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Synthesis of Mixed Strategy Games in Eco-industrial Park using Integrated Analytic Hierarchy Process

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Selection problems from a set of alternatives are common in process engineering. Decision makers are often faced in the selection process with multiple criteria which are often conflicting and in some cases may be intangible or qualitative. The analytic hierarchy process (AHP) is a systematic approach to decompose complex decisions into simple sub-problems. Due to its mathematical simplicity and flexibility, AHP are integrated with different techniques such as mathematical programming, and SWOT analysis to solve complex engineering design problems involving multiple decision criteria and decision-maker. In this work, we aim to propose the application of integrated AHP (IAHP) for the formation of eco-industrial park (EIP). Due to the involvement of multiple decision-makers in an EIP, the selection of optimum resource network for EIP results in a complex decision making process to be solved by conventional mathematical optimization technique. Therefore, in this work we use IAHP to form an optimum resource conservation network in an EIP. The consensus on the cooperation among industrial players is necessary since a network cannot be established without the consent of all parties involved. Thus, the proposed IAHP models the interaction among independent and self-interested industrial players, forming a mixed strategy game. The incorporation of criteria weightings into mathematical programming using the proposed IAHP for the formation of EIP ensures Pareto optimality in the solution. A case study using a centralized chilled and cooling water network system is used to illustrate the proposed methodology.

1. Introduction

Due to stringent local regulation on industrial plant emission and growing awareness of environmental protection, resources conservation through in-plant process recovery becomes a common strategy for industrial sustainable development. Process integration techniques have been applied to study resources recovery, for example, in bromine plant (Boldyryev and Varbanov, 2014), steel industry (Porzio et al., 2014), chilled water network (Foo et al., 2014a), and chilled and cooling water network (Foo et al., 2014b). To further improve resources conservation, the possible way is through the establishment of eco-industrial park (EIP). EIP refers to symbiotic program among several independent industrial plants in a region for common resources sharing. Since the formation of EIP relies on the decision made from the participating plants, a systematic decision making framework is required to establish the EIP.

Game theory is the mathematical study of strategic decision making of independent, and self-interested players (von Neumann and Morgenstern, 1944). It assists the players to make a decision upon their interaction. Several works have been done using game theory approach to the development of EIP. Chew et al. (2009) used game theory to analyse different schemes of inter-plant water integration. Chew et al. used the game theory to aid the participating plants to make decisions for selecting the alternative schemes of inter-plant water integration. Cheng et al. (2014) proposed game-theory based optimization strategy to configure inter-plant heat integration. Sequential design methodologies were presented in Cheng et al. works to maximize all participating plants financial benefits and to achieve the maximum cost saving for the entire EIP. Computational game theory can efficiently model the strategic interactions

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among multiple players. In the aspect of engineering design problems, it can clearly state the problem setting aiding the self-interested players to Pareto optimal outcomes.

A strategy usually consists of several possible moves for players in a game. In the context of game theory, mixed strategy is a probability (or weights) distribution over a set of available moves (or decision criteria) that the players would rank in terms of their relative importance (von Neumann and Morgenstern, 1944).The modelling unit for forming an EIP resemble a cooperative game, aim to optimize the group rather than individual benefit. Formation of mixed strategy game within the EIP can be presented through the integrated analytic hierarchy process (IAHP). Analytic hierarchy process (AHP) (Saaty, 1980) is a structured technique for decomposing complex decision problem into a hierarchy of simple sub-problems, as to easily compare the alternatives based on selected list of decision criteria. Meanwhile, the IAHP is also proven to be a more efficient decision making tool than the stand alone AHP (Ho, 2007). Since decision criteria for the establishment of EIP are often conflicting, IAHP would be a systematic optimization tool for multiple industrial players to address their problem settings in the formation of EIP.

In our previous work, fuzzy AHP was adopted to select the optimum EIP design among the alternatives (Leong et al., 2015). However, generating alternative network designs itself is a time-consuming process thus making it less efficient. This paper extends the previous work of Leong et al. (2015) by using the integration of AHP with mathematical programming for the establishment of EIP. The main aim of this paper is to develop multi-criteria group decision making model for the establishment of EIP. The AHP weightings are incorporated in the mathematical programming model for mixed strategy game optimization. This paper focuses on developing an EIP based on the preferences of all the participating industrial plants. The rest of this paper is organized as follows: a formal problem statement is given followed by the methodology, a case study is used to illustrate the proposed methodology and finally, conclusions are drawn based on the proposed methodology.

2. Problem statement

Given is a set of industrial plants $k \in K$, each of which is planning to reduce fresh resources consumption and improve cost savings by optimizing individual network and establishing inter-plant network within an EIP. Each plant has its own predefined resources input requirement (sinks) and available output sources for reuse/recycle. Fresh resources from external facility will supplement the insufficient supply of internal sources. Given also is a set of predefined criteria $c \in C$, the main problem is to design an optimal network of EIP based on the predefined criteria. The weights of criteria are independently set by each participating plant so as to optimize the network based on individual preference.

3. Integration of analytic hierarchy process with mathematical programming

The objective function is to maximize the overall final score for optimizing network of each participating plant, Sc_k, as given in Eq(1). The final score for optimizing network of each participating plant is next derived in Eq(2).

$$\max \sum_k Sc_k \tag{1}$$

$$Sc_k = \sum_c w_{c,k} r_{c,k} \qquad \forall k \tag{2}$$

The weight of criterion c, $w_{c,k}$, is referred to the input of importance, or preferences considered by the individual plant. It aids in determining priorities of criteria for network optimization. Say for Plant 1, if criterion c_1 is relatively more important than the other criterion c_2, weight of criterion c_1 is higher than criterion c_2. Weights of criteria are scaled between 0 and 1. Designing an EIP network over a set of predefined criteria with their respective weights forms a mixed-strategy game for the industrial players. In addition, the sum of all the weights of criteria is equal to 1 as shown in Eq(3). Figure 1 illustrates the hierarchical representation of the problem. Unlike the conventional AHP, integration of AHP with mathematical programming does not create alternatives. The goal is to derive an optimal EIP network based on participant's preference. The respective score of each criteria for the optimal network, $r_{c,k}$, is derived based on pairwise comparison between the individual optimized network of each participating plant with and without implementing EIP (base case). Score $r_{c,k}$ can be expressed as linear equation described in Eq(4). In Eq(4), $m_{c,k}$ and $z_{c,k}$ are constant parameter and $e_{c,k}$ is the variable derived from optimal EIP network to determine criterion score c in industrial plant k.

$$\sum_c w_{c,k} = 1 \qquad \forall k \tag{3}$$

$$r_{c,k} = m_{c,k} e_{c,k} + z_{c,k} \qquad \forall k, c \tag{4}$$

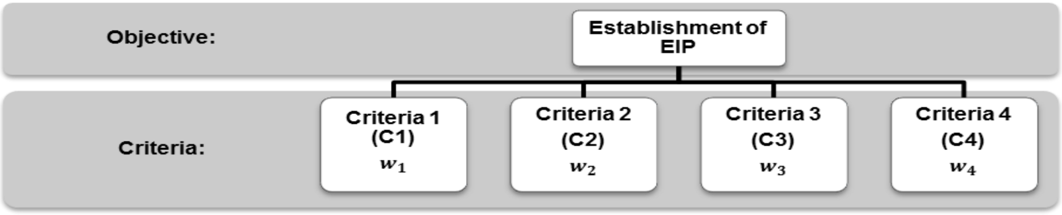

Figure 1. IAHP hierarchy for the individual industrial plant

4. Case study

This case study involves three industrial plants deciding to form a symbiotic chilled and cooling water network within an EIP. In this case study, each plant has its own set of sources $i \in I$ and sinks $j \in J$. Water limiting data of each participating plant are given in Table 1. This case study was solved using LINGO v13.0 with global solver in a 8.0 GB RAM desktop computer with Intel Core I7 CPU at 3.4 GHz and a Windows 8 operating system.

Table 1: Water limiting data of the case study

	Sink, *j*	Flow rate, Fd_j (kg/h)	Temperature, Tin_j (^{o}C)	Source, *i*	Flow rate, Fs_i (kg/h)	Temperature, $Tout_i$ (^{o}C)
Plant 1	1	604.86	6.67	1	224.82	10.00
	2	9.98	8.00	2	31.24	10.50
	3	41.98	10.00	3	31.32	11.11
	4	56.20	15.00	4	76.20	16.67
	5	32.20	17.00	5	258.09	17.70
				6	21.70	19.00
				7	34.50	20.00
				8	35.15	20.88
				9	6.40	22.60
				10	25.80	24.01
Plant 2	6	150.00	6.67	11	50.00	11.67
	7	30.00	8.00	12	100.00	17.67
	8	60.00	15.00	13	60.00	20.00
	9	130.00	17.00	14	30.00	21.00
	10	200.00	20.00	15	20.00	23.00
	11	470.00	30.00	16	110.00	24.00
	12	300.00	55.00	17	450.00	40.00
				18	520.00	75.00
Plant 3	13	119.81	6.67	19	132.00	8.67
	14	154.43	9.67	20	231.72	19.00
	15	162.42	16.67	21	72.94	26.67

In this case study, the source and sink flow rate balance are described in Eqs(5)-(6) while the energy balance is described in Eq(7).

$$\sum_j F_{i,j} + W_i = Fs_i \qquad \forall i \tag{5}$$

$$\sum_j F_{i,j} + Fchw_j + Fcw_j = Fd_j \qquad \forall j \tag{6}$$

$$\sum_i F_{i,j} Tout_i + Fchw_j Tchw + Fcw_j Tcw = Fd_j Tin_j \qquad \forall j \tag{7}$$

where $F_{i,j}$ is the flow rate of water from source i to sink j, W_i is the return stream flow rate, Fs_i is the available water flow rate of source i,$Fchw_j$ is the fresh chilled water flow rate, Fcw_j is the fresh cooling water flow rate, Fd_j is the required flow rate of sink j, $Tout_i$ is the temperature of source i, Tchw is the temperature of fresh chilled water, *Tcw* is the temperature of fresh cooling water, and Tin_j is the required water temperature of sink *j*.

The total annualized cost (TAC_k) of each plant, given in Eq.(8), includes the annualized costs for: (1) return streams (WC_k); (2) fresh chilled and cooling water (FC_k); (3) reused streams (TRC_k) and; (4) cross-plant pipelines (TPC_k) as described in Eqs.(9)-(12).

$$TAC_k = WC_k + FC_k + TRC_k + TPC_k \qquad \forall k \qquad (8)$$

$$WC_k = \sum_{i \in I_k} W_i UwHy \qquad \forall k \qquad (9)$$

$$FC_k = (\sum_{j \in J_k} Fchw_j Uchw + \sum_{j \in J_k} Fcw_j Ucw)Hy \qquad \forall k \qquad (10)$$

$$TRC_k = \sum_{k'} RC_{k,k'} \qquad \forall k, k \neq k' \qquad (11)$$

$$TPC_k = \sum_{k'} PCE_{k,k'} + \sum_{k'} PCR_{k,k'} \qquad \forall k, k \neq k' \qquad (12)$$

where Uw is the unit cost of return stream, Hy is the yearly operating time, Uchw is the unit cost of fresh chilled water, Ucw is the unit cost of fresh cooling water, $RC_{k,k'}$ is the cost associated with reused streams in plant k, $PCE_{k,k'}$ is the cross-plant piping cost of plant k as source exporter for plant k', and $PCR_{k,k'}$ is the cross-plant piping cost of plant k as source receiver from plant k'.

The cost $RC_{k,k'}$ as described in Eq.(11) accounts for the cumulative flow that sinks j in plant k receive from sources i in plant k' and also the cumulative flow rate that sources i in plant k export to sinks j in plant k'

$$RC_{k,k'} = (\sum_{i \in I_{k'}} \sum_{j \in J_k} F_{i,j} - \sum_{j \in J_{k'}} \sum_{i \in I_k} F_{i,j})UrHy \qquad \forall k, k \neq k' \qquad (13)$$

where *Ur* is the unit cost of reused water.

The cost TPC_k as described in Eq.(12) accounts for both the cross-plant flow rate that each plant *k* receives from and exports to plant *k'*. The existence of cross-plant pipeline is determined by the constraint as described in Eq.(14). The cross-plant piping cost $PCE_{k,k'}$ and $PCR_{k,k'}$ of plant *k* as both the exporter and receiver of reused stream are given in Eqs.(15)-(16) respectively.

$$x_{i,j} F_{LB} \leq F_{i,j} \leq x_{i,j} F_{UB} \qquad \forall i \in I_k, \forall j \in J_{k'}, \forall k \in K, k \neq k' \qquad (14)$$

$$PCE_{k,k'} = \frac{1}{2} L_{k,k'} [\frac{p}{\rho v} (\sum_{j \in J_{k'}} \sum_{i \in I_k} F_{i,j}) + q(\sum_{j \in J_{k'}} \sum_{i \in I_k} x_{i,j})]AF \qquad \forall k, k' \in K, k \neq k' \qquad (15)$$

$$PCR_{k,k'} = \frac{1}{2} L_{k,k'} [\frac{p}{\rho v} (\sum_{i \in I_{k'}} \sum_{j \in J_k} F_{i,j}) + q(\sum_{i \in I_{k'}} \sum_{j \in J_k} x_{i,j})]AF \qquad \forall k, k' \in K, k \neq k' \qquad (16)$$

where $x_{i,j}$ is the binary variable to determine the existence of cross-plant pipeline, F_{LB} is the lower limit of cross-plant flow rate, F_{UB} is the upper limit of cross-plant flow rate, $L_{k,k'}$ is the distance between two plants, *p* is the incremental cost parameter based on the cross-sectional area of pipelines, *q* is the cost parameter for building one pipeline, and *AF* in the annualized factor.

The IAHP hierarchy and the respective weights of the criteria in the case study are shown in Figure 2. The decision criteria for the establishment of EIP are defined as follow: fresh chilled and cooling water consumption (C_1), total cost saving (C_2), number of inter-plant pipelines (C_3) and risk for building the EIP (C_4). Criteria C_1 and C_2 are assessed by having the pairwise comparison between the base case of each participating plant without implementing the EIP and the case with implementation of EIP. For example, the lesser the fresh chilled and cooling water consumption of the participating plant in the EIP than the base case the higher the criteria score for C_1. Same to the criterion C_2, the higher the cost savings of the participating plant in the EIP than the base case the higher the criterion score C_2. Criterion C_3 is assessed by identifying the number of new pipelines required in connecting the participating plants. The more number of inter-plant pipelines involved in all the participating plants is unfavourable and therefore will result in the lower criteria score for C_3. Criterion C_4 is assessed by identifying the interdependency network among the participating plants. High interdependence of sources between participating plants results in a more vulnerable network especially when dealing with process inoperability of unit operations which will result in a deviation from an initial network configuration within an EIP. In essence, a source receiving plant would be assigned a lower criterion score for C_4 as compared to its counterpart which is giving out the sources.

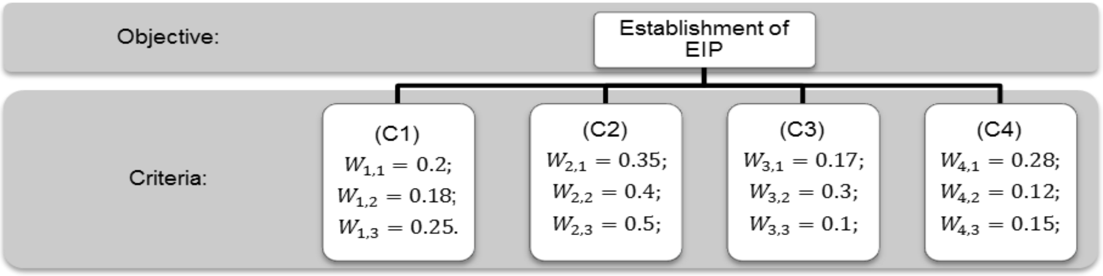

Figure 2: IAHP hierarchy and the respective carried weights of the criteria in the case study

The optimal symbiotic network of EIP in this case study is shown in Figure 3. Table 2 summarized mixed strategy game optimization results. From Table 2, Plant 1 has the highest final score for the optimal network of EIP (0.698), followed by Plant 3 (0.615) and Plant 2 (0.519). Plant 3 has the highest criterion score for C_1 (0.245) and this criterion score is close to its targeted fresh reduction since the carried weights of C_1 in Plant 3 is 0.25. Plant 1 has the highest criterion score for C_2 (0.302) and this criterion score is close to the carried weights of C_2 (0.35). In Figure 3, three inter-plant pipelines (bold line) consist of two cross-plant pipelines from Plant 1 to Plant 2 and one cross-plant pipelines from Plant 1 to Plant 3. Plant 2 has the highest carried weights for criterion C_3 among the participating plants. Thus, Plant 3 is more sensitive to the number of cross-plant pipelines involved in it. Since Plant 1 did not receive any sources from other plants, it obtains the full criterion score for C_4 (0.28). Plant 2 receives the most sources from Plant 1, it has the least criterion score for C_4.

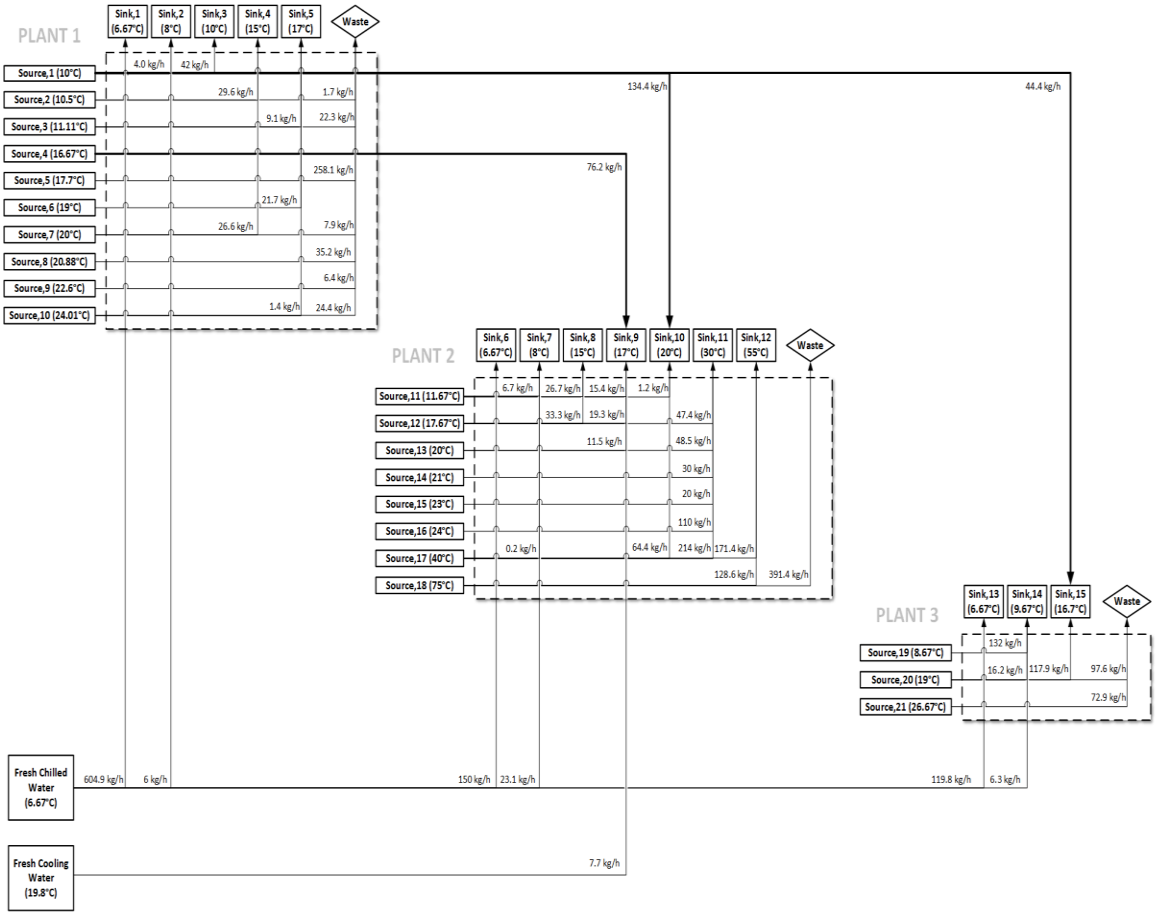

Figure 3: The optimal resources network configuration of the EIP

Table 2: Results of mixed strategy game optimization in an EIP

Plant	Criteria score (C_1),	Criteria score (C_2),	Criteria score (C_3),	Criteria score (C_4),	Final score
1	0.022	0.302	0.094	0.280	0.698
2	0.112	0.133	0.233	0.041	0.519
3	0.245	0.169	0.100	0.101	0.615

5. Conclusion

An IAHP model for the establishment of EIP has been developed in this study. Forming an EIP requires the collaboration of each participating plant to reach the consensus on cooperation. Thus, the proposed design methodology forms a mixed-strategy game which is capable of optimizing a list a pre-defined preferences that aids in the decision making process in forming an EIP. IAHP mathematical optimization is used to synthesize the symbiotic network based on the preferences of each participating plant. This study has developed an EIP with the design methodology that saves time in creating alternative network designs and selecting optimum network among the alternatives. The model can be readily extended to incorporate other material (i.e. waste, by-products) and social environment (i.e. environmental hazards, carbon footprint) network systems.

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