IMPLEMENTATION PLANS FOR SUPERVISORY CONTROL OF PAN STAGE OPERATIONS

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Abstract

PAN STAGE operations have a major influence on the quality of shipment sugar production, the processing efficiency of the centrifugal and dryer stations, the sugar recovery from final molasses and the steam consumption of raw sugar factories. As well, for many factories, the production capacity of the pan stage is often the rate limiting station of the factory. Several Australian factories now operate with only one pan stage operator and a management tool such as a smart supervisory control system (SSCS) would assist the operator in making better decisions for managing the stage. The SSCS integrates the projected boil-on rates for syrup and molasses to each pan on the stage with the forecast production of syrup based on cane receival data and molasses from the centrifugals. By using the phase of each pan into an operational model the levels of syrup, A molasses and B molasses in the respective stock tanks are forecast and the information used to forewarn of potential problems or inefficiencies if current operating strategies are maintained. A hybrid fuzzy logic based expert system is employed to advise corrective procedures. While the system is not yet adopted commercially each phase of the development plan has been undertaken. Forecast tank levels have been found to compare favourably with actual tank levels. The SSCS should result in improved use of the installed equipment on the pan stage to achieve increased sugar recovery, improved sugar quality and reduced steam consumption while fulfilling the production rate requirements. One of the important benefits of the control system should be reduced variability in the steam consumption on the pan stage, leading to improved steam economy for the factory.

Introduction

Australian sugar factories face two major costs, viz. high unit labour costs and high capital costs for equipment. As a consequence, each factory employs only a few operators/supervisors and capital items are generally large (and few in number) in order to capture the benefits of economies of scale. For example, for the pan stage, several factories have only one operator to manage the whole stage (typically 8 pans) and batch pans of 200 t dropping capacity are common through the industry.

Most Australian factories employ only one supervisor to oversee all operations from the cane weighbridge, milling and boiler stations, through to the sugar bin and outloading. The number of operators on shift for the whole plant is about 11.

For several years, the benefit of a supervisory/advisory support tool for pan stage operations in sugar factories has been recognised (Frew and Wright, 1977; Merensky, 1985; Watson, 1989; Verwater-Lukszo *et al.*, 2003), but it appears no system is currently operating to the extent considered necessary for strongly beneficial results.

Supervisors and operators currently rely on their knowledge and experience of the process, and the operational plan nominated by the production manager, to manage the operations of the shift. However, the complexity of the task in operating the pan and fugal stations in an optimal way has increased and at the same time the financial implications of those outcomes have increased. To achieve a truly optimal result, management decisions for the pan and centrifugal stations must be undertaken in relatively short time frames e.g. during each hour, and compliance with a rigid operational plan set by the production manager may not be appropriate. Ideally the production manager will set the production objectives for the shift and the supervisor/operators will make real time optimal decisions to meet those objectives.

A smart supervisory control system (SSCS) was developed as a management tool to assist the operator in making better decisions for managing the stage.

Pan stage operations in Australian sugar factories

Figure 1 shows the typical flowscheme adopted by Australian mills to produce raw sugar with polarisation between 98 and 99.4, depending on the customer requirements. The syrup from the evaporators is usually at 88 to 92.5 purity. The flowscheme incorporates three grades of massecuite (A, B and C) with the mixture of the A and B sugar production being combined and dried to produce the shipment sugar of mean size 0.8 to 1.0 mm. The C sugar provides the crystal seed material to produce a high grade seed (after boiling on syrup) for the A and B massecuite production. The flowscheme incorporates a complex combination of feedforward (e.g. some syrup fed onto the B strikes; A molasses (or syrup) onto the grainings for the C strikes) and feedback (e.g. A molasses onto the A strikes). Both batch and continuous pans are used and batch and continuous centrifugals are used for processing the A and B massecuites. Only continuous centrifugals are used for processing the C massecuite.

The high interdependency of operations on the pan stage and the centrifugal station requires that optimal supervision of the two stations is considered collectively and not in isolation. The management of the centrifugals/dryer station is undertaken by a different operator from the pan stage.

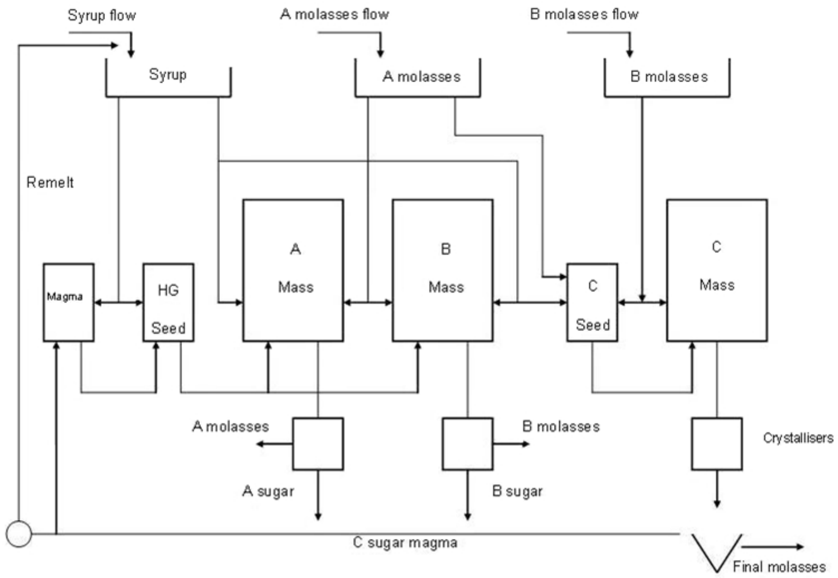

Fig. 1—Flowscheme for the pan stage operations in Australian sugar factories.

Operational objectives for managing the pan and centrifugal stations

The operational objectives for the pan and centrifugal stations are a combination of the following:

- Throughput rate. The A, B and C massecuite production rates per tonne of cane crushed changes as the sucrose and soluble impurity content of the cane supply changes. A farmer's supply of cane to the factory (known as a rake of cane) may vary from four minutes to 30 minutes of cane crushed by the milling train and the composition will vary from rake to rake and to a lesser extent within the rake. In addition to this variation is the more significant variation in the cane composition through the season. The cane supply has a lower sucrose content and higher soluble impurity content in the early and late periods of the crushing season and a higher sucrose content and lower soluble impurity content in the mid-season period. The typical effect of the seasonal change in cane composition on the A, B and C massecuite production rates is shown in Table 1 (Broadfoot and Pennisi, 2001).

Table 1—Typical massecuite production rates.

Massecuite type	Massecuite % cane	
	Early season	Mid-season
A	12.8	22.6
B	11.5	8.1
C	6.6	4.6

- Sugar quality. The main sugar quality parameter that is influenced directly by pan stage operations is the mean size (and uniformity) of the A and B sugars. The centrifugal station impacts directly on the polarisation of the shipment sugar. Variations in the wash water addition in the A and B fugals to meet the pol specification directly affect the extent of sugar dissolution during fugalling and consequently affect the A and B massecuite production quantities. Sugar of premium quality receives a bonus payment so revenue for sugar production is directly affected by the quality.
- Sugar recovery. Improved exhaustion of the C massecuites, yielding final molasses of lower purity directly results in increased sugar production from the sucrose in the syrup supply to the pan stage. For the three-massecuite boiling scheme used in Australian factories, a critical operational target for the pan stage is to ensure that the B molasses is at an appropriately low purity, otherwise the production of a higher purity C massecuite will result in increased sucrose loss to final molasses. Reduced sugar recovery occurs when the soluble impurity content of the cane supply is high, resulting in increased production of B and C massecuites, and final molasses.
- Steam/vapour consumption for the pan stage. As a consequence of the large batch pans that are used in Australian factories, the steam/vapour consumption on the pan stage commonly varies through the pan stage cycle by +/–25% about the mean. These fluctuations impact negatively on the steady operation of the evaporators (where bleed vapour is used on the pan stage) or increase the make up of high pressure steam to the exhaust steam mains and venting of steam to atmosphere. The fluctuations in steam/vapour consumption on the pan stage usually result in inefficient use of steam and reduced revenue from attached cogeneration plants. Smoothing of the steam/vapour usage on the pan stage is highly beneficial.

The optimal operational plan set by the production manager for a shift (or perhaps 24 h period) is a weighted consideration of all four criteria with the weighting (importance) placed on the individual criterion varying in the short and long term. For example, during mid season when the sucrose content in the cane supply is at its peak, stronger emphasis will be given to throughput rate; if the cane crop is reduced, greater emphasis will be placed on sucrose recovery and quality; if there is a mechanical breakdown in a section of plant and crushing rate is reduced, greater emphasis will be given to sugar recovery, sugar quality and perhaps steam consumption.

It is possible to produce a single weighted objective function for the pan and fugal stations for the shift and use the supervisory/advisory control system to manage the operations to best meet the requirements of that objective function. The supervisory system uses real time data and input from the supervisor and operators to take into account the operational circumstances for the shift. For example, if a particular pan experiences a vacuum leak and its boil-on rate is affected, then this needs to be included in the supervisory plan.

Overview of the framework for the smart supervisory control system

Figure 2(a) shows the information transfer between the operator, the pan stage control system and the pan stage plant that is currently used in most Australian factories. The smart supervisory control scheme (SSCS) works in tandem with the pan stage operator and the current pan stage control systems to make projections of performance against the nominated objective and to provide advice. Figure 2(b) shows the information transfer for the pan stage incorporating the SSCS.

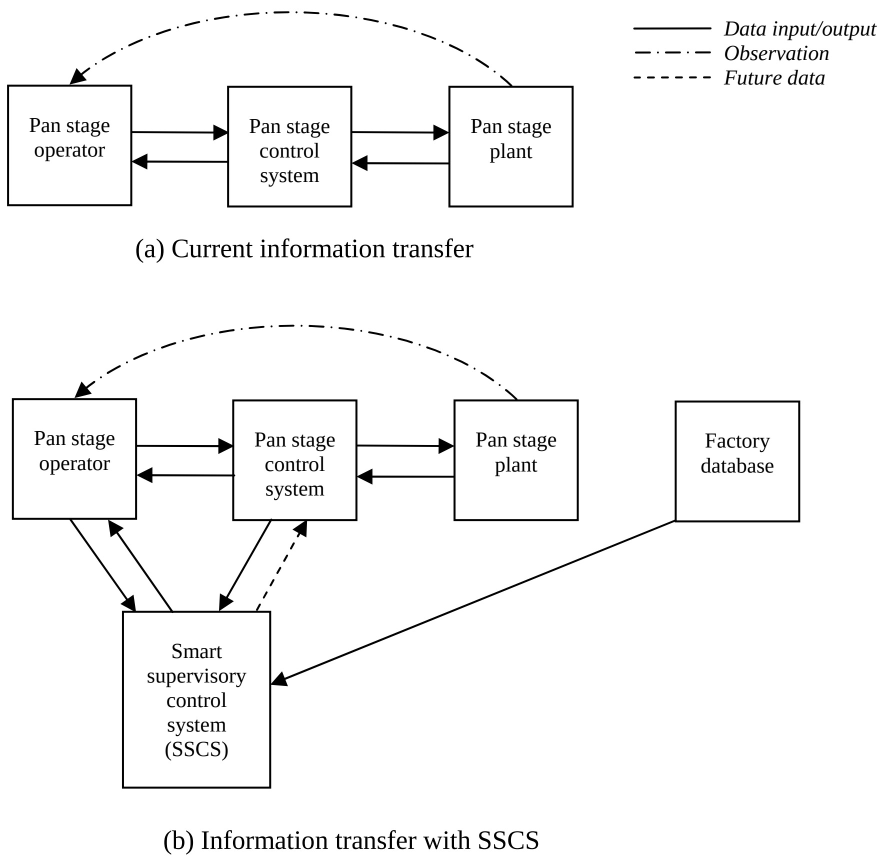

Fig. 2—Information transfer for current pan stage control and with the SSCS.

The SSCS takes operator input along with information from the existing sugar mill control system and factory databases (such as cane receival information) and provides recommendations and expert advice. The operators use the advice/recommendations from the SSCS to influence their management of the pan stage and fugal station operations e.g. through the values they input to the pan stage and fugal station control systems, allocation of pans to A or B massecuite boiling etc.

There are four primary outputs provided by the SSCS, viz.

1. Pan duties management;
2. Pan control strategies;
3. Pan scheduling management; and
4. Stock tank management.

In addition the SSCS provides support information to the operators in two categories, viz.

1. Prediction of future pan stage operating conditions; and
2. Explanatory and justification capabilities.

The SSCS is a hybrid fuzzy logic based expert system design incorporating rule based decision making, explanatory capabilities and process models (Dodd *et al.,* 2005a; Dodd *et al.*, 2009). The knowledge base is composed of human expert knowledge coupled with mathematical models simulating the pan stage and centrifugal station processes.

This arrangement maintains significant human interaction with the SSCS as part of the process, which is considered to be highly desirable.

Framework of the supervisory control system

The framework of the SSCS is based upon conventional expert systems (Leung and Wong, 1990; Gisolfi and Balzano, 1993) and conventional If-Then fuzzy rule based systems design (Goel *et al*., 1995; Berkan and Trubatch, 1997). Dodd (2009) provides a detailed description of the framework and core operations of the SSCS.

As depicted in Figure 3 the SSCS incorporates several modules performing multiple tasks. This modular structure aids in maintenance, upgradeability and flexibility. A brief description of each of the modules follows.

Input module

The input module draws real time information directly from the sugar mill control system through relevant databases including information on cane receival (rate, juice analyses), juice processing station, laboratory analyses (syrup purity), the pan stage and centrifugal station.

Pan stage operators provide information such as equipment performance ratings, operational problems, plus characteristics of the syrup, molasses and sugar process streams.

Editor module

The editor module provides the capabilities to modify the functional parameters for the process model input parameters and output data to match the local operating conditions. As well, this module can assign or modify the explanations tagged to each of the rules.

Data module

The data module contains several databases for information storage including the fuzzy If-Then rule knowledge base, the parameters specific to the pan stage models, databases storing text based information for presentation to the operators, a blackboard system for storing the predicted values of the process variables (from the process models) and from the rule based decision making block, information from the sugar mill control system (including information from cane receival, the juice processing station, laboratory, pan stage and the centrifugal station).

Input data from the operators on the pan and centrifugal stations are also captured in this module. The information flows in Figure 3 show the important role of the blackboard system, as the working memory for results from the pan stage process models, and the rule based decision making block. Output data are obtained from the blackboard data system.

System module

The system module carries out data processing of the two major sources of input information and transforms these to six system outputs. The system module is the most complex and essentially comprises the majority of the system software operations. The system module contains three subsystems as shown in Figure 3 viz.:

- Process models of the pan stage;
- Rule based decision module adjusting process models for local conditions; and
- Explanatory communications.

In total six process models are used for the predictions of pan stage and fugal station conditions and these are described in Table 2.

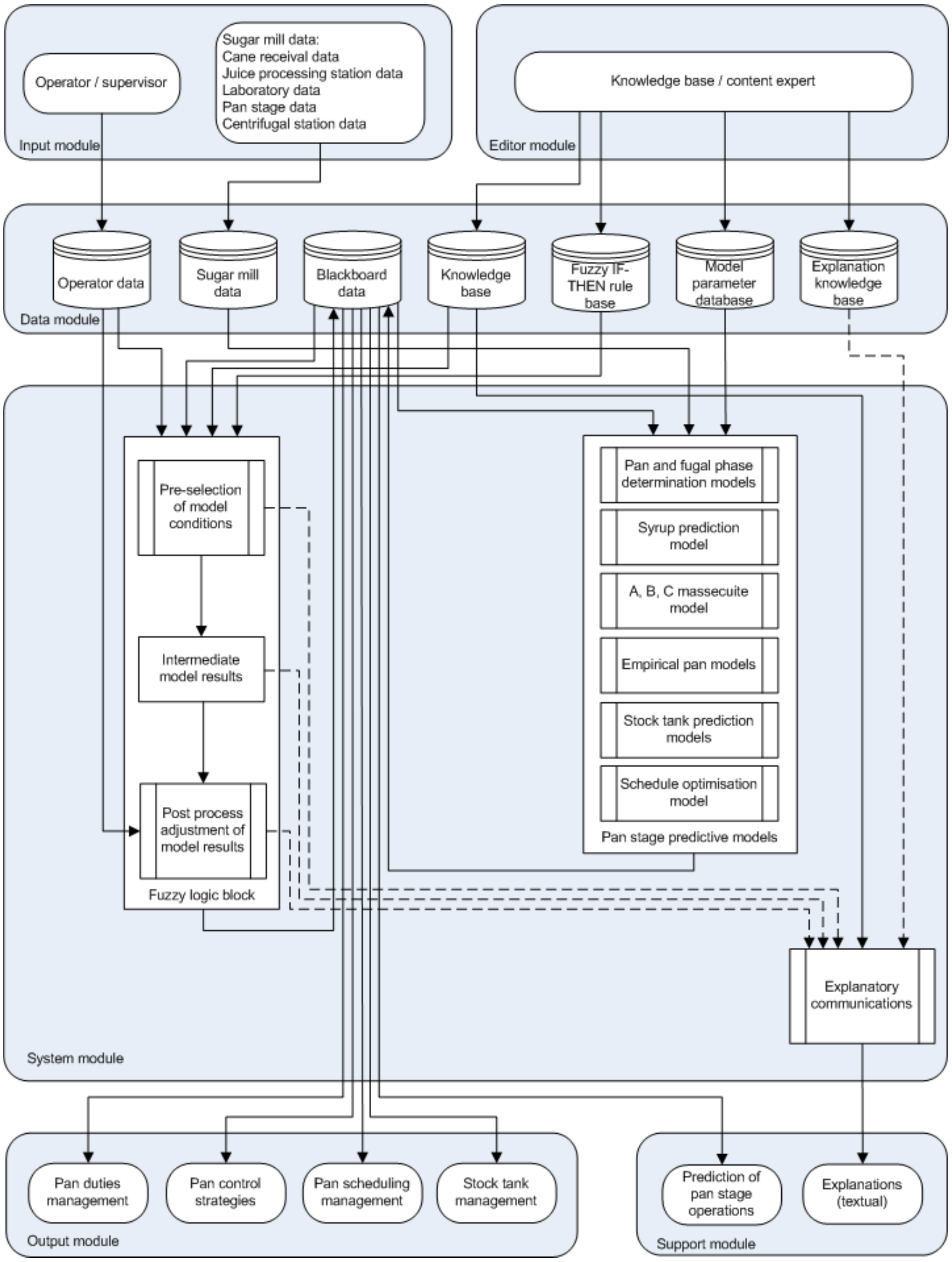

Fig. 3—Framework of the SSCS.

Table 2—Descriptions of the models used in the SSCS.

Model name	Model description
Pan and fugal phase determination models	Determines the current status and phase within the pan stage schedule for each vacuum pan and the status of the centrifugal station. For the pans, a simple classification procedure based upon steam usage, level and change in level as presented by Frew and Wright (1976) is used. Receiver levels and change in receiver levels allow fugal station status to be inferred. Once this determination is made, this model is coupled with the pan stage schedule and the other process models for prediction of future pan stage operating conditions.
Syrup prediction model	Determines the future flow of syrup to the pan stage based on cane receival data at the weighbridge and laboratory. The prediction of the quantities of sucrose and impurities in the syrup stream allows a forward forecasting of the stocks of syrup. The forward predictions of syrup rate and composition are key inputs to predicting the massecuite production loadings.
A, B, C massecuite model	Calculates the average production rates of A, B and C massecuites, C sugar remelt, molasses and sugar streams given the syrup purity and flow rate to the pan stage. Crystal sizing determinations assist in calculating the necessary quantities of C sugar needed for the A and B pans to ensure final product sugar is of the required size. Typical parameters for crystal content, sugar size, coefficient of size variation and purity rise at the fugals are assumed in this model.
Empirical pan models	The rate at which each pan takes feed material (syrup, A molasses or B molasses) during the different phases of the pan's operation is determined by experimentation and modelling. This boil-on rate for feed materials is a function of the massecuite level and phase of the pan, steam rate, head space pressure (vacuum), brix and purity of the feed syrup/molasses.
Stock tank prediction models	By using the empirical pan models, the boil-on rates for each feed stream at the different stages of the pan stage schedule can be determined by summing the syrup, A molasses and B molasses feed rates for all the pans at that point in the schedule. Given the expected syrup production rate and C sugar remelt production rate, the predicted tank levels can be determined for the syrup tank for a series of intervals. Similarly, the predicted tank levels for the A and B molasses can be calculated from the production rates of the molasses at the centrifugal station and the sum of the consumption rates on the individual pans at the specific point in the pan stage schedule.
Schedule optimisation model	Manages the schedule e.g. determines when pans should start and complete strikes to avoid pan idling, while minimising and smoothing steam usage on the overall pan stage and adhering to sugar production productivity, recovery and quality requirements. This model optimises the objective function. The information from this model is used in conjunction with information gathered through the input module, the rule based decision making process and from the other process models to provide information on: • Recommended steam rates for the specific phases of the individual vacuum pans; • Choice of A/B massecuite duties for the ‘swing’ vacuum pans; • Forecasting of stock tank levels and future disturbances e.g. tank overflow; • Footing quantities to the vacuum pans; and • Scheduling when pans should start and complete strikes.

The SSCS uses default parameters for the process models from the pre-defined knowledge base. However, to customise the SSCS for the current or defined operating circumstances, the fuzzy logic rule block uses the input data from the operator/supervisor to pre-process the pan stage models input parameters and, likewise, to post-process the output results from the models to align with the current and defined operating conditions. The post-processing results take precedence over the pan stage model output values and these are stored on the blackboard system for subsequent use by the models.

Examples of pre-processing and post-processing adjustments to match local operating conditions are:

- If cane is fresh and A massecuite purity is greater than 88 and the target pol of A sugar at the fugals is between 99.0 and 99.1, then A fugal purity rise = 1.75 units;
- If a vacuum leak exists on a particular pan, then set the boil-on rate characteristic for the pan to 0.92. It would be 1.0 at typical vacuum;

For a particular factory, the refinements that are undertaken through the fuzzy logic rule block customise the SSCS to suit the specific equipment and operational circumstances for the factory.

Output and support modules

The four control strategy recommendations are passed from the blackboard data system to the output module. The supporting results, including justifications for the presented advice and predictions for future pan stage operations, are provided in the support module.

Application of the SSCS

While the SSCS system is not yet adopted commercially, each phase of the development plan has been undertaken. Dodd (2009) provides the detailed specification for the framework, the incorporation of the process models, the software for implementing the fuzzy logic block and the procedures for communicating data among the modules.

Factory data were obtained from the databases at Racecourse Mill to assess the suitability of the prediction models for use in the SSCS. Information on these assessments is provided in the sections to follow.

Syrup rate prediction

Dodd *et al.* (2005a) outlined the procedure using cane receival data (cane rate and pol % cane) to forward predict the quantity of sucrose in syrup to the pan stage from cane and subsequently, using laboratory analysis of the purity of syrup, to determine the quantity of impurities in syrup. The model uses rolling average error corrections to accommodate the analytical errors in syrup and cane analyses and the variations in impurity/sucrose losses between cane receival and the pan stage (i.e. to allow for losses in mud, bagasse, degradation and analytical anomalies). Dodd *et al.* (2005a) demonstrated a high level of agreement of the predictions with syrup rates measured by magnetic flowmeters for a whole season at two factories.

Empirical pan models

For each phase in each pan at Racecourse Mill, the syrup or molasses boil-on rate was determined from the change in level in the pan (as measured by a differential pressure transducer), the brix of the feed material and the brix of massecuite at the start and finish of the phase (Dodd *et al.*, 2005b).

The measured boil-on rate was assigned to the current operating status for the pan using the classification procedure based on steam rate, level and change in level according to the procedure of Frew and Wright (1976). An iterative computer simulation for a batch pan was used to determine the change in syrup or molasses boil-on rate with change in steam rate to the pan.

Thus, within practical operational constraints, the steam rate during a phase of a pan, and collectively for all pans, can be adjusted to provide an improved outcome for the total pan cycle by avoiding idling time, increasing productivity, smoothing steam demand etc.

A, B and C massecuite model

This model develops steady state mass balances for all streams (massecuite, sugar, molasses, remelt, magma) on the pan stage and is well tested against factory data (Broadfoot and Pennisi, 2001).

Stock tank models

These models determine the stock tank levels for the syrup, A molasses and B molasses by utilising the above models plus the pan and fugal phase determination model and the schedule optimisation model. Figure 4 shows a comparison between the actual quantity of syrup in the stock tank and the predicted quantity for an 8 h period at Racecourse Mill. Similarly, Figure 5 shows the comparison of the predicted and actual levels for A molasses over the same 8 h period.

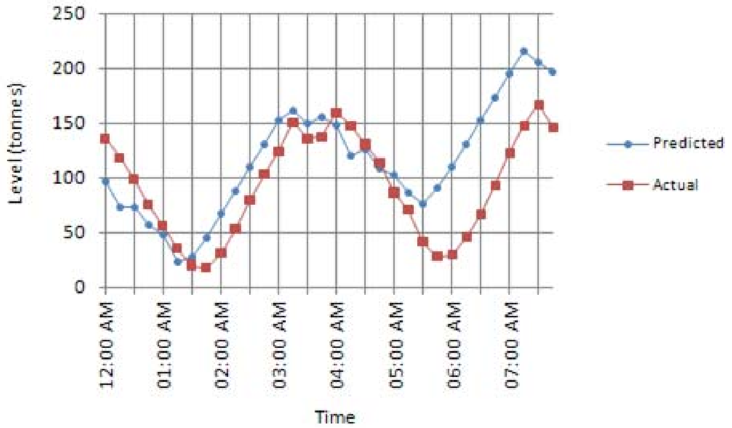

Fig.4—Comparison of forward prediction of syrup stock tank levels with actual data.

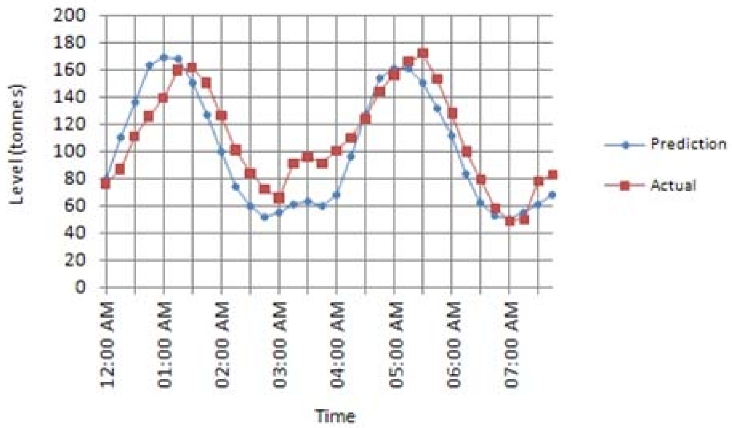

Fig. 1—Comparison of forward prediction of A molasses stock tank levels with actual data.

The data provided in Figures 4 and 5 are snap-shot data from an on-going forecast. In practice, when the SSCS is implemented, the projection for a specific time period will use the actual tank level as the starting position, resulting in closer alignment.

Conclusions

The SSCS is a hybrid fuzzy logic based expert system incorporating rule based decision making, explanatory capabilities and industrial process models of the pan stage and fugal stations. While the SSCS has not yet been commercially adopted, all components have been developed and its forecasting capability appears to be satisfactory.

The next step is to implement the system into a factory. The objective of the SSCS is to provide advice to supervisors and operators so that early decisions, such as changes to steam rates or allocation of pans to different duties, result in improved outcomes with respect to avoiding production rate difficulties, and maintaining good operational performance with respect to sugar quality, sugar recovery and minimisation of steam consumption on the pan stage.

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PLANS POUR L'INTRODUCTION D'UN SYSTÈME DE CONTROL POUR CONDUIRE LES CUITES

Par

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MOTS CLEFS: Control, Logique Fuzzy, Logiciels, Models pour les Cuites.

Résume

LES OPERATIONS aux cuites ont une influence majeure sur la qualité du sucre, l'efficacité des centrifuges et du sécheur, le recouvrement du sucre dans la mélasse finale et sur la consommation de vapeur des usines de sucre roux. Pour beaucoup d'usines, la production est limitée par la capacité de la station des cuites. Plusieurs usines australiennes fonctionnent maintenant avec un seul opérateur aux cuites; un outil de gestion, comme un système de contrôle intelligent (SSCS), pourrait aider l'opérateur à prendre de meilleures décisions. Le SSCS intègre les taux d'ébullition projetés pour sirop et mélasses a la production de sirop basée sur le tonnage de canne et a la production de mélasses des centrifuges. En utilisant la phase de chaque cuite dans un modèle opérationnel, on prédit les niveaux de sirop, de mélasse-A et de mélasse-B dans les réservoirs; ces informations évitent d'éventuels problèmes. Un logiciel est employé pour donner des procédures correctives. Quoique le système ne soit pas encore adopté commercialement, chaque phase du plan de développement a été entreprise; les niveaux calcules dans les réservoirs se comparent favorablement avec les niveaux mesures. Le SSCS doit aboutir à une meilleure utilisation de l'équipement installé, il devrait aussi donner une augmentation du sucre produit, une meilleure qualité de sucre et une consommation de vapeur réduite. L'un des avantages importants du système de contrôle est une réduction de la variabilité de la consommation de vapeur, et donc une économie de vapeur pour l'usine.

PLANES DE IMPLEMENTACIÓN PARA UN CONTROL SUPERVISORIO DE LAS OPERACIONES EN LA ESTACIÓN DE TACHOS

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PALABRAS CLAVE: Control Supervisorio, Lógica Fuzzy, Sistemas Expertos, Modelos De Cocimiento.

Resumen

LAS OPERACIONES en tachos tienen una influencia clave en la calidad del azúcar final, la eficiencia de las estaciones de centrífugas y secado, las pérdidas en miel final y el consumo de vapor de las fábricas de azúcar crudo. También, para muchas fábricas, la capacidad de la estación de tachos es a menudo la estación que limita la tasa de molienda. Actualmente varios ingenios australianos tienen un único operador de la estación de tachos y una herramienta de gestión como el Sistema de control supervisorio inteligente, (SSCS) asiste al operador en la toma de las mejores decisiones. El SSCS integra las tasas proyectadas para meladura y mieles para cada tacho con la producción prevista de meladura basada en la recepción de caña y las mieles de las centrífugas. Usando la fase de cada tacho en un modelo operacional, se predicen los niveles de meladura, mieles A y B en los respectivos tanques y la información es usada para anticipar problemas o ineficiencias potenciales, de mantenerse las estrategias de operación vigentes. Un sistema experto basado en lógica fuzzy híbrida se emplea para recomendar procedimientos correctivos. Aunque el sistema no ha sido adoptado todavía comercialmente, cada fase del plan de desarrollo ha sido considerada. Los niveles de tanques emitidos por el sistema se comparan favorablemente con los niveles reales. El SSCS debe resultar en un mejor uso del equipo instalado en tachos para lograr incrementos en recuperación, mejor calidad de azúcar y menor consumo de vapor, manteniendo los requerimientos en cuanto a las tasas de producción. Un beneficio importante del sistema de control debe ser la reducción de la variabilidad en el consumo de vapor en tachos, lo que conduce a economías de vapor en la fábrica.