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Modelling and multi-objective optimisation of a sugar mill based multi-effect evaporator set

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Abstract: This paper examines the multi-effect evaporator (MEE) set used as part of the process of raw sugar manufacture at Pioneer Mill. A steady-state model is developed and used to solve for unmeasured variables across the set to characterise the current operating conditions. Multi-objective optimisations (MOO) are then run to determine the Pareto-optimal front where juice flow through the MEE set is maximised and steam consumption minimised. The results of these MOO runs can be used to provide data to assist staff at the mill to operate the MEE set optimally. Future work is proposed that looks at the combined effects with other units in the factory to gain a more complete understanding of the entire milling process.

1. INTRODUCTION

The manufacture of raw sugar requires the management of a number of separate processes that interact to have significant impacts on profitability. This manufacturing process also requires a considerable amount of energy that can be provided through combustion of a by-product. This releases more energy than is required for the manufacture of sugar so in the past energy efficiency has not been a priority. With the increasing use of cogeneration in sugar mills there is now potential to increase revenue through the sale of excess energy to the electricity grid. As a result there is now a greater focus on managing energy usage in the factory, particularly at the evaporation stage where the majority of the energy is used.

1.1 Sugar mill operation

In Australia, raw sugar is manufactured from sugarcane that is made up of approximately one seventh sucrose, one seventh fibrous material and most of the remainder being water. A series of crushing mills extract the juice from the cane leaving behind a mixture of fibrous material and water called bagasse. This bagasse is used as fuel in boilers to generate the steam required to drive steam turbines and for process heating in the factory.

The extracted juice is heated by a series of juice heaters and then fed into a clarifier where the majority of the insoluble impurities are removed. The resulting clear juice is then pumped to a multi-effect evaporator (MEE) set where more than 90% of the water in juice is evaporated.

A MEE set comprises a number of vessels through which juice flows in series while steam is cascaded from the vapour space of one vessel and into the calandria (steam chamber) of the next. The first vessel is heated with low pressure (LP) steam and a condenser is used after the final vessel to generate a vacuum. The main advantages of a MEE set are explained by Rillieux's principles (Rein [2007]) the first of which describes that a set with n vessels will evaporate approximately n units of water per unit of LP steam consumed, assuming all steam is cascaded between vessels.

Juice from the clarifier is typically 15 brix (percent soluble solids by mass) and the concentrated juice (liquor) after going through the MEE set can have a brix of up to 72. This upper limit is due to the liquor being close to the sucrose saturation point and at higher levels there is a risk of spontaneous crystal formation. Crystal growth must be carefully controlled. This is performed at the pan stage which functions in a similar manner to an individual evaporator vessel. However, as the vessels at the pan stage are not cascaded, they operate less efficiently with respect to steam usage.

The pan stage produces massecuite which is a product made up of sugar crystals surrounded by molasses. This is fed to centrifuges where the crystals are separated and, after drying, become the raw sugar product.

1.2 Cogeneration at Pioneer Mill

In 2005, Pioneer Mill, owned and operated by Wilmar Sugar and located near Brandon in North Queensland, Australia, underwent a significant expansion during which 68MW of generation capacity was installed. All pre-existing steam turbines were replaced with electric drives and two steam turbine generator (STG) sets installed. One STG operates as a back pressure turbine with the exhaust steam being used for process heating in the sugar mill. The other is a condensing type turbine which is used exclusively for electricity generation. More electricity can be generated per tonne of bagasse burnt using the generation STG rather than the back pressure STG therefore any reduction in factory steam usage results in more electrical energy being generated to sell into the Australian electricity market.

Modifications were also made to the factory to reduce the process heating steam requirements. This was primarily achieved through the installation of two large pre-

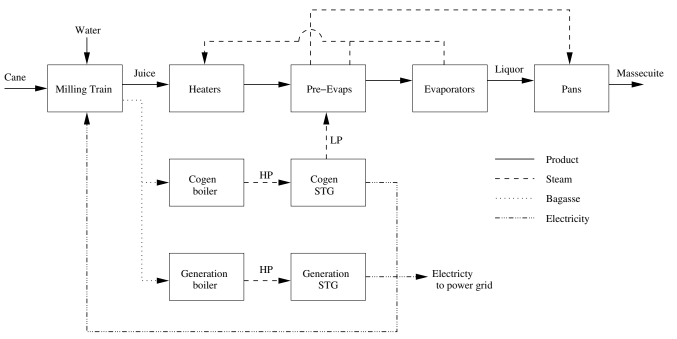

Fig. 1. Simplified block diagram of the creation of massecuite at Pioneer Mill.

evaporators at the front end of the existing MEE set, shown in Figure 1. Steam is bled from the vapour space of these vessels to the pan stage reducing the amount of LP steam required by the factory. Steam pipes were installed so that the juice heaters could also make use of steam bled from vessels along the MEE set. In total, these changes were expected to drop the factory LP steam requirement, as a percentage of cane processed by the factory, from 51.6% to less than 40% (Lavarack et al. [2004]).

1.3 Focus of work

Day-to-day running of a sugar mill requires trade-offs to be made to factory operation in response to changes in the incoming sugarcane, condition of the plant and various other external influences. In particular, scaling and fouling of heating surfaces in the juice heaters, the MEE set and at the pan stage has a substantial impact on the performance of the mill. Typically, scale in the MEE set will build up to a point where overall factory throughput is reduced in about three weeks. At this point a stop of production is necessary to conduct a chemical clean that removes this scale.

It is important to adjust factory operation to maintain throughput as scale builds up across the MEE set. This was previously done with minimal consideration to energy efficiency and occasionally involved venting steam directly to atmosphere. This current work has been undertaken to provide knowledge and tools to staff operating the plant in order to better manage the factory with a focus around the MEE set.

2. MULTI-EFFECT EVAPORATOR MODELLING

To better understand the operation of the MEE set and to predict its performance under different conditions, a model is required. This work is primarily based around the Pioneer Mill so a model was developed that matches this configuration of plant.

Due to numerous expansions over many years, the current Pioneer MEE set is made up of 13 separate vessels as shown in Figure 2. Juice flows through the two pre-evaporators at the front of the set in series while LP steam is supplied to these vessels in parallel. The remaining 11 vessels effectively make a quintuple (five cascaded vessels) MEE set as there are up to three vessels in parallel at each stage of the set.

2.1 Assumptions

Due to limitations in the instrumentation available and to allow for the development of a simplified model, a number of assumptions are made:

- Perfect mixing occurs so that juice leaving the vessel has the same properties as the juice in the vessel.
- All steam is considered to be saturated.
- The level of juice in all vessels is constant and at the optimal level for heat transfer.
- All steam entering the evaporator calandria condenses and then exits after losing only its latent heat.
- Energy loss as steam passes across a restriction, such as a steam valve, is negligible.
- The two pre-evaporators can be modelled together as a single vessel and similarly any small vessels in a parallel configuration can be grouped and modelled as a single vessel.

During normal conditions the MEE set operates smoothly with the main disturbance being variations in steam demand to the pan stage due to its batch operation. This disturbance is periodic with a period of about 4 hours. The time constants involved for variations in the condition of the MEE set are in the order of days and weeks. Given that data fed to the model is based on measurements averaged over at least 8 hour periods, it is assumed that a steady-state model of the MEE set will be sufficient.

2.2 Model development

A dynamic model of an evaporator vessel was developed in Adams et al. [2008] to examine the final brix control of the Pioneer Mill MEE set and possible interactions due to juice level. For the purpose of this work, this model has been reduced to steady-state and extended to encompass the entire MEE set.

Each stage of the MEE set is defined by eleven variables: steam flow in F_{si} (tonnes per hour), pressure of steam in calandria P_{si}, flow of juice in F_{ji}, brix of juice in B_{ji}, temperature of juice in T_{ji}, flow of steam out F_{so}, pressure of steam in head space P_{so}, flow of juice out F_{jo}, brix of juice out B_{jo}, temperature of juice out T_{jo}, and a cleanliness factor C_f.

Mass balance, brix balance and energy balance equations can be written for each stage of the set, see (1), (2) and (3) respectively. Note that in (3), h_{ji} represents the enthalpy of the juice going into the stage, Q represents the heat flow due to steam condensing in the calandria, h_{jo} the enthalpy of the juice leaving the stage and h_{so} the enthalpy of the steam leaving the stage.

$$F_{ji} = F_{jo} + F_{so} \tag{1}$$

$$B_{ji}F_{ji} = B_{jo}F_{jo} \tag{2}$$

$$F_{ji}h_{ji}(B_{ji}, T_{ji}) + Q = F_{jo}h_{jo}(B_{jo}, T_{jo}) + F_{so}h_{so} \tag{3}$$

The heat transfer, Q, also needs to be modelled hence (4) calculates this in terms of the flow of steam in to and the flow of condensate out of the calandria where h_{si} and h_{co} represent the enthalpies of the steam in and condensate out respectively. Q can also be calculated in terms of

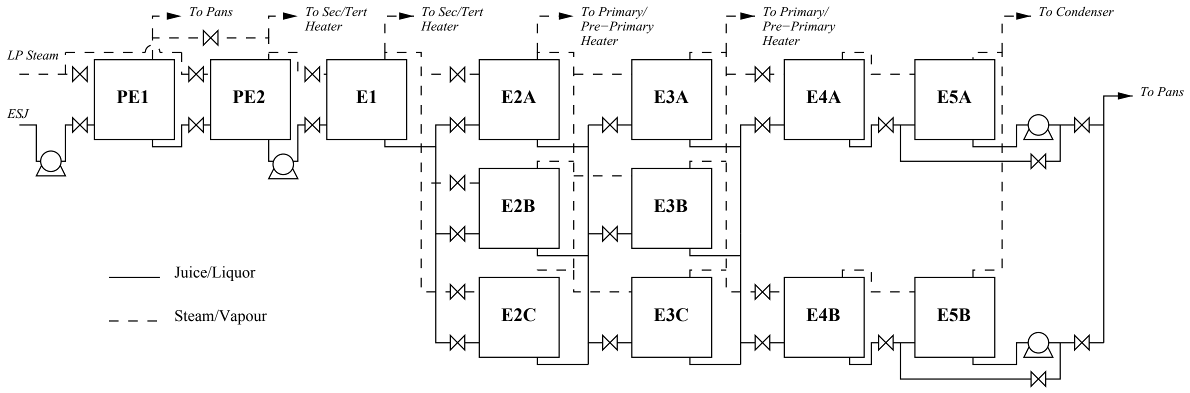

Fig. 2. Diagram of multi-effect evaporator set layout at Pioneer Mill.

the temperature difference across the calandria, the area of heating surface, A, and the heat transfer coefficient (HTC), U_{act} as given by (5).

$$\begin{aligned} Q &= F_{si}(h_{si}(T_{si}) - h_{co}(T_{si})) && (4)\\ Q &= U_{act}A(T_{si} - T_{jo}) && (5) \end{aligned}$$

Watson [1987] described an empirical relationship (6) between the operating conditions of a vessel in a MEE set and the expected HTC when the vessel is clean. By taking a ratio of this expected HTC against U_{act} a cleanliness factor, C_f, can be defined that represents the cleanliness of the heating surfaces on the evaporators. Here,

$$\begin{aligned} U &= 0.025879(T_{si} - T_{jo})^{-0.32}T_{jo}^{0.53}(100 - B_{jo})^{0.62} && (6)\\ U_{act} &= C_f U(T_{si}, T_{jo}, B_{jo}). && (7) \end{aligned}$$

Another important consideration is the effect of boiling point rise, (8), which describes the increase in temperature required for the juice to boil when compared with water at the same pressure. This work makes use of a proprietary relationship developed across the Australian sugar industry by the Sugar Research Institute. Rein [2007] describes an approximation, (9), that is indicative of the relationship. The enthalpy of the juice is also represented by an empirical equation, (10), based on the work in Ensinas et al. [2007]. Enthalpies of all steam and condensates are calculated from the IAPWS IF-97 standard, Holmgren [2007].

$$\begin{aligned} T_{jo} &= T_{so} + Bpr(B_{jo}, T_{jo}) && (8)\\ Bpr &= \frac{2B_{jo}}{100 - B_{jo}} && (9)\\ h_{jo} &= 4.1868T_{jo} - 0.0297B_{jo}T_{jo}\\ &\quad + 0.000046B_{jo}T_{jo}Pur + 0.0000375B_{jo}T_{jo}^2 && (10) \end{aligned}$$

Relationships between stages of the evaporators are straightforward with the bleed steam, Bs, being the only loss from the output of one evaporator to the input of the next evaporator,

$$\begin{aligned} F_{ji}^k &= F_{jo}^{k-1}\\ B_{ji}^k &= B_{jo}^{k-1}\\ T_{ji}^k &= T_{jo}^{k-1} && (11)\\ F_{si}^k &= F_{so}^{k-1} - Bs^{k-1}\\ P_{si}^k &= P_{so}^{k-1}. \end{aligned}$$

Finally, a basic model of the juice heater is required in order to determine the amount of steam it uses, which is bled from the evaporator set. This can be done using an energy balance similar to that used for an evaporator vessel,

$$\begin{aligned} F_{ji}h_{ji}(B_{ji}, T_{ji}) + Q &= F_{jo}h_{jo}(B_{jo}, T_{jo}) \\ Q &= F_{si}(h_{si} - h_{co}). \end{aligned} \quad (12)$$

2.3 Application

Using these equations and the assumptions in Section 2.1, the Pioneer Mill MEE set can be modelled as a system of 30 non-linear equations with a total of 35 variables. Several methods were trialled to solve this system of equations and it was found that Broyden's method, specifically method 1 from Broyden [1965], provided a good compromise between the number of steps required to converge to a solution and the number of model executions required per step.

The model can be used in two ways. The first is to input data measured from the operation of the MEE set into the model and solve for the unmeasured variables. This way the cleanliness factors for each stage can be determined, allowing the cleanliness of the entire set to be represented. This allows for monitoring of individual stages of the MEE set, an example of which is shown in Figure 3 where it can be seen that the cleanliness drops over a period of about 20 days followed by a step increase after a chemical clean has been conducted. Through monitoring the cleanliness at each stage of the set, the overall performance of the set can be tracked and potential problems recognised and diagnosed more easily.

The second use of the model is to apply the previously calculated cleanliness factors and some selected operating parameters as inputs. The expected performance of the MEE set can then be determined as operating parameters are varied.

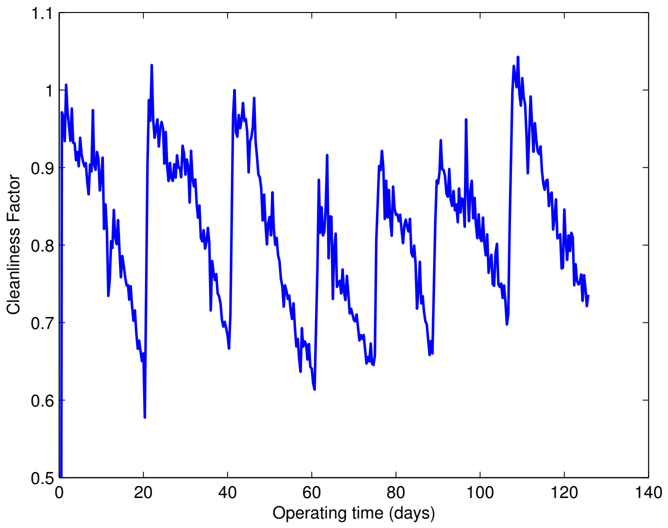

Fig. 3. Cleanliness factor of an individual evaporator stage during 2013 crushing season

3. MULTI-OBJECTIVE OPTIMISATION

Using the proposed model of the MEE set, optimisation of the operating parameters can be performed. Ideally this would be treated as a single objective optimisation problem to maximise profit however there are a number of external and non-monetary factors that also need to be considered. As these external factors can vary over the course of a year, a multi-objective optimisation (MOO) approach needs to be taken.

Multi-objective optimisation involves finding the set of solutions that are non-dominated, that is, there is no way to further minimise any of the objectives without having a negative impact on one, or more, of the other objectives. This set is called the Pareto-optimal front and MOO will find an approximation to it. By calculating the Pareto-optimal front for the MEE set in its current condition, the optimal operation point can be selected by staff to match the desired trade-offs at the sugar mill and the operating parameters determined that can achieve this.

3.1 Objectives and decision variables

Factory rate is an important criteria for the mill so one objective for the MEE set is to maximise juice flow rate. A MEE set is intended to evaporate water using a minimal amount of steam while not negatively impacting the rest of the factory so a second objective is to minimise steam consumed. Further objectives that would be useful in managing the factory require consideration of other sections of the mill so are outside the current scope of this work.

There are a number of operating parameters that can be altered that effect the performance of the MEE set:

- Supply steam pressure (100–135 kPag)
- Final brix (65–72Bx)
- Final vacuum (-85 – -91 kPag)
- Pressure drop across steam valve between E1 vapour space and E2 calandria (0–30 kPa)
- Source for primary juice heating (0–100% of steam bled from E3 as opposed to E2)
- Source for secondary juice heating (0–100% of steam bled from E1 as opposed to PE)
- Venting steam to atmosphere from E2 (0–10tph)
- Venting steam to atmosphere from E1 (0–10tph)
- Venting steam to atmosphere from PE (0–10tph)

These are the decision variables for the MOO problem. The limits shown in brackets are the constraints that will be used and are based on a combination of physical limits and what are considered to be normal operating limits.

3.2 Method

Multi-objective problems can be solved by repeatedly solving single-objective problems to find multiple Pareto-optimal solutions. However, it is possible that certain Pareto-optimal solutions may not be found in some applications, Deb [2005]. Other optimisation techniques such as simulated annealing, particle swarm optimisation and genetic algorithms can also be used. Genetic algorithms, in particular, have been well developed for use with MOO Fonseca and Fleming [1993, 1995], Deb et al. [2002] as they can determine the entire Pareto-optimal front in a single optimisation run by choosing the fitness of each member in a generation based on how many other members dominate it. Genetic algorithms also have the advantage of not requiring information on the derivatives of the objective population and lend themselves to be run in parallel by splitting up the model calculations for each generation over a number of processes.

To implement the MOO, the *NSGA-II: A multi-objective optimization algorithm* toolbox, Seshadri [2009], was used. It implements non-dominated sorting as given in Deb et al. [2002], and uses simulated binary crossover and polynomial mutation, Deb and Agrawal [1995], Raghuwanshi and Kakde [2004], for the crossover and mutation genetic operators respectively. In testing it was found that, despite counter-measures in the NSGA-II algorithm, the members of the populations were crowding together and not giving a good representation along the entire Pareto-optimal front. To work around this, the distribution indices for the crossover and mutation operators were both reduced from 20 down to 1 to increase the spread of members resulting from the crossover and mutation operations.

4. ANALYSIS OF OPTIMISATION RESULTS

Multi-objective optimisations were run on three sample cases based on data collected during the 2013 season, shown in Table 1. The data points were selected at different points in the MEE scaling/cleaning cycle to represent when the MEE set was clean, in the middle of a cycle and dirty.

The optimisations were run for each of these three cases using a population of 250 members and run for 500 generations. While it is possible to reduce these values and, in turn, speed up the MOO, a good approximation and coverage of the Pareto-optimal front was desired. The resulting fronts are shown in Figure 4 and, for reference, the measured performance of the set at these times is represented by a circular symbol on the graph.

		Days since	Cleanliness factors					
Sample	Comment	cleaned	PE	E1	E2	E3	E4	E5
1	Clean	3	0.96	0.92	0.90	1.13	0.90	0.90
2	Mid-cycle	11	0.88	0.98	0.90	0.99	0.90	0.90
3	Dirty	20	0.83	0.95	0.82	0.91	0.69	0.69

Table 1. Cleanliness factors for multi-objective optimisation runs

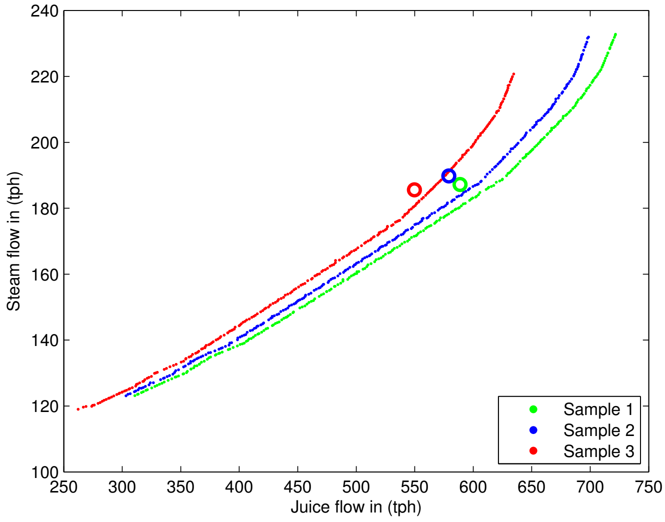

Fig. 4. Pareto-optimal fronts based on operating conditions of Pioneer Mill MEE at different times in 2013 crushing season

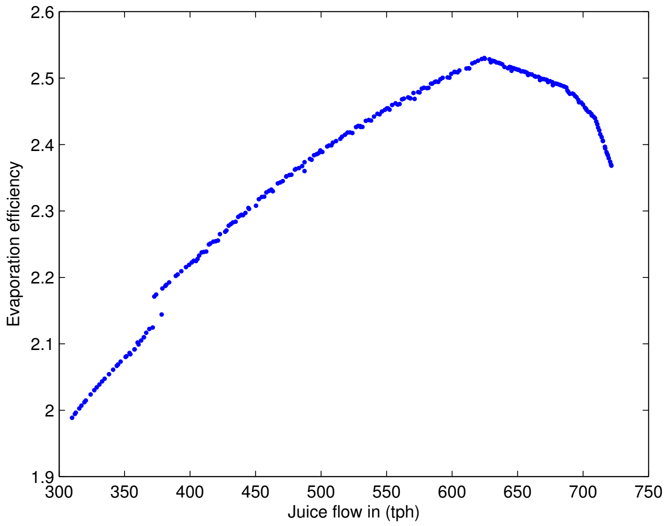

Fig. 5. Mapping of Pareto-optimal front to juice flow vs evaporation efficiency plot

As there are only two objectives, each point on the Pareto-optimal front represents the minimum possible steam flow to achieve a given juice flow. It can be seen that varying the operating parameters allows for the MEE set to be run over a wide range of juice rates though the steam required starts to increase rapidly at the higher juice rates. It can also be seen that as the set becomes dirtier, the maximum rate becomes limited and more steam is required to run at a given rate compared to when the set was clean.

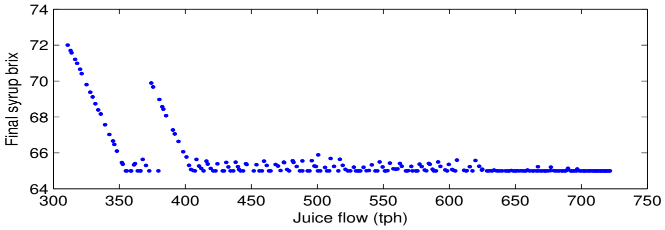

Fig. 6. Mapping of Pareto-optimal front to juice flow vs final brix

The results from the MOO run on sample 1 were investigated further. Evaporation efficiency, defined as the ratio of water evaporated to steam consumed, is a possible alternative objective and so was calculated at each point of the Pareto-optimal front and plotted against juice flow, see Figure 5. It can be seen that efficiency peaks at a juice flow of around 625 tph indicating that for a given cleanliness there is a flow rate at which the MEE is most steam efficient and this efficiency cannot be maintained if the rate is changed. Also, if evaporation efficiency had been used as an objective for the MOO then only the points to the right of this peak would have made up the Pareto-optimal front and thus not cover a sufficient range of juice flows.

Plots were also constructed showing each individual operating parameter against juice flow, again for the sample 1 MOO results. From examination of these results it is clear that there is an order in which the operating parameters are applied as the juice flow increases along the Pareto-optimal front.

To start with, it was found that at all points on the Pareto-optimal front the primary heaters were supplied with steam from E3 and the secondary heaters with steam from E1.

Figure 6 shows that the final brix should be maintained at the lower allowable limit, except at low juice rates. A low final brix means that the MEE set will be evaporating less water overall so this result is expected but is only valid when considered in isolation. Since any extra remaining water in the liquor must be evaporated at the pan stage, which is a less steam efficient process, a lower final brix means that in the real plant more steam must be bled from the PE. This has not yet been accounted for in the model.

In a similar manner, the final vacuum (Figure 7) should be kept as low as possible when operating at higher juice flows.

The throttling of the MEE set at the E2 steam valve is the optimal way to control juice flow through the set at rates between 400 tph and 625 tph, as shown in Figure 8. To achieve flows higher than this, the supply steam pressure must be increased (Figure 9), though this further increase is at the cost of evaporation efficiency.

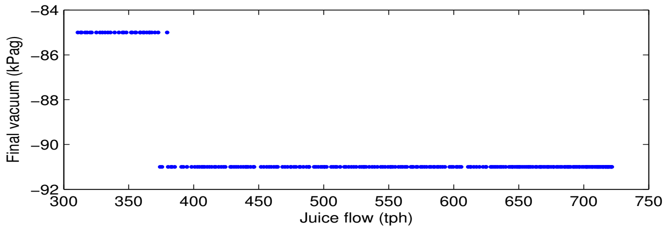

Fig. 7. Mapping of Pareto-optimal front to juice flow vs final vacuum

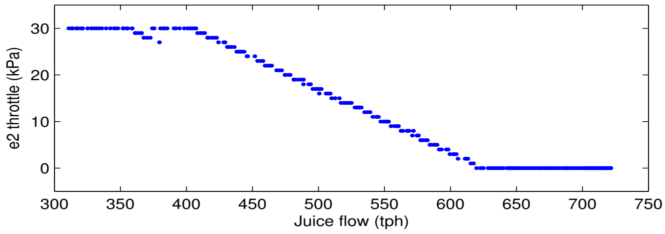

Fig. 8. Mapping of Pareto-optimal front to juice flow vs E2 steam throttling

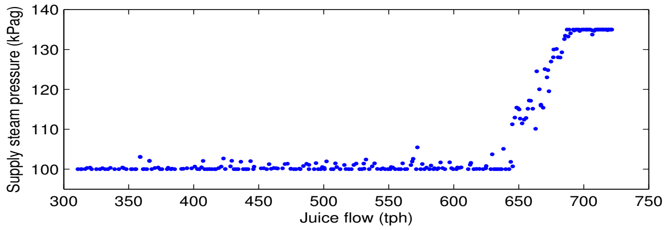

Fig. 9. Mapping of Pareto-optimal front to juice flow vs steam supply pressure

Venting steam was found to be the least steam efficient way of increasing juice flow rate but, if required, venting from as far back in the set as possible is preferable.

5. CONCLUSION

In this paper a multi-effect evaporator model was developed and applied to the Pioneer Mill set. Multi-objective optimisations were run to determine the optimal way to operate this set across a number of states of cleanliness. The majority of the results correspond with what is already considered good practice at Pioneer Mill: supply the juice heaters with steam from as far back in the set as possible, keep the supply steam pressure as low as possible, maintain the vacuum as low as possible, and when required, throttle the rate using the E2 steam valve. The positive impact of the low supply pressure is novel as this was previously only kept low for reasons external to the MEE set. Due to this result, staff at the mill will now place more focus on keeping this pressure low.

Some results are difficult to consider in isolation, in particular the result indicating that a lower final brix was optimal. Further work is required to develop a model of the pan stage to properly understand how this operating parameter should be set. Additionally, work to develop models of the crushing mills and boilers would assist in setting up realistic constraints and allow MOO objectives to be considered that can be more closely linked to profitability of a sugar mill.

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