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An optimization-based negotiation framework for energy systems in an eco-industrial park

Viknesh Andiappan [a], Raymond R. Tan [b], Denny K.S. Ng [a, *]

[a] Department of Chemical and Environmental Engineering/Centre of Sustainable Palm Oil Research (CESPOR), The University of Nottingham, Malaysia Campus, Broga Road, Semenyih 43500, Malaysia
[b] Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines

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ABSTRACT

This work presents an optimization-based negotiation framework for plants in an eco-industrial park (EIP). The framework combines the principles of rational allocation of benefits with the consideration of stability and robustness of the coalition to changes in cost assumptions by analyzing its stability threshold. The stability threshold allows stakeholders to make informed managerial decisions concerning the current or future plant interactions in an EIP. The proposed framework is presented via a palm oil eco-industrial park (PEIP) case study consisting of a biomass tri-generation system (BTS), palm-based biorefinery (PBB) and palm oil mill (POM). The results of the case study indicate that the deserving annual cost savings allocation for BTS, PBB and POM are 38% (USD 2,100,000), 14% (USD 800,000) and 48% (USD 2,600,000) of the total annual cost savings respectively. Based on these allocations, the stability analysis determined that the PEIP coalition will stable as long as the symbiosis costs of BTS, PBB and POM fall within 37–46%, 10–30% and 20–25% of their respective raw material costs. Otherwise, the stability of the PEIP coalition is compromised and further action can be taken as stipulated in the proposed framework.

1. Introduction

Industrial development has brought rapid gains in wealth and prosperity over the past few centuries. However, it has also resulted in various unintended environmental problems, such as global warming, ozone depletion, deforestation and etc. (Shrivastava, 1995). In response to such problems, policy makers have sanctioned forceful pollution taxes and regulations in order to push corporations to seek more sustainable approaches toward industrial development (Yong et al., 2016). The desire to build a sustainable industry has led to the emergence of the concept of industrial symbiosis (IS). IS originates from the concept of industrial ecology (IE), which was popularized by Frosch and Gallopoulos (1989) based on its analogy with symbiotic flows in natural ecosystems. IE emphasizes the importance of potential benefits arising from symbiotic interactions among various industrial plants. In particular, waste generated from one production process may be used as raw materials in another. Formative examples of such symbiotic network include the well-known Kalundborg IS complex in Denmark (Jacobsen, 2006), Handelö bioenergy complex in Sweden (Martin and Eklund, 2011), Environment Park in Turin, Italy (Greenroofs.com, 2016) and Technology Park in the Basque Country (Metropolitan Bilbao, 2016). When successfully implemented, IS reduces overall waste from the entire system as well as raw material and energy consumption (Korhonen, 2001). Since such symbiotic relationships normally occur among processes co-located within the same vicinity, the concept of eco-industrial parks (EIPs) emerged (Lowe et al., 1996). Due to geographic proximity, plants in an EIP are more likely to cooperate through infrastructure, material, water and energy exchange programs. As a result, the collective benefit will always be greater than the sum of individual benefits that could be achieved without establishing a symbiotic relationship in an EIP. In this respect, several systematic approaches have been developed for designing shared infrastructure in EIPs (Boix et al., 2015).

One type of shared infrastructures commonly found in the literature is inter-plant water integration in EIPs (Boix et al., 2015). In the area of inter-plant water integration, several contributions focused on minimizing fresh water (Chew and Foo, 2009),

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

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regeneration and waste treatment flow rates (Chew et al., 2010a, 2010b) as well as emergy (Taskhiri et al., 2011). Meanwhile, other works focused on minimizing environmental impacts (Lim and Park, 2010) and total annualized costs (López-Díaz et al., 2015). More recently, Aviso (2014) presented a robust optimization approach to determine the optimal inter-plant water network which can operate under multiple scenarios such as changes in process conditions, number of plants, water quality, etc.

Besides inter-plant water integration, several contributions have considered the designing energy networks for an EIP (Boix et al., 2015). These energy networks include waste heat network (Chae et al., 2010), utility network (Kim et al., 2010), biorefineries (Atkins et al., 2011), steam power plant (Chen and Lin, 2012), palm oil processing complex (Ng and Ng, 2013) and central utility system (Liew et al., 2013) using total site integration (Dhole and Linnhoff, 1993). Meanwhile, other contributions focused on aspects such as improving production (Gonela and Zhang, 2014) and analyzing criticality of systems (Benjamin et al., 2015, 2014) in bioenergy-based EIPs. However, aforementioned EIPs may prove unsuccessful if the self-interest of each participating plant is not met. In reality, every participant plant in an EIP has unique individual goals that may conflict with other potential partners (Jackson and Clift, 1998). This aspect is not adequately addressed by many conventional Process Systems Engineering (PSE) techniques derived from Process Integration (PI) methods.

Several contributions have proposed mathematical optimization models that consider satisfaction of participants in EIPs. For instance, Aviso et al. (2010a, 2010b) presented a bi-level fuzzy optimization model for optimizing water, wastewater reuse in an EIP based on individual goals of each participant and introduced the role of an external agent (government) to induce cooperation among companies. Taskhiri et al. (2014) developed a similar approach to optimize allocation of waste-to-energy streams in an EIP. Ng et al. (2013) presented a fuzzy programming approach to consider the individual targets of multiple owners instead of just one owner. This approach is then extended to disjunctive fuzzy programming to determine the optimum pathways based on each owner's targets and allow withdrawal if any target is not satisfied (Ng et al., 2014). Wang et al. (2013) introduced a novel approach for analyzing the stability of EIP system based on the equitable distribution of symbiosis profit and cost. They defined stability as the tendency of the coalition of companies in an EIP to remain intact based on equitability considerations. The asymmetric distribution coefficients of each participating plant are calculated and the IE system is considered stable as long as asymmetric distribution coefficients are within the agreed range. This approach implies that an IE system is stable for as long as no partner bears a disproportionate share of symbiosis costs relative to benefits gained from cooperation; otherwise, a firm which finds itself in an unfavorable position becomes liable to withdraw from the coalition. Such approach is later adapted by Ng et al. (2015) to analyses the stability of each participating plant in a palm oil processing complex (POPC) in Ng et al. (2014).

Besides mathematical optimization approaches, game theory-based approaches have been presented to consider conflicting interests in EIPs (Boix et al., 2015). Game theory is a framework that mathematically models the behavior of multiple parties with potentially conflicting interests in various domains (von Neumann and Morgenstern, 1944). For instance, Chew et al. (2009) presented a game theory approach for inter-plant water integration and demonstrated how incentives assist in inducing cooperation in an EIP. Hiete et al. (2012) adapted the Shapley value (Shapley, 1953) to allocate energy savings between partners based on their marginal contributions in a pulp and woody bioenergy EIP. Zhang et al. (2013) presented mathematical formulation based on Nash bargaining solution approach to fairly allocate cost amongst facilities in a general micro-grid. More recently, Tan et al. (2015) developed a game theoretic approach using the method of Maali (2009) for allocating benefits among participants in an EIP. Tan et al. (2015) also concluded that the method of Maali (2009) can be used as an alternative approach to Shapley value (Shapley, 1953) for allocating benefits (e.g., energy savings, cost savings, profits, etc.) in an EIP. However, the allocating benefits alone would be inadequate to guarantee a stable EIP coalition.

Stability in the context of EIPs, refers to the robustness of an EIP coalition toward changes in costs associated with investment and operations (Holling, 1996; Kronenberg, 2007; Mayer, 2008). In a coalition, each plant is prone to deviations in symbiosis costs. Symbiosis cost is the investment cost that each plant requires to engage in material and energy exchange with other plants in an EIP. Symbiosis costs may include expenditure on transportation, piping and instrumentation, shipment, labor, conveyor systems, etc. If deviations in symbiosis costs are ignored, changes in profit margins may cause dissatisfaction among plant stakeholders and consequently disrupt the overall stability of the coalition. Thus, this work extends the contribution in Tan et al. (2015) by proposing an optimization-based negotiation framework which is able to analyze the stability of EIP coalitions. In this enhanced framework, Maali's cooperative game model is adapted to rationally and fairly allocate the pooled annual cost savings among participating plants in an EIP based on their respective contributions (Maali, 2009). Following this, a stability analysis method developed by Wang et al. (2013) is used to introduce and investigate the stability threshold of an EIP coalition. The stability threshold measures the robustness of the coalition to deviations in key assumptions pertaining to symbiosis costs. Moreover, the stability threshold functions as a basis of negotiation when symbiosis costs fall outside the feasible range or when changes in costs are anticipated in the future. Such function offers significant and practical implications as it allows stakeholders to make informed managerial decisions concerning not only current, but also future plant interactions in an EIP.

The rest of the paper is organized as follows. Section 2 presents a formal problem statement. Section 3 describes the proposed negotiation framework while Section 4 presents the corresponding mathematical formulation. A palm oil EIP (PEIP) case study is then solved in Section 5 and discussed in Section 6. Finally, conclusions and prospects for future work are given in Section 7.

2. Problem statement

The problem address in this work is stated as follows: A given set of plants ($u = 1, 2, \ldots, U$) are interested in forming a coalition within an EIP. However, as each plant contributes uniquely to the EIP, it is not clear as to how much a plant is entitled to receive from the collective annual cost savings obtained by the coalition. As such, the objective of this work is to present a systematic negotiation framework to determine the fair allocation of annual cost savings among participating plants based on their respective contributions toward the EIP. Following this, a stability analysis is conducted to investigate the stability threshold of the EIP coalition to in order to remain stable.

3. Optimization-based negotiation framework

An optimization-based negotiation framework for coalitions in EIPs is presented in Fig. 1. The framework begins with interested plants discussing and proposing initial terms (e.g., the price of raw materials, energy and subsidies offered to one another, etc.) of interaction in the EIP coalition. These interactions are then mathematically formulated (discussed in the next section) and solved via