ANALYSIS OF FACTORY PERFORMANCE FIGURES AS AN AID TO IDENTIFYING SOURCES OF UNDETERMINED LOSS

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Abstract

The South African sugar industry possesses arguably the best technical information systems in the global sugar industry. All factories in the country (as well as a number of affiliate member factories external to South Africa) provide accurate cross-checked figures on a weekly and monthly basis to the Sugar Milling Research Institute (SMRI), who collate the data and produce consolidated performance reports. This extensive database is of great value for benchmarking and evaluating performance and is already a useful resource for technologists. However, the potential exists to further increase the usefulness of the collected data by means of detailed analysis, as an aid to troubleshooting and for the ongoing monitoring of factory performance.

The estimated undetermined loss for a factory is a key performance measurement and an important guide for production management. Due to inherent problems in the measurement of undetermined loss, making effective use of these measurements normally requires a high degree of processing knowledge, experience and judgement. Although a range of secondary measurements can be used to help identify sources of undetermined loss, these usually require extra flow measurements, sampling and specialist analyses. A new approach to trying to identify possible sources of undetermined loss is proposed. This involves comparing available process measurements with the predictions of a boiling house mass balance. Assumed loss streams are introduced into the boiling house mass balance and their magnitudes are adjusted to match the mass balance to factory performance figures. Details of this approach are presented.

Keywords: performance figures, analysis, troubleshooting, monitoring, modelling

Introduction

The South African sugar industry possesses arguably the best technical information systems in the global sugar industry. All factories in the country (as well as a number of affiliate member factories external to South Africa) provide accurate cross-checked figures on a weekly and monthly basis to the Sugar Milling Research Institute (SMRI), who collate the data and produce consolidated performance reports. This extensive database is of great value for benchmarking and evaluating performance and thus is a very useful resource for technologists. Of particular interest are the data that quantify the extent to which factories are able to recover the sucrose from the cane into saleable product sugar.

To give guidance as to how this overall recovery might be maximised, the 'non-recovered' sucrose is expressed as the sum of a number of losses, *viz:*

- sucrose loss in bagasse
- sucrose loss in filter cake
- sucrose loss in molasses
- undetermined sucrose loss.

Maximising sucrose recovery in a factory can then be pursued as a process of minimising these sucrose losses, using the weekly performance reports to benchmark the factory against performance achieved elsewhere in the industry and to track improvement (or deterioration) with time.

Love and Muzzell (2009) focused on techniques to minimise sucrose loss in molasses, stressing the importance of this loss because it is normally the largest of the losses (being approximately equal to all the other losses combined). Although the undetermined loss is often around 2% compared with around 10% for molasses loss (Davis *et al*., 2009) the undetermined loss can, at times, rise to more than double the normal levels, triggering the need for concerted action to identify and eliminate the cause of the increased loss. Undetermined loss, as defined and used in the South African sugar industry, is discussed by Love (2001) and in more detail by Rein (2007).

The calculation of undetermined loss

In the South African sugar industry, the measurement of factory performance is carried out within the framework of an overall factory mass balance that focuses primarily on dissolved solids and sucrose (or pol). On a weekly basis, a material balance is carried out on the process streams entering and leaving the factory. This balance is used to assess the recovery of sucrose in sugar, as well as to determine the magnitude of the various losses from the factory (namely those which occur in the bagasse, filter cake and final molasses leaving the mill). Any sucrose losses not accounted for in this way are categorised as an 'undetermined loss'. This simple definition of undetermined loss needs to be refined to take into account the impact of the stock of intermediate products within the factory. The sucrose and dissolved solids within the stock (both at the beginning and end of the measurement period) need to be incorporated into the weekly mass balance calculation to obtain a true representation of the performance of the plant. Estimating the quantity and quality of the stock is an additional potential source of error. However, to make the explanation of the calculations easier to follow, the effect of factory stock is omitted in this simplified description of the calculations.

Although the quantity of sucrose in individual cane deliveries is estimated from the mass of cane delivered and from the analysis of samples of the cane (DAC analysis), this estimate is used primarily for the distribution of payment between growers and not as the primary estimate of sucrose entering the factory. Due to the difficulties associated with obtaining representative samples of the cane stream entering the factory and the fact that only a portion of all deliveries are sampled and analysed, the South African industry assumes that all of the sucrose and dissolved solids in the cane may be measured in the mixed juice and bagasse streams, and the quantity in cane then estimated by mass balance. The quantity of sucrose in cane estimated from the mass of cane and the DAC analysis is used only in a secondary role as a cross-check on that estimated from mixed juice and bagasse. Thus, the primary estimate of sucrose in cane is as shown in equation 1.

$$sucrose\ in\ cane \ = \ sucrose\ in\ mixed\ juice \ + \ sucrose\ in\ bagasse \qquad \ldots \qquad \textbf{(1)}$$

This concept is represented in Figure 1, which also shows the other process streams that enter or leave a 'conventional' factory of older design (incorporating a filter station to process the mud from the juice clarifiers).

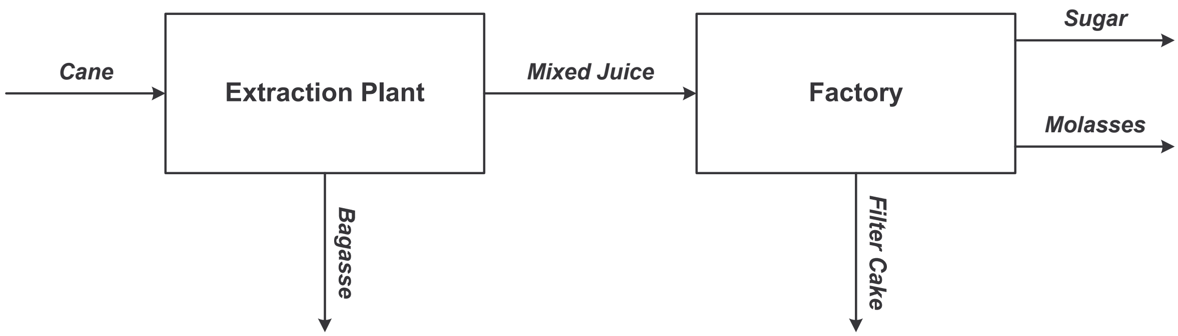

Figure 1. Mass balance representation for a raw mill with filter station.

The calculation of undetermined sucrose loss from a factory of this design is calculated as per equation 2 below. It is apparent from the equation that the mass of sucrose in bagasse appears both in the incoming cane stream (made up of sucrose in mixed juice and sucrose in bagasse) as well as in the outgoing bagasse stream. It thus cancels out and is not required[1]. The quantity of sucrose lost through the mechanism of undetermined loss is usually expressed as a percentage of the sucrose entering the factory in the cane.

$$\begin{array}{ll} & mass\ of\ sucrose\ in\ mixed\ juice \\ + & mass\ of\ sucrose\ in\ bagasse \\ \hline - & mass\ of\ sucrose\ in\ sugar \\ - & mass\ of\ sucrose\ in\ bagasse \\ - & mass\ of\ sucrose\ in\ filter\ cake \\ - & mass\ of\ sucrose\ in\ final\ molasses \\ \hline = & mass\ of\ sucrose\ lost\ undetermined \\ \hline \end{array} \qquad \ldots \qquad \textbf{(2)}$$

However, most sugar mills in South Africa with diffusers now carry out clarifier mud recycling to the extraction plant, which eliminates filter station operation. This complicates the material balance for the factory, as the mixed juice stream is now 'contaminated' with sucrose that has been recycled to the extraction plant from the clarifiers. In order to avoid

[1]There is an error in the paper on undetermined loss by Love (2001), where the calculation of undetermined loss incorrectly includes a term for the mass of sucrose in bagasse, which is not required.

'double accounting', the mass balance needs to be adjusted to accommodate this sucrose. The conceptual flow of materials into and out of the factory is shown in Figure 2.

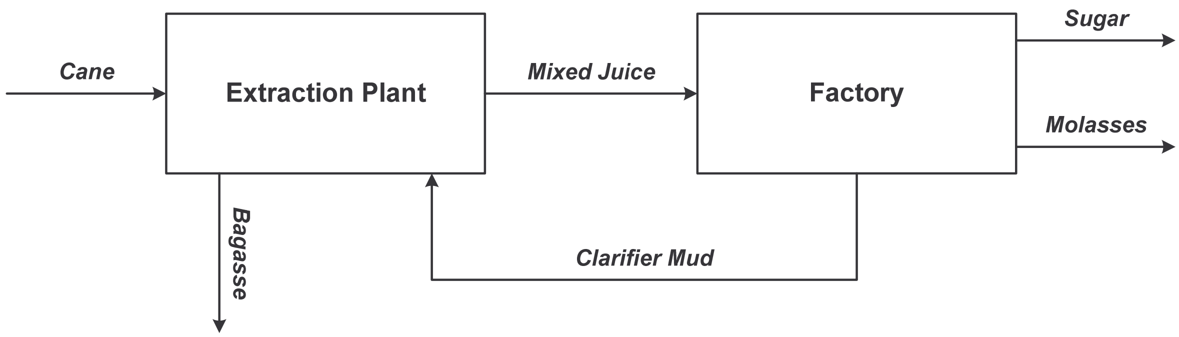

Figure 2. Mass balance representation for a raw mill with mud recycle.

The sucrose content of the mixed juice stream is adjusted for the presence of mud recycle by means of equation 3. Jensen and Govender (2000) presented full details of the associated calculations.

$$\begin{aligned} mass\ of\ sucrose\ in\ mixed\ juice(adjusted) = {} & mass\ of\ sucrose\ in\ mixed\ juice(measured) - \\ & mass\ of\ sucrose\ in\ recycled\ mud \end{aligned} \quad \ldots \quad \textbf{(3)}$$

The calculation of undetermined sucrose loss from a factory of this design is calculated as per equation 4 below.

$$\begin{array}{ll} & mass\ of\ sucrose\ in\ mixed\ juice(adjusted) \\ + & mass\ of\ sucrose\ in\ bagasse \\ \hline - & mass\ of\ sucrose\ in\ sugar \\ - & mass\ of\ sucrose\ in\ bagasse \\ - & mass\ of\ sucrose\ in\ final\ molasses \\ \hline = & mass\ of\ sucrose\ lost\ undetermined \\ \hline \end{array} \quad \ldots \quad \textbf{(4)}$$

Interpretation of undetermined loss results

The undetermined loss measurement itself is only really useful if it can be used to identify and eliminate the source of the loss. This is not a simple task and is often more of an art than a science, relying on experience and intuition rather than proceeding by means of a clear logical process. The primary problem with interpreting the reported undetermined loss figures is the inherent lack of precision of the measurement. This arises from two major factors.

Firstly, undetermined loss is not measured directly (as is molasses loss) but is primarily determined as the difference between sucrose input and sucrose output. This method of estimating a small quantity from the difference between two large quantities is notoriously imprecise. Small percentage errors in each of the large quantities translate into a large percentage error in the quantity estimated by difference.

Secondly, errors in the estimate of the quantity of sucrose in stock within the factory may have a substantial influence on the estimated undetermined loss. The influence of the error in the stock depends on whether the stock is constant or changing. If the stock remains constant (both in reality and in the estimated quantity) then the influence of any error in the estimated stock will cancel out and have no influence on the estimated undetermined loss. On the other hand, if the stock varies substantially from week to week (as it will do for a number of weeks at both the end and the beginning of each season) errors in the stock estimate can cause substantial errors in the estimated undetermined loss. The influence of the error in the stock on the estimated undetermined loss is relative to the size of the stock in relation to the quantity of sucrose processed over the period. Consequently the undetermined loss for a month will be more reliable than that estimated for a week. Conversely, the undetermined loss estimated for a week with slow crushing and/or multiple stops will inevitably be less reliable.

A substantial degree of circumspection is clearly necessary in interpreting undetermined loss measurements. With undetermined loss measurements generated only once per week and a strong financial incentive to identify and eliminate losses rapidly, process knowledge, judgement and experience are important to extract the maximum information from a minimum of data points of very limited precision.

Even where the magnitude of an undetermined loss is known, it is still necessary to identify the cause (or causes). A classification of the potential causes of undetermined losses (Love, 2001) is a useful starting point for identifying the sources of the loss:

- Apparent loss (which can apply either to process streams or to factory stock)
  - Mass measurement errors
  - Sampling errors
  - Analytical errors.

- Real loss
  - Physical loss
    - Entrainment into cooling water
    - Losses to effluent
    - Theft
  - Sucrose destruction
    - Microbial destruction
    - Chemical destruction.

There is always a strong incentive to identify apparent losses since they are essentially an issue of accounting, rather than sugar technology or engineering, and most easily corrected (even retrospectively).

Some real loss is inevitable, particularly in the evaporator station where sucrose inversion occurs as a result of the time that the juice is held at relatively high temperatures. Schäffler (1987) and Purchase *et al*. (1987) give details on the estimation of this loss, indicating that it is of the order of 0.5 to 1.0%. The quantity of this loss will depend on the particular details of the evaporator station, with substantially higher losses when Robert evaporator vessels are used as first effect vessels rather than Kestner type evaporators (Rein and Love, 1996).

Identifying the individual sources of loss (real or apparent) is often particularly difficult, as a relatively large undetermined loss may be the result of the sum of numerous small losses. A standard approach to dealing with an undetermined loss problem is one of 'close attention to detail'. An effective means of achieving this is to use a comprehensive, structured checklist that covers as many sources of loss as possible. Such a checklist, incorporating the experience of many production personnel, has been used in Tongaat Hulett factories for many years. A version of this checklist can be found in Rein (2007).

Additional measurements that can be used in the attempt to identify major contributors to undetermined loss are:

- Lactic acid as an indicator of microbial sucrose destruction (Madaree *et al.*, 1991).
- Changes in purity across evaporators or clarifiers as an indication of sucrose destruction.
- The non-sucrose (or non-pol) ratio as an indicator of the under-estimation of molasses losses (Rouillard, 1979).
- Changes in the ratio between glucose and brix over the evaporator station as an indicator of sucrose inversion (Schäffler *et al.*, 1985).
- Discrepancies in mass measurements where comparative measurements are available (e.g. comparison of dispatch weights and receiver weights for product sugar).
- Direct measurement of losses into cooling water and effluent (de Robillard and Purchase, 1986; Crebo, 1991).

Direct loss of sucrose in products that end up in drains and effluent is always a major concern and the simple management procedure of restricting the use of hosepipes (Purchase *et al.*, 1984) has been an effective means of minimising this loss. The ideal situation is full recovery of spills and overflows back into process – as is practiced under a zero-effluent philosophy (Jensen and Schumann, 2001).

It would be particularly useful to be able to determine the split in undetermined loss between that attributable to clarification and evaporation (mixed juice to syrup) and that attributable to the boiling house (syrup to sugar and final molasses). Attempts at weighing and analysing syrup to achieve this have had variable results (Archibald and Karlson, 1970; Purchase *et al.*, 1984) and even an industry sponsored study at Felixton over three seasons (between 1987 to 1990) gave results with "a general picture … of data that was not sufficiently reliable to give meaningful balance data."[2]

Given the difficulty of identifying the causes of undetermined loss, Tongaat Hulett attempted collaboration with a university computer science department to use expert system techniques to capture the knowledge of experienced sugar technologists and make the expertise available either as a computerised advisory system, or as an automated analysis system. Unfortunately two student projects failed to produce acceptable results, possibly due to the extent and complexity of the sugar technology involved.

[2]Tongaat Hulett internal correspondence on 'problems with weighing and analysis of high brix streams'.

The continuing need for improved methods of identifying sources of undetermined loss prompted the investigation into the use of boiling house mass balances to analyse factory data from the perspective of sources of loss.

A boiling house mass balance as an aid to identifying the source of undetermined loss

The wealth of figures relating to boiling house performance that are part of the weekly factory performance report are normally used as a guide when attempting to identify sources of undetermined loss. However, rather than relying on experience and judgement, it is possible to interpret some of these factory figures in a structured and quantitative way by comparing the figures with the predictions of a boiling house mass balance.

Boiling house mass balances are well known sugar technology and have progressed from hand calculations (Birkett, 1978) to dedicated computer programs (Hoekstra, 1983) and more recently to calculations performed within standard spreadsheets (Schorn *et al*., 2005). Loubser (2004) provides a useful review of different approaches that have been used to undertake heat and mass balance calculations.

When Hoekstra (1983) developed his dedicated computer program for boiling house mass balances, he considered three possible approaches:

- Simulating hand calculation procedures.
- Iterative simulation of successive process units.
- Setting up and solving a set of simultaneous equations.

He rated the ‘simultaneous equations’ approach as most appropriate and used this as the basis for his program.

The approach used in the current work for developing a spreadsheet-based boiling house mass balance uses ‘iterative simulation of successive process units’. The following factors mitigate against the disadvantages that Hoekstra (1983) pointed out as inherent in this approach:

- Modular simulations of individual process units are programmed and tested independently of the whole boiling house model.
- The modules are ‘piped up’ to match the boiling scheme by simply naming all the input and output streams.
- The ‘circular reference’ capability of modern spreadsheets is used to accommodate recycle streams (incorporating an initialisation feature to recover from calculation errors).
- Simulated ‘Proportional Integral (PI) controllers’ are used to converge the model to desired conditions (a concept borrowed from automatic control theory rather than using a conventional mathematical optimisation technique).
- Delays (of a specified number of iterations) are incorporated into the recycle streams and the actions of the PI controllers to allow the full process simulation to complete before taking control action or adjusting the recycle. This greatly improves the numerical stability of the calculations.

- Damping factors (first order filters in automatic control theory terminology) can be included in recycle streams to help stabilise the calculations and prevent numerical convergence problems.

The boiling house mass balance needs to be based on a process flow diagram (PFD) that shows all the major process flows. Figure 3 is a PFD of the boiling scheme that is widely used in the South African sugar industry – the very high pol (VHP) or three boiling partial remelt scheme.

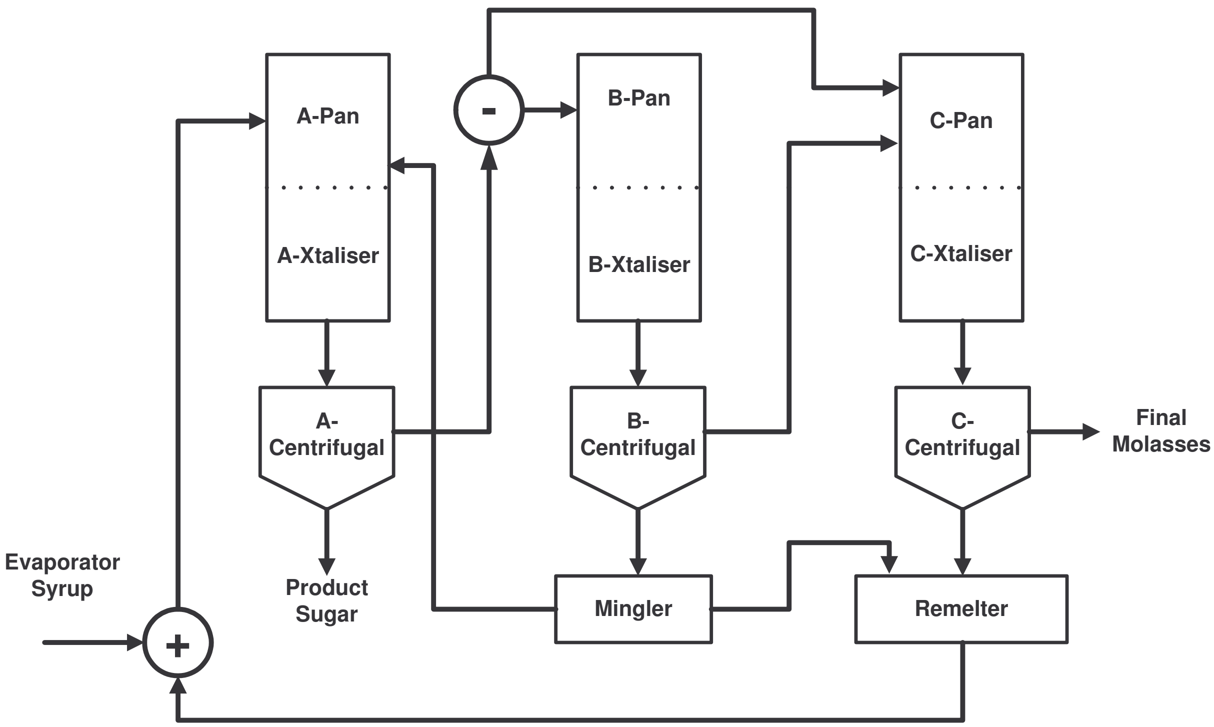

Figure 3. Process flow diagram of very high pol (VHP) or three boiling partial remelt boiling scheme.

For the purposes of interpreting undetermined loss in terms of boiling house figures, the level of detail modelled by Hoekstra (1983) is not required. Thus, the current modelling considers seed pans, massecuite pans and crystallisers as a single process unit. Although it is not necessary to model the water flow through the boiling house, Hoekstra's approach of a four component mass balance (sucrose, crystal, non-sucrose and water) has been followed, both to allow direct comparison between the current model and other versions, and also to work directly with the reported factory figures (e.g. total mass flows and solids concentrations of specific streams). The blow-up tanks have not been modelled and the extra water addition is assumed to have been added to the centrifugals.

Without a reliable, direct measurement of syrup mass flow (as discussed earlier) it is necessary to estimate the syrup flow from the (adjusted) mixed juice flow. This means that any estimated loss of syrup actually applies to the whole of the process from mixed juice through to syrup (i.e. clarification and evaporation).

A conventional boiling house mass balance assumes no losses. The performance of each of the process units (including simple flow splitters) needs to be defined in sufficient detail for the outlet streams to be calculated from the inlet streams. Thus, with the syrup flow into the boiling house fully specified, the product sugar and final molasses produced can be calculated. The undetermined loss will be reflected in the difference between the calculated and actual quantities of product sugar and final molasses.

The boiling house balance will predict the quantities of each grade of massecuite boiled. When independent measurements of massecuite quantities are available (as is normally the case when batch pans are used) these can be compared with model predictions. Figure 4 shows the situation of a factory where independent measurements of both the quantity of A-massecuite and B-massecuite are available. A possible loss stream has been chosen to be associated with each measurement. The loss streams are then built into the boiling house mass balance (as if they were part of the process flow diagram). Simulated PI controllers are then added to the spreadsheet and used to adjust each loss stream to ensure that the mass balance model matches the actual measurement. The measurements and the associated loss streams (coded according to colour) shown in Figure 4 are:

- The quantity of A-massecuite produced is matched by varying the loss of A-Pan feed syrup.
- The quantity of product sugar manufactured is matched by varying a direct loss of A-sugar.
- The quantity of B-massecuite produced is matched by varying the loss of A-molasses produced.
- The quantity of final molasses produced is matched by varying the loss of B-molasses produced.

For the purposes of the mass balance model, the loss streams need to have a specific location on the process flow diagram. There is no guarantee that these loss streams originate where shown on the process flow diagram or that they even exist in reality. Figure 4 includes ‘clouds’ to indicate the area of applicability of each loss stream, but even that cannot be specified with full certainty. The intention of these fitted losses is that they be trended and interpreted with a similar degree of circumspection to that used on all other measurements associated with undetermined loss rather than necessarily interpreted as a real process stream.

The measurements that are used to calculate the undetermined loss (the overall sucrose balance) are all based on the analysis of sucrose and dry solids whilst most of the rest of the measurements internal to the boiling house are based on brix and pol. To make the internal measurements comparable with the overall sucrose balance figures it is possible to use the procedures outlined by Love (2002) to estimate sucrose and dry solids measurements from pol and brix measurements.

Preliminary work on using this technique for investigating undetermined loss with the use of a boiling house mass balance has shown some interesting results and it is intended to continue evaluating the technique during the coming season. The probability is that the technique will have the most value when very high levels of undetermined loss occur – a situation that is obviously undesirable!

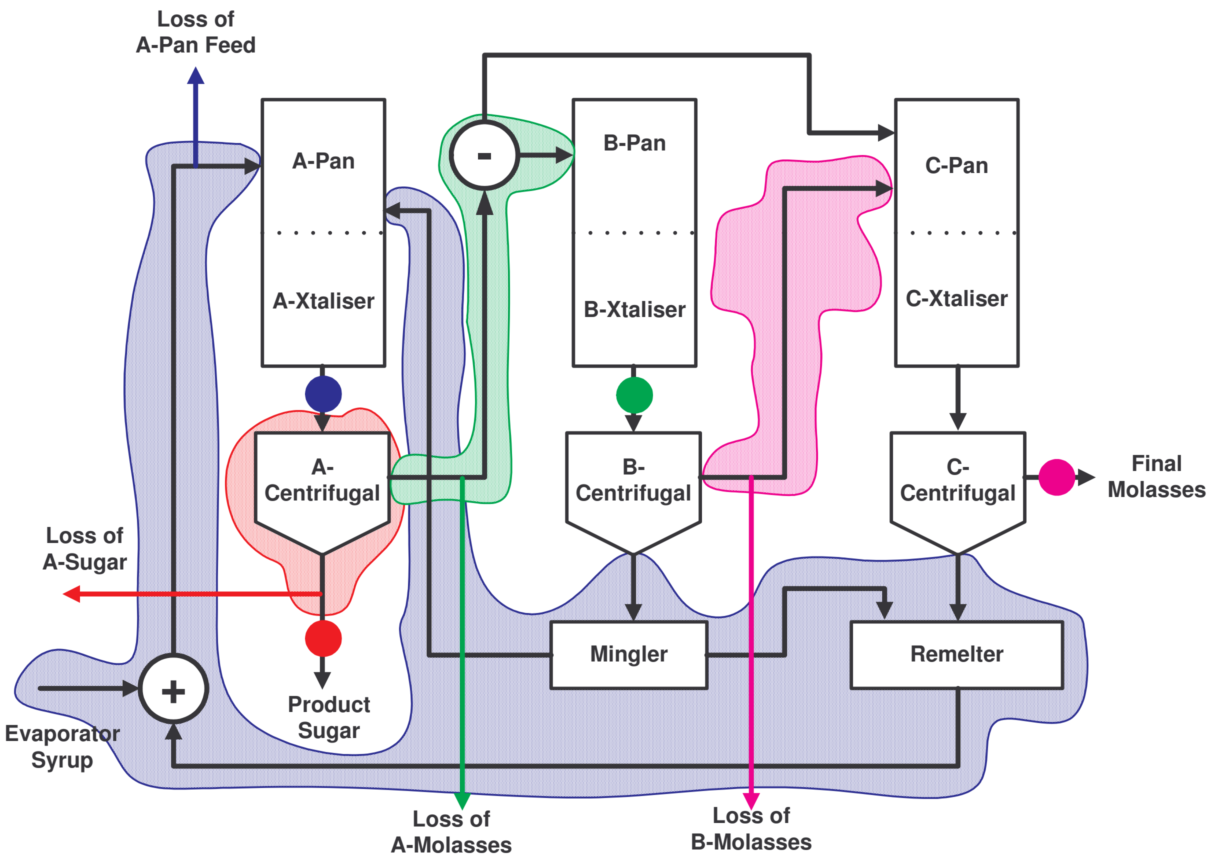

Figure 4. Simulated losses selected to make model predictions match measurements.

Possible refinements to the technique as presented above are:

- Incorporate stock changes into the balance to allow this to be fully accounted for.
- Where continuous pans are in use (and thus no independent measurement of massecuite quantities produced is available) install coriolis flow meters on the feed to the pan. Measurements of mass flow and density from the coriolis flow meter, when combined with the known quantities of seed produced in batch pans, can provide an independent estimate of the quantity of massecuite produced from the continuous pan.
- Where independent measurements of A, B and C-massecuite quantities are available, the B-molasses loss can be adjusted to match the C-massecuite quantity and a direct loss of C-molasses included and adjusted to match the measured quantity of C-molasses.

Conclusions

The estimated undetermined loss for a factory is a key performance measurement and an important guide for production management. Due to inherent problems in the measurement of undetermined loss, making effective use of these measurements normally requires a high degree of processing knowledge, experience and judgement. A new approach to trying to identify possible sources of undetermined loss has been proposed.

This involves comparing available process measurements with the predictions of a boiling house mass balance. A boiling house mass balance has been constructed in a modular form on a spreadsheet allowing extra streams (representing assumed losses) to be easily added to the balance. The magnitudes of the loss streams are then automatically adjusted to get the predictions of the mass balance to match factory performance figures.

This technique of interpreting undetermined loss using a mass balance has yielded only preliminary results, and it is intended to further evaluate the technique during the coming season.

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