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Heat Exchanger Network Retrofit Using Particle Swarm Optimisation Algorithm

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Heat exchanger network (HEN) retrofit is an effective way to reduce energy consumption and improve energy efficiency. A key criterion in industrial practice to evaluate the performance of a retrofit plan is the minimising total annualised cost. However, when pursuing the goal of minimising total annualised cost by graphical tools, sub-optimal solutions are inevitable because of the difficulty in finding the balance of utility cost and investment. In this study, a method based on constrained particle swarm optimisation (PSO) algorithm is developed for the annual cost minimisation when retrofitting HENs. The proposed method is applied based on an initial retrofit plan obtained by graphical tools. It can achieve the aim of total annualised cost reduction by adjusting the inlet and outlet temperatures of each heat exchanger through PSO with the consideration of different utility prices and investment. The results show that this method can find optimal temperature spans for heat exchangers to reduce the total annualised cost.

1. Introduction

Heat exchanger network (HEN) retrofit is an essential task in the heat integration to achieve the goal of heat recovery and to increase energy efficiency. Many methods were proposed and applied in HEN retrofit. The detailed list can be found in the works of Klemeš et al. (2020) which reviewed the history and the recent developments in the areas of Heat Transfer Enhancement and the retrofit of HENs, and Wang et al. (2020a) which reviewed the features of various types of heat exchangers and the state-of-the-art of the current methods for HEN synthesis and retrofit.
Pinch Analysis, for more comprehensive information, see, e.g. (Klemeš, 2013) is mainly operated through graphical and numerical tools to target the maximum energy recovery plan for HEN synthesis and retrofit. The Pinch Analysis-based methods such as Stream Temperature vs Enthalpy Plot (STEP) (Wan Alwi and Manan, 2010), Energy Transfer Diagram (ETD) (Bonhivers et al., 2014), and extended Advanced Grid Diagram (AGD) (Wang et al., 2020b) have the advantages that the results are based on the thermodynamic insights, and they can provide the thermodynamic global optimum (Klemeš et al., 2018). The Pinch Analysis has a strong ability to target minimum energy consumption. However, when considering the network topology and its related investment cost in the retrofit application, some follow-up methods should be developed to find a trade-off between utility saving and capital cost. These topology modifications include where to place the new/additional heat transfer area and how large it should be. The results obtained by Pinch Analysis in the first step are a substantial base to be further developed and modified to achieve a lower total annualised cost or a higher synthesis/retrofit profit.
To further optimise the results obtained from Pinch Analysis-based methods, Particle Swarm Optimisation (PSO) can be used. PSO is inspired by nature, and it has a strong ability to search for the optimal results in

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continuous problems. It also has the advantage of avoiding trapping into local optimum (Eberhart and Kennedy, 1995).

In the HEN retrofit problem, temperatures of heat exchangers are continuous variables, while PSO is suitable for this type of continuous domain optimisation problem. For the HEN retrofit application, Silva et al. (2009) developed a PSO-based methodology for HEN cost minimisation. The heat transfer area and utility cost were considered. For the synthesis application, Silva et al. (2010) minimised the total annualised cost, which includes the investment of heat exchangers, and the energy cost for utilities and pumping duties by the PSO method. Pavão et al. (2017) developed a method that combined two algorithms, simulated annealing (SA) and the PSO. Continuous heat load variables were optimised by the PSO method based on the results of topology optimisation done by SA. Zhang et al. (2016) divided the problem of synthesis for large-scale HEN into two parts, the first part grouped the process streams to form sub-networks, and the second part optimised the sub-networks. The sub-network was optimised by a Powell PSO method.

In the current work, to reduce the total annualised cost obtained by the Pinch Analysis-based graphical method, a method based on the PSO algorithm is developed to consider both utility cost and investment cost when retrofitting HENs. The proposed method is applied based on an initial retrofit plan obtained by graphical tools. It can achieve the aim of total annualised cost reduction by adjusting the inlet and outlet temperatures of each heat exchanger through PSO with the consideration of different utility prices and investment. The method is demonstrated through a case study.

The contributions of this research are as follows:

- A constrained PSO algorithm is developed to minimise the total annualised cost by optimising the temperatures of heat exchangers according to the structure solved by graphical tools.
- The developed method considers the trade-off between the utility cost and the new heat exchanger investment cost.
- A case is optimised to show the effectiveness of the proposed algorithm. The original retrofit results obtained by the graphical method and the improved results obtained by the proposed method are compared.

The remaining sections of the paper are organised as follows. A constrained PSO algorithm to optimise the total annualised cost of the retrofit application of HEN is introduced in Section 2. In Section 3, a case is optimised to verify the method proposed in this study, and the results are compared with the original solution obtained by the graphical method to show how the method introduced in this study can improve the solution of graphical tools. Section 4 summarises the conclusions.

2. Method developed

In this study, it is assumed the topology is obtained by the graphical tools in advance, while the inlet and outlet temperatures of heat exchangers can still be optimised to achieve the minimised total annualised cost by finding a trade-off between capital cost and utility saving. As these temperatures are continuous variables, the improved PSO algorithm which can solve the optimisation problem with constraints is proposed. The PSO algorithm has the advantage of optimising variables in real numbers and finding the global optimum of the studied problem.

In the standard PSO algorithm, a group of particles is randomly generated to form a swarm, and each particle can be regarded as a solution to the problem that should be solved. In the iterations, each particle is updated according to its position and velocity. In every step, the fitness function should be evaluated to determine the global best position. The velocity is generated according to the best position of each particle and the global best position of the entire swarm.

There are several PSO variants developed to improve the application and performance of the original one. For the constrained optimisation problem, the fly-back method introduced by He et al. (2004) was widely used to improve the performance of standard PSO. If a particle violates any of the boundaries of the problem, it turns back into its previous best position.

In this study, it is assumed that the optimisation is based on the fixed HEN structure solved by other graphical tools, then further optimisation of the outlet and inlet temperatures of each heat exchanger is done by the PSO to find the minimised total annualised cost. The variables in this problem are the outlet temperatures of heat exchangers on hot streams. The detailed steps are explained as follows.

Step 1 Initialisation

As the results of graphical methods should be used in the proposed constrained PSO algorithm, the information of the first particle in the initialisation is obtained from the retrofit results of the graphical tool. The inherited information includes the number of heat exchangers, and the temperatures of modified and new heat exchangers.

Other particles are generated to form the whole swarm. But the number of heat exchangers are fixed, only the temperatures are randomly generated.
According to Marini and Walczak (2015), when the number of particles is more than 50, the PSO is not sensitive to the size of the population. In this case, 50 particles are used to form the first generation of a swarm.
For heat exchangers connecting hot streams, their lowest temperatures should be higher than the target temperatures of connected hot streams, and their highest temperatures have to be lower than supply temperatures. For the heat exchanger which is adjacent to a heat exchanger whose temperature cannot be changed, then the temperature of the first heat exchanger on the adjacent side remains unchanged. It is also set as a constraint. The upper bound of each heat exchanger, which has the highest temperature on each stream is dependent on the supply temperature of the hot stream. For the rest of heat exchangers, the upper bounds are the temperatures of their upstream heat exchangers. The temperatures of heat exchangers on the cold streams are also constrained. The inlet temperatures of heat exchangers on cold streams cannot be higher than the outlet shifted temperatures of heat exchangers on hot streams, and the outlet temperatures of heat exchangers on cold streams cannot be higher than the inlet shifted temperatures of heat exchangers on hot streams.
Step 2 Evaluate fitness
The evolution of particles aims to achieve the best fitness of the objective function. In this study, the objective function Eq(1) is set as the total annualised cost, which combines annual cost on utilities and annualised capital cost. The first and second items are the hot utility cost and cold utility cost, and the third item represents the annualised capital cost.

$$f = \sum_{i \in I} QU_i^C \times C_i^C + \sum_{i' \in I'} QU_{i'}^H \times C_{i'}^H + \alpha \sum_{k \in K} INV_k \quad (1)$$

QU_i^C represents the heat load of the hot utility on cold stream i, kW; C_i^C represents the unit utility price for the cold stream, USD/kW; $QU_{i'}^H$ represents the heat load of the cold utility on hot stream i', kW; $C_{i'}^H$ represents the unit utility price for hot stream i', USD/kW; α is the annualisation factor which uses to transfer the total investment to the annualised investment cost, INV_k is the total investment of new heat exchanger k, USD.
Step 3 Update velocity and position
Velocity and position of particles are vital values that are used to find the optimal solution in the PSO algorithm. The velocity and position are updated, according to Eq(2) and Eq(3).

$$v_{p,d}(t+1) = \omega v_{p,d}(t) + c_1 r_1 (b_{p,d}(t) - x_{p,d}(t)) + c_2 r_2 (g_d(t) - x_{p,d}(t)) \quad (2)$$

$$x_{p,d}(t+1) = x_{p,d}(t) + v_{p,d}(t+1) \quad (3)$$

Subscript p represents the particle, d represents the dimension, and t represents the number of iterations. v is the velocity, and x is the position. b records the individual historical best position, and g records the global historical best position of all particles. In this study, 1 is set as the value of inertia weight ω. Two uniformly generated random numbers r_1 and r_2 are in the range [0, 1].
In Eq(2), c_1 and c_2 are acceleration constants. They are both set as 2 in this study as the number works well for most of the applications (Kennedy and Eberhart, 1995).
When the position and velocity of each particle are updated in the iteration, the retrofit plan dedicated by that particle would be checked to ensure feasibility. As this is a constrained problem, when a particle violates the constraints of the problem, it would return to its previous best position.
There are two termination criteria set for this method. The optimal solution remains unchanged in 30 iterations, or the maximum iteration step is reached. When either of the termination criteria is satisfied, the iteration steps would stop, and the optimised results can be obtained.

3. Case study

In this case study, the retrofit solution obtained from Lai et al. (2019) was used to test the method. It has four heat exchangers after retrofitted by the graphical method in the work of Lai et al. (2019). The hot utility for the current HEN is 355.24 kW, and the cold utility is 60.64 kW. The grid diagram of the HEN is shown in Figure 1. The data of streams are shown in Table 1.
The unit cost of several types of utilities can be found in Table 2. For this case, the same annualisation factor of 0.1175 is applied (interest rate = 10 %, plant lifetime = 20 y).
The capital cost of new heat exchangers can be calculated by Eq(4) (Lai et al., 2019).

$$\text{New heat exchanger capital cost (USD)} = 29{,}073 + 727A^{0.81} \tag{4}$$

where A represents the heat transfer area of the new heat exchanger, m^2.
Then the constrained PSO algorithm is applied to this HEN structure to search for the minimum total annualised cost.

Table 1: Stream Data of the HEN

Stream	T_S (°C)	T_T (°C)	*h* (kW/m^2·°C)	*CP* (kW/°C)
1	20	50	0.85	3.72
2	50	70	0.85	3.9
3	20	70	0.72	0.08
4	70	100	0.72	4.02
5	20	90	0.72	0.84
6	75	90	0.85	4.04
7	100	100.01	0.7	2400
8	85	90	0.7	4.04
9	85	250	0.7	5
10	250	60	0.8	4.54
11	60	20	0.85	3.64

Note: T_S represents the supply temperature, (°C); T_T represents the target temperature, (°C); *CP* represents the heat capacity, (kW/°C); and h represents the heat transfer coefficient, (kW/m^2·°C).

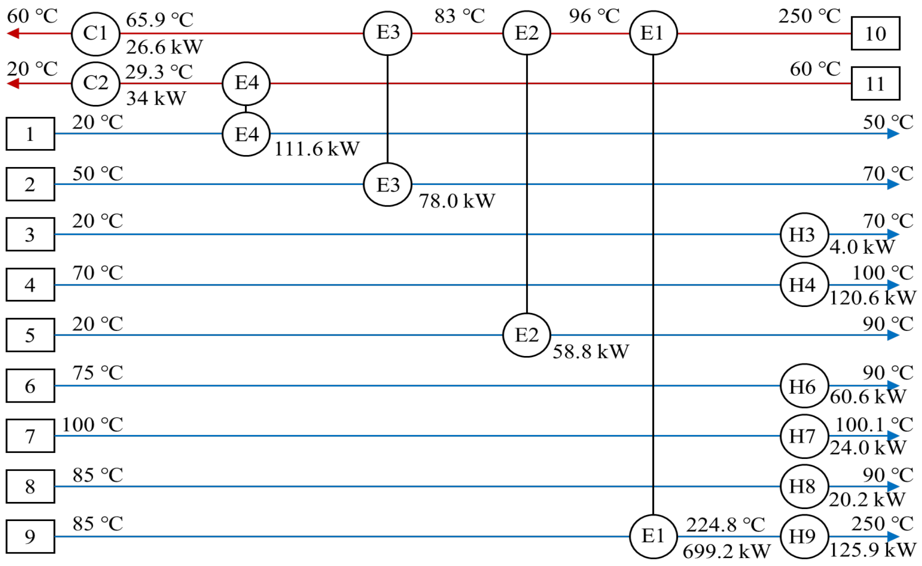

Figure 1: Grid Diagram of the HEN retrofitted by the graphical method proposed by Lai et al. (2019)

Table 2: Unit cost of multiple utilities (Shethna et al., 2000)

Utility	T_S (°C)	T_T (°C)	Unit cost, *C* (USD/kW.y)
Steam 9 bar	175	174	125
Steam 2.3 bar	125	124	25
Steam 1.5 bar	111	110	20
Flue gas	800	280	105
Cooling water	10	40	16

The grid diagram of the HEN after retrofitting using constrained PSO is shown in Figure 2. When comparing Figure 1 and Figure 2, it can be found that the number of heat exchangers is not changed, but the inlet and outlet temperatures are different from these two solutions. More heat is recovered from stream 10 and transferred to stream 9, which decreases both hot and cold utilities. The duty of heat exchanger 3 remains unchanged, as it can recover a maximum of 78 kW due to the heat requirement of stream 2.

The results of the two HENs are shown in Table 3. For the HEN solved by the PSO algorithm, it has a lower total annualised cost, a reduction of 2.4 % compared with the original retrofit plan obtained by the graphical method. This is achieved by reducing the annualised utility cost of the previous results obtained in Solution 1. Although the annualised capital cost increases, it is still profitable to increase the heat transfer area.
Besides, the results in this study are compared with the results obtained by Wang et al. (2020c) who optimised the retrofit plan by a Shifted Retrofit Thermodynamic Grid Diagram (SRTGD)-Based mathematical programming model. Three new heat exchangers are used in their results. Although the annualised utility cost increases, a lower total annualised cost can be found due to the significant reduction of investment cost. This illustrates that the HEN structure has a strong influence on the total annualised cost.

Table 3: Comparison of the results

Case	Solution 1 (Lai et al., 2019)	Solution 2 (PSO)	Solution 3 (Wang et al., 2020c)
Hot utilitiy (kW)	355.2	337.5	440.2
Cold utility (kW)	60.6	42.9	145.6
Reduced hot utility	63.26%	65.09%	54.47%
Reduced cold utility	90.98%	93.62%	78.34%
Annualised utility cost (USD/y)	18,772	16,058	19,900
Utility saving (USD/y)	52,884	55,598	51,756
Additional units	4	4	3
Additional heat transfer area (m^2)	156	220	173
Investment cost (USD)	168,650	183,675	137,679
Annualised capital cost (USD/y)	19,816	21,582	16,177
Total annualised cost (USD/y)	38,582	37,640	36,078

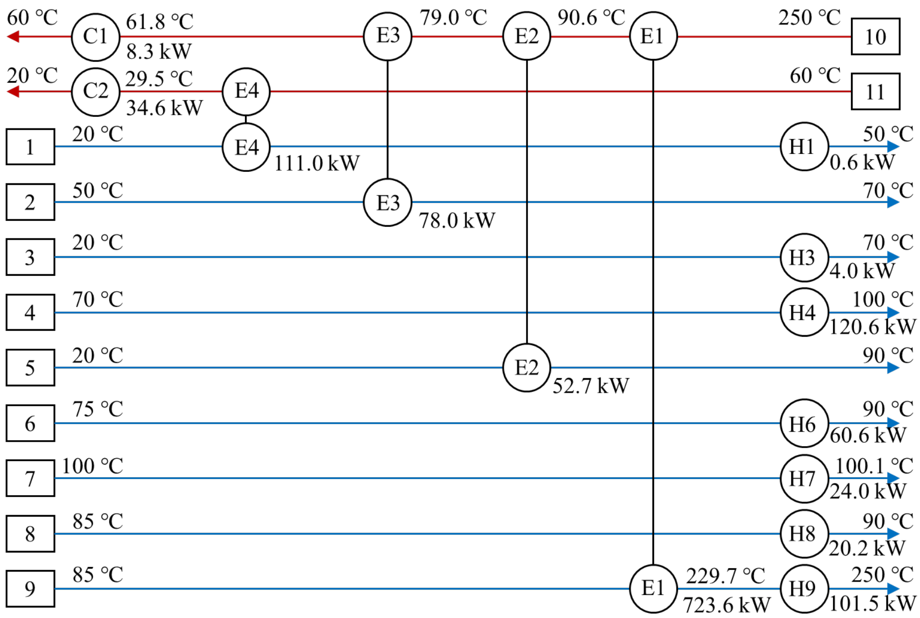

Figure 2: Grid diagram of the HEN after retrofitting using constrained PSO

4. Conclusions

The proposed PSO algorithm for minimising the total annualised cost in the HEN retrofit design was studied through a case study in this paper. The algorithm optimises the heat exchanger temperatures considering different utility prices and investment cost.
Although the graphical tools have a strong ability to target minimum energy consumption, they could also be trapped in the local optimum, and the investment cost is difficult to be considered. To solve this issue, a constrained PSO algorithm is proposed as an effective tool to find a better retrofit plan based on the HEN structure obtained from graphical tools. The unit utility cost and the investment cost can be considered. It is

helpful for designers to find a cost-minimised HEN retrofit plan. This method can work as a supplementary tool to support the decision making after the initial retrofit plan is solved by other graphical tools or made according to the experience of engineers. The proposed method is applied to a case study to verify its effectiveness. The solutions show that the total annualised cost solved by the proposed method is less than the original solution obtained by the graphical method. The total annualised cost of the proposed method decreases by 2.4 %.
Future research should focus on other factors that would affect the investment cost, such as the heat exchanger types and material types. A systematic method should be developed for utility cost and investment cost minimisation.

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