Journal of Cleaner Production 87 (2015) 291–302

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Optimal planning, design and synthesis of symbiotic bioenergy parks

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ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form
9 October 2014
Accepted 14 October 2014
Available online 24 October 2014

Keywords:
Stability analysis
Symbiotic bioenergy park
Incentives/subsidies
Two-sided fuzzy optimisation
Incremental investment return

ABSTRACT

In this paper, a systematic approach for synthesising and optimising a symbiotic bioenergy park is presented. A novel stability analysis criterion of the symbiotic bioenergy park is developed based on the concept of incremental investment return analysis. The synthesised symbiotic bioenergy park is stable as long as no partner bears a disproportionate share of additional investment costs relative to benefits gained from cooperation. In case the symbiotic bioenergy park is not stable, re-evaluation (e.g., additional incentives from government, subsidies from high profit companies, etc.) can be conducted amongst all participants. In this work, fuzzy optimisation is adapted to trade-off individual economic interest and stability of each processing plant. The optimised network configuration which achieves the targets with minimum biomass value losses can be determined prior to detailed design. A palm-based symbiotic bioenergy park case study is solved to illustrate the proposed approach.

1. Introduction

Biomass has been identified as a high potential renewable energy source for generating biofuels, biochemicals, bioenergy and other bioproducts using various processing technologies. Biomass utilisation is highly encouraged to conserve scarce resources over the last decades. In general, biomass conversion technologies are classified as biochemical, physical and thermochemical conversions (Bridgwater, 2003). In biochemical conversion, biomass can be degraded via anaerobic digestion for biogas production (Nallathambi Gunaseelan, 1997) or via fermentation for alcohol production (Saxena et al., 2009). Solid fuels (e.g., pellets, briquettes, etc.) and replacement for wood products (e.g., plywood, fibreboard, etc.) can be produced via physical conversion processes (e.g., crushing, drying, densification, etc.). Meanwhile, combustion, gasification and pyrolysis are typical thermochemical conversion technologies that produce heat and power, syngas and bio-oil, respectively (Bridgwater, 2003). Products generated from thermochemical conversion technologies (e.g., syngas, bio-oil, etc.) can then be further upgraded in other processes for high value-added products production (e.g., biofuels and biochemicals) (Ng and Ng, 2013a).

Over the last decade, the concept of integrated biorefinery was introduced to integrate multiple biomass conversion technologies for multiple value-added products production (Fernando et al., 2006). An integrated biorefinery has more flexibility in product generation, with energy self-sufficiency being achieved through the use of part of the biomass flows as fuel (Ng, 2010). Various systematic process systems engineering (PSE) approaches have been used for optimal design of integrated biorefineries (e.g., hierarchical-based, insight-based, mathematical optimisation-based, etc.). Most of the recently published works are summarised in Table 1. Note that these works focus mainly on profitability via single objective optimisation. In order to enhance the sustainability of integrated biorefineries, economic, environmental and social aspects have also been included in synthesising integrated biorefineries (Ng et al., 2013a). Recent works on multi-objective optimisation approaches (e.g., Pareto optimality analysis and fuzzy optimisation) are then summarised in Table 2. Apart from the initial utilisation of biomass within integrated biorefineries, its application has also been extended to encompass upstream and downstream processing facilities (Kasivisvanathan et al., 2012; Ng and Ng, 2013b). A systematic approach for retrofitting existing palm oil mill into integrated biorefinery with consideration of both economic and environmental perspectives was presented (Kasivisvanathan et al., 2012). Ng and Ng (2013b) then introduced the concept of palm oil processing complex (POPC) consisting of palm oil mill (POM), palm oil refinery (POR), palm oil-based

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http://dx.doi.org/10.1016/j.jclepro.2014.10.045
0959-6526/

Table 1
Recent works on PSE approaches in screening and selection of technologies in integrated biorefineries.

PSE approach	Authors (year)	Study scopes
Hierarchical-based	Ng et al. (2009)	A hierarchical procedure for quick synthesis and screening of potential pathways in early design of integrated biorefineries was developed.
	Mansoornejad et al. (2010)	A hierarchical methodology was proposed to integrate forest biorefinery based on market analysis, supply chain optimisation and techno-economic study.
Insight-based	Tay et al. (2011a)	An insight-based approach for the evaluation of gas phase equilibrium composition of biomass gasification via C—H—O ternary diagram was proposed.
Mathematical optimisation-based	Bao et al. (2011)	A systematic approach that combines superstructure development and tree-branching and searching technique was developed.
	Pham and El-Halwagi (2012)	A “forward-backward” approach that involves forward synthesis of biomass to possible intermediates and backward synthesis starting with desired products was introduced in identifying necessary species and pathways.
	Voll and Marquardt (2012)	An integrated design of biofuels production pathways via Reaction Network Flux Analysis (RNFA) was presented and trade-offs between alternative production routes were discussed.
	Ponce-Ortega et al. (2012)	A disjunctive programming approach for synthesis of optimal configuration of a biorefinery was presented.
	Ng et al. (2012)	Simultaneous process, heat and power integration were considered in synthesising an integrated biorefinery via modular optimisation
	Tang et al. (2013)	Robust optimisation was adapted to synthesise integrated biorefinery with consideration of uncertainties in market demand and raw material supply.
	Chemmangattuvalappil and Ng (2013)	A systematic methodology which integrates both molecular design and chemical reaction pathway synthesis for optimal product design that considered customer requirement was presented
Combination of both insight-based and mathematical optimisation-based	Ng (2010)	Automated targeting was adapted to synthesise integrated biorefinery in determining the maximum biofuel production and revenue levels.
	Tay and Ng (2012)	Multiple-cascade automated targeting (MCAT) was proposed in targeting maximum revenue of an integrated gasification-based biorefinery.

biorefinery (POB) and combined heat and power (CHP) to promote the interaction (e.g., mass and energy integration) of all processing facilities in palm oil industry.

Note that these previous works were focused on the single-owner case, where the processing facilities are owned by same company and individual economic performance is neglected. However, in reality, the processing facilities are normally owned by different owners. Thus, the concept of industrial symbiosis (IS) or eco-industrial park (EIP) shall be included in promoting process integration within the processing plants with processing facilities owned by different owners. Besides, carbon emission reduction can be achieved through the implementation of EIPs (Sokka et al., 2011; Chen et al., 2013; Yu et al., 2014). Since every participant in EIP is a “self-interested maximiser of individual profit” (Jackson and Clift, 1998), conflicts of interest among participants in an EIP need to be considered (Aviso et al., 2010; Taskhiri et al., 2011; Ng et al., 2013b; Gonela and Zhang, 2014; Ng et al., 2014). Aviso et al. (2010) presented a bi-level fuzzy optimisation in optimising the water exchange networks in an EIP by considering both plants' fuzzy goal and the centralised park authority. Taskhiri et al. (2011) then developed an emergy-based fuzzy mixed integer linear programming (MILP) model to optimise EIP authority's emergy goal with considering the individual plants' economic interests. Besides, Ng et al. (2013b) presented the concept of IS in synthesising an integrated POPC and all processing facilities in an integrated POPC were predefined to join IS scheme. Gonela and Zhang (2014) proposed a decision framework that determines optimal network configuration in the bioenergy-based industrial symbiosis (BBIS). Most recently, Ng et al. (2014) introduced a disjunctive fuzzy optimisation approach to enhance the flexibility of potential participants' decision in the BBIS. The proposed approach utilises disjunctive constraints to deactivate the processing plants if their interest (e.g., economic performance) unsatisfied the agreed upon bounds. In the case study shown in Ng et al. (2014), one of the processing plants was advised to withdraw from the BBIS.

Table 2
Recent works that considered multiple objectives in synthesising integrated biorefineries.

Objective function	Authors (year)	Study scopes
Economic + environmental	Santibañez-Aguilar et al. (2011)	Pareto optimality analysis was performed for planning the biofuel production in integrated biorefinery.
	Tay et al. (2011b)	Fuzzy optimisation was adapted for selecting production pathway, which considers both objectives simultaneously in kraft pulp and paper industry.
	Shabbir et al. (2012)	A hybrid optimisation that combines both fuzzy optimisation and automated targeting in synthesising a gasification-based integrated biorefinery was presented
Economic + safety	Pokoo-Aikins et al. (2010)	Safety metrics evaluation alongside process and economic metrics was included in designing, screening and analysing biorefineries.
	El-Halwagi et al. (2013)	Pareto curves were performed to trade-off both economic factors and risk associated with the biorefinery supply chain.
Economic + environment + job opportunities	You et al. (2012)	An ε-constraint method and Pareto-optimal curves were applied to trade-off objectives in designing sustainable biofuel supply chain.
	Santibañez-Aguilar et al. (2014)	An ε-constraint method was applied to trade-off between objectives in planning a biorefinery supply chain based on expected ethanol and biodiesel demands in Mexico.
Economic + environment + safety + health	Ng et al. (2013a)	Fuzzy optimisation was adapted to trade-off all four objectives in an integrated biorefinery based on the pre-defined fuzzy limits of each objective.