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Analysis on the Relationship between Eco-Connectance and Economic Performance of an Eco-Industrial Park

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The establishment of eco-industrial parks (EIPs) has been regarded as a sustainable approach in solving environmental issues, including the energy crisis. Environmentalists have further recognised the formation of EIP as one of the effective solutions for waste minimization. In the context of industrial ecology, an EIP represents an urban industrial area where multiple industries cooperate together through the exchange of material and energy. The higher interchange of material and energy streams leads to a greater ownership over the process, resulting in greater fresh resource savings as compared to unilateral initiatives. Recent literature has reported various quantitative measures to design and implement an EIP. For instance, eco-connectance (CE) has been proposed to quantify the level of connectivity in an EIP. CE is defined as the ratio of the number of actual linkages over the maximum number of potential linkages in an EIP. In the previous works, high level of CE is desirable to maximise resource savings. However, the effect of CE on the economic performance in an EIP has not been well studied. In this work, an optimization approach is developed to analyse the relationship between eco-connectance against the economic performance of an EIP. A hypothetical EIP network is synthesized to illustrate the proposed approach. Based on the result, it is noted that with a high eco-connectance, the resulting payback period of the EIP would be higher. This is a result of a higher number of participating industries, thereby increasing the initial capital expenditure.

1. Introduction

In a conventional eco-industrial park (EIP), multiple industries engage with each other for the exchange of material and energy streams. Often, the waste and by-product of one industry can be utilized as raw materials for another industry, forming an industrial symbiosis. Consequently, this would reduce the overall fresh resource requirement. Given the high level of integration between process streams among the industries, Hardy and Graedel (2002) proposed a quantitative index to determine the level of connectivity of an EIP, coined connectance (C),

$$C = \frac{L}{\mathrm{S}(\mathrm{S}-1)/2} \tag{1}$$

where L is the number of links (or streams exchanged) between industries and S is the number of industries in an EIP. Connectance can be defined as “the ratio of the number of actual linkages to the number of potential linkages” in an EIP. The index draws analogy from biological ecology, where instead of food links between organisms, the links would refer to the sharing of process streams in the context of industrial ecology (Hardy and Graedel, 2002). Later, Tiejun (2010) classified the total number of linkages (L) into linkages for product flow (L^{P}) and linkages for by-product or waste flow (L^{E}). A revised index, termed eco-connectance (C^{E}), is then expressed specifically for L^{E}, as below

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$$C^{\mathrm{E}} = \frac{L^{\mathrm{E}}}{\mathrm{S}(\mathrm{S}-1)/2} \tag{2}$$

A closer look at the relationship between C^{E} and L^{E} in Eq(2) suggests that a high eco-connectance can be achieved by maximizing the number of by-product and waste linkages between industries. Consequently, this would reduce the overall waste generated as more process streams are being traded within the EIP. As such, a higher C^{E} can improve the environmental performance of an EIP. Besides, Chew et al. (2011) optimized the water and energy network of a pulp and paper mill to improve resource efficiency, which was later extended by Lee et al. (2014) for an integrated pulp and paper biorefinery (IPPB). More recently, Ng et al. (2014) studied the stability of industrial symbiosis schemes based on the individual economic interests of all participating industries.

Nonetheless, eco-connectance does not relay any relationship with the economic performance in an EIP. This is evident in Eq(2), where eco-connectance does not report the magnitude (i.e. flow rate) of the process streams being traded. Clearly, as more participants are introduced into the EIP, it would require an initial capital investment into the EIP. As the implementation of EIP becomes more widespread, proper planning is critical to ensure optimum economic performance for all parties involved. In this work, an optimization approach is developed to analyse the relationship between eco-connectance against the economic performance of an EIP. A case study using a pulp and paper mill (PPM) is solved to illustrate the proposed approach.

2. Problem Statement

The problem statement of the current work is stated as such: It is desired to set up an EIP with a PPM as the core of the EIP network. First, biomass, $i \in I$ generated from PPM is sent to potential bioenergy or bio-product related industries $j \in J$, where it is converted into bio-product and by-products. Later, the bio-products and by-product streams has the potential to be sent to PPM or any of the industries. In this work, it is desired to maximise the number of linkages to synthesize an EIP with high eco-connectance. Linkages are present as biomass links (L^{B}) and by-product links (L^{BP}). Concurrently, the optimized EIP network is constrained by a pre-determined payback period to ensure a positive economic performance.

3. Model Formulation

In a PPM, biomass i is produced (F_i^{B}) and sent to each industry j with a flow rate of F_{ij}^{B}. It is noted that PPM is not considered as a member in index j, but instead serves as a stand-alone plant producing biomass to all industry j.

$$F_i^{\mathrm{B}} = \sum_j F_{ij}^{\mathrm{B}} \ , \ \forall i \tag{3}$$

Next, Eq(4) and Eq(5) relates the conversion of biomass (F_{ij}^{B}) into product (F_j^{P}) and by-product (F_j^{BP}) for each industry j. $\mathrm{Y}_{ij}^{\mathrm{P}}$ and $\mathrm{Y}_{ij}^{\mathrm{BP}}$ denote the conversion factors, which relates the amount of output generated for a given process over a certain amount of input. In this work, each industry j does not generate any biomass i, but instead receives it from PPM to produce its output.

$$F_j^{\mathrm{P}} = \sum_i F_{ij}^{\mathrm{B}} \mathrm{Y}_{ij}^{\mathrm{P}} \ , \ \forall j \tag{4}$$

$$F_j^{\mathrm{BP}} = \sum_i F_{ij}^{\mathrm{B}} \mathrm{Y}_{ij}^{\mathrm{BP}} \ , \ \forall j \tag{5}$$

Besides, Eq(6) expresses the relationship for industries j generating process steam as their main product (F_j^{PS}), where the index l represent steam header and $\mathrm{Y}_{ijl}^{\mathrm{PS}}$ is the conversion factor. Process steam can be extracted as medium pressure steam (MPS) or low pressure steam (LPS).

$$F_{jl}^{\mathrm{PS}} = \sum_i F_{ij}^{\mathrm{B}} \mathrm{Y}_{ijl}^{\mathrm{PS}} \ , \ \forall j \quad \forall l \tag{6}$$

In this work, by-product generated from each industry j (F_j^{BP}) can be used as input material to other industries in the EIP. The index k denotes the industry sink requirement for the by-product (F_j^{BP}). Eq(7) relates the by-product source balance, where F_{jk}^{BP} denotes the allocation of by-product from industry source j to industry sink k while the excess is exported to an external party ($F_j^{\mathrm{BP\text{-}EXP}}$).

$$F_j^{\text{BP}} = \sum_k F_{jk}^{\text{BP}} + F_j^{\text{BP-EXP}} \text{ , } \forall j \tag{7}$$

Following this, the by-product sink balance ($F_k^{\text{BP-SK}}$) can be determined via Eq(8), where $F_j^{\text{BP-IMP}}$ denotes imported by-product.

$$F_k^{\text{BP-SK}} = \sum_j F_{jk}^{\text{BP}} + F_k^{\text{BP-IMP}} \text{ , } \forall k \tag{8}$$

Next, an analogous source and sink balance for process steam at each steam header l can be expressed as Eqs(9) and (10), where the index m represents steam sink.

$$F_{jl}^{\text{PS}} = \sum_m F_{jlm}^{\text{PS}} + F_{jl}^{\text{PS-EXP}} \text{ , } \forall j \quad \forall l \tag{9}$$

$$F_{lm}^{\text{PS-SK}} = \sum_j F_{jlm}^{\text{PS}} + F_{lm}^{\text{PS-IMP}} \text{ , } \forall l \quad \forall m \tag{10}$$

In this work, linkages in an EIP are formed when there is an exchange of biomass or by-product between PPM with an industry. The presence of a biomass linkage can be related through an inequality as presented in Eq(11). Here, $F_{ij}^{\text{B-MIN}}$ denotes the minimum biomass flow rate required while L_{ij}^{B} is a binary integer representing the biomass link. The minimum biomass flow rate is introduced to ensure a logical value of flow rate would be generated before it can be considered as a linkage. Thus, a linkage is present (L_{ij}^{B}= 1) when the biomass stream (F_{ij}^{B}) is greater than or equal to the minimum biomass flow rate constraint ($F_{ij}^{\text{B-MIN}}$), and vice versa.

$$\frac{F_{ij}^{\text{B}}}{F_{ij}^{\text{B-MIN}}} \geq L_{ij}^{\text{B}} \text{ , } \forall i \quad \forall j \tag{11}$$

Similarly, Eq(12) expresses the presence of a by-product link (L_{jk}^{BP}), analogous to Eq(11).

$$\frac{F_{jk}^{\text{BP}}}{F_{jk}^{\text{BP-MIN}}} \geq L_{jk}^{\text{BP}} \text{ , } \forall j \quad \forall k \tag{12}$$

Subsequently, the total number of linkages in an EIP (L^{E}) can be determined via Eq(13).

$$L^{\text{E}} = \sum_j \left(\sum_i L_{ij}^{\text{B}} + \sum_k L_{jk}^{\text{BP}} \right) \tag{13}$$

Then, the eco-connectance of an EIP can be determined as shown in Eq(2). In this work, payback period (*PP*) is used as a tool to determine the economic performance of an EIP. This is expressed in Eq(14), where *CAPEX* denotes total capital expenditure (USD) of an EIP and *PROFIT* is the profitability of an EIP (USD/y)

$$PP = {CAPEX}/{PROFIT} \tag{14}$$

CAPEX of an EIP can be represented by Eq(15) where X_{ij}^{CAPEX} denotes the capital investment cost parameter for each industry *j*, which covers for the purchasing of equipments and the cost of installation. In this work, *CAPEX* of an EIP is computed based on how many industry *j* participates in the EIP. This is determined by the number of biomass linkages (L_{ij}^{B}) between PPM with industry *j*. For instance, in the presence of a biomass linkage (L_{ij}^{B}= 1), *CAPEX* for industry *j* would be calculated as the product of L_{ij}^{B} and X_{ij}^{CAPEX}.

$$CAPEX = \sum_i \sum_j L_{ij}^{\text{B}} X_{ij}^{\text{CAPEX}} \tag{15}$$

Next, profitability is determined from the revenue generated and the incurred operating costs in Eq(16).

$$PROFIT = REVENUE - COST \tag{16}$$

Revenue generated from EIP consists of revenue from product (G^{P}) and the internal exchange of by-product (G^{BP}) and process steam (G^{PS}), with cost units of USD/y.

$$REVENUE = G^{\mathrm{P}} + G^{\mathrm{BP}} + G^{\mathrm{PS}} \tag{17}$$

The relationship for G^{P}, G^{BP} and G^{PS} can be determined via Eq(18) to Eq(20), where t^{OT} and t^{OH} denote operating time (s/h) and operating hour (h/y) of an EIP. The selling cost parameters are presented for product (X_j^{P}), by-product (X^{BP} and $X^{\mathrm{BP\text{-}EXP}}$), and process steam ($X_l^{\mathrm{PS\text{-}EXP}}$ and $X_l^{\mathrm{PS\text{-}EXP}}$).

$$G^{\mathrm{P}} = \sum_j (F_j^{\mathrm{P}} \mathrm{X}_j^{\mathrm{P}}) \mathrm{t}^{\mathrm{OT}} \mathrm{t}^{\mathrm{OH}} \tag{18}$$

$$G^{\mathrm{BP}} = \sum_j (\sum_k (F_{jk}^{\mathrm{BP}} \mathrm{X}^{\mathrm{BP}}) + F_j^{\mathrm{BP\text{-}EXP}} \mathrm{X}^{\mathrm{BP\text{-}EXP}}) \mathrm{t}^{\mathrm{OH}} \tag{19}$$

$$G^{\mathrm{PS}} = \sum_j \sum_l (\sum_m (F_{jlm}^{\mathrm{PS}} \mathrm{X}_l^{\mathrm{PS}}) + F_{jl}^{\mathrm{PS\text{-}EXP}} \mathrm{X}_l^{\mathrm{PS\text{-}EXP}}) \mathrm{t}^{\mathrm{OT}} \mathrm{t}^{\mathrm{OH}} \tag{20}$$

Next, the operating cost of an EIP includes expenses for the by-product and process steam requirement. $X^{\mathrm{BP\text{-}IMP}}$ and $X_l^{\mathrm{PS\text{-}IMP}}$ denote the purchase cost parameter for imported by-product and process steam.

$$COST = \sum_k (F_k^{\mathrm{BP\text{-}IMP}} \mathrm{X}^{\mathrm{BP\text{-}IMP}}) \mathrm{t}^{\mathrm{OH}} + \sum_m \sum_l (F_{lm}^{\mathrm{PS\text{-}IMP}} \mathrm{X}_l^{\mathrm{PS\text{-}IMP}}) \mathrm{t}^{\mathrm{OT}} \mathrm{t}^{\mathrm{OH}} \tag{21}$$

4. Case Study

In this work, a PPM is planning to set up a joint venture to form an EIP with five potential bioenergy or bio-product related industries, termed biorefineries. Each of the biorefineries receives PPM biomass and converts it into different bio-product and by-products. The five biorefineries considered are: a boiler plant (j = 1), an integrated gasification combined cycle (IGCC) plant (j = 2) and three different biofuel producing biorefineries; dimethyl ether (DME) biorefinery (j = 3), Fischer-Tropsch (FT) biorefinery (j = 4) and mixed-alcohol (MA) biorefinery (j = 5). To synthesize the pulp and paper based EIP network, the formulated optimization model in Eqs(2 - 21) is solved by setting the objective function as

Maximise C^{E} (22)

subjected to $PP \leq 5$ (23)

Table 1: Conversion factors and investment cost parameter for each biorefinery

	Boiler	IGCC	DME-Biorefinery	FT-Biorefinery	MA-Biorefinery
Conversion factors (from black liquor)					
Product, Y_j^{P}	-	-	0.0649	0.0265	0.0157
By-product, Y_j^{BP}	1.632	3.225	-	-	-
MPS (as product), Y_{jl}^{PS}	0.893	0.925	-	-	-
LPS (as product), Y_{jl}^{PS}	1.717	1.801	-	-	-
Investment cost parameter, X_j^{CAPEX} (USD million)	136	218	197	170	232

Besides, the following assumptions were made:

a. Biomass is limited to a single source, i.e. black liquor generated from PPM at 50 kg/s (F_i^{B}).
b. Conversion factors (Y_{ij}^{P}, Y_{ij}^{BP}, Y_{ijl}^{PS}) and investment cost parameters (X_{ij}^{CAPEX}, X_j^{P}, X^{BP}, $X^{\mathrm{BP\text{-}EXP}}$, X_l^{PS}, $X_l^{\mathrm{PS\text{-}EXP}}$, $X^{\mathrm{BP\text{-}IMP}}$, $X_l^{\mathrm{PS\text{-}IMP}}$) for each of the biorefineries are adapted from Larson et al. (2006) and Sammons Jr (2009), which are tabulated in Table 1 and Table 2.
c. Capital investment for each biorefinery is estimated based on the maximum capacity in the EIP.
d. The minimum black liquor flow rate ($F_{ij}^{\mathrm{B\text{-}MIN}}$) and electricity ($F_{jk}^{\mathrm{BP\text{-}MIN}}$) to generate a linkage is set at 3 kg/s and 1 MW.
e. The total number of participating industries in the EIP is six (S = 6). This consists of PPM and the five studied biorefineries, giving a maximum possible linkage of 15.
f. PPM consumes 35.14 kg/s of MPS, 67.6 kg/s of LPS and 60 MW of electricity.
g. Boiler and IGCC plant produce MPS and LPS as their main product and electricity as by-product.
h. Electricity demand for DME-biorefinery, FT-biorefinery and MA-biorefinery are 34.9 MW, 31.8 MW and 41.6 MW.
i. Operating time (t^{OT}) is 3,600 s/h while operating hour (t^{OH}) of the EIP is 8,330 h/y

Table 2: Selling and purchasing cost parameter for all product and by-products

Cost Parameter	Cost
Biofuel, X_j^{P}	
DME (USD/gal)	1.57
FT (USD/gal)	2.09
MA (USD/gal)	2.04
Process steam, X_l^{PS}	
MPS (USD/t)	9 (X_j^{PS}) and 10 ($X_j^{PS\text{-}IMP}$)
LPS (USD/t)	6 (X_j^{PS}) and 7 ($X_j^{PS\text{-}IMP}$)
Electricity, X^{BP} (USD/kWh)	0.09 (X^{BP}) and 0.010 ($X^{BP\text{-}IMP}$)

The mixed integer nonlinear programming (MINLP) model is solved using commercial optimization software LINGO v13 with Global Solver in a HP Intel(R) Core(TM) i5-2400 CPU (3.10 GHz) and 4.00 GB RAM. A global optimum solution is reported in 5 seconds. Figure 1 depicts the optimized EIP network, where PPM is to set a joint venture with a boiler plant, IGCC plant and a biorefinery producing DME. The reported eco-connectance, C^{E} is 0.467, consisting of three biomass links (L^{B}) and four by-product links (L^{BP}), resulting in a total linkage (L^{E}) of seven. Next, a payback period of 4.34 y is reported.

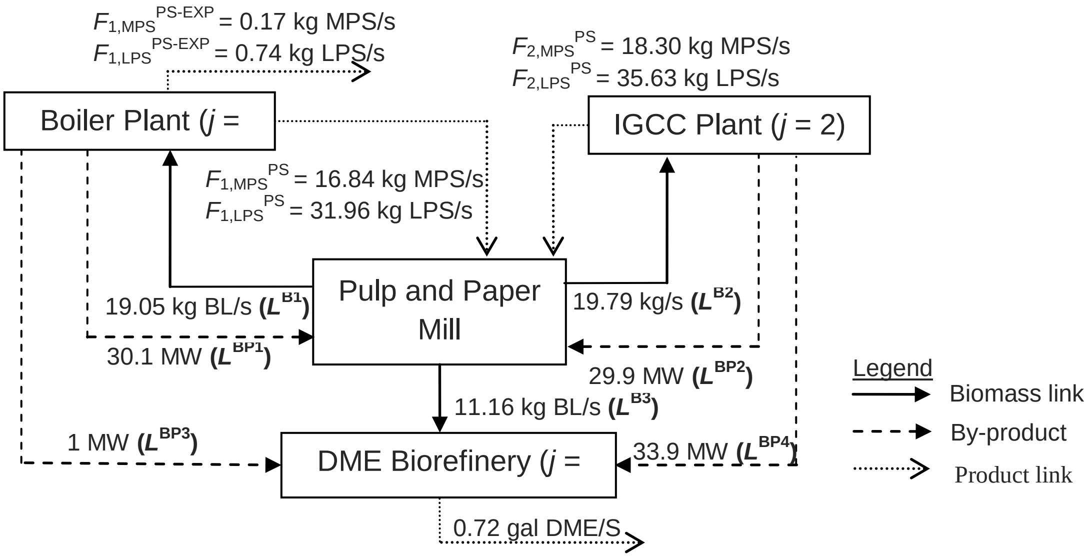

*Figure 1: Optimized EIP network for PPM (Linkage labels are highlighted in **bold**)*

As shown in Figure 1, black liquor generated is sent to the boiler plant (19.05 kg/s), IGCC plant (19.79 kg/s) and DME-biorefinery (11.16 kg/s). Next, both the boiler plant and IGCC plant generate process steam (i.e. MPS and LPS). In IGCC plant, all process steam produced is sent to meet the partial steam demand of PPM. The balance steam demand of PPM is then satisfied by the boiler plant. Subsequently, the boiler plant would generate an excess of process steam, which is sold to an external party (0.17 kg/s of MPS and 0.74 kg/s of LPS). Meanwhile, through the expansion of steam turbines in boiler plant and IGCC plant, electricity is generated as by-product. A total of four by-product linkages (L^{BP}) are present. PPM receives an electrical load of 30.1 MW from boiler plant and 29.9 MW from IGCC plant. Next, the electrical load balance from the boiler and IGCC plant is sent to satisfy the demand in DME-biorefinery. The low electrical load of 1 MW from boiler plant to DME-biorefinery is a result of the minimum electricity constraint ($F_{jk}^{BP\text{-}MIN}$) set in Eq(12). Lastly, DME-biorefinery receives black liquor from PPM to generate 0.72 gal DME/s, to be sold as revenue. The utility demand of DME-biorefinery is supplied from boiler and IGCC plant.

Next, the relationship between maximum allowable payback period with the eco-connectance of an EIP is analysed through sensitivity analysis. The results are tabulated in Table 3. A trend is observed where, as the maximum allowable payback period increases from 2.5 y to 6 y, the eco-connectance increases from 0.13 to 0.67. It is concluded with an increase in the number of industry participation in an EIP, the eco-connectance increases. However, this would require a substantial amount of capital expenditure, resulting in a longer payback period for the EIP to generate a positive economic performance. Besides, it is found that a boiler plant and, in most scenarios an IGCC plant always participates in the EIP. This is driven by the process steam demand in PPM, which can only be supplied from boiler and IGCC plant. Next, the selection of biofuel producing biorefineries is dependent on the individual conversion factors and capital investment of each technology.

Table 3: Relationship between maximum payback period with eco-connectance of EIP

	Maximum allowable payback period (y)				
	2.5	3	4	5 (Figure 1)	6
Reported payback period, (y)	2.34	2.58	4	4.34	5.07
Eco-connectance, (C^E)	0.13	0.27	0.47	0.47	0.67
Biomass links, (L^B)	1	2	3	3	4
Number of industries	2	3	4	4	5
Participating biorefineries	Boiler	Boiler IGCC	Boiler IGCC FT-Biorefinery	Boiler IGCC DME-Biorefinery	Boiler IGCC DME-Biorefinery FT-Biorefinery

5. Conclusions

The current work has developed an optimization model which analyses the relationship between payback period with eco-connectance of EIP. As reported, although a high eco-connectance is desired to maximise the exchange of waste and by-product, the initial capital expenditure of introducing multiple industries might hinder the beneficial exchange of waste and by-product. The information provided by this model would contribute towards business management, ecological study and environmental policy making. Future work aims to minimize the financial risk associated with the eco-connectance in designing an EIP.

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