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A Sequential Design Strategy for Heat Integration across Plant Boundaries with Nash-Equilibrium Constrained Energy Trades

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Abstract - The conventional heat exchanger network (HEN) synthesis method is useful only for achieving the minimum total annual cost within a single chemical plant. If this method is directly applied to the hot and cold process streams in more than one plant on an industrial park, the resulting cost savings may be distributed unfairly among all involved parties. In the present study, a systematic design procedure is developed on the basis of game theory to circumvent such a drawback. Specifically, the inter-plant HEN design is generated in four consecutive steps to determine (1) the minimum overall utility cost, (2) the heat flows between every pair of plants and also their fair trade prices (under the constraints of minimum utility cost and Nash equilibrium), (3) the minimum number of exchangers and the corresponding heat duties, and (4) the optimal network configuration. This sequential strategy allows every plant to maximize its own financial benefit at every step while simultaneously striving for the largest cost saving for the entire site. The feasibility of the proposed procedure has been confirmed with extensive case studies.

INTRODUCTION

HEN synthesis in a single chemical plant is a practical research issue which has received considerable attention in the last three decades. A number of rigorous mathematical programming models have already been developed for creating the optimal network structures [1-4]. Since it is generally believed that a greater level of energy/cost saving can be achieved by expanding the scope of integration, the emphases of some of the recent studies, e.g., Bagajewicz and Rodera [5] and Anita [6], were shifted to the development of heat recovery schemes across plant boundaries. The common optimization objective of these studies was to minimize total energy usage of the entire site, while the economic incentives of individual plants were in large part neglected. Consequently, the resulting integration arrangements may not be acceptable to all participating parties. Although the cooperative game theory was utilized in a recent study [7] for deriving a sharing plan to distribute cost savings among partners based on the traditional Pinch analysis, a more rigorous programming approach is still needed for generating the optimal solutions systematically without heuristic manual manipulations.

Traditionally, an optimal HEN design may be produced with either a simultaneous [8] or a sequential [3,4] approach. The former usually yields a better trade-off between energy and capital costs since the sum of these two costs, i.e., the total annual cost (TAC), is minimized in a single step, but the computation load needed to solve the corresponding mixed-integer nonlinear program (MINLP) is overwhelming. On the other hand, although only suboptimal solutions can be obtained in the latter case, implementing a step-by-step procedure is expected to be much easier. In principle, these two traditional approaches can both be applied directly to produce the "optimal" inter-plant HEN designs if all process streams on site are handled indiscriminately. Since the resulting schemes may not be acceptable, the practical issues encountered in distributing the cost savings are addressed in this work with a modified version of the latter approach. The sequential strategy is adopted not only because of the lighter implementation effort but also the fact that the game theoretic models can be more naturally incorporated into this design practice.

More specifically, since the traded commodities are energies of different grades, the total-site heat integration problem is treated here as a nonzero-sum matrix game, in which the proportions of heat exchanges at different temperature levels are regarded as alternative *game strategies*. With this view, the Nash equilibrium constraints [9,10] can be imposed for solving the game according to a nonlinear program while still keeping the overall utility cost at the minimum level. Such an approach allows us to not only cut down the overall energy consumption rate but also to facilitate every plant to gain maximum achievable benefit under the most appropriate price structure. Following is a detailed description of this design procedure:

SEQUENTIAL DESIGN PROCEDURE BASED ON GAME THEORY

In order to incorporate the Nash constraints, the traditional HEN design procedure has been modified and applied in four steps:

1. The minimum utility cost problem is solved with a linear program, which can be formulated by modifying the conventional transshipment model [4].
2. By incorporating the constraints of minimum overall utility cost (obtained in Step 1) and also Nash equilibrium in a nonlinear program, the inter-plant heat flows and also their fair trade prices can be

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calculated accordingly.

3. By fixing the inter-plant heat-flow patterns determined in Step 2, the minimum number of matches and the corresponding heat duties can be determined with an extended version of the conventional MILP model [4].
4. By following the approach suggested by Floudas et al. [3], a superstructure can be built to facilitate the matches identified in Step 3 and a nonlinear programming model can then be constructed for generating the optimal HEN configuration.

Due to space limitation, a simple example is utilized throughout this paper to illustrate the proposed design procedure. The more detailed formulations can be found elsewhere [11]. Let us consider the process and utility data of three fictitious plants (see Table I and Table II). Under the condition that inter-plant heat integration is not allowed, one can obtain their heat-flow cascades and pinch points (see Fig. 1). The hot utility consumption rates of P1, P2 and P3 can be found to be 800, 100 and 255 kW respectively, while the cold utility consumption rates are 210, 160 and 670 kW respectively.

Step 1: Calculating the minimum total utility cost

The minimum total utility cost of the *integrated* system can be determined on the basis of a transshipment model [4]. In this model, the entire temperature range must be partitioned first according to the inlet and outlet temperatures of all process streams. The heat flows surrounding a temperature interval in each plant are characterized in Fig. 2 and the corresponding energy balance can be expressed as

$$R_k^p - R_{k-1}^p - \sum_{m\in \mathbb{S}_k^p} Q_m^S - \sum_{\substack{q=1\\ q\neq p}}^{P} Q_k^{qp} + \sum_{n\in \mathbb{W}_k^p} Q_n^W + \sum_{\substack{q'=1\\ q'\neq p}}^{P} Q_k^{pq'} = \Delta H_k^p \tag{1}$$
$$k = 1,2,3...K \qquad p = 1,2,3,\cdots,P$$

where, R_k^p denotes the heat residue of the interval k in plant p; Q_m^S denotes the heat supplied by hot utility m; Q_n^W denotes the heat rejected to cold utility n; Q_k^{qp} denotes the heat flow transferred from interval k in plant q to interval k in plant p; $Q_k^{pq'}$ denote the heat flow transferred from interval k in plant p to interval k in plant q'; ΔH_k^p is the enthalpy difference of the hot and cold process streams in interval k of plant p; $\mathbb{S}_k^p$ denotes the set of hot utilities in interval k of plant p; $\mathbb{W}_k^p$ denotes the set of cold utilities in interval k of plant p.

A linear program (LP) was formulated accordingly to determine the minimum total utility cost and the corresponding heat-flow cascade in Fig. 3. The optimal hot utility consumption rates of P1, P2 and P3 were found to be 0, 220 and 440 kW respectively, while those of the cooling utilities were 485, 0 and 60 kW. Note that not all utility consumption rates are reduced in this scheme. This is due to the fact that the overall utility cost is minimized under the cost structure given in Table II.

TABLE I: PROCESS DATA

Plants	stream	T_{in} (℃)	T_{out} (℃)	F_{cp} (kW/℃)
P1	H1	150	40	7
P2	H1	200	70	5.5
P3	H1	370	150	3.0
P3	H2	200	40	5.5
P1	C1	60	140	9
P1	C2	110	190	8
P2	C1	30	110	3.5
P2	C2	140	190	7.5
P3	C1	110	360	4.5

TABLE II: UTILITY DATA

Plants	Utility stream	T(℃)	Cost(US$/kW-yr)	Maximum Usage(kW)
P1	Cooling Water	25	10	1000
P1	HPS(240psig)	200	90	1000
P1	Fuel	500	80	1000
P2	Cooling Water	25	22.5	1000
P2	HPS(240psig)	200	30	1000
P2	Fuel	500	120	1000
P3	Cooling Water	25	30	1000
P3	HPS(240psig)	200	60	1000
P3	Fuel	500	40	1000

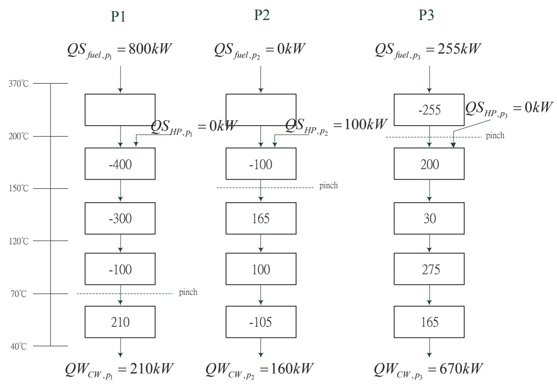

Fig. 1 The heat-flow cascades without inter-plant integration

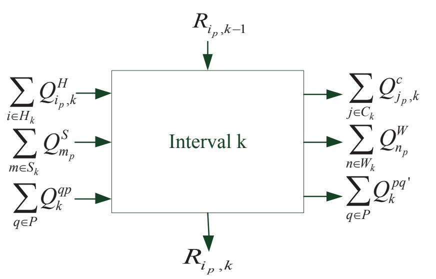

Fig.2: The heat flows around interval k in plant p

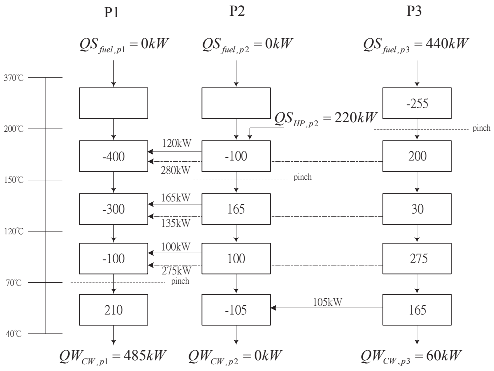

Fig. 3 The integrated heat-flow cascade obtained without energy trades.

Step 2: Identifying the inter-plant heat flows and their trade prices

A NLP model is adopted in the present step to determine the inter-plant heat flows and their trade prices. The key model components, i.e., the payoff matrix, the game strategies, the equilibrium constraints and the objective function, are outlined below:

Payoff matrix:

In a multi-player game, each player (say plant p) can select one strategy from four alternatives, i.e., exporting heat at a temperature above or below the pinch (denoted respectively as UD and LD) or importing heat at a temperature above or below the pinch (denoted respectively as UA and LA). The structure of the payoff matrix $\mathbf{A}_p(=[\mathbf{A}_{pq_1}|\mathbf{A}_{pq_2}|\ldots|\mathbf{A}_{pq_N}])$ for plant p can be expressed as

$$\begin{array}{c} \\ \\ UD \\ LD \\ UA \\ LA \end{array} \begin{array}{c} \qquad\text{plant } q_1 \qquad\qquad \cdots \qquad\qquad \text{plant } q_N \\ \begin{array}{cccc|cccc} UA & LA & UD & LD & UA & LA & UD & LD \end{array} \\ \left[\begin{array}{cccc|c|cccc} \Re^{pUq_1U} & \Re^{pUq_1L} & NA & NA & & \Re^{pUq_NU} & \Re^{pUq_NL} & NA & NA \\ \Re^{pLq_1U} & \Re^{pLq_1L} & NA & NA & & \Re^{pLq_NU} & \Re^{pLq_NL} & NA & NA \\ NA & NA & \Re^{q_1UpU} & \Re^{q_1LpU} & \cdots & NA & NA & \Re^{q_NUpU} & \Re^{q_NLpU} \\ NA & NA & \Re^{q_1UpL} & \Re^{q_1LpL} & & NA & NA & \Re^{q_NUpL} & \Re^{q_NLpL} \end{array}\right] \end{array}$$

where, $N=P-1$; $q_i \in \{1,2,...,p-1,p+1,...,P\}$ and $i=1,2,\cdots,N$. In this game, plant p and plant q_i are treated respectively as the row and column players. Notice that the symbol NA denotes the corresponding heat exchange is forbidden and, also, the remaining payoff values (of plant p) can be calculated according to the following formulas:

$$\begin{aligned} \Re^{pUq_iU} &= -C_{HU}^{p} - C_{trd}^{pUq_iU}; & \Re^{pUq_iL} &= -C_{HU}^{p} - C_{trd}^{pUq_iL}; \\ \Re^{pLq_iU} &= C_{CU}^{p} - C_{trd}^{pLq_iU}; & \Re^{pLq_iL} &= C_{CU}^{p} - C_{trd}^{pLq_iL}; \\ \Re^{q_iUpU} &= C_{HU}^{p} + C_{trd}^{q_iUpU}; & \Re^{q_iLpU} &= C_{HU}^{p} + C_{trd}^{q_iLpU}; \\ \Re^{q_iUpL} &= -C_{CU}^{p} + C_{trd}^{q_iUpL}; & \Re^{q_iLpL} &= -C_{CU}^{p} + C_{trd}^{q_iLpL}. \end{aligned} \qquad (2)$$

The first term on the right side of each equation, i.e., C_{HU}^{p} or C_{CU}^{p}, is the unit cost of hot or cold utility of plant p, while the second term denotes the trade price to be determined.

Game strategies**:**

The proportions of plant p adopting the aforementioned strategies can be determined with the following formulas

$$\begin{aligned} PR_p^{UD} &= \frac{1}{Q_p^E}\left(\sum_{k\in K_p^U}\sum_{\substack{q=1\\q\neq p}}^{P} Q_k^{pq}\right); & PR_p^{LD} &= \frac{1}{Q_p^E}\left(\sum_{k\in K_p^L}\sum_{\substack{q=1\\q\neq p}}^{P} Q_k^{pq}\right); \\ PR_p^{UA} &= \frac{1}{Q_p^E}\left(\sum_{k\in K_p^U}\sum_{\substack{q=1\\q\neq p}}^{P} Q_k^{qp}\right); & PR_p^{LA} &= \frac{1}{Q_p^E}\left(\sum_{k\in K_p^L}\sum_{\substack{q=1\\q\neq p}}^{P} Q_k^{qp}\right). \end{aligned} \qquad (3)$$

where, Q_k^{pq} and Q_k^{qp} respectively denote the heat flow transferred from interval k in plant p to interval k in plant q and vice versa; $Q_p^E=\sum_{k\in K}\sum_{q=1,q\neq p}^{P}(Q_k^{pq}+Q_k^{qp})$ is the total amount of heat exchanged externally by plant p; K_p^U and K_p^L denote the sets of temperature intervals above and below the pinch point of plant p respectively. It is clear that $K_p^U \cap K_p^L = \varnothing$, $K_p^U \cup K_p^L = K$ and $PR_p^{UD}+PR_p^{LD}+PR_p^{UA}+PR_p^{LA}=1$.

Equilibrium constraints:

The Nash equilibrium constraints can be expressed as [10]

$$\mathbf{x}_p{}^T\sum_{\substack{q=1\\q\neq p}}^{P}\mathbf{A}_{pq}\mathbf{x}_q=\alpha_p; \quad \sum_{\substack{q=1\\q\neq p}}^{P}\mathbf{A}_{pq}\mathbf{x}_q \le \alpha_p\mathbf{J}_p; \quad \mathbf{x}_p^T\mathbf{J}_p=1. \qquad (4)$$

where, $\mathbf{J}_p=[1\ \ 1\ \ 1\ \ 1]^T$; $\mathbf{A}_{pq}$ is a sub-matrix of the payoff matrix $\mathbf{A}_p$ in which the payoff values between plant p and plant q are specified; α_p denotes the average payoff value of plant p; $\mathbf{x}_p^T=[PR_p^{UD},PR_p^{LD},PR_p^{UA},PR_p^{LA}]$; $\mathbf{x}_q^T=[PR_q^{UA},PR_q^{LA},PR_q^{UD},PR_q^{LD}]$. The above constraints should be incorporated into the proposed NLP model to ensure that the energy trades in the inter-plant integration scheme are acceptable to all parties.

Objective function:

The objective function of the maximization problem in step 2 is formulated as

$$\max\prod_{p=1}^{P}S_p^U \qquad (5)$$

In this equation, S_p^U denotes the utility cost saving achieved by plant p after the inter-plant integration with energy trades, and its value is calculated with the following formula

$$S_p^U=\overline{Z}_p-Z_p^{'}+pf_p \qquad (6)$$

where, $\overline{Z}_p$ denotes the minimum utility cost achieved by heat integration only *within* plant p; $Z_p^{'}$ represents the utility cost of plant p after inter-plant heat integration with energy trades; pf_p denotes the profit gained by plant p via energy trades. For the sake of brevity, the formulas for computing these terms are presented elsewhere [11].

The above objective function can be used in a NLP model in which the energy balances and all aforementioned constraints are imposed. From the optimal solution of this model for the example problem, one can identify the following strategy vectors and the corresponding payoff matrices:

$$\mathbf{x}_1=\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}^T$$

$$\mathbf{x}_2=\begin{bmatrix}0.415 & 0.361 & 0.0 & 0.224\end{bmatrix}^T$$

$$\mathbf{x}_3=\begin{bmatrix}0 & 1 & 0 & 0\end{bmatrix}^T$$

$$\mathbf{A}_1=\begin{bmatrix}\mathbf{A}_{12} & \mathbf{A}_{13}\end{bmatrix}=\left[\begin{array}{cccc|cccc}-60 & 0 & NA & NA & 0 & 0 & NA & NA\\ 40 & 0 & NA & NA & 70 & 0 & NA & NA\\ NA & NA & 52.2 & 105 & NA & NA & 0 & 51.7\\ NA & NA & 0 & 12.5 & NA & NA & -70 & 0\end{array}\right]$$

$$\mathbf{A}_2=\begin{bmatrix}\mathbf{A}_{21} & \mathbf{A}_{23}\end{bmatrix}=\left[\begin{array}{cccc|cccc}7.5 & -40 & NA & NA & 0 & -10.7 & NA & NA\\ 7.5 & 0 & NA & NA & 82.5 & 0 & NA & NA\\ NA & NA & 0 & 0 & NA & NA & -30 & 0\\ NA & NA & -112.5 & -12.5 & NA & NA & -82.5 & 7.5\end{array}\right]$$

$$\mathbf{A}_3=\begin{bmatrix}\mathbf{A}_{31} & \mathbf{A}_{32}\end{bmatrix}=\left[\begin{array}{cccc|cccc}30 & 0 & NA & NA & 0 & 0 & NA & NA\\ 68.3 & 20 & NA & NA & 60 & 0 & NA & NA\\ NA & NA & -30 & 0 & NA & NA & 30 & 0\\ NA & NA & -120 & -20 & NA & NA & -49.3 & -7.5\end{array}\right]$$

The resulting trade prices are shown in Table III. The average payoffs received by the plants can be respectively determined to be 111.4 USD/yr, 7.5 USD/yr and 68.3 USD/yr, which indicate that plant P1 is the largest beneficiary of the inter-plant heat integration scheme. The required utility costs of every plant before and after inter-plant integration are presented in Table IV, and the corresponding cost savings are also listed in the same table. The total revenue received by each plant via energy trades and the resulting saving in utility cost can be found in Table V. To provide further insights into the optimal integration scheme, the utility consumption rates of each plant and the inter-plant heat flows are also presented in Table VI and Table VII respectively.

TABLE III: THE OPTIMAL TRADE PRICES FOR INTER-PLANT HEAT TRANSFERS

	Trade Price (USD/yr-kW)		Trade Price (USD/yr-kW)		Trade Price (USD/yr-kW)
C_{trd}^{1U2U}	-30	C_{trd}^{2U1U}	-37.5	C_{trd}^{3U1U}	-90
C_{trd}^{1U2L}	-90	C_{trd}^{2U1L}	10	C_{trd}^{3U1L}	-60
C_{trd}^{1U3U}	-90	C_{trd}^{2U3U}	-30	C_{trd}^{3U2U}	-60
C_{trd}^{1U3L}	-90	C_{trd}^{2U3L}	-19.3	C_{trd}^{3U2L}	-60
C_{trd}^{1L2U}	-30	C_{trd}^{2L1U}	15	C_{trd}^{3L1U}	-38.3
C_{trd}^{1L2L}	10	C_{trd}^{2L1L}	22.5	C_{trd}^{3L1L}	10
C_{trd}^{1L3U}	-60	C_{trd}^{2L3U}	-60	C_{trd}^{3L2U}	-30
C_{trd}^{1L3L}	10	C_{trd}^{2L3L}	22.5	C_{trd}^{3L2L}	30

Step 3: Determining the minimum number of matches and the corresponding heat duties

The minimum number of exchangers is obtained by solving a modified version of the conventional MILP model [4]. This model can be formulated on the basis of the generalized heat flow pattern associated with each temperature interval (see Fig. 4).

TABLE IV: UTILITY COST ANALYSIS

Plant	Utility	Cost Before Integration (USD/yr)	Cost After Integration (USD/yr)	Saving (USD/yr)
P1	Fuel	64,000	0	64,000
P1	CW	2,100	4,850	-2,750
P2	Fuel	0	0	0
P2	Steam (240psig)	3,000	12,150	-9,150
P2	CW	3,600	1,350	2,250
P3	Fuel	10,200	10,200	0
P3	CW	20,100	0	20,100

TABLE V: UTILITY COST SAVINGS

Plant	Trade Revenue (USD/yr)	Cost Saving (USD/yr)
P1	-26,781	34,469
P2	12,413	5,513
P3	14,368	34,468

TABLE VI: UTILITY CONSUMPTION RATES

Plant	Fuel (kW)	Steam (kW)	CW (kW)
P1	0	0	485
P1	0	405	60
P3	255	0	0

TABLE VII: INTER-PLANT HEAT FLOWS

Interval	P2→P1(kW)	P3→P1(kW)	P3→P2(kW)
1	0	0	0
2	305	95	0
3	165	135	0
4	100	275	0
5	0	0	165

In particular, the energy-balance constraints at six different nodes in this interval, i.e., from node A to node F, must all be imposed in the proposed model. As an example, the constraint corresponding to node A can be written as:

$$R_{i_p,k}-R_{i_p,k-1}+\sum_{j_p\in C_k^p}Q_{i_pj_pk}+\sum_{n_p\in W_k^p}Q_{i_pn_pk}+\sum_{\substack{q'=1\\ q'\neq p}}^{P}\sum_{j_{q'}\in C_k^{q'}\cup W_k^{q'}}Q_{i_pj_{q'}k}=Q_{i_p,k}^H \qquad (7)$$

$$i_p\in H_k^p$$

where, $R_{i_p,k}$ denotes the heat residue from hot utility i_p in interval k of plant p; $Q_{i_pj_pk}$ denotes the amount of heat exchanged between hot stream i_p and cold stream j_p in interval k of plant p; $Q_{i_pn_pk}$ denotes the amount of heat exchanged between hot stream i_p and cold utility n_p in interval k of plant p; $Q_{i_p j_{q'} k}$ denotes the amount of heat exchanged between hot stream i_p in interval k of plant p and cold process or utility stream $j_{q'}$ in interval k of plant q'; $Q^H_{i_p,k}$ is the amount of heat supplied by hot stream i_p in interval k of plant p; C_k^p and $C_k^{q'}$ respectively denote the sets of cold streams in interval k of plant p and plant q'; W_k^p and $W_k^{q'}$ respectively denote the sets of cold utilities in interval k of plant p and q'; H_k^p represents the set of hot process streams in interval k of plant p. Note that the energy balances at the other nodes can be formulated in the same fashion.

After constructing the MILP model and carrying out the corresponding optimization run, the minimum unit number for the example problem can be found to be 14 and these optimal matches are shown in Table VIII.

Step 4: Generating the optimal network configuration

Since only the matches are fixed in Step 3, further information about the network structure and the design specifications of each embedded exchanger must be obtained for calculating the total capital cost of a HEN design. This work has been traditionally done with a superstructure-based NLP model [3]. Essentially the same approach is taken here to formulate the model constraints, while a different objective function is adopted to facilitate fair distribution of financial benefits. In particular, the objective of this step is to maximize the product of TAC savings, i.e.

$$\max \prod_{p=1}^{P} S_p^T \tag{8}$$

where,

$$S_p^T = S_p^U + Af\left(\bar{Z}_p^C - \hat{Z}_p^C - \sum_{\substack{q'=1\\ q'\neq p}}^{P} SC_{pq'} - \sum_{\substack{q=1\\ q\neq p}}^{P} SC_{qp}\right) \tag{9}$$

$$\hat{Z}_p^C = \sum_{i_p\in H^p\cup S^p}\ \sum_{j_p\in C^p\cup W^p} z_{i_p j_p} c_{i_p j_p} A^{\beta}_{i_p j_p} \tag{10}$$

$$SC_{pq'} = \sum_{i_p\in H^p\cup S^p}\ \sum_{j_{q'}\in C^{q'}\cup W^p} z_{i_p j_{q'}} \gamma^p_{i_p j_{q'}} c_{i_p j_{q'}} A^{\beta}_{i_p j_{q'}} \tag{11}$$

$$SC_{qp} = \sum_{i_q\in H^q\cup S^q}\ \sum_{j_p\in C^p\cup W^p} z_{i_q j_p} \gamma^p_{i_q j_p} c_{i_q j_p} A^{\beta}_{i_q j_p} \tag{12}$$

$$\gamma^p_{i_p j_{q'}} + \gamma^{q'}_{i_p j_{q'}} = 1 \tag{13}$$

$$\gamma^q_{i_q j_p} + \gamma^p_{i_q j_p} = 1 \tag{14}$$

where, S_p^U denotes the utility cost saving achieved by plant p, i.e., equation (6); Af is the annualization factor; $\bar{Z}_p^C$ is the minimum capital cost of HEN in plant p without inter-plant integration; $\hat{Z}_p^C$ denotes total capital cost of all inner-plant heat exchangers in plant p after inter-plant heat integration; $SC_{pq'}$ is the capital cost shared by plant p for the inter-plant exchangers facilitating heat exports from plant p to plant q'; SC_{qp} is the capital cost shared by plant p for the inter-plant exchangers facilitating heat imports from plant q to plant p; $z_{i_p j_p}$, $z_{i_p j_{q'}}$ and $z_{i_q j_p}$ are binary parameters determined in Step 3 reflecting if the corresponding matches are present in HEN, and $A_{i_p j_p}$, $A_{i_p j_{q'}}$ and $A_{i_q j_p}$ are the heat-transfer areas in the corresponding exchangers; β, $c_{i_p j_p}$, $c_{i_p j_{q'}}$ and $c_{i_q j_p}$ are coefficients in the cost model of heat exchanger; $\gamma^p_{i_p j_{q'}}$ and $\gamma^{q'}_{i_p j_{q'}}$ respectively denote the proportions of capital cost shared by plant p and plant q' for the heat exchanger facilitating heat export from hot stream i_p to cold stream $j_{q'}$; $\gamma^p_{i_q j_p}$ and $\gamma^q_{i_q j_p}$ respectively denote the proportions of capital cost shared by plant p and plant q for the exchanger facilitating heat import from hot stream i_q to cold stream j_p. The resulting optimal HEN design can be found in Fig. 5.

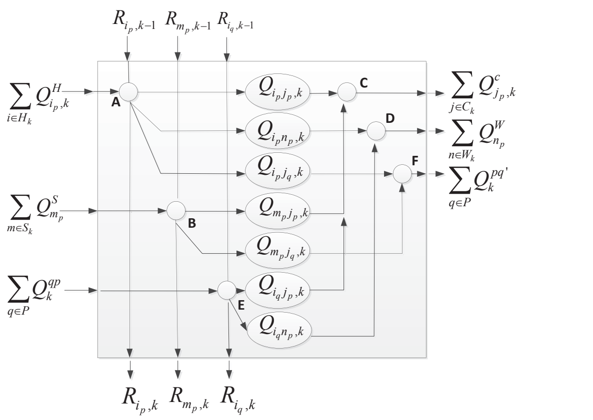

Fig. 4: The generalized heat flow pattern around and within interval k in plant p.

TABLE VIII: OPTIMAL MATCHES

Match #	Hot Stream	Cold Stream	Heat Duty (kW)
1	P1_H1	P1_C1	285
2	P1_H1	P1_CW	485
3	P2_H1	P1_C1	160
4	P2_H1	P1_C2	380
5	P2_H1	P2_C1	175
6	P3_H1	P3_C1	660
7	P3_H2	P1_C1	275
8	P3_H2	P1_C2	230
9	P3_H2	P2_C1	105
10	P3_H2	P3_C1	210
11	P3_H2	P2_CW	60
12	P2_HP	P1_C2	30
13	P2_HP	P2_C2	375
14	P2_Fuel	P3_C1	255

The capital costs of all inter-plant exchangers in this design can be found in Table IX. Note that, in this work, the capital cost of every inter-plant unit is shared by the two parties involved in the corresponding heat exchange. The optimized proportions of their payments are shown in Table X. Finally, a summary of the economic analysis is given in Table XI. It can be observed that, although the inter-plant heat integration scheme results in an increase in the capital cost, the reduction in the utility cost is more than enough to justify the extra investment. The proposed optimization procedure also ensures fair distribution of financial benefits among all participating members. Finally, it should be noted that the additional energy saving achieved with inter-plant integration also implies that the corresponding CO_2 emission rate is much less.

CONCLUSIONS

A game-theory based optimization strategy is presented in this paper for the purpose of generating the optimal inter-plant heat integration schemes. This HEN design can be generated by following four consecutive steps to determine (1) the minimum overall utility cost, (2) the inter-plant heat flows and also their fair trading prices, (3) the minimum number of heat-exchanger units and the corresponding heat duties, and (4) the optimal network configuration. A simple example is adopted to illustrate the proposed method. It can also be observed from the optimization results obtained in additional case studies that the proposed heat integration approach is feasible and effective.

TABLE IX: THE CAPITAL COSTS OF INTER-PLANT HEAT EXCHANGERS IN OPTIMAL HEN DESIGN.

Hot stream	Cold Stream	Area (m^2)	Capital Cost (USD)
P2_H1	P1_C1	16	13,291
P2_H1	P1_C2	34.25	19,185
P2_HP	P1_C2	1.375	7,473
P3_H2	P1_C1	18.698	14,215
P3_H2	P1_C2	17.970	13,968
P3_H2	P2_C1	7.102	10,010
P3_H2	P2_CW	3.372	8,438

TABLE X: CAPITAL COST (PAY PROPORTION)

Hot stream	Cold Stream	Plant 1	Plant 2	Plant 3
P2_H1	P1_C1	1	0	-
P2_H1	P1_C2	1	0	-
P2_HP	P1_C2	1	0	-
P3_H2	P1_C1	0.411	-	0.589
P3_H2	P1_C2	0.054	-	0.946
P3_H2	P2_C1	-	0	1
P3_H2	P2_CW	-	0	1

TABLE XI: SUMMARY OF ECONOMIC ANALYSIS

Plant	Utility cost saving (USD/yr)	Capital cost saving (USD/yr)	TAC Saving (USD/yr)
P1	34,469	-4,370	30,099
P2	5,513	2,526	8,039
P3	34,468	-4,370	30,099

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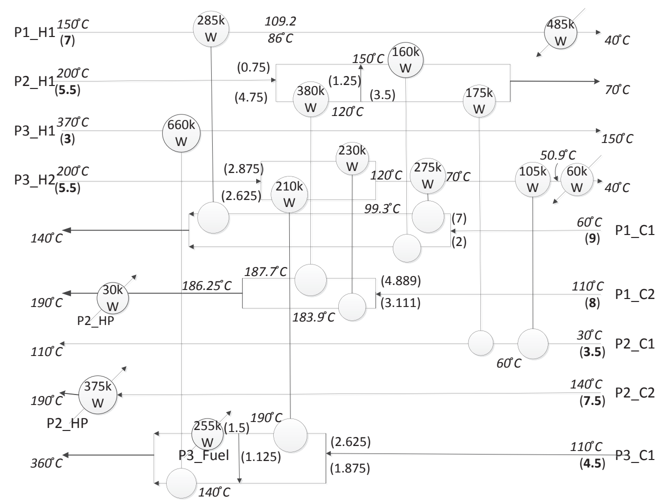

Fig. 5: The optimal inter-plant HEN design.