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Systematic Allocation of Cost Savings among Energy Systems in an Eco-Industrial Park

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To achieve sustainability goals, various strategies have been used which include symbiotic strategies with other companies. Such symbiotic strategies are based on the concept of industrial ecology (IE). IE emphasises on the importance of symbiotic interactions among various companies as it would reduce overall waste emission, raw material and energy consumption. Since symbiotic relationships normally occur among processes co-located within the same vicinity, the concept of eco-industrial parks (EIPs) emerged. Companies in an EIP engage in material and energy exchange programmes in a mutually beneficial manner, as a result of geographic proximity that facilitates cooperation among partners. 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. However, since each company would have its own profit-oriented goals, it would be important to analyse the potential advantage (or disadvantage) each plant can experience when forming a partnership in EIP. Cooperative game theory provides a scientific basis for the analysis of such issues. In this respect, this work presents a cooperative game theory approach developed by Maali (2009) to fairly allocate cost savings among cooperative companies of an EIP based on their respective contributions.

1. Introduction

In recent years, symbiotic strategies have gained increasing attention toward achieving sustainable development in industrial activities. These strategies originate from the concept of industrial ecology (IE), which was introduced by Frosch and Gallopoulos (1989) based on analogies with symbiotic flows in natural ecosystems. IE emphasises on the importance and the potential benefits of symbiotic interactions among various companies. For instance, waste generated from one production process may be used as raw materials in another process. When successfully implemented, IE would reduce overall waste and emission from the entire system as well as the raw material and energy consumption to other systems (Korhonen, 2001). Since 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 the geographic proximity, companies in an EIP facilitate cooperation through infrastructure, material, water and energy exchange programmes. However, such cooperation can only be realised if the (conflicting) self-interest of each participating facility in an EIP is met. In this respect, game theory is a suitable framework that mathematically models the behaviour of multiple agents with potentially conflicting interests in various domains (von Neumann and Morgenstern, 1944).

Several studies have been directed toward Game theory-based approaches for effective decision making in various EIP schemes. For instance, Chew et al. (2009) demonstrated how incentives play a role in inducing cooperation to yield Pareto optimal solutions for an EIP water integration scheme. On the other hand, Hiete et al. (2012) proposed a cooperative game theory approach based on the Shapley value (Shapley, 1953) to allocate energy savings between partners based on their marginal contributions in a pulp and woody bio-energy EIP scheme. Zhang et al. (2013) presented mathematical formulation based

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on the game theory Nash bargaining solution approach to fairly determine cost allocation amongst facilities in a general microgrid.

Despite the usefulness of the aforementioned works, it is found that an important aspect of EIP implementation has not been explicitly discussed. This aspect is in regard to the importance of an "anchor tenant" in an EIP. An anchor tenant is a facility that will attract other companies and could represent a core around which complementary facilities can be sought (Eilering and Vermeulen, 2004). Such facility is able to process waste flows and provide other members of an EIP with usable products and energy. If such facility is the only energy producer and distributor in the EIP, it could be seen as an impartial body that initiates cooperation between different companies (Korhonen, 2001). In this sense, several works have considered anchor tenants such as steam power plants (Chen and Lin, 2012), total site heat exchanger networks (Liew et al., 2013) and water networks (Alnouri et al., 2014) for an EIP. Apart from these facilities, a biomass-based trigeneration system (BTS) could serve as an anchor tenant for an EIP. A BTS is a facility that utilises biomass feedstock to produce heat, power and cooling energy simultaneously. However, it is still arguable whether it is economically viable to implement a BTS within an EIP. As such, this work aims to address the economic viability of a BTS by examining its potential cost savings in an EIP. To do so, a systematic approach is developed to rationally and fairly allocate the pooled cost savings to each company in an EIP. This approach is an alternative cooperative game theory approach developed by Maali (2009). The rest of the paper is organised as follows. Section 2 presents the formal problem statement. Section 3 describes the mathematical formulation. A palm oil EIP (PEIP) case study is then solved in Section 4 and results are discussed. Finally, conclusions and prospects for future work are given in Section 5.

2. Problem Statement

The cost savings allocation problem is stated as follows: A given set of facilities (u = 1, 2,….,U) are interested in forming a cooperative partnership within an EIP. However, as each facility contributes uniquely to the EIP, it is not clear as to how much a facility is entitled to receive from the collective cost savings. As such, this objective of this work presents a systematic approach to determine the fair allocation of cost savings among participating facilities within an EIP.

3. Mathematical Formulation

As mentioned previously, Maali's cooperative game approach (Maali, 2009) is used to determine the fair allocation of cost savings for an EIP. In this work, u represents a set of plants in an EIP (u = 1, 2,…., U). In addition, z is a set of plants which form a cooperative partnership (z =1, 2; 1, 3; 1, U), where z is a subset of u. Eq.1 is included in the optimisation model to determine the weightage ($\mathrm{C_u}$) of cost savings allocation ($\mathrm{SA_u}$) for plant u. The weighting is determined based on the incremental contribution of plant u in a cooperative partnership as shown in Eq.2, where $\mathrm{CS_z}$ represents the cost savings for a cooperative partnership while $\mathrm{CS_w}$ is the cost savings of a cooperative partnership without plant u. Additionally, $\mathrm{CS_v}$ is the total cost savings of a cooperative partnership with U plants. Eq.3 is included in the model to determine $\mathrm{SA_u}$ for each plant u. In Eq.3, $\mathrm{SA_u}$ for each plant u must be greater than the cost savings attained individually by each plant u ($\mathrm{CS_u}$). Meanwhile, Eq.4 is included to ensure that the sum of all $\mathrm{SA_u}$ is equal to $\mathrm{CS_v}$. The objective function for this model is shown in Eq.5, where λ is maximised to give the optimum savings allocation in Eq.1.

$$\frac{1}{C_u} SA_u \geq \lambda \qquad \forall u \qquad (1)$$

where C_u is given by;

$$C_u = \sum_z \left[\mathrm{CS}_z - \mathrm{CS}_w\right] \Big/ \mathrm{CS}_v \qquad \forall u \qquad (2)$$

where w is the cooperative partnership without plant u

$$SA_u \geq \mathrm{CS}_u \qquad \forall u \qquad (3)$$

$$\sum_{u=1}^{U} SA_u = \mathrm{CS}_v \qquad (4)$$

Maximise λ (5)

4. Case Study

Malaysian palm oil industry generates high amounts of palm-based biomass (e.g., empty fruit bunches (EFB), palm kernel shells (PKS), palm mesocarp fibre (PMF), and palm oil mill effluent (POME)) as by-products or wastes. These palm-based biomasses contain useful amount of energy which can be recovered to meet energy demands in the industry and export to the national grid, and to produce renewable biofuels. In order to exploit this potential, several specialised facilities must be co-located to a palm oil mill (POM) to form a palm oil eco-industrial park (PEIP). Among these facilities, a palm-based biorefinery (PBB) can be considered to convert palm-based biomass into value added biofuels. However, the POM and PBB would require various utilities for their operations, which can be costly if purchased from external facilities operating away from site. As such, a palm biomass-based tri-generation system (BTS) could be a driver for the PEIP, as it utilises biomass feedstock to produce heat, power and cooling energy on site simultaneously. With this in view, it is important to analyse the cost benefit each facility would potentially gain within an EIP. In this respect, this case study aims to analyse the economic viability of PEIP by evaluating its potential allocation of cost savings among its participating facilities.

In this case study, the PEIP consists of a POM (existing), BTS (to be synthesised) and PBB (to be synthesised), where each facility has its respective owner. The interaction between these facilities is illustrated in Figure 1. As shown, the POM would require fresh fruit bunches (FBBs) from the palm tree plantations as raw material for its operation. Meanwhile, the POM also requires utilities such as low pressure steam (LPS), cooling water, chilled water and power. These utilities can be purchased from the BTS within the PEIP or from an external facility at higher prices (listed in Table 1). The POM operation produces crude palm oil (CPO) as its main product and EFB, PMF, PKS and POME biomass as by-products. The biomass is then sold as raw materials to the BTS and PBB at the given selling prices in Table 2. On the other hand, the biomass can also be purchased from external facilities at the prices listed in Table 2. In addition, the PBB would require utilities such as mid pressure steam (MPS) and power for its operation. These utilities can be purchased from the BTS or from an external facility at higher prices (listed in Table 1). The potential end products of the PBB are biofuels such as methanol (MeOH), dimethyl-ester (DME), biodiesel and bio-gasoline. These fuels are then sold to an external customer at the given prices in Table 3.

Table 1: Utility Prices from BTS and External Facility

Utility	BTS (RM)	External (RM)
Low Pressure Steam (LPS)	0.0800/ kg	0.0900/ kg
Mid Pressure Steam (MPS)	0.2000/ kg	0.2100/ kg
Cooling Water	0.0003/ kg	0.0004/ kg
Chilled Water	0.0020/ kg	0.0030/ kg
Power	0.2900/ kWh	0.3900/ kWh

Table 2: Material Prices from POM and External Facility

Material	POM (RM)	External (RM)
Crude Palm Oil (CPO)	3.000/ kg	-
Empty Fruit Bunches (EFBs)	0.020/ kg	0.030/ kg
Palm Mesocarp Fiber (PMF)	0.070/ kg	0.080/ kg
Palm Kernel Shell (PKS)	0.162/ kg	0.180/ kg

Table 3: Material Prices from PBB

Material	Price (RM)
Dimethyl-Ester (DME)	2.06/ kg
Biodiesel	0.53/ kg
Biogasoline	1.05/ kg
Methanol (MeOH)	3.50/ kg

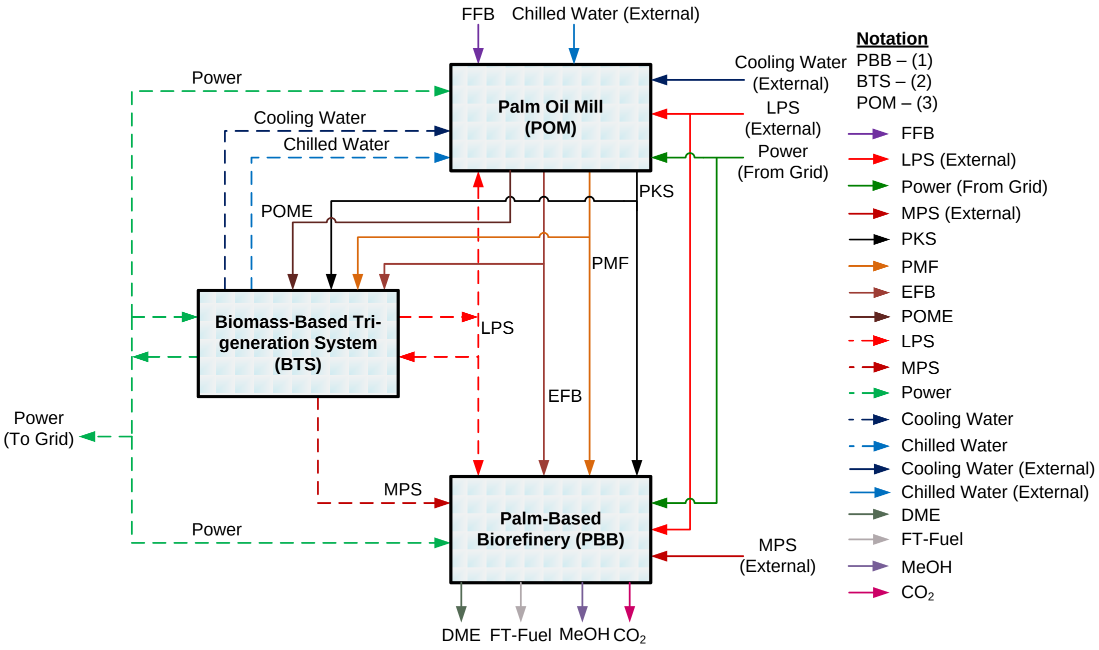

Figure 1: Block Diagram of PEIP in Case Study

Based on data in Tables 1 – 3, the material and energy balance for POM, BTS and PBB are mathematically modelled to allow quantitative analysis and optimisation. As the PEIP consists of three facilities, the number of players in a cooperative game is three with indices u = 1, u = 2 and u = 3 representing the BTS, PBB and POM respectively. The annual cost savings of each plant are then obtained from repeated optimisations for each possible coalition (Hiete et al., 2012) and are represented by the index z as shown in Table 4. These values are then used an input for the proposed approach described earlier (Eqs. 1 – 4). The formulation for this case study is as shown in Eqs. 5 – 10. The fair allocation of cost savings is then determined by maximising λ as shown in Eq.5. The model output is shown in Table 5 while the final PEIP layout is illustrated in Figure 2.

$$\frac{1}{C_1} SA_1 \geq \lambda \text{ , } \frac{1}{C_2} SA_2 \geq \lambda \text{ , } \frac{1}{C_3} SA_3 \geq \lambda \tag{6}$$

$$C_1 = (\mathrm{CS}_{123} - \mathrm{CS}_{23} + \mathrm{CS}_{12} - \mathrm{CS}_2 + \mathrm{CS}_{13} - \mathrm{CS}_3 + \mathrm{CS}_1)/\mathrm{CS}_{123} \tag{7}$$

$$C_2 = (\mathrm{CS}_{123} - \mathrm{CS}_{13} + \mathrm{CS}_{12} - \mathrm{CS}_1 + \mathrm{CS}_{23} - \mathrm{CS}_3 + \mathrm{CS}_2)/\mathrm{CS}_{123} \tag{8}$$

$$C_3 = (\mathrm{CS}_{123} - \mathrm{CS}_{12} + \mathrm{CS}_{13} - \mathrm{CS}_1 + \mathrm{CS}_{23} - \mathrm{CS}_2 + \mathrm{CS}_3)/\mathrm{CS}_{123} \tag{9}$$

$$SA_1 \geq \mathrm{CS}_1 \text{ , } SA_2 \geq \mathrm{CS}_2 \text{ , } SA_3 \geq \mathrm{CS}_3 \tag{10}$$

$$SA_1 + SA_2 + SA_3 = \mathrm{CS}_{123} \tag{11}$$

Table 4: Cost Savings for each Cooperative Partnership

Cooperative partnership	Cost Savings (10^6 RM/y)
CS_1	1.64
CS_2	0.83
CS_3	2.77
CS_{13}	17.75
CS_{23}	5.88
CS_{12}	5.06
CS_{123}	23.26

Table 5: Allocated Cost Savings for each Facility in PEIP

Cooperative partnership	Cost Savings (10^6 RM/y)	Allocation from Total Savings (%)
SA_1	9.54	41
SA_2	3.21	14
SA_3	10.51	45

Results in Tables 4 and 5 generally indicate that cost savings allocated to each facility within the cooperation is significantly higher compared to when there is no cooperation. This evidently means that it would be very beneficial for the BTS facility to take part in a cooperative partnership with the POM and PBB in the PEIP.

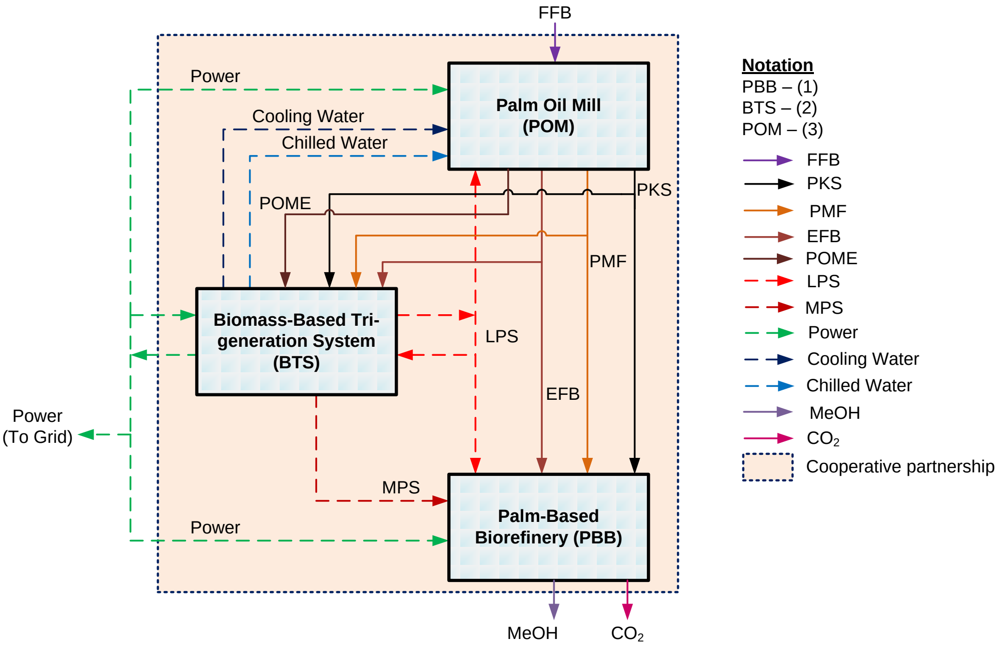

Figure 2: Final diagram of PEIP

On a different note, the presented approach can be used as a pre-negotiation tool, to provide a rational starting point for companies to analyse and engage in future cooperative partnerships.

5. Conclusions

In this work, an approach towards fair allocation of total cost savings of a cooperative partnership within an eco-industrial park has been demonstrated. This approach is based on the cooperative game approach developed by Maali (2009). The presented approach can used as a pre-negotiation tool for companies to analyse and engage in future cooperative partnerships, as it can provide a rational basis for an initial profit-sharing scheme. In future work, this approach will be extended to cost allocation for shared infrastructure (e.g. central utility plant, waste water treatment plant, etc.).

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