td>55.3</td>
<td>59.4</td>
<td>62.9*</td>
</tr>
</tbody>
</table>

*maximum boiler capacity.

STEP 2: Find bottlenecks and current potential without any new equipment:
- Numerical simulations with current configuration but with cane processing of +5%, +10% and +15%.
- Simulation results analysis to define maximum capacity of the plant in the current situation and define the bottlenecks.

If we simulate with 15% more cane, the steam flow needed is about 64 t/h for cane type A1, 68 t/h for A2 and 72 t/h for A3. The nominal boiler capacity is 60 t/h and the maximum is about 63 t/h. Hence, the steam consumption needs to be reduced by 15% to be able to operate well in all cases. The maximum cane flows are 113 t/h for A1, 106 t/h for A2 and 100 t/h for A3.

Moreover, two other elements limit the cane crushing capacity augmentation; the capacities of the C pans (Table 3) and of the spray pond (Table 4).

Table 3. C pans balance.

<table>
<thead>
<tr>
<th>C strike</th>
<th>A1+</th>
<th>A2+</th>
<th>A3+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum capacity of C pans t/h</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>C massecuite flow at 115 tc/h</td>
<td>5.1</td>
<td>5.8</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Table 4. Spray pond balance.

<table>
<thead>
<tr>
<th>Spray pond at 115 tc/h</th>
<th>A1+</th>
<th>A2+</th>
<th>A3+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam flow to condenser t/h</td>
<td>35</td>
<td>40</td>
<td>44</td>
</tr>
<tr>
<td>Spray nozzles installed</td>
<td>212</td>
<td>212</td>
<td>212</td>
</tr>
<tr>
<td>Spray nozzles needed</td>
<td>270</td>
<td>308</td>
<td>338</td>
</tr>
</tbody>
</table>

Finally the factory would not be able to treat more than 100 t/h for all cane types with the current settings. The maximum cane flow is 105 t/h for cane A2 and 110 t/h for cane A1. Even with optimized settings such as water dilutions, the goal of +15% of crushing rate with a similar sugar extraction could not be reached. With optimized settings, the maximum cane flow for cane A2 is 7% (12% for A1 and 3% for A3).

STEP 3: Find the best improvement scenario to reach the goal of +15% of cane crushing.

Because the maximum production can reach 7% instead of the desired 15% only with optimized settings and without investment, investment scenarios should be defined.

The steps are:
- Definition of improvement solutions to achieve the maximum capacity of +15%.
- Numerical simulations to determine the impact of the identified solutions.
- Establishment of an investment/modification plan and adjustments to achieve the final objective.
In this case we defined different modifications on the plant and simulated the impact on the steam consumption with CAMEIO™. The results are given in Table 5 and Figures 1-2.

**Table 5.** Predicted steam savings (CAMEIO™ simulations).

<table>
<thead>
<tr>
<th>Modifications with investments</th>
<th>Steam savings (t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JM 1: Adjustment of temperature of mixed juice</td>
<td>0.4 0.45 0.5</td>
</tr>
<tr>
<td>Ev 1: New condensate system for juice concentration</td>
<td>1.6 1.6 1.7</td>
</tr>
<tr>
<td>JM2: Modifications on mixed juice heat exchanger areas</td>
<td>1.6 1.7 1.85</td>
</tr>
<tr>
<td>JC1 &amp; JC2: Modifications on clear juice heat exchanger areas</td>
<td>0.5 0.45 0.45</td>
</tr>
<tr>
<td>Ev 2: Modifications on evaporators areas and brix set point (Bx=68)</td>
<td>2.5 2.4 2.45</td>
</tr>
<tr>
<td>CR1: CVP in strike A for bleedings on V2</td>
<td>1.2 1.5 1.85</td>
</tr>
<tr>
<td>RA1: Concentrator for standard liquor in refinery</td>
<td>0.5 0.6 0.7</td>
</tr>
<tr>
<td>FE: Electrification on mills</td>
<td>2.0 2.0 2.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10.3 10.7 11.5</strong></td>
</tr>
</tbody>
</table>

**Fig. 1.** Steam consumption reduction for each improvement scenario.

**Fig. 2.** Final results of steam consumption.

In all cases, the target of 60 t/h of steam consumption was reached.

Using this approach in combination with the numerical model CAMEIO™ and human expertise, the factory management could make informed decisions on the best ways of improvement for this factory without inefficient investment.
VALUE MONITORING FOR FACTORIES IN OPERATION

Definition

‘Value monitoring’ corresponds to a techno-economical optimization of an entire sugar factory during the crushing season. This type of study consists in setting the configuration of the plant so as to maximize the global income of the harvest by maximizing production (sugar, electricity and ethanol) and/or minimizing consumption (steam, electricity) without any large investments. In fact, once set, the settings must adapt to changing external variables during the harvest season in order to obtain maximum value for a given environment.

Value monitoring can be equated to a techno-economical real-time optimization of the factory, but the time taken is not the same. A real-time optimization with low time taken can be used for equipment or a part of the factory, but is not adapted to an entire factory because of the large number of data that are not measured on-line and that needs to be sampled at fixed times and because of the non-linearity of the process and the high number of intermediate products in storage.

The good time taken for value monitoring and techno economical optimization seems to be a minimum of 1 hour. In fact, doing optimization simulations with daily average data is often enough to enhance factory performances and increase income.

Comparison between standard and value monitoring

In standard monitoring, the production is monitored in volume and the settings are mainly based on experience and guided by laboratory balances. The link between settings and incomes is not obvious, and there is no tool able to check quickly if the plant runs at its economical optimal operating point. The target in value monitoring is monitored through total production incomes and consumption costs and the settings of all lines are monitored globally to optimize entire plant incomes. Moreover, the settings are reviewed frequently to adapt to environment changes (cane quality and product prices).

Context of case study

We consider here a real case studied in 2015. The sugar factory studied was composed of the milling part, the raw house CBA, a refinery in three strikes and a distillery – the latter was excluded from the study. The extraction section was a bagasse diffuser with one pre-extractor mill ahead and two dewatering mills. The average steam consumption for the complex was initially about 560 kg/t cane for the whole sugar factory.

The sugar factory and the power house are managed by different companies and the steam consumption is based on a contract between them. The sugar factory sends the bagasse to the powerhouse and the powerhouse delivers steam and electricity to the factory. When the steam or electricity consumption is higher than provided in the contract, the sugar factory pays penalties to the power house company.

The sugar factory did not want to invest too much in steam reduction but wanted to avoid paying penalties due to excessive steam or electricity consumption, whilst maintaining sugar production and sugar quality unchanged. Electricity was not limiting in this case, so we focused on the steam consumption.

Results of the study

The study was divided into 2 steps:

STEP 1: Improvements during the off-crop period.

The first step consisted of simulating the plant during the off-crop period using the results of the previous crop to prepare the factory for the new crop. After simulating the current situation, some recommendations were been made to decrease steam consumption with new settings and small investments (Table 6). The impact of all those solutions was simulated to define a new target consumption of 5.1% lower compared to the steam consumption during the previous crop. This 5.1% steam reduction represents 29 kg/tc, attainable only through thermal insulation, bleedings optimization and settings adjustments. The new target point for STEP 2 was also set to ~531 kg/tc.
Table 6. Examples of recommendations done during STEP 1.

<table>
<thead>
<tr>
<th>Examples of actions</th>
<th>Steam saved (kg/tc)</th>
<th>Total steam saved (kg/tc)</th>
<th>Return on investment (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process returns heating before diffuser</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Condensate system optimization</td>
<td>9</td>
<td>13</td>
<td>2.8</td>
</tr>
<tr>
<td>Thermal insulation on piping for the diffuser</td>
<td>2</td>
<td>15</td>
<td>2.2</td>
</tr>
<tr>
<td>Bleedings adjustment for mixed and clear juices</td>
<td>4</td>
<td>19</td>
<td>3.8</td>
</tr>
<tr>
<td>Partial use of V2 for the refinery</td>
<td>4</td>
<td>23</td>
<td>2.2</td>
</tr>
<tr>
<td>Scalding juice heater on V3</td>
<td>6</td>
<td>29</td>
<td>1.9</td>
</tr>
</tbody>
</table>

This step is very important because it defines the reference situation for the rest of the study.

STEP 2: Value monitoring.

The second step started with the beginning of the harvest. The goal was to consume less steam through regular settings adjustment. The study was done during an entire harvest.

The procedure chosen was (Fig. 3):

- Each week the plant sent the weekly data by mail or directly from the equipment through the smart control system. Laboratory data had to be sent manually. In this datasheet are parameters for the model (such as imbition ratio, temperature set points, etc) and sensor results such as mass flows, brix, purity, pressures and temperatures.

- After receiving the data, the team simulated the factory with CAMEIO™ and checked the results to compare model and reality. During this phase some abnormal values can appear. Because of the numerical optimization, the optimized parameters could be found according to the cane quality chosen (pol and fibre).

- Simulations were done with new external parameter changes and recommendation sent to the factory management to anticipate the new income target for the next weeks.

![Fig. 3. Value-monitoring procedure.](image-url)
During STEP 2, there were no new investments. The aim was to optimize steam consumption according to setting changes during the harvest. During this step the steam consumption saved represented an average of 5% of the steam consumed in the reference situation with peaks at 18% in some weeks.

The results of the STEP2 are presented in Figures 4 and 5.

**Fig. 4.** Steam consumption results during the crop (step 2 value monitoring).

**Fig. 5.** Steam earnings during the crop (step 2).

The start of the harvest is not representative because of the high steam consumption due to the start-up of the factory. The last month of the harvest is not representative because it corresponds to a rainy period with difficulties in cane supply. In these two extreme cases, the number of stops was very high and more steam was consumed to maintain the temperatures in the diffuser and in the entire system such as in heat exchangers.

In addition to the first and last weeks, some weeks, such as weeks 31 and 35, were not as good as others, due to more stops than usual for mechanical problems. However, during weeks 34, 37, 39 and 42 there was a reduction of more than 10% of steam compared to the end of step 1 and more than 15% compared to the previous crop.
Impact of cane quality variations on steam consumption

The final savings (Fig. 6) have to be compared to the initial average consumption during previous harvests and to the consumption of the reference situation without any changes. In this study we were looking for decreasing steam consumption while keeping the same sugar extraction ratio. Hence, if the pol of the cane is higher than expected, we need more steam to extract the sugar. For example, if the pol increases by 2 points, the steam consumption will increase by 15 kg steam per tonne of cane (numerical simulation on this configuration). That is why the baseline reference consumption is adjusted each week according to pol and fibre variation in the cane supply.

![Fig. 6. Final balance sheet of the study.](image)

CONCLUSIONS

Numerical models are increasingly being used to simulate factory performance. The complexity of sugar plants, due to the high number of parameters and products, drives the development of software. Such models cannot replace human experience and expertise but well designed and well used, they can be powerful tools for management to optimize the performance of the sugar plants, find abnormal values and bottlenecks, or make the right choice for investment.

Although a factory may be well operated, it is always difficult for management or the chief operators to know if the plant runs at its optimal techno-economical point. Numerical models can help by providing a global view of the plant and, if combined with human expertise, can determine the best strategies for improving the plant performance.

Numerical tools such as CAMEIO™ can help decision makers to make the correct choice for investment or for combinations of settings. Moreover, if these models are coupled with smart controls, the experts have a complete set of tools for helping factory management to run plants near their optimal techno-economical running points.

ACKNOWLEDGEMENTS

We thank our colleagues from Fives Cail who helped us during these two studies, especially Matthieu Chanzy for the value monitoring study and during the development of CAMEIO™. We thank the innovation department of FIVES which helped us in the development of CAMEIO™.
REFERENCES

¿Cómo los modelos numéricos pueden ayudar a los tomadores de decisiones y mejorar las fábricas de caña existentes?

Resumen. Las decisiones en la industria azucarera son laboriosas cuando se trata de elegir la mejor configuración de una planta para un nuevo proyecto o la mejor combinación de ajustes para una fábrica existente debido a la compleja interconexión entre los flujos y parámetros. Para encontrar los ajustes óptimos de operación con el objetivo de maximizar la renta, o para determinar la mejor configuración al buscar el máximo del ROI para las futuras inversiones, se necesitan modelos técnico-económicos potentes y bien diseñados. Nuestro enfoque es apoyar a los inversores, a los directores de fábricas y al personal técnico en la definición y actualización de sus elecciones y de los ajustes óptimos sobre una base técnico-económica. Lo que se propone es unir investigaciones in situ por toda la fábrica y simulaciones precisas utilizando modelos numéricos con el fin de encontrar la mejor combinación de ajustes o las mejores estrategias de inversión. Se recurrió a un modelo desarrollado internamente, cuyo nombre es CAMEIO™, que ayuda a proyectar la situación actual de la fábrica, encontrando cifras anormales o atascos, y luego simular el funcionamiento de la fábrica tomando en consideración diferentes escenarios con nuevos ajustes o equipos con la finalidad de elegir la mejor manera de alcanzar el progreso. Los estudios que se han completado con éxito enfocaron todo lo que el cliente necesita, como el proyecto de una nueva planta, la ampliación y la reforma de la fábrica (refinería, planta de jarabe, cogeneración de energía, etanol), ahorro de energía y asistencia optimizada de configuración durante la molienda. Los resultados obtenidos son convincentes y permitieron a las fábricas reducir el consumo de energía y las pérdidas de azúcar, además de mejorar la producción. Por ejemplo, en una fábrica sin inversiones adicionales, durante la cosecha de caña de azúcar, los beneficios económicos pueden llegar al 2% de los ingresos iniciales. El poder de los modelos numéricos, combinado con las investigaciones in situ por equipos de expertos, es una nueva manera de determinar la correcta elección de los ajustes e inversiones con el fin de que la planta opere en su más alto nivel técnico-económico.

Palabras clave: Optimización de fábrica de azúcar, consumo de energía, estudio técnico-económico, escenarios de inversión, configuraciones optimizadas