Computers and Chemical Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Synthesis of tri-generation systems: Technology selection, sizing and redundancy allocation based on operational strategy

Viknesh Andiappan, Denny K.S. Ng*

Department of Chemical and Environmental Engineering/Centre of Sustainable Palm Oil Research (CESPOR), The University of Nottingham Malaysia Campus, Broga Road, Semenyih 43500, Malaysia

ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form 16 March 2016
Accepted 3 April 2016
Available online xxx

Keywords:
Tri-generation
Operation strategy
Redundancy allocation
Palm-based biomass

ABSTRACT

Tri-generation system is a facility which produces heat, power and cooling simultaneously from a single fuel source. In the industry, such system is commonly operated via two strategies; *Following Electrical Load* (FEL) or *Following Thermal Load* (FTL). However, these operating strategies may lead to huge amount of energy that is wasted. In this respect, several works have proposed a switching strategy, whereby tri-generation systems would interchange between FEL and FTL modes depending on energy demand. Unfortunately, the design of tri-generation based on this strategy has received limited attention. Besides, tri-generation operations often face challenges in equipment reliability. As tri-generation systems contain a network of interconnected equipment, equipment failures would disrupt the overall performance of a tri-generation system. As such, this work proposes a novel systematic optimisation approach to design a robust tri-generation system which can operate optimally in its operating strategies. In addition, the proposed approach can simultaneously determine type, size and required equipment redundancy (e.g. operating and standby units) of technologies while considering operating strategies in a tri-generation system. A palm biomass-based tri-generation system (BTS) case study is solved to illustrate the proposed approach.

1. Introduction

Industrial utility systems are vital components that produce and supply required energy for various industrial processes. A tri-generation plant is a utility system which produces heat, power and cooling simultaneously, usually from a single fuel source (Stojkov et al., 2011). Since a single fuel source is used to produce several forms of energy, the overall fuel utilisation efficiency in tri-generation systems is much higher as compared to conventional methods (Angrisani et al., 2012). Such feature allows industrial plants to reduce importation of external power from the grid, and subsequently reducing operating costs. When tri-generation systems are installed on-site to utilise locally available fuel resources, quality and reliability of the energy supply is improved. However, such features can only be realised when technical and operational aspects are incorporated during the design phase of a tri-generation system. These aspects include technology selection, equipment sizing, system configuration, demand profiles, etc.

In the past, a number of approaches have been proposed to address the aforementioned aspects to design utility systems. For instance, Papaulias and Grossmann (1983) proposed a mixed integer linear programming (MILP) approach for the synthesis of flexible utility systems accounting for anticipated variations in process demands via a multi-period optimisation. Later, Hui and Natori (1996) presented a MILP formulation for multi-period synthesis and operation planning for utility systems. Maia and Qassim (1997) proposed an approach which uses simulated annealing algorithm to synthesise utility systems with variable utility demands. Iyer and Grossmann (1998) proposed a multi-period MILP approach for the synthesis and planning of a utility system under multiple periods based on superstructure-based design approach. Yokoyama et al. (2002) presented a decomposition method to determine the optimal structural design of energy supply systems in consideration of multi-period operations. Next, Shang and Kokossis (2005) presented a systematic approach to synthesise utility systems based on varying energy demands. The proposed approach (Shang and Kokossis, 2005) combines the features of Total Sites Analysis (Linnhoff et al., 1982), thermodynamic analysis and mathematical optimisation. Aguilar et al. (2007a,b) presented a systematic methodology to simultaneously synthesise, design and optimise the capital investment of a utility system subject to variable design

* Corresponding author. Fax: +60 3 89248017.
E-mail address: Denny.Ng@nottingham.edu.my (D.K.S. Ng).

http://dx.doi.org/10.1016/j.compchemeng.2016.04.003
0098-1354/

Nomenclature

Indices

i	Index for raw material
j, j'	Index for technologies
p	Index for primary products
p'	Index for final products
q	Index for component balance of raw material i
q'	Index for component balance of primary product p
n, n'	Index for available design capacities for technology
l	Index for jn and $j'n'$
t	Index for strategies
e	Index for energy

Variables

F_i^{RM}	Flow rate of raw material i in kg/h
f_{iq}^{RM}	Flow rate of component q in raw material i in kg/h
F_{ij}^{I}	Flow rate of raw material i to technology j in kg/h
f_{qj}^{I}	Flow rate of component q in raw material to technology j in kg/h
F_{jp}^{I}	Production rate of primary product p in kg/h at technology j
F_p	Total production rate of primary product p in kg/h at technology j
$F_{pj'}^{II}$	Flow rate of primary product p to technology j' in kg/h
$f_{q'j'}^{II}$	Flow rate of component q' in product p to technology j' in kg/h
$F_{j'p'}^{II}$	Production rate of final product p' in kg/h at technology j'
$F_{p'}$	Total production rate of final product p' in kg/h at technology j'
R_{jn}	Reliability of design capacity n in technology j
$R_{j'n'}$	Reliability of design capacity n' in technology j'
E_e^{Gen}	Total energy generated by technology j and j' in kWh
E_e^{Con}	Total energy consumed by technology j and j' in kWh
E_e^{Imp}	Total external energy imported in kWh
E_e^{Exp}	Total excess energy exported in kWh
E_e^{Demand}	Total energy demand in kWh
TAC	Total annualized cost in USD/year
OP_t	Total operating cost in USD/year for strategy t
CAP	Total annualized capital cost in USD/year
MAC	Total maintenance cost in USD
z_{jn}	Number of units of design capacity n operating in technology j
$z_{j'n'}$	Number of units of design capacity n' operating in technology j'
m_{jn}	Number of units of design capacity n installed in technology j
$m_{j'n'}$	Number of units of design capacity n' installed in technology j'

Parameters

t_l^{max}	Operation lifespan (year)
r	Discount rate
θ_{iq}	Fraction of composition q in raw material i
$\theta_{pq'}$	Fraction of composition q' in product p
X_{qjp}^{I}	Component mass conversion of raw material i
$X_{q'j'p'}^{II}$	Component mass conversion of primary product p
V_{qje}^{I}	Component energy conversion at technology j
$V_{q'j'e}^{II}$	Component energy conversion at technology j'
Y_{pje}^{I}	Specific energy consumption of technology j
$Y_{p'j'e}^{II}$	Specific energy consumption of technology j'
P_{jn}	Reliability of design capacity n in technology j
$P_{j'n'}$	Reliability of design capacity n' in technology j'
R_{jn}^{Min}	Minimum reliability level of design capacity n in technology j
$R_{j'n'}^{Min}$	Minimum reliability level of design capacity n' in technology j'
AOT	Annual operating time in h/y
C_i^{RM}	Cost of raw material i in USD/kg
$C_{p'}$	Revenue from primary product p' in USD/kg
C_e^{Imp}	Purchase cost of importing energy in USD/kWh
C_e^{Exp}	Selling cost of exporting excess energy in USD/kWh
C_{jn}	Capital cost of design capacity n for technology j in USD
$C_{j'n'}$	Capital cost of design capacity n' for technology j' in USD
C_{jn}^{Main}	Maintenance cost of design capacity n for technology j in USD
$C_{j'n'}^{Main}$	Maintenance cost of design capacity n' for technology j' in USD
CRF_l	Capital recovery factor for technologies l
F_{jn}^{Design}	Available design capacity for technology j in kg/h
$F_{j'n'}^{Design}$	Available design capacity for technology j' in kg/h

conditions. Dimopoulos et al. (2008) presented an approach which uses evolutionary algorithm to solve the synthesis, design and operation optimisation of a marine co-generation system. Buoro et al. (2010) presented an optimisation model to determine the optimal synthesis and operation of an urban tri-generation system based on total annual costs of operations. This work is then extended in Buoro et al. (2011) to determine the optimal tri-generation system based on varying amortisation periods. Later, Buoro et al. (2012) presented a model which obtains the optimal synthesis, design and operation of a co-generation systems for standard and domotic homes. More recently, Arcuri et al. (2015) presented an iterative optimisation approach for determining the optimal design of a tri-generation system based on return of investment subject to technology, size, and daily operations. These contributions evidently show that a range of technical and operational aspects were incorporated into designing tri-generation systems. However, based on the abovementioned works, it is worth noting that the operating strategy of a tri-generation system has received limited focus.

The operation strategy is a critical factor which governs the overall layout and performance of any tri-generation system (Jradi and Riffat, 2014). With a suitable operating strategy, a tri-generation system is able to reduce overall fuel consumption and operational costs (Cho et al., 2014; Jradi and Riffat, 2014). According to Kavvadias et al. (2010), the two commonly investigated operation strategies in industry are;

- Following Electrical Load (FEL)

In FEL strategy, a tri-generation system is independent of the power utility from the grid. All site power requirements, including the reserves needed during scheduled and unscheduled maintenance, are taken into account when sizing the system. Such system is also referred to as “stand-alone” system. If the site heat demand is higher than the available heat generated by the tri-generation sys-