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Stability Analysis of Symbiotic Bioenergy Parks

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In this work, a novel stability analysis for symbiotic bioenergy park is introduced. The concept of incremental investment return (IIR) analysis is adapted to determine the distribution of the savings associated with the additional investment required for implementation of industrial symbiosis (IS) scheme. Deviation from the ideal status of IS system can be obtained by determining the asymmetric distribution coefficient of each processing plant. An IS system is stable for as long as no partner bears a disproportionate share of additional investment costs relative to benefits gained from cooperation. To ensure a stable IS system, the asymmetric distribution coefficient must be bounded within maximum and minimum limits that can be determined based on the individual plants' requirements or company policies. In case where the asymmetric distribution coefficient of one of the processing plants falls outside of the predefined limits, the symbiotic bioenergy park is not stable, and the proposed IS scheme cannot be implemented. A palm-based symbiotic bioenergy park case study is solved to illustrate the proposed approach.

1. Introduction

Lignocellulosic biomass is the material that mainly consists of lignin, cellulose, and hemicellulose. Such biomass can be converted to bioenergy, biofuel and biochemicals via different conversion technologies through biological (i.e., anaerobic digestion, fermentation, etc.), physical (i.e., densification, etc.) and thermochemical conversion (e.g., combustion, pyrolysis, gasification, liquefaction, etc.) technologies (Ng and Ng, 2013). The concept of integrated biorefinery, which integrates multiple conversion technologies with combined heat and power (CHP) as a whole, has been proposed to optimise the utilisation and allocation of biomass (Fernando et al., 2006). Various systematic approaches were developed in screening and selection of numerous potential technologies available in integrated biorefineries. Ng et al. (2009) proposed a hierarchical procedure for identification and screening of potential pathways in early design of integrated biorefineries. Odjo et al. (2011) proposed a disjunctive-genetic programming (D-GP) approach that integrates both genetic algorithm (GA) and generalised disjunctive programming (GDP) for optimal product allocation in biorefinery. Tay and Ng (2011) proposed multiple-cascade automated targeting (MCAT) by considering multiple process parameters in a gasification-based integrated biorefinery. Furthermore, Voll and Marquardt (2012) also used Reaction Network Flux Analysis (RNFA) to detect the potential production routes on reaction pathways in biofuel production and discussed trade-offs between alternative production routes.

Other than to economic factors, environmental and social aspects were also included in synthesising sustainable integrated biorefineries. Tay et al. (2011) adapted fuzzy mathematical programming approach in synthesising an integrated biorefinery with consideration of both economic and environmental perspectives. The ε-constraint method and Pareto-optimality analysis were conducted in designing sustainable integrated biofuel production to trade-off economic performance, environment impact and job opportunities (You et al., 2012). El-Halwagi et al. (2013) proposed an approach that relates the number of

fatalities per year and the amount of biofuels produced/bought per year. Recently, inherent occupational health was included in the synthesis of a sustainable integrated biorefinery (Ng et al., 2013a).
The concept of industrial symbiosis (IS) was adapted to develop symbiotic bioenergy parks comprised of processing plants (i.e., milling facilities, biorefineries, cogeneration plants, etc.) with multiple owners. In such cases, multiple plants exchange material and energy with each other to enhance the overall sustainability of the symbiotic energy park. Ng et al. (2013b) presented a systematic approach in synthesising and optimising an integrated palm oil processing complex (POPC) where the owners' individual economic interests are taken into consideration. Besides, the selection of optimum configuration of bioenergy-based industrial symbiosis (BBIS) was conducted by performing a comparison between standalone plant and overall profit of participated plants in BBIS (Gonela and Zhang, 2014). Most recently, Ng et al. (2014) introduced disjunctive fuzzy optimisation approach to handle decision flexibility of potential participants' participation in palm-based symbiotic bioenergy park. A heuristic framework that can be used to design a symbiotic bioenergy park is shown in Figure 1(a). Note that the previous works only focused on the economic individual interests as the decision criterion of each participant.

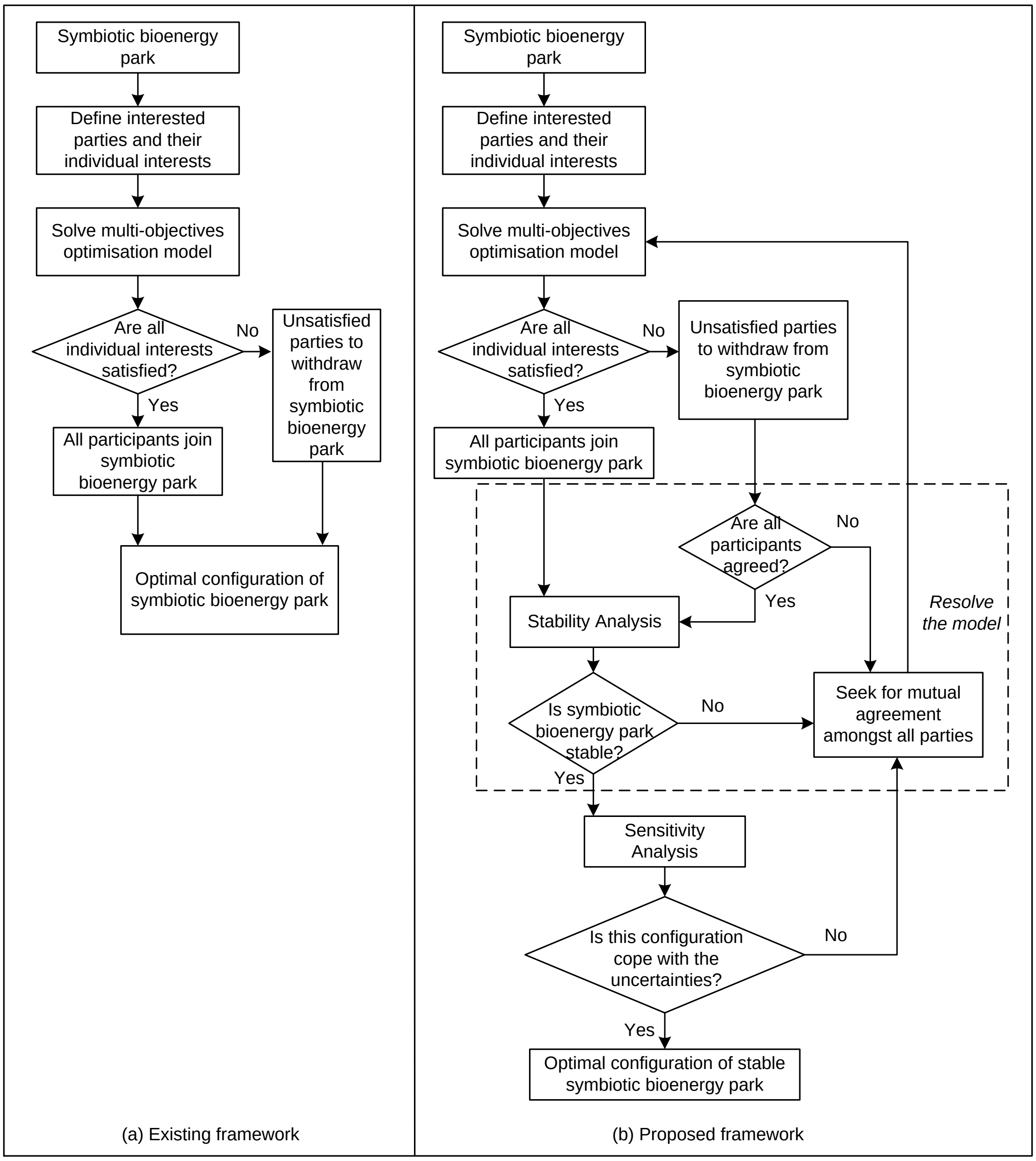

Figure 1: Heuristic framework for the synthesis of symbiotic bioenergy parks

Other than individual interests of each participant in symbiotic bioenergy parks, stability of symbiotic bioenergy parks is also another important factor for effective planning of such schemes. The instability of an IS system may happens due to lack of diversity (Geng and Côté, 2007), lack of management systems (Dong et al., 2013) and undistributed symbiosis profit of an IS system (Wang et al., 2013). Recently, Wang et al. (2013) introduced a novel approach for analysing the stability of IS system based on the equitable distribution of symbiosis profits/savings and costs. The asymmetric distribution coefficients of each participating plant were calculated and the IS system is stable as long as asymmetric distribution coefficients are within the agreed range (Wang et al., 2013).

For effective planning of symbiotic bioenergy park, a systematic stability analysis approach is proposed and in cooperated in the heuristic framework, as highlighted in Figure 1(b). This paper presents a novel stability analysis for symbiotic bioenergy parks which is developed based on the concept of incremental investment return (IIR) analysis. The distribution of the savings associated with the additional investment required for implementation of IS scheme can be determined. Note that this proposed work differs from the index of Wang et al. (2013) which focuses on the distribution of additional profit gained from IS and overall cost associated with the implementation of IS.

In this paper, problem statement is presented in the next section and it is followed by model formulation. To illustrate the proposed approach, palm-based symbiotic bioenergy park case study is then solved. Finally, conclusion and future works are given.

2. Problem statement

The problem definition for the synthesis of symbiotic bioenergy park is stated as follows: Given a number of processing plants $a \in A$ are interested in joining the symbiotic bioenergy park. The major synthesis issue is to ensure the stability of IS system while satisfying the individual economic interests of all processing plants. Based on the proposed approach, the contribution coefficients of processing plant *a* (DC^a) and overall IS system (DC^{IS}) based on the ratio of symbiosis savings and investment required are determined. DC^{IS} can be identified as ideal status of an overall IS system. The asymmetric distribution coefficient of processing plant *a* (ADC^a) which is the difference of DC^a and DC^{IS} is calculated and can be used to identify the stability of each plant in symbiotic bioenergy park.

3. Model formulation

In this work, incremental investment return (IIR) analysis is adapted to determine the relationship of the savings associated with the additional investment required for implementation of IS scheme. Symbiosis savings of processing plant *a* (SS^a) can be determined by the difference of gross profit of processing plant a with the implementation of IS scheme (GP^a) and original gross profit of processing plant *a* without IS scheme (GP^{oa}). Symbiosis savings is computed as:

$$SS^a = GP^a - GP^{oa} \qquad \forall a \tag{1}$$

Total symbiosis savings (SS^{tot}) in an IS system can be determined by the summation of SS^{a}, as given below:

$$SS^{\mathrm{tot}} = \sum_{a=1}^{A} SS^a \tag{2}$$

Symbiosis investment of processing plant *a* (SI^a) is defined as additional capital investment ($CAPEX^a_{\mathrm{add}}$) to be included in each processing plant *a* in case where IS scheme is implemented. The examples of additional capital investment are piping and instrumentation systems, heat recovery plant, conveyor system, etc. SI^a is given as:

$$SI^a = CAPEX^a_{\mathrm{add}} \qquad \forall a \tag{3}$$

Total symbiosis investment (SI^{tot}) is determined by the summation of SI^a that participated in IS scheme. SI^{tot} is computed as:

$$SI^{\mathrm{tot}} = \sum_{a=1}^{A} SI^a \tag{3}$$

The distribution of savings and investment required with the implementation of IS scheme in a processing plant can be determined based on ratio of symbiosis savings and symbiosis investment. It is similar to the concept of IIR analysis. The overall distribution coefficient (DC^{IS}) is determined as ratio of total symbiosis savings (SS^{tot}) and total symbiosis investment (SI^{tot}). DC^{IS} can be defined as the ideal status of an IS system, and given as:

$$DC^{IS} = \frac{SS^{tot}}{SI^{tot}} \tag{4}$$

The distributions of symbiosis savings and symbiosis investment of each processing plant *a* might be different from overall distribution coefficient (DC^{IS}). Thus, the distribution coefficient of each processing plant *a* (DC^{a}) is given as:

$$DC^{a} = \frac{SS^{a}}{SI^{a}} \qquad \forall a \tag{5}$$

The asymmetric distribution coefficient of each processing plant *a* (ADC^{a}) is introduced to indicate the deviation from the ideal status of an IS system (Wang et al., 2013). ADC^{a} is written as:

$$ADC^{a} = \frac{DC^{a}}{DC^{IS}} - 1 \qquad \forall a \tag{6}$$

Note that ADC^{a} can be positive, negative or zero and it highly depends on the savings associated with the additional investment required for implementation of IS scheme. Based on Eq(6), higher ADC^{a} represents higher symbiosis savings can be obtained and thus results higher DC^{a} in processing plant *a* and vice versa. In the event where ADC^{a} is equal to 0, there is no deviation of the distribution coefficient of processing plant *a* from the ideal status as DC^{a} is equal to DC^{IS}. In case where $ADC^{a} = -1$, there is no symbiosis savings of processing plant gained from IS system as $DC^{a} = 0$. Thus, ADC^{a} must be greater than -1 in order to encourage processing plant in participating IS system (Wang et al., 2013).

To ensure a stable symbiotic bioenergy park, ADC^{a} is bounded within maximum (ADC^{a}_{max}) and minimum (ADC^{a}_{min}) limits of asymmetric distribution coefficient that is predefined by the participants, where $ADC^{a} \in (ADC^{a}_{min}, ADC^{a}_{max})$. The processing plant is considered as stable if ADC^{a} is located within the predefined limits. In case where ADC^{a} falls out of the given range, the stability of symbiotic bioenergy park will be affected because the symbiosis savings is distributed unreasonably. IS system is not stable and IS scheme cannot be implemented (Wang et al., 2013).

As mentioned by Wang et al. (2013), ADC^{a}_{min} and ADC^{a}_{max} might not be the same for all processing plants, and the limits can be altered based on plants' requirements or company policies. For example, a processing plant requires a very high capital investment for IS implementation that results lower the distribution of savings and investment required; thus, ADC^{a}_{min} and ADC^{a}_{max} can be adjusted accordingly. However, the determination of ADC^{a}_{min} and ADC^{a}_{max} must be negotiated and agreed by all processing plants to maintain a stable IS system (Wang et al., 2013).

4. Illustrative case study

Palm-based symbiotic bioenergy park case presented by Ng et al. (2014) is adapted to perform the proposed stability analysis in previous section. In this case study, there are four processing plants interested in participating in IS scheme. Palm-based biomasses are generated as by-products from palm oil mill (POM). Palm-based biomasses can be converted to pellet or briquette in palm oil-based biorefinery I (POB I) or to dried long fibre (DLF) in palm oil-based biorefinery II (POB II). Besides, palm-based biomasses also can be sent to combined heat and power (CHP) for electricity and steams generation.

In this case study, it is assumed that original raw material costs of all processing plants without IS scheme are 10 % higher than the raw material costs of all processing plants with IS scheme. It is further assumed that original energy import costs (i.e., electricity and steams costs) without considering IS scheme is 20 % higher than energy import costs of all processing plants with IS scheme. Meanwhile, additional symbiosis maintenance costs are applied to IS of bioenergy system. The symbiosis maintenance costs of POM, POB I, POB II and CHP are given as 5 % of the energy cost sold from CHP to POM; 5 % of the energy cost from CHP and 5 % of raw material cost from POM to POB I and POB II; 5 % of raw material cost needed from POM to CHP, respectively (Ng et al., 2014).

In addition, symbiosis investment, which can be defined as additional capital cost with the implementation of IS scheme (e.g., biomass conveyor, electricity cable, piping, etc.), will be included in total capital cost of each processing plant. Based on interview from industry partners, additional capital costs of USD 0.20 million, USD 0.10 million, USD 0.30 million and USD 0.08 million will be applied to POM, POB I, POB II, and CHP, respectively in palm-based symbiotic bioenergy park. Furthermore, it is assumed that all plants

agree that ADC^a at the range of −0.5 to 0.5. In case where individual ADC of processing plant *a* (ADC^a) fall out of the range, the respective party will withdraw from the palm-based symbiotic bioenergy park.
A case study with two scenarios presented in previous work (Ng et al., 2014) is extended by examining the stability of palm-based symbiotic bioenergy park. In Scenario 1, all processing plants are predefined to join this palm-based symbiotic bioenergy park. Maximum economic performance was targeted with the participation of of all processing plants, i.e., POM, POB I, POB II, and CHP (Ng et al., 2014). In Scenario 2, POB I is advised to withdraw from IS scheme and therefore, optimum configuration of palm-based symbiotic bioenergy park without the participation of POB I was determined via disjunctive fuzzy optimisation. The stability analysis of both scenarios will be performed in the next sub-section.

4.1 Scenario 1

In this scenario, stability analysis is carried out by adapting economic results presented in Scenario 1 of previous work (Ng et al., 2014). Based on the proposed stability analysis, asymmetric distribution coefficients of each processing plant (ADC^a) are tabulated in Table 1. As shown, both ADC^{POM} and ADC^{POBII} are higher than zero, which are 0.069 and 0.246, respectively. On the contrary, the value of ADC^{CHP} is less than zero, which is -0.152. However, the ADC^{POBI} is targeted at -0.729 which lies beyond the acceptable range. In POB I, symbiosis investment is much higher than symbiosis savings; thus, distribution coefficient of POB I is much lower (DC^{POBI} = 0.48) compared to other processing plants. Therefore, the IS scheme in this scenario is unstable due to the occurrence of the outlier of ADC^{POBI} and lower distribution coefficient compared to ideal IS system (DC^{IS} = 2.08). Based on the result, POB I is advised not to participate in the IS scheme.

4.2 Scenario 2

In this scenario, the configuration of palm-based symbiotic bioenergy park without participation of POB I based on Scenario 2 of previous work (Ng et al., 2014) is taken as a base case. The stability of this configuration is analysed. The result of stability analysis in this scenario is summarised in Table 2. As shown, the ADC^{POM} ADC^{POBII} and ADC^{CHP} are determined as -0.060, 0.115 and -0265. This configuration (without the participation of POB I) implies that the IS system is stable as all ADC^{POM} ADC^{POBII} and ADC^{CHP} are within the range of -0.5 and 0.5. Based on this result, the IS scheme is accepted by all parties and can be implemented.

5. Conclusion

This paper presents a novel approach for stability analysis of symbiotic bioenergy parks. Based on the proposed approach, the concept of asymmetric distribution coefficient is adapted to evaluate the stability of symbiotic bioenergy parks based on the satisfaction of each participant company. As shown in the case

Table 1: Stability Analysis of Scenario 1

Description	Unit	Processing plant				Overall
		POM	POB I	POB II	CHP	IS
Net present value, *NPV*	x10^6 USD	12.50	2.39	12.96	6.41	34.26
Gross profit, *GP*	x10^6 USD/y	1.83	0.35	1.89	0.94	5.14
Original gross profit, GP^o	x10^6 USD/y	1.34	0.30	1.11	0.80	3.55
Symbiosis savings, *SS*	x10^6 USD/y	0.49	0.05	0.78	0.14	1.46
Symbiosis investment, *SI*	x10^6 USD	0.22	0.10	0.30	0.08	0.70
Distribution coefficient, *DC*	-	2.22	0.48	2.59	1.76	2.08
Asymmetric distribution coefficient, *ADC*	-	0.069	-0.769	0.246	-0.152	-

Table 2: Stability Analysis of Scenario 2

Description	Unit	Processing plant			Overall
		POM	POB II	CHP	IS
Net present value, NPV	x10^6 USD	12.50	16.34	6.36	35.20
Gross profit, GP	x10^6 USD/y	1.83	2.39	0.93	5.14
Original gross profit, GP^o	x10^6 USD/y	1.34	1.60	0.79	3.72
Symbiosis savings, SS	x10^6 USD/y	0.49	0.79	0.14	1.42
Symbiosis investment, SI	x10^6 USD	0.22	0.30	0.08	0.60
Distribution coefficient, DC	-	2.22	2.64	1.74	2.37
Asymmetric distribution coefficient, ADC	-	-0.060	0.115	-0.265	-

study, the initial symbiotic bioenergy park configuration (Scenario 1) is unstable, but upon withdrawal of one of the partners (POB I), a stable configuration is achieved (Scenario 2). Stability analysis can be included to synthesise and optimise symbiotic bioenergy parks in the future works. As shown in Figure 1(b), re-evaluation from all related parties (e.g., additional incentives from government, subsidies from high profit companies, amendment of company policies, etc.) to encourage withdrawn parties in joining IS scheme can be conducted. In addition, the flexible design of symbiotic bioenergy parks which able to handle worst case scenario based on various uncertainties (e.g., fluctuations in the price data, biomass quality, availability, product demands, etc.) can be studied in the future works.

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