Computers and Chemical Engineering 52 (2013) 77–89

Contents lists available at SciVerse ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

A multi-period model for optimal planning of an integrated, resource-efficient rice mill

Jeng Shiun Lim, Zainuddin Abdul Manan*, Sharifah Rafidah Wan Alwi, Haslenda Hashim

Process Systems Engineering Centre (PROSPECT), Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

ARTICLE INFO

Article history:
Received 19 July 2012
Received in revised form
23 November 2012
Accepted 15 December 2012
Available online 6 January 2013

Keywords:
Rice mill
Multi-period
Optimisation
Product portfolio
Rice supply chain

ABSTRACT

Rice is one of the world's most important staple foods. Previous studies have focused on the yield improvement for an individual rice mill. There is a need to develop a framework to address the multitude of variables influencing the design of a rice mill complex, which include fluctuating thermal and electrical energy demands, diverse energy supply options, fluctuating product demands, resource availability and product degradation. The objective of this study is to develop a framework for the optimal design and planning of the product portfolio and processing route of an integrated, resource-efficient (IRE) rice mill complex. The objective function is to maximise the profitability of the rice mill by using the developed multi-period mathematical model. Sensitivity analysis was performed on the case study to evaluate the impact of fluctuating product demands, product prices and electricity cost on the production throughput, process configuration and profitability of the IRE rice mill complex.

1. Introduction

Rice is one of the most important staple foods for over three billion people worldwide, particularly for the people of Asia, the Middle East and West Africa (Haas et al., 2005). Due to rapid population growth, five billion rice consumers are anticipated by the year 2030 (Khush, 2005). The rising demand for rice has encouraged various government agencies to closely monitor and check the rice prices because price increases can potentially lead to social issues. For example, the price increase in rice between 2005 and 2007 worsened the socio-economic situation of rice consumers, particularly in underdeveloped countries (Ivanic & Martin, 2008). The strong impact of the global rice economy on a country's food security and socio-economic well-being provides motivation for scientists to improve rice yield and production stability and reduce post-harvest losses. These motivations are aligned with the five key elements highlighted by the International Rice Research Institute (IRRI) (Pandey et al., 2010). Among others, the elements that stipulate the need to "enhance the efficiency of resource utilisation in rice value chain" and "reduce the environmental footprint" emphasise the role of the rice mill in stabilising the global rice economy.

Rice milling is part of the upstream industry in the rice value chain. In rice mills, harvested paddy is processed into full head rice, broken rice and other by-products, including rice bran and rice husk. Selling by-products directly to the downstream industries at subsistent price is common practice for rice millers. In certain underdeveloped countries, rice husk is often treated as a waste and disposed of, leading to environment problems (Mansaray & Ghaly, 1998). However, the by-products from rice milling can be used as feed to produce value-added products or used as a source of renewable fuel in a utility system. For example, rice bran oil extraction technology can be used to produce rice bran oil with rice bran from a rice mill as a feed. Additionally, rice mills can use the broken rice to manufacture rice flour or vermicelli. The efficient use of by-products, such as feed, for these value-added processes increases long-term profit. In contrast, by installing established energy conversion technologies (for example, a cogeneration system), rice husks can be used as fuel to simultaneously generate heat and electricity to satisfy the utility demands of the rice mill and reduce the mill's utility bills. Thus, the significant potential to enhance the profitability of a rice mill while addressing environmental issues has motivated the transformation of a conventional rice mill into an integrated, resource-efficient (IRE) rice mill complex.

Most studies related to rice industries have focused on the improvement of individual processes, such as drying and milling. For paddy drying, Atthajariyakul and Leephakpreeda (2006) proposed a systematic approach to determine the optimal conditions for fluidised bed paddy drying via adaptive fuzzy logic control to ensure good quality and energy efficiency. Indexed parameters included paddy moisture content and drying air-heating load. In another study, Rao, Bal, and Goswami (2007) formulated an

* Corresponding author. Tel.: +60 7 5535478; fax: +60 7 5581463.
E-mail addresses: zainmanan@gmail.com, zain@cheme.utm.my (Z.A. Manan).

0098-1354/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compchemeng.2012.12.007

Nomenclature

Acronyms
CHF cyclonic husk furnace
IRE integrated, resource-efficient
MILP mixed integer linear programming
MPR material–process–resource

Sets
i resource
p process/technology
t period
u utility
v venue
z capacity size

Parameters
$AVERES_{ivt}$ amount of available external resources i from venue v during period t (units per month)
CAP_{pz} capacity of process p with size z
FUD_{up} fixed demand of utility u from process p
MOU number of operating hours per month (h per month)
MCM_{ip} material composition matrix of material i for process p
$OPEINV_i$ amount of opening inventory for resource i (unit)
PDI_i maximum product demand indicator for resource i (unit)
$PRCM_p$ process–resource conversion matrix between resource i and process p
$PRICE_i$ unit price of product i (USD per unit)
$PUCM_p$ process–utility conversion matrix between utility u and process p
$URCOST_i$ unit resource cost i (USD per unit)
$UPCOST_p$ unit processing cost of process p (USD per unit)
$ULCOST_{iv}$ unit transportation cost of resource i from venue v (USD per unit)
$UUCOST_u$ unit utility cost of utility u (USD per unit)
VUD_{up} variance demand of utility u for process p

Binary parameters
BI_i by-product indicator; 1 if resource i is a by-product; 0 otherwise
EUI_u external utility indicator; 1 if external utility u is allowed to be supplied into the system; 0 otherwise
ICI_{ip} capacity indicator; 1 if the capacity of process p is constrained by the input material i; 0 otherwise
INV_i inventory indicator; 1 if resource i can be shifted into next period as inventory; 0 otherwise
OCI_{ip} capacity indicator; 1 if the capacity of process p is constrained by the system-generated resource i; 0 otherwise
OCU_{up} capacity indicator; 1 if the capacity of process p is constrained by the system-generated utility u; 0 otherwise
PI_i product indicator; 1 if resource i is a product; 0 otherwise

Variables
$BYPRO_{it}$ amount of by-product i during period t (units per hour)
$CCOST$ total capital cost (USD)
$EXLRES_{it}$ amount of external intake resource i during period t (tonnes per hour)
$EXRES_{it}$ amount of external intake resource i during period t (tonnes per hour)
EXU_{ut} amount of external intake utility u during period t (tonnes per hour)
$INVRES_{it}$ inventory level of resource i during period t
$LCOST$ logistics cost (USD)
MAT_{ipmt} amount of primary material i fed into process p under operating mode m during period t (units per hour)
$PCOST$ total processing cost (USD)
$PRES_{pmt}$ amount of processing resource in process p under operating mode m during period t (units per hour)
PRO_{it} amount of product i during period t (units per hour)
$PROFIT$ profit of value chain (USD)
$RCOST$ total resource cost (USD)
RES_{it} quantity of resource i in the system during period t (tonnes per hour)
REV revenue of product (USD)
$BYREV$ revenue of by-product (USD)
$SGRES_{ipmt}$ amount of system-generated resource i from process p under operating mode m during period t (tonnes per hour)
SGU_{upmt} amount of system-generated utility u from process p under operating m during period t (tonnes per hour)
$UCOST$ utility cost of system (USD)
$UDEM_{ut}$ demand of utility u during period t

Binary variables
YP_{pz} 1 if the technology p with capacity size z is purchased; 0 otherwise
YOP_{pzt} 1 if process p with size z is operated at period t; 0 otherwise

optimisation model with multiple objectives, including achieving a maximum head yield, minimum specific energy and minimum drying time, by optimising certain process parameters, such as bed depth air velocity and air drying temperature. Recently, Zare and Chen (2009) developed a simulation model to predict the profiles of the grain moisture content, grain temperature and air humidity during the drying process prior to the optimisation to achieve the minimum specific energy consumption. To verify the performance of the simulation model, a laboratory-scale deep-bed batch dryer was designed and fabricated. For rice processing, Roy et al. (2008) studied the effects of operating conditions (degree of milling) on head rice recovery and energy consumption.

For the downstream process, rice bran oil extraction has received a significant amount of attention due to the benefits of rice bran (Jariwalla, 2001; Kahlon, 2009; Sugano, Koba, & Tsuji, 1999). Rodrigues, Onoyama, and Meirelles (2006) maximised the free fatty acid transfer while minimising the losses of neutral oils and minor components by analysing the relationship between several process variables. The transfer and losses were also predicted by the UNIQUAC equation. Renuka Devi and Arumughan (2007) conducted various experiments with different extraction conditions (extracted using methanol) to optimise the parameters that affected the solubility of oryzanols, tocols, and ferulic acid. In recent years, Jahani, Alizadeh, Pirozifard, and Qudsevali (2008) applied the response surface methodology (RSM) to identify the optimum processing conditions (reaction time, enzyme dosage, added water and temperature) for the enzymatic degumming process.

From a utility perspective, cogeneration system optimisation has been continuously studied. From actual measured equipment conditions, Manolas, Frangopoulos, Gialamas, and Tsahalis (1997) developed a simulation model coupled with a genetic algorithm to identify the optimal operating conditions of a cogeneration system.