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Simultaneous Optimization Strategy of Cost-optimal Heat Exchanger Network Synthesis with PSO Algorithm

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Abstract: In this paper, a novel solution strategy based on particle swarm optimization (PSO) algorithm is developed for simultaneous optimization of cost-optimal heat exchanger network synthesis (HENS). Compared to sequential method, simultaneous approach usually needs establishing a more complicated mixed integer nonlinear program (MINLP) model that has complex multi-peak search space. Our work is trying to develop an efficient optimization algorithm to solve the complicated model. The proposed strategy is applied to four examples taken from previous research about HENS, and the results prove that the method is more effective to HENS problems.

Key words: Heat exchanger network synthesis, Particle swarm optimization, MINLP

1. INTRODUCTION

Heat exchanger network (HEN) is an important subsystem in chemical industrial plant, which has proud significance on wasting heat recovery and reducing energy consumption. The investigation on heat exchanger network synthesis (HENS) has been hot research subject during the last three decades. During HEN system, hot process streams and cold process streams exchange heat through heat exchangers, and hot and cold utilities are utilized to make process streams achieve their target temperatures. Ordinarily, the cost-optimal HEN has the feature of capital-energy tradeoff.

For cost-optimal HENS, there are two well-known groups of methods with fast evolution, namely sequential and simultaneous method. The sequential method divided the HENS problem into several sub-problems to simplify solution space, through which minimum utility cost, minimum number of equipments, and total cost are obtained step by step. The optimal network configuration is determined in the end. The pinch design method is the most popular approach of sequential methods, which was first discovery by Linnhoff & Hindmarsh(Linnhoff,1982). In the beginning, the pinch design method was developed for solve problems by hands, because of its simpleness and straight-way. Then, the calculation efficiency was realized so that the pinch method is cooperated with mathematical programming and implemented by computers. Zhu developed a method based on pinch design method and proposed an algorithm for automated HENS. Because of step-optimization, the sequential method has less ability in obtaining minimum total annual cost considering both utility consumption and equipment cost (Zhu,1997). The simultaneous method does not need decomposing HENS problem to find out optimal structure. As shown by Yee and Grossmann, a stage-wise superstructure representation was proposed for HEN formulated as mixed integer nonlinear programming(MINLP) model not relying on pinch theory (Yee,1990). The model can simultaneously optimize running cost and capital cost without decomposition. During the following 20 years, the superstructure representation and MINLP model have been extended to make the approach more appropriable to practical problems. Considering the removal of isothermal mixing assumption, Kaj-Mikael and Tapio presented a modified model from Yee and Grossamnn, a new global optimization algorithm being developed for MINLP model containing non-convex terms in both objection and constraints equations(Björk,2002). Josè et al. proposed a new modified MINLP model for HENS including streams with phase change . The research by Juha , Verheyen and Zang developed a multi-period simultaneous flexible HENS model over a specified range of variations in the flow rates and temperatures of the streams based on superstructure by Yee and Grossamnn. Attempting to release assumption of constant stream heat transfer coefficients, the MINLP model of HENS considering pressure drop effects or with detailed heat transfer equipment design was proposed by Ravagnani and Caballero . Besides modification on the model, the development of global optimization algorithms has more contribution to HENS. Recently, some more efficient optimization algorithms have been found for synthesis complex HEN structure such as Genetic Algorithm (GA) (Ravagnani,2004), simulated Annealing techniques(SA) . In this paper, the modified MINLP model considering non-isothermal mixing is used for HENS, and a new efficient and simple optimization technique based on particle swarm optimization algorithm is proposed for MINLP problem. This paper is organized as follows:

section 2 describes the MINLP model in general considering split-streams and non-isothermal case. In section 3, a new optimization algorithm is described in detail. Several different-scale problems are studied in section 4. The paper ends with some general concluding remarks.

2. THE HENS MODEL

The general representation of HEN superstructure is shown in Fig. 1. The HENS problem aims to determine a reasonable structure with the minimum total costs consisting of investment charge and operating costs. In this paper, the general stage-wise MINLP model first presented by Yee and Grossmann is used to synthesize HEN. During their models, there are non-linear terms only in the objective function because of the isothermal-mixing assumption, which makes solutions robust and easy to search at the expense of narrow the search region. In order to obtain better optimum solution, the assumption of isothermal-mixing is removed in this paper. The modified model can then be written as follows.

2.1. Objective function

The objective function contains the following elements:
(1) unit costs for all heat exchangers including utility exchangers;
(2) cold utility costs;
(3) hot utility costs.
Therefore, the objective function is defined as below:

$$\text{Minimize Cost} = \sum_{i=1}^{HN}\sum_{j=1}^{CN}\sum_{k=1}^{KN}\left[C_{ij}^{\mathrm{ef}} B_{ijk}^{\mathrm{e}} + C_{ij}^{\mathrm{ea}}\left(A_{ijk}^{\mathrm{e}}\right)^{H_{ij}^{\mathrm{e}}}\right] + \sum_{i=1}^{HN}\left[C_i^{\mathrm{cf}} B_i^{\mathrm{c}} + C_i^{\mathrm{ca}}\left(A_i^{\mathrm{c}}\right)^{H_i^{\mathrm{c}}} + C_i^{\mathrm{cu}} q_i^{\mathrm{c}}\right] + \sum_{j=1}^{CN}\left[C_j^{\mathrm{hf}} B_j^{\mathrm{h}} + C_j^{\mathrm{ha}}\left(A_j^{\mathrm{h}}\right)^{H_j^{\mathrm{h}}} + C_j^{\mathrm{hu}} q_j^{\mathrm{h}}\right] \quad (1)$$

Where, the areas are defined as a relation of the heat load and LMTD as follows:

$$A_{ijk}^{\mathrm{e}} = \frac{q_{ijk}}{K_{ij} LMTD_{ijk}} \quad (2)$$

$$A_j^{\mathrm{h}} = \frac{q_j^{\mathrm{h}}}{K_{ij} LMTD_{ijk}} \quad (3)$$

$$A_i^{\mathrm{c}} = \frac{q_i^{\mathrm{c}}}{K_{ij} LMTD_{ijk}} \quad (4)$$

Here, Kij is overall heat transfer coefficient when the heat and cold stream matching, according to the following formula:

$$K_{ij} = \frac{K_i K_j}{K_i + K_j} \quad (5)$$

LMTDijkis the log-mean approaching temperature for the mating of hot stream i and cold stream j at the kth stage. Chen's approximation equation is used for calculation of $LMTD_{ijk}$. $LMTD_{i,cu}$ and $LMTD_{j,hu}$.

$$LMTD_{ijk} \approx \left[\left(t_{i,k,out}^{h} - t_{j,k,out}^{c}\right)\left(t_{i,k+1,out}^{h} - t_{j,k+1,in}^{c}\right)\left(\frac{\left(t_{i,k,out}^{h} + t_{i,k+1,out}^{h}\right) - \left(t_{j,k,out}^{c} + t_{i,k+1,out}^{h}\right)}{2}\right)\right]^{1/3} \quad (6)$$

$$LMTD_{\mathrm{cu},i} \approx \left[\left(T_{cu,out} - t_{i,KN,\mathrm{out}}^{h}\right)\left(T_{i,out}^{h} - T_{cu,in}\right)\left(\frac{\left(T_{cu,out} - t_{i,KN,\mathrm{out}}^{h}\right) + \left(T_{i,out}^{h} - T_{cu,in}\right)}{2}\right)\right]^{1/3} \quad (7)$$

$$LMTD_{hu,j} \approx \left[\left(T_{Hu,in} - t_{j,1,out}^{c}\right)\left(T_{Hu,out} - t_{j,1,in}^{c}\right)\left(\frac{\left(T_{Hu,in} - t_{j,1,out}^{c}\right) + \left(T_{Hu,out} - t_{j,1,in}^{c}\right)}{2}\right)\right]^{1/3} \quad (8)$$

2.2. Constraint equations

2.2.1 Overall heat balance of each stream

$$\left(T_{i,\mathrm{in}}^{\mathrm{h}} - T_{i,\mathrm{out}}^{\mathrm{h}}\right)W_i^{\mathrm{h}} = \sum_{k=1}^{KN}\sum_{j=1}^{CN} q_{ijk} + q_i^{\mathrm{c}} \quad (9)$$

$$\left(T_{j,\mathrm{out}}^{\mathrm{c}} - T_{j,\mathrm{in}}^{\mathrm{c}}\right)W_j^{\mathrm{c}} = \sum_{k=1}^{KN}\sum_{i=1}^{HN} q_{ijk} + q_j^{\mathrm{h}} \quad (10)$$

2.2.2 Energy balance of each heat exchanger

$$\left(t_{\mathrm{i,j,k,in}}^{\mathrm{h}} - t_{\mathrm{i,j,k,out}}^{\mathrm{h}}\right)W_{i,j,k}^{\mathrm{h}} = q_{ijk} \quad (11)$$

$$\left(t_{\mathrm{i,j,k,out}}^{\mathrm{c}} - t_{\mathrm{i,j,k,in}}^{\mathrm{c}}\right)W_{i,j,k}^{\mathrm{c}} = q_{ijk} \quad (12)$$

2.2.3 Energy balance for utility

$$q_i^c = \left(t_{i,KN,out}^h - T_{i,out}^h\right)W_i^h \quad (13)$$

$$q_j^h = \left(T_{j,out}^c - t_{i,1,out}^c\right)W_j^c \quad (14)$$

2.2.4 Inlet temperatures assignment

$$T_{i,in}^h = t_{i,1,in}^h = t_{i,j,k,in}^h \quad (15)$$

$$T_{i,in}^c = t_{j,KN,in}^c = t_{i,j,KN,in}^c \quad (16)$$

2.2.5 Minimum temperature difference constraints

$$t_{i,j,k,in}^h - t_{i,j,k,out}^c \geq EMAT \quad (17)$$

$$t_{i,j,k,out}^h - t_{i,j,k,in}^c \geq EMAT \quad (18)$$

Here, EMAT is minimum temperature approach of exchanger.

2.2.6 Feasibility of temperature constraints

$$T_{i,\mathrm{out}}^{\mathrm{h}} \leq t_{i,k,out}^{\mathrm{h}} \leq t_{i,k,in}^{\mathrm{h}} \leq T_{i,\mathrm{in}}^{\mathrm{h}} \quad (19)$$

$$T_{i,in}^c \leq t_{j,k,in}^c \leq t_{j,k,out}^c \leq T_{j,out}^c \quad (20)$$

2.2.7 Non-negative constraints

$$q_{i,j,k} \geq 0 \quad (21)$$

$$q_i^{\mathrm{c}} \geqslant 0 \quad (22)$$

$$q_j^{\mathrm{h}} \geqslant 0 \quad (23)$$

2.2.8 Mass balance of mixers

$$W_i = \sum_{j=1}^{NC} W^h{}_{i,j,k} \quad (24)$$

$$W_j = \sum_{i=1}^{NH} W^c{}_{i,j,k} \quad (25)$$

2.2.9 Energy balance of mixers

$$W_i t_{i,k,out} = W^h{}_{i,j,k} t^h{}_{i,j,k,out} + W^h{}_{i,j+1.k} t^h{}_{i,j+1,k,out} \quad (26)$$

$$W_j t_{j,k,out} = W^c{}_{i,j,k} t^c{}_{i,j,k,out} + W^c{}_{i+1,j,k} t^c{}_{i+1,j,k,out} \quad (27)$$

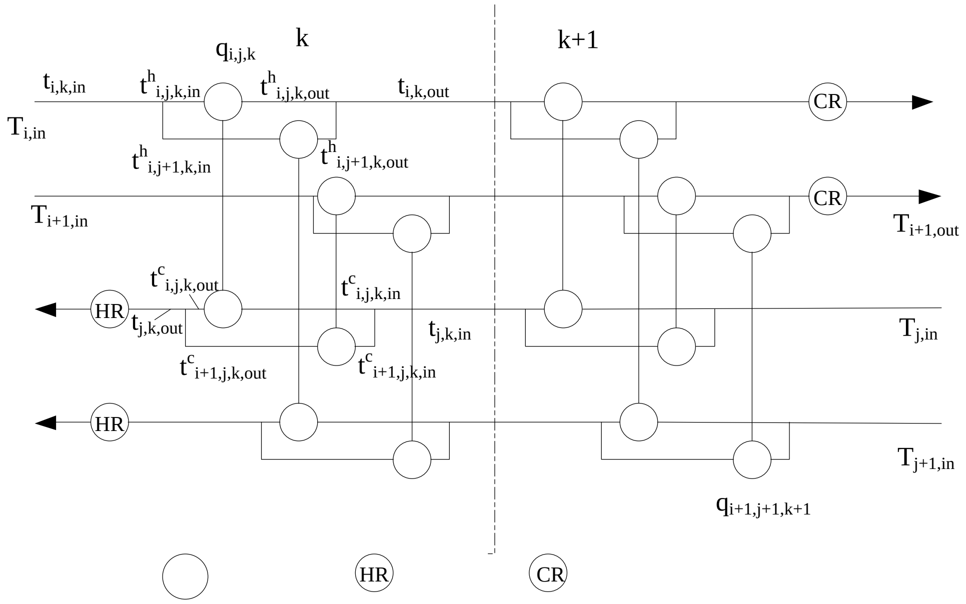

Figure 1. General HEN Superstructure with Splitting Stream

3. **THE PSO ALGORITHM**

The PSO algorithm is a newer member of the wide category of Intelligence methods for solving optimization problems. Its theory and application in optimization were first introduced by Kennedy and Eberhart (Eberhart,1995; Kennedy,1995). The PSO can be easily implemented and have inexpensive computational time, since its memory and CPU speed requirements are low. During the PSO algorithm, each particle represents a potential solution to an optimization problem, which can hold in the better position comparing with itself and has ability of finding other particles in particle swarm.

During the searching process, particles improve their velocity and positions according to the following two equations:

$$v_{\mathrm{id}}^{k+1} = wv_{id}^{k} + c_1 r_1 (p_{id} - x_{id}^{k}) + c_2 r_2 (p_{gd} - x_{id}^{k}) \quad (28)$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad (29)$$

Where, v_{id}^{k} represents the velocity of particle i with d-dimensions in the kth iterative stage. w is inertial weight; c_1, c_2 are constant values representing learning factors; r_1 and r_2 are two random values between the range [0,1]; x_{id}^{k} represents the current position of particle i; p_{id} is the personal best position of particle; p_{gd} is the best position of all particles found at present.

In this paper, each particle represents a determined HEN structure containing all the information such as transfer match, heat load, split ratios, transfer area, etc. In initial, the split number, split ratio and heat load are given arbitrary values to determine some initial structures, then through running PSO algorithm, the velocity of split ratio and heat load updates to rebuild more better solutions till to obtain optimum value. Fig. 2 gives a general procedure of HENS strategy based on PSO algorithm.

The detailed presentation of calculation is as follows:

Step1: Supplying data determination

To obtain a complete HEN structure, enough information has to be supplied definitely before the beginning. Each input fault or shortage will make the resulting HEN failure in saving energy and even influence production target. The input data needing is shown as follows: the input temperature and the outlet temperature of each process stream, including hot and cold utility; heat capacity flow rate of each process stream except utility; heat transfer coefficient; Cost of unit utility and cost model of exchangers.

Step 2: Particles initialization

(1) Select N≥1, T≥1, n≥1, KN≥1. where, N is the number of particles; T is the number of maximum iteration; n is the maximum number of potential split, which can be set to obtain completely different structure. For instance, when n is presumed to 1, the structure is a non-split case; when n is set to greater than 1, the structure contains split streams. n can be defined to different value between stages to obtain various structures; KN is the number of stages.

(2) Determine conventional factors of PSO algorithm. c1 and c2 are learning factors, which are usually spans between 1.0 and 2.0; w is inertial weight of particle velocity varying from 0.4 to 0.9 during iterative process.

(3) Initialize heat load of exchangers including heaters and coolers. Seeing as Fig. 1, we calculate heat load and temperature of heat exchangers from outlet end of cold streams (left end in the figure).This is achieved as follows:

(i) Initialization of heating load and calculation of outlet temperature for cold stream in stage 1.

$$qhu_j = rand()qhu_j \max \tag{30}$$

$$t^c_{j,1,out} = T^c_{j,out} - qhu_j / W^c_j \tag{31}$$

Where, qhu_jmax is upper bound of heater load, calculating in the equation as below.

$$\begin{aligned} & if\ \ T_{hu,in} - T_{j,out} \le EMAT \\ & qhu_j \max = 0 \\ & else \\ & qhu_j \max = W_j (T_{j,out} - T_{j,in}) \\ & end \end{aligned} \tag{32}$$

(ii) Initialization of heat capacity of process streams

$$W^h{}_{i,j,k} = rand()\left(W^h{}_i - \sum_{r=1}^{j-1} W^h{}_{i,r,k}\right); W^h{}_{i,j,k} = W^h{}_i - \sum_{r=1}^{j-1} W^h{}_{i,r,k} \tag{33}$$

$$W^c{}_{i,j,k} = rand()\left(W^c{}_j - \sum_{r=1}^{i-1} W^c{}_{r,j,k}\right); W^c{}_{i,j,k} = W^c{}_j - \sum_{r=1}^{i-1} W^c{}_{r,j,k} \tag{34}$$

Where, rand() represents a random value between 0 and 1.

(iii) Calculation of heat load and temperature for each exchanger.

$$\begin{aligned} & q_{ijk} = rand()q_{ijk} \max; \\ & th_{i,j,k,out} = th_{i,j,k,in} - q_{ijk} / Wh_{i,j,k}; \\ & tc_{i,j,k,in} = tc_{i,j,k,out} - q_{ijk} / Wc_{i,j,k} \end{aligned} \tag{35}$$

Where, q_{ijk}max is determined as follows.

$$\begin{aligned} & if\ \ t^h{}_{i,j,k,in} - t^c{}_{i,j,k,out} \le EMAT \\ & q_{ijk} \max = 0 \\ & elseif\ \ t^h{}_{i,j,k,in} - t^c{}_{i,j,k,out} > EMAT \ \ \&\ \ W^h{}_{i,j,k} \ge W^c{}_{i,j,k} \\ & q_{ijk} \max = \min\left(W^h{}_{i,j,k}\left(t^h{}_{i,j,k,in} - T_{i,out}\right), W^c{}_{i,j,k}\left(t^c{}_{i,j,k,out} - T_{j,in}\right)\right) \\ & elseif\ \ t^h{}_{i,j,k,in} - t^c{}_{i,j,k,out} > EMAT \ \ \&\ \ W^h{}_{i,j,k} < W^c{}_{i,j,k} \\ & q_{ijk} \max = \min\left(W^h{}_{i,j,k}\left(t^h{}_{i,j,k,in} - T_{i,out}\right), W^c{}_{i,j,k}\left(t^c{}_{i,j,k,out} - T_{j,in}\right), \frac{t^h{}_{i,j,k,in} - t^c{}_{i,j,k,out} - EMAT}{1/W^h{}_{i,j,k} - 1/W^c{}_{i,j,k}}\right) \\ & end \end{aligned} \tag{36}$$

Step 3: Evaluate fitness value of each particle.

Calculate annual cost of HEN as fitness value of particles using equation (1).

Step 4: Identify termination criterion and renovate particles with velocity and position

(1) Update heat capacity flow

$$wv^h_{n,i,j,k}(iter+1) = w(iter)wv^h_{n,i,j,k}(iter) + c_1 rand()(wb^h_{n,i,j,k} - w^h{}_{n,i,j,k}(iter)) + c_2 rand()(wg^h_{n,i,j,k} - w^h{}_{n,i,j,k}(iter)) \tag{37}$$

$$w^h{}_{n,i,j,k}(iter+1) = w^h{}_{n,i,j,k}(iter) + wv^h_{n,i,j,k}(iter+1) \tag{38}$$

$$wv^c_{n,i,j,k}(iter+1) = w(iter)wv^c_{n,i,j,k}(iter) + c_1 rand()(wb^c_{n,i,j,k} - w^c{}_{n,i,j,k}(iter)) + c_2 rand()(wg^c_{n,i,j,k} - w^c{}_{n,i,j,k}(iter)) \tag{39}$$

$$w^{c}_{n,i,j,k}(iter+1)=w^{c}_{n,i,j,k}(iter)+wv^{c}_{n,i,j,k}(iter+1) \quad (40)$$

(2) Update heat load of exchanger

$$qv^{n}_{i,j,k}(iter+1)=w(iter)qv^{n}_{i,j,k}(iter)+c_1 rand()\left(qb^{n}_{i,j,k}-q^{n}_{i,j,k}(iter)\right)+c_2 rand()\left(qg_{i,j,k}-q^{n}_{i,j,k}(iter)\right) \quad (41)$$

$$q^{n}_{i,j,k}(iter+1)=q^{n}_{i,j,k}(iter)+qv^{n}_{i,j,k}(iter+1) \quad (42)$$

During each renewal process, other parameters such as temperature of heat exchanger can be calculate by heat load and heat capacity flow as step 2.

Step 5: Export final optimum solution.

If termination criterion is not satisfied, then return to step 2 and continue to iterate. Otherwise, export final optimization results.

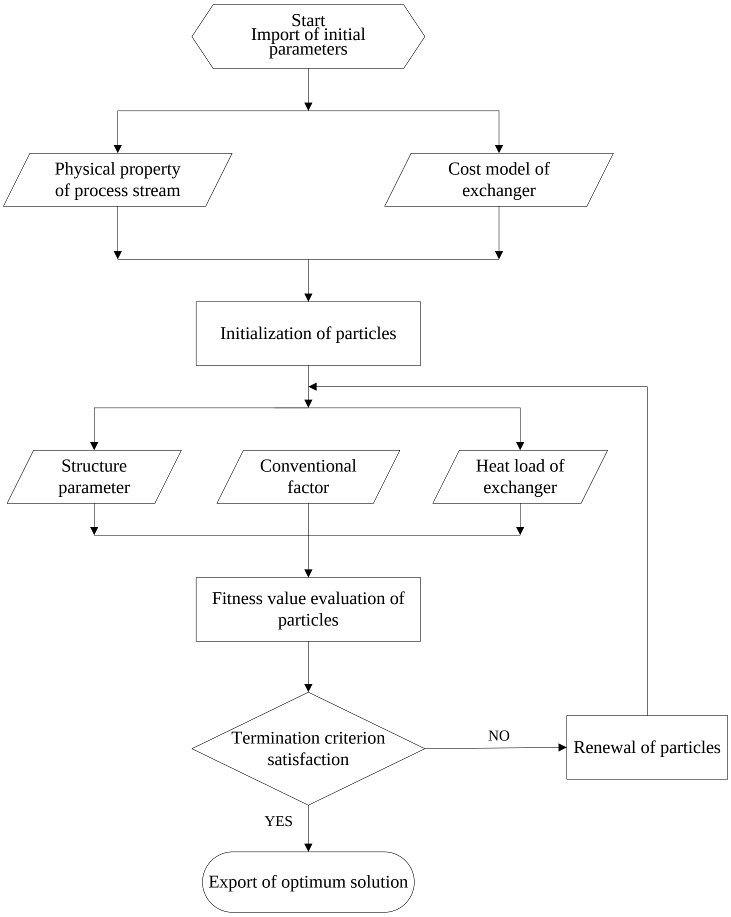

Figure 2. The Synthesis Procedure

4. EXAMPLES

In this section, three examples coming from different literatures have been studied adopting the synthesis technique proposed in section 2 and section 3, which reflect HENS problems with different scales and structures. The results obtained in the proposed approach are comparing with previous research to examine the method performance.

Example A: This example taken from Ravagnani et al. is a relative small-scale HENS problem , which involves two hot and two cold streams, a hot utility stream and a cold utility stream. The data of process streams and exchanger cost are presented in Table 1.

Table 1. Supplying Parameters of HENS for Example A

Stream	Inlet temp.(℃)	Outlet temp.(℃)	CP (kW/℃)	h (kW/m2·℃)

H1	175	45	10	2.615
H2	125	65	40	1.333
C1	20	155	20	0.917
C2	40	112	15	0.166
Steam	180	179	-	5.000
CW	15	25	-	2.500

Cost data:
Cost of hot utility: 110 \$/kWyr; Cost of cold utility: 10\$/kWyr
Exchanger cost model: cost(\$/yr)=1200area$^{0.57}$.

Ravagnani et al. applied mathematical programming method for synthesizing HEN based on pinch theory. GA is utilized to optimize the ΔTmin and obtain the optimal network considering stream splitting. In their work, Example A was studied to obtain a lower cost of HEN. In this work, based on simultaneous stage-wise MINLP model, the PSO algorithm is applied for HENS to provide a better solution. In this case study, the maximum number of stages is set to 2 and the population size is 100. By applying the MATLAB software and the proposed methodology, the optimal network configuration is obtained after 450 iteration times. As can be seen in Tab.2, the cost of the network for PSO is 116011, which is about \$1050 lower than the value obtained by Ravagnani et al. Fig.3 shows the final structure of HEN, where heat load of each exchanger and target temperatures of each exchanging match are marking out.

Table 2. Comparison with the Literature for Example A

Method	Frausto-Hernandez et al.	Ravagnani and Caballero	This paper
Hot utility(kW)	605	200	237.50
Cold utility(kW)	525	120.32	157.50
Total area(m^2)	423.26	706.45	729.37
Energy cost(\$/yr)	71800	23203.20	27700.29
Capital cost(\$/yr)	7553.75	93866.14	88311.66
Total annual cost(\$/yr)	147353.75	117069.34	116011.9

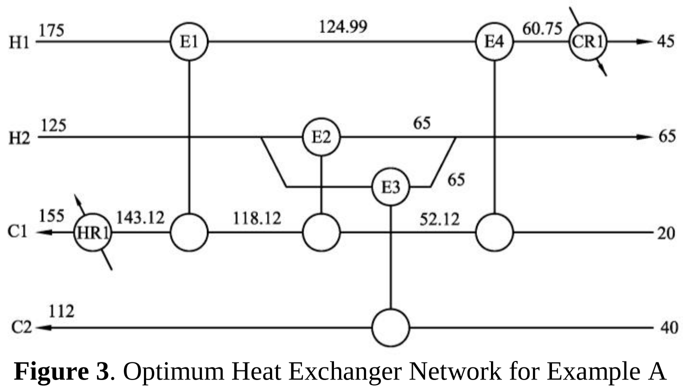

Figure 3. Optimum Heat Exchanger Network for Example A

Example B: This studied problem contains three hot streams and two cold streams, being selected from the paper written by Zhu . All stream and cost data are shown in Tab.3. For this case, the parameters of the PSO were the same as those of case 1. By applying the MATLAB software and the proposed methodology, the optimal network configuration obtained is presented in Fig.4. The value of the HEN global annual cost is 44562 \$/year. Table 3 shows the comparison with literature. Comparing with previous optimum, this work presents a wholly different structure, seeing Fig. 4 and Tab. 4, which has less utility consumption, less equipment areas and finally less total annual cost. Obviously, the proposed method is still applied successfully in this case.

Table 3. Supplying Parameters for HENS for Example B

Stream	Supply temp.(℃)	Target temp.(℃)	CP (kW/℃)	h (W/m^2·℃)

H1	159	77	2.285	100
H2	267	80	0.204	40
H3	343	90	0.538	500
C1	26	127	0.933	10
C2	118	265	1.961	500
steam	300	300		50
CW	20	60		200

Cost data.
Cost of hot utility: 110 $/kWyr; Cost of cold utility: 10$/kWyr.
Exchanger cost model: cost($)=3800+750 area$^{0.83}$.
Plant lifetime: 6 years; Interest rate: 10% per annum.

Table 4. Comparison with the Literature for Example B

Method	Zhu(1997)	This work
Hot utility(kW)	148.3	123.55
Cold utility(kW)	169.2	144.42
Total area(m^2)	242	238.18
Energy cost($/yr)	20095	17121.64
Capital cost($/yr)	26456	27440.44
Total annual cost($/yr)	46551	44562

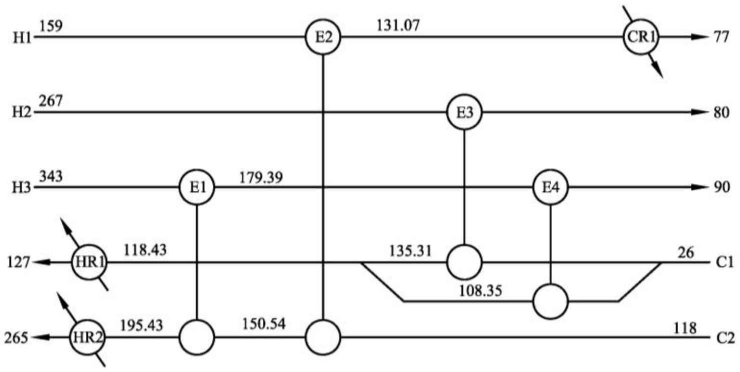

Figure 4. Optimum Heat Exchanger Network for Example B

Example C: The final example contains five hot streams and five cold streams needing match between each other, whose initial design parameters is included in Tab.5. This is a more complex case since it has large number of possible combination. This example is initially investigated by Flower and Linnhoff , where the minimum annual cost is 43934. Lewin applied a generalized method based on GA to the same example, in which the optimal value is 43799. In this paper, the simultaneous stage-wise MINLP model based on PSO is used for this example. Here, the maximum number of stages is set to 2 and the population size is 200. The optimal network configuration is obtained after 800 iteration times. According to the results obtained in this paper, the total annual cost for the obtained network is $43551, which is lower than that obtained by Lewin . The detail comparison between the results obtained from this paper and those obtained by other researchers is presented in Tab. 6. The new structure of Example C is illustrated by Fig.6

Table 5. Supplying Parameters for HENS Example C

Stream	Supply temp.(K)	Target temp.(K)	CP (kW/K)
H1	433	366	8.79
H2	522	411	10.55
H3	544	422	12.56
H4	500	339*	14.77
H5	472	339	17.73

C1	355	450	17.28
C2	366	478	13.90
C3	311	494	8.44
C4	333	433	7.62
C5	389	495	6.08
steam	603	523	-
CW	288	303	-

Cost data.
Cost of hot utility: 37.64 \$/kWyr; Cost of cold utility: 18.12\$/kWyr.
Exchanger cost model: cost(\$)=145.63area$^{0.6.}$
Heat transfer efficient for all matches except those involving steam: U=0.852 kW/m^{2}K
Heat transfer efficient for all matches involving steam: U=1.136 kW/m^{2}K

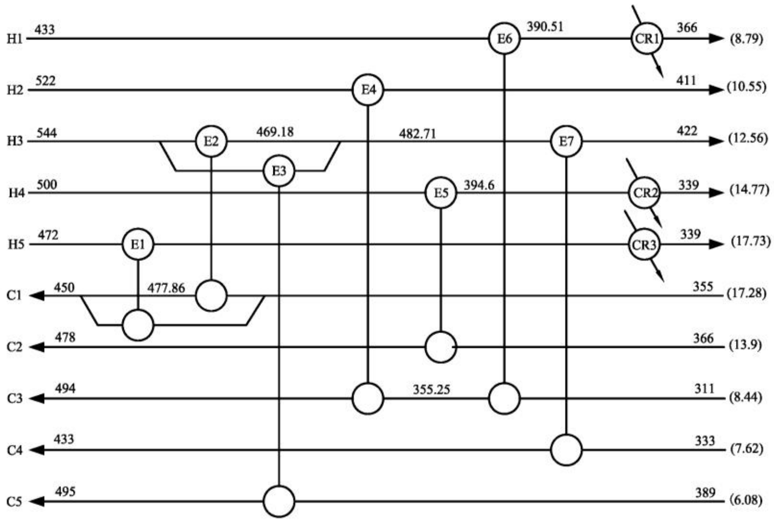

Figure 5. Optimum Heat Exchanger Network for Example C

Table 6. Comparison with the Literature for Example C

	Flower and Linnhoff	Lewin	This work
Hot utility(kW)	0	0	0
Cold utility(kW)	1975	1879	1878.96
Energy cost(\$/yr)	35787	34046.94	34046.76
Capital cost(\$/yr)	8147	9732.06	9504.47
Total annual cost(\$/yr)	43934	43779	43551.22

5. CONCLUSION

The optimization strategy based on PSO algorithm considering both stream splitting and non-isothermal mixing is proposed in this work. Four multiform problems are studied here to prove the availability of the proposed method. All of them obtained HENs having lower or nearly the same costs than values of previous literature. During our research, the PSO algorithm was found to much suitable for solution of MINLP model representing HENS, which exhibits even more advantageous than other intelligent algorithms such as GA and SA presented before. The method is very simple to implement on a computer. We believe that the proposed method can be further developed for more complex HENS problems considering removing assumptions such as varied heat-transfer coefficient, multi-utility assignment, flexibility and controllability.

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Nomenclature

Indices

i hot process stream
j cold process stream
k stage
n particle

Sets

HN number of hot process stream
CN number of cold process stream
KN number of stage in the superstructure

Parameters

H exponent for area cost, dimensionless
C_{ij}^{ef} fixed charge for heat exchanger, \$/unit
C_{i}^{cf} fixed charge for cooler, \$/unit
C_{j}^{hf} fixed charge for heater, \$/unit

C_{ij}^{ea} area cost coefficient for heat exchanger, \$/unit
C_i^{ca} area cost coefficient for cooler, \$/unit
C_j^{ha} area cost coefficient for heater, \$/unit
C_i^{cu} per unit cost for cold utility, \$/unit
C_j^{hu} per unit cost for hot utility, \$/unit
K overall heat transfer coefficient, kW/m^2K
$T_{i,in}$ inlet temperature of hot stream, K
$T_{i,out}$ outlet temperature of hot stream, K
$T_{j,in}$ inlet temperature of cold stream, K
$T_{j,out}$ outlet temperature of cold stream, K
Min_{cost} minimum total annual cost
W^h_i heat capacity flow rate of hot stream i, kW/K
W^c_j heat capacity flow rate of cold stream j, kW/K
w inertia weight
c_1 and c_2 constants
iter iteration times

Variables

A_{ijk}^e area for match of hot stream i and cold stream j in stage k, m^2
A_i^c area for match of hot stream i and cold utility, m^2
A_j^h area for match of cold stream j and hot utility, m^2
q_i^c heat exchanged between hot stream i and cold utility, kW
q_j^h heat exchanged between cold stream j and hot utility, kW
q_{ijk} heat exchanged between hot stream i and cold stream j, kW
$t^c_{j,k,in}$ inlet temperature of cold stream j in stage k before splitting
$t^c_{j,k,out}$ outlet temperature of cold stream j in stage k after mixing
$t^h_{i,k,in}$ inlet temperature of hot stream i in stage k before splitting
$t^h_{i,k,out}$ outlet temperature of hot stream i in stage k after mixing
$t^h_{i,j,k,in}$ inlet temperature of hot stream i matching with cold stream j in stage k
$t^h_{i,j,k,out}$ outlet temperature of hot stream i matching with cold stream j in stage k
$t^c_{i,j,k,in}$ inlet temperature of cold stream j matching with hot stream i in stage k
$t^c_{i,j,k,out}$ outlet temperature of cold stream j matching with hot stream i in stage k
$W^h_{i,j,k}$ heat capacity flow rate of hot stream i matching with cold stream j in stage k, kW/K
$W^c_{i,j,k}$ heat capacity flow rate of cold stream j matching with hot stream i in stage k, kW/K

Binary variables

B_{ijk}^e binary variable to represent existence of match between i and j in stage k, dimensionless
B_i^c binary variable to existence of cold utility match for hot stream i, dimensionless
B_j^h binary variable to existence of hot utility match for cold stream j, dimensionless