Multi-Objective Optimisation of an Integrated Sugar Mill for Economic Enhancement

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Declaration

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision.

The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.

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Abstract

This thesis covers the development and implementation of an integrated sugar mill (ISM) model and its subsequent use to perform multi-objective optimisation (MOO) to generate valuable data that assists production staff to optimally operate a sugar cane mill with extensive co-generation capability.

A sugar cane mill manufactures crystallised sugar from sugar cane. There is an extensive history around milling and it is a well understood process. The introduction of large scale electricity generation through the combustion of excess bagasse, a renewable energy source made from the fibrous remainder of processed sugar cane, provides new opportunities. Significant, and currently increasing, revenue can be made through generation and traditional operating strategies do not fully take this into account.

Steady-state models of Pioneer Mill in Queensland, Australia, a sugar cane mill with substantial co-generation and generation capabilities, are developed. These models can be redeveloped and applied to other mills. Each section of the mill is modelled separately, using a combination of existing models in the literature, building from first principles and using empirical relationships.

These models are used to estimate the system parameters representing the state of the sugar mill, using routinely measured operational data. Combining the separate models into an ISM and using these parameters, predictions are made on the performance of Pioneer Mill in response to changes in operating parameters.

MOO is applied to the ISM using four objectives: cane throughput, sugar lost, electricity generated and bagasse produced. In the optimisation, sugar lost is minimised while other objectives are maximised. The Pareto-optimal solution, representing the set of solutions where there are optimal trade-offs among objectives, is analysed for guidelines on the characteristics of optimal operation. A simple method of weighting is used to allow production staff to easily select a point from this solution that meets current priorities and determine the operating parameters for optimal operation of the mill.

Contents

Abbreviations and Symbols

Abbreviations

ABMA	American Boiler Manufacturers Association
BOM	Bureau of Meteorology
CPU	Central Processing Unit
DEAP	Distributed Evolutionary Algorithms in Python
EA	Evolutionary Algorithm
ESJ	Evaporator Supply Juice
FEJ	First Expressed Juice
GA	Genetic Algorithm
GCV	Gross Calorific Value
HTC	Heat Transfer Coefficient
IS	Insoluble Solids
ISM	Integrated Sugar Mill
LP	Low Pressure (steam)
MCR	Maximum Continuous Ratings
MEE	Multi-Effect Evaporator
MJ	Mixed Juice
MOO	Multi-Objective Optimisation
NSGA-II	Nondominated Sorting Genetic Algorithm II
OEM	Original Equipment Manufacturer
PC	Personal Computer
PE	Pre-Evaporator
PLC	Programmable Logic Controller
RJS	Rotary Juice Screen
SCADA	Supervisory Control And Data Acquisition
SCOOP	Scalable COncurrent Operations in Python
SLSQP	Sequential Least Squares Programming
SMRI	Sugar Milling Research Institute (South Africa)
SRI	Sugar Research Institute (Australia)
STG	Steam Turbine Generator

Symbols

Variables

A	Area (m^2)
A	Ash content (%) (boiler model)
B	Brix (bx)
C	Filling ratio
C_f	Cleanliness factor
E	Extraction (%)
E_k	Theoretical mill extraction (%)
F	Fibre content (%) (milling train model)

F	Flow (tph) (MEE set model)
GCV	Gross calorific value ($\mathrm{kJ/kg}$)
h	Enthalpy ($\mathrm{kJ/kg}$)
I_c	Imbibition coefficient
IS	Insoluble solids content (%)
K	Reabsorbtion factor
L	Loss (%)
$\dot{m}$	Mass flow rate (tph)
M	Moisture (%)
P	Purity (%) (pans and fugals model)
P	Pressure (kPa) (MEE and steam and power models)
Q	Energy flow (MW)
R	Ratio
r	Ratio
r	Retention (%) (mud filter model)
s	Entropy ($\mathrm{kJ/K}$)
S	Sucrose content (%)
S	Mill separation efficiency (%)
S_c	RJS separation efficiency (%)
T	Temperature (°C)
U	Heat transfer coefficient ($\mathrm{kJ/m^2/K}$)
UA	Product of HTC and Area ($\mathrm{kW/K}$)
$\dot{V}$	Volume flow rate ($\mathrm{m^3/s}$)
W	Moisture content (%)
x	Steam dryness fraction (steam and power model)
x_{air}	Humidity ratio (boiler model)
η	Efficiency (%)
ρ	Density ($\mathrm{kg/m^3}$)

Subscripts

$2mj$	Second mixed juice stream
ah	Air heater
ai	Air in
air	Air stream
air	Air
$air\ req$	Air required for combustion
amb	Ambient
ao	Air out
ap	Added product to MJ
$\frac{B}{IS}$	Fraction mud brix to insoluble solids
$b2$	Boiler 2
$b3$	Boiler 3
bag	Bagasse stream
$bag\ prod$	Bagasse produced
bd	Boiler drum blowdown stream
$belt$	Belt mud filter
bp	Bleed port (on STG 3)

bs	Bleed steam (from STG 3)
bs	Bleed steam (from MEE stages)
$c\ loss$	Carbon loss
$c\ to\ co$	Carbon to CO
$cane$	Cane stream
co	Condensate out
$cond$	Condensate
ct	Cooling tower
cw	Cooling water (STG3)
cwi	Cooling water in
cwo	Cooling water out
da	Deaerator
$desup$	Desuperheater
$dry\ gas$	Dry flue gas
e	Turbine exhaust
$E1th$	Steam from evaporator 1 to tertiary heater
$E3ph$	Steam from evaporator 3 to primary heaters
$econ$	Economiser
esj	Evaporator supply juice stream
$filt$	Filtrate stream
$flash$	Flash tank stream
ft	Flash tank
$furnace$	Boiler furnace
fw	Feed water stream
gi	Flue gas in
go	Flue gas out
$hgtp$	High grade pan/fugal throughput of sucrose
$\frac{imbib}{fibre}$	Imbibition relative to fibre
$imbib$	Imbibition water added to milling train
$isen$	Isentropic
ji	Juice in
jo	Juice out
$juice$	Juice stream
ld	Letdown station
$lgtp$	Low grade pan/fugal throughput of impurities
liq	Liquor stream
lrg	Large rotary mud filters
mj	Mixed juice stream
mol	Molasses stream
mud	Final mud stream
mw	Boiler make-up water
paw	Pans added water
pe	Pre-evaporators
$pesj$	Pans added ESJ
ph	Primary heaters
phx	Process heat exchanger
pow	Generated power
$prim$	Primary mud stream
ps	Pan stage steam stream

pwe	Pans water evaporated
rad	Radiation
$recirc$	Boiler 3 economiser recirculation stream
$\frac{s}{we}$	Steam consumed relatve to water evaporated
$screen$	Fibrous material off RJS
sh	Secondary heaters
si	Steam in
sml	Small rotary mud filters
so	Steam out
$stg2$	STG 2
$stg3$	STG 3
$stg3\ s1$	STG 3 stage 1
$stg3\ s2$	STG 3 stage 2
sug	Sugar
$unacc$	Unaccounted
v	Steam vented to atmosphere
$vent$	Steam vent to atmosphere
$\frac{w}{i}$	Water added to low grade pans relative to low grade throughput
$\frac{W}{IS}$	Fraction mud water to insoluble solids
$\frac{w}{s}$	Water added to high grade pans relative to high grade throughput
$\frac{WW}{IS}$	Fraction wash water applied to mud insoluble solids
$wet\ bulb$	Wet bulb temperature
$wet\ gas$	Wet flue gas
wi	Water in
wo	Water out
WW	Wash water to mud filter

Superscripts

n	Index used in the milling train model. 0 – 4 indicates mill 1 to 5 respectively
k	Index used in the MEE set model. 0 indicates the pre-evaporators while 1 – 5 indicates evaporators 1 to 5 respectively.

List of Author's Publications

G. J. Adams, B. J. Burke, G. C. Goodwin, J. T. Gravdahl, R. D. Peirce, and A. J. Rojas. Managing Steam and concentration disturbances in multi-effect evaporators via nonlinear modelling and control. In *Proceedings of the 17th IFAC World Congress*, pages 13919–13924, Seoul, Korea, July 2008.

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