COMPARISON OF NONTRADITIONAL OPTIMIZATION TECHNIQUES IN OPTIMIZATION OF SHELL AND TUBE HEAT EXCHANGER

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ABSTRACT

Heat exchangers, which are the systems that allow heat transfer between two or more uids, are widely used in industry, and they are an indispensable part of chemical processes. Thus, a considerable amount of research has been conducted in the optimization of these systems, especially regarding cost optimization. There are two main parameters affecting the cost of a heat exchanger. One is the surface area of the exchanger, which mainly affects the capital investment cost. The other one is the pressure drop, which mainly affects the operating cost. These parameters are interlinked; however, since the change in the surface area may result in a change in the pressure drop and vice versa due to the physical laws. In the case which is analyzed in this study, there are four main variables for the heat exchanger, which will be adjusted in order to obtain the optimum values for surface area and pressure drop: the number of tube side passages, shell inside diameter, bafes spacing, and tube outside diameter. In this study, we compare the success of the nontraditional optimization techniques such as generic algorithms, particle swarm optimization, articial bee colony, and biography-based optimization for a shell and tube heat exchanger. In the considered three processes in which these optimization methods are utilized, we see that biography-based optimization has given the minimum cost for each process.

***K*eywords** Optimization · Heat Exchanger · Cost Minimization

1 Introduction

A heat exchanger is a system that is used to transfer heat between two or more fluids. They are utilized in almost all production lines, since temperature control is critical in most chemical or physical processes. Heat exchangers can be designed to tolerate wide range of pressure and temperature; thus, they are widely used in industry [1]. There are several kinds of heat exchangers,

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and one of the most used ones is shell and tube heat exchanger [2]. The schematic representation of shell and tube heat exchangers is given in Figure 1.

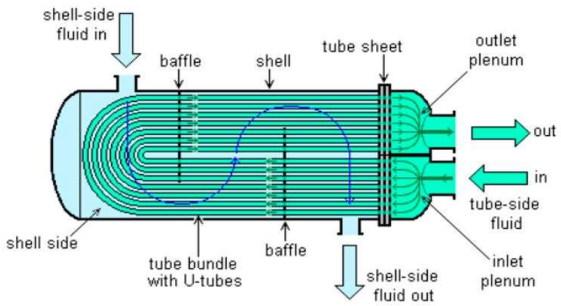

Figure 1: Schematic representation of shell and tube heat exchanger [3].

These exchangers allow indirect contact between two fluids, and thus heat transfer between the fluids takes place. In shell and tube heat exchangers, baffles are used in order to increase the turbulence and contact time to increase the heat transfer as much as possible.

Optimization of shell and tube heat exchangers is of great importance since slight changes in the temperature of process fluids may substantively affect other chemical and physical properties of the materials that are produced in a process. Different options for the optimization of shell and tube heat exchangers exist where gradient descent etc. are utilized. The traditional design methods for shell and tube heat exchangers includes evaluation of a large number of different heat exchanger geometries to identify those that meet a particular heat duty and a range of geometric and operational constraints. Since the optimization problem highly interconnected and nonlinear, obtainment of the optimum parameters has proven to be challenging.

In this study we will be focusing on cost optimization shell and tube heat exchangers. The optimum heat exchanger parameters which are obtained by different optimization algorithms will be examined for three different scenarios. In terms of helping engineers and producers in determining which optimization method should be used to yield the minimum cost for the production of a shell and tube heat exchanger, the presented study is remarkable.

2 Nontraditional Optimization Algorithms

There have been several heat exchanger designs proposed as a result of different kind of optimization methods. These methods include generic algorithm (GA), particle swarm optimization (PSO), artificial bee colony algorithm (ABC) and biography-based optimization (BBO). The first design for three different cases was conducted by Sinnot R.K. [10], in 2005, which will be referred as “Original Study” from now on. Then, in 2008, Caputo A.C. et. al. [11] used GA and obtained lower cost than before. Later, Patel V.K. et. al. [12] used PSO in 2010 and Şahin A.Ş. et. al. [4] used ABC algorithm in 2011 to further improve the design parameters and obtained better results. And then BBO is used in 2013 by Hadidi A. [9] and the cost is slightly more minimized by this algorithm.

2.1 Generic Algorithm

GA is an evolution inspired optimization procedure in a binary search space, where a set of solutions called population are evaluated rather than a single solution like in traditional hill climbers [14]. The most interesting advantages of GA when compared to the conventional optimization algorithms are parallelism, simple programmability, robustness regarding the input data and its large and wide solution space search ability [15].

2.2 Particle Swarm Optimization

PSO was developed in 1995 by Kennedy and Eberhart, inspired by behavior of social organisms such as ants and fish in a group [15]. This procedure emulates the interaction of each individual in a social group to share information. The optimal solution is obtained by evaluating these individual solutions, referred as particles, whose trajectories are adjusted accordingly. In each iteration, the particles adjust their velocity according to the "best particle" in the group [16].

2.3 Artificial Bee Colony Algorithm

ABC is a type of swarm intelligence method where, the behavior of honeybees is emulated. It combines local search methods, carried out by employed and onlooker bees, with global search methods, managed by onlookers and scouts, attempting to balance exploration and exploitation process. [4, 17]

2.4 Biography Based Optimization

BBO is based on biography theory, where the geographical distribution of biological species is investigated. It is developed through simulation of emigrations, immigrations, evolutions and extinctions of species between habitats which are in the multi-dimensional solution space [18].

3 Calculation of the Surface Area

The main variable determining the capital cost of heat exchanger is the surface area of the heat exchanger. This variable can be obtained in the following manner. The subindices in the equations s and t represent belonging to the shell and tube side fluid respectively.

The necessary energy rate to change the temperature of a flowing fluid is represented as in Equation 1.

$$q = \dot{m} c_p \Delta T \tag{1}$$

In order to provide this energy, a fluid can be contacted with another fluid in a heat exchanger. The surface area of this connection is calculated as in Equation 2.

$$S = q/(FU\Delta T_{LM}) \tag{2}$$

where,

$$U = 1/(1/h_s + R_{fs} + d_o/d_i(R_{fs} + 1/h_t)) \tag{3}$$

To evaluate U, the overall heat transfer coefficient, heat transfer coefficients should be evaluated by experimental correlations of Reynolds and Prandtl numbers. One such correlation for tube side is given in Equation 4 [4, 5, 6].

$$Nu = (h_t d_i)/k = 0.023 Re_t^{0.8} Pr_t^{0.4} \tag{4}$$

Thus, the tube side heat transfer coefficient can be written as in Equation 5 [4, 5, 6].

$$h_t = (kNu)/d_i \tag{5}$$

A similar correlation for the shell side heat transfer coefficient is given as in Equation 6 [4, 5, 6].

$$Nu = (\mu_t/\mu_w)^{0.14} 36 Re_s^{0.55} Pr_s^{0.4} \tag{6}$$

And, the shell side heat transfer coefficient can be determined as in Equation 7.

$$h_s = (kNu)/D_e \tag{7}$$

here, the equivalent diameter represents the diameter of the crossectional area which the fluid flows. For square tube pitch with two tube side passages, equivalent shell diameter can be obtained by the Equation 8. For triangular tube pitch with four tube side passages, equivalent shell diameter can be obtained by the Equation 9.

$$D_e = 4(Pt^2 - \pi d_o/4)/(\pi d_o) \tag{8}$$

$$D_e = 8((0.43Pt^2 - \pi d_o/2))/(\pi d_o) \tag{9}$$

To be used in the calculation of Reynolds number, which is defined as in Equation 10, and to be used in the calculations of heat transfer coefficients above, the velocities of shell and tube side fluids are given as in Equations 11 and 12, respectively.

$$Re = (vd)/\nu \tag{10}$$

$$v_t = n/N_t\dot{(m)}_t/((\pi d_o)/4\rho_t) \tag{11}$$

$$v_s = \dot{m}_s/(a_s\rho_s) \tag{12}$$

where the shell side crossectional area clearance is given in Equation 13.

$$a_s = (D_s B(Pt - d_o))/Pt \tag{13}$$

Also, the Prandtl number is defined from the properties of the fluids as in Equation 14.

$$Pr = (c_p\mu)/k \tag{14}$$

Thus, by using Equations 1 - 14, overall heat transfer coefficient (U) can be computed to be used in the determination of heat transfer surface area. The surface area is one of the two main parameters which will be considered in the cost optimization. From the equations, the number of tubes and the necessary tube length can also be obtained by the Equations 15 and 16, respectively. The length of the tube, among with velocities of shell and tube side fluids interling the surface area and pressure drop, resulting the highly nonlinear system of equations for the cost optimization.

$$N_t = K_1(D_s/d_o)^{n_1} \tag{15}$$

$$L = S/(\pi d_o N_t) \tag{16}$$

4 Calculation of the Pressure Drop

While the capital investment is a function of the surface area, operating cost of the heat exchanger is a function of pressure drop. The surface area and the pressure drop are interlinked, however, since the parameters which affect the surface area also affects the pressure drop of the fluids.

The pressure drop for the tube side can be calculated as in Equation 17 [4, 5, 6].

$$\Delta P_t = \Delta P_{tube_elbow} + \Delta P_{tube_length} = (1/2)\rho_t v_t^2 (L/d_i f_t + p)n \tag{17}$$

where, for the tube side, the friction factor is as in Equation 18.

$$f_t = (1.82 log_{10}(Re_t) - 1.64)^2 \tag{18}$$

The pressure drop for the shell side can be calculated as in Equation 19 [4, 5, 6]..

$$\Delta P_s = (1/2)\rho_t v_s^2 f_s L D_s/(D_e B) \tag{19}$$

where, for the shell side, the friction factor is as in Equation 20 [9].

$$f_s = 2b_0 Re_s^{-0.15} \tag{20}$$

here, b_0=0.72 is valid for Re<40000 [9].

5 Cost Optimization of Heat Exchangers

The objective function for the optimization problem is the total cost of the heat exchanger, consisting of the summation of the capital investment Ci and discounted operating cost CoD. This total cost is given Equation 21 [4, 7].

$$C_{total} = C_i + C_{oD} \tag{21}$$

here, the capital investment can be obtained from the Hall's correlation as a function of surface only as in Equation 22 [7].

$$C_i = a_1 + a_2 S^{a_3} \tag{22}$$

where, for heat exchangers made of stainless steel for both tubes and shells, a_1=8000, a_2=259.2 and a_3=0.91.

The operating cost is related to the pumping power to overcome the pressure drops resulted from friction losses. This can be computed as in Equation 23 [7].

$$C_o = PC_E H \tag{23}$$

where, P is the energy needed to overcome the total pressure drop (given in Equation 24), C_E is the cost of electricity and H is the yearly operation duration.

$$P = 1/\mu((\dot{m}_t/\rho_t)\Delta P_t + (\dot{m}_s/\rho_s)\Delta P_s) \tag{24}$$

Thus, the discounted operating cost at the beggining of the production of heat exchanger is obtained as in Equation 25.

$$C_{oD} = \sum_{k=1}^{n_y} (C_o/(1+i)^k) \tag{25}$$

6 Cost Optimization Problem

In this study, optimization of heat exchangers for three different processes is investigated. The design parameters for the processes are explained in the Table 1. The parameters can be considered as fixed optimization constraints or fixed parameters.

Table 1: Design parameters for different processes [11].

Processes	ṁ(kg/s)	T_i (°C)	T_o (°C)	ρ (kg/m^3)	c_p (kj/kg K)	μ (Pa s)	k (W/m K)	R_f (m^2 K/W)
Process 1								
Shellside: Methanol	27.8	95	40	750	2.84	0.00034	0.19	0.00033
Tubeside: Sea Water	68.9	25	40	995	4.2	0.00080	0.59	0.00020
Process 2								
Shellside: Kerosene	5.52	199	93.3	850	2.47	0.00040	0.13	0.00061
Tubeside: Crude Oil	18.8	37.8	76.7	995	2.05	0.00358	0.13	0.00061
Process 3								
Shellside: Distilled Water	22.07	33.9	29.4	995	4.18	0.00080	0.62	0.00017
Tubeside: Raw Water	35.31	23.9	26.7	999	4.18	0.00092	0.62	0.00017

There are four optimization variables to be computed by these parameters, which are number of tube side passages (2, triangular pitch or 4, square pitch), shell inside diameter (D_s), baffles spacing (B) and tube outside diameter (d_o). Here, to simplify the problem, the binary variable (number of tube side passages) can be reduced by conducting two different optimization at both values. Then, the minimum value obtained by these two optimizations can be compared, and the one with the lower value can be taken as the result. In example, Şahin A.Ş. et. al. [4] only considered the square pitch shell and tube heat exchangers in their work. However, Hadidi A. [9] considered 5 different tube pass scenarios for both triangular pitch and square pitch heat exchangers.

7 Results and Discussion

The optimization studies are conducted by using GA, PSO, ABC and BBO algorithms in the literature. Their results for crucial parameters of each process is given in the following Tables 2-4.

Table 2: Optimum values of the heat exchanger parameters evaluated for the process 1.

	Original Design[10]	GA[11]	PSO[12]	ABC[4]	BBO[9]
S (m^2)	278.6	262.8	243.2	230.109	229.95
U (W/m^2K)	615	660	713.9	832	755
L (m)	4.830	3.379	3.115	3.963	2.040
D_s (m)	0.894	0.830	0.81	1.3905	0.801
d_o (m)	0.020	0.016	0.015	0.0104	0.010
B (m)	0.356	0.500	0.424	0.4669	0.500
N_t	918	1567	1658	1528	3587
v_t (m/s)	0.75	0.69	0.67	0.36	0.77
v_s (m/s)	0.58	0.44	0.53	0.118	0.46
ΔP_t (Pa)	6251	4298	4171	3043	6156
ΔP_s (Pa)	35789	13267	20551	8390	13799
C_i (€)	51507	49259	46453	44559	44536
C_{oD} (€)	12973	5818	6778.2	6233.8	6046
C_{tot} (€)	64480	55077	53231.1	50793	50582

Table 3: Optimum values of the heat exchanger parameters evaluated for the process 2.

	Original Design[10]	GA[11]	PSO[12]	ABC[4]	BBO[9]
S (m^2)	61.5	52.9	47.5	61.566	60.35
U (W/m^2K)	317	376	409.3	323	317.75
L (m)	4.88	2.153	1.56	3.6468	1.199
D_s (m)	0.539	0.63	0.59	0.3293	0.74
d_o (m)	0.025	0.02	0.015	0.0105	0.015
B (m)	0.127	0.12	0.1112	0.0924	0.1066
N_t	158	391	646	511	1061
v_t (m/s)	1.44	0.87	0.93	0.43	0.69
v_s (m/s)	0.47	0.43	0.495	0.37	0.432
ΔP_t (Pa)	49245	14009	16926	1696	5109
ΔP_s (Pa)	24909	15717	21745	10667	15275
C_i (€)	19007	17599	16707	19014	18799
C_{oD} (€)	8012	2704	3215.6	1211.3	1010.25
C_{tot} (€)	27020	20303	19922.6	20225	19810

For process 1, the surface area has gradually decreased to reach 229.95 m^2 with each optimization method. This suggest that an absolute minimum may have been obtained for the capital investment amount. For process 2, the surface area firstly decreased for GA and PSO methods, but then increased to the original design value for the other algorithms. Thus, we conclude that two different local minimums have been reached, one with a higher capital investment and smaller operating cost, and one with a higher operating cost and smaller capital investment. These results are both candidates for being the absolute minimum value. For process 3, we see that the surface area is firstly increased to 62.5 m^2 by GA method, which resulted massive decrease in the operating costs. Then, the following studies decreased the surface area while managing to keep the operating costs close to each other.

Table 4: Optimum values of the heat exchanger parameters evaluated for the process 3.

	Original Design[10]	GA[11]	PSO[12]	ABC[4]	BBO[9]
S (m^2)	46.6	62.5	59.2	54.72	55.73
U (W/m^2K)	1471	1121	1177	1187	1384
L (m)	4.880	1.548	1.45	2.4	1.133
D_s (m)	0.387	0.62	0.0181	1.0024	0.55798
d_o (m)	0.019	0.016	0.0145	0.0103	0.01
B (m)	0.305	0.440	0.423	0.354	0.5
N_t	160	803	894	704	1565
v_t (m/s)	1.76	0.68	0.74	0.36	0.898
v_s (m/s)	0.94	0.41	0.375	0.12	0.398
ΔP_t (Pa)	62812	3673	4474	2046	4176
ΔP_s (Pa)	67684	4365	4271	2716	5917
C_i (€)	16549	19163	18614	17893	18059
C_{oD} (€)	27440	1671	1696	1584.2	1251.5
C_{tot} (€)	43989	20834	20310	19478	19310

The cost comparison of the optimization algorithms are illustrated in Figures 2-4 for each process. It is seen that; for all cases, the best results have been obtained by using BBO algorithm. However, when the pressure drop values and discounted operating cost are compared for each study (Figures 5-7), we see that BBO algorithm has resulted higher pressure drop values than ABC algorithm for each process, but nevertheless obtained lower discounted operating cost. This is a contradiction, since the discounted operating cost is obtained as in Equations 23 - 25, higher pressure drop values should result in higher discounted operating cost.

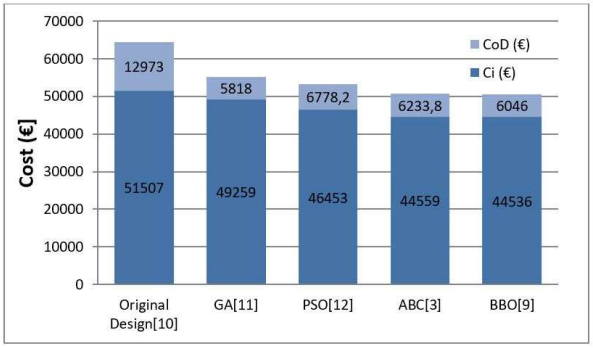

Figure 2: Optimum cost comparison for process 1.

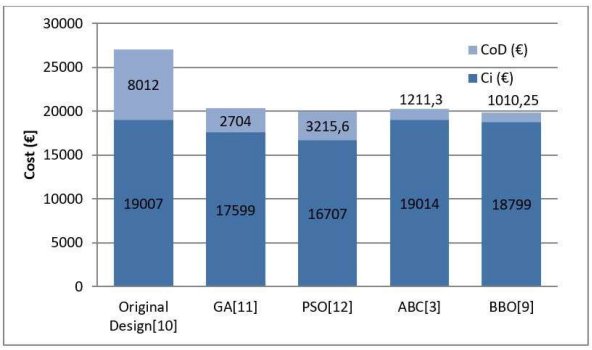

Figure 3: Optimum cost comparison for process 2.

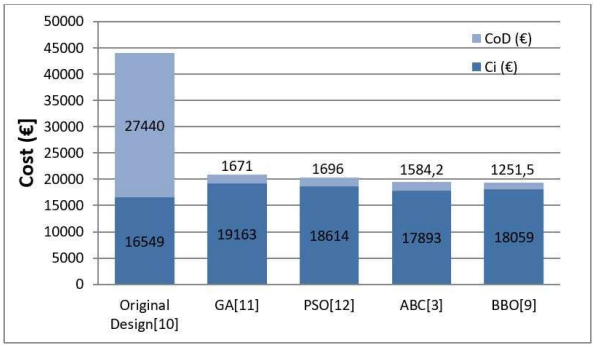

Figure 4: Optimum cost comparison for process 3.

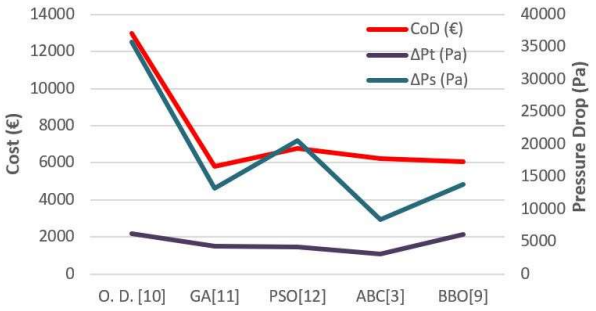

Figure 5: Resulted pressure drop and discounted operating cost values of optimization methods for process 1.

8 Conclusion

In this study, non-traditional optimization algorithms GA, PSO, ABC and BBO are considered for the optimization of heat exchanger. The results of each optimization method is compared by considering three different processes. While the best results are obtained by using BBO in each process, it is observed that the operating costs obtained by the BBO algorithm is contradicting with the operating costs obtained by other algorithms. Also, while ABC algorithm has resulted lower or similar values for surface area and pressure drop values than BBO algorithm, which are the fundamental optimization parameters directly linked to the objective function, the total cost of the ABC algorithm is reported higher than the cost of BBO algorithm. Thus, further investigation regarding to the validity and comparability of the algorithms is needed.

In addition, we have observed that the results of these non-traditional optimization algorithms seem to converge to a singular local minimum for process 1 and process 3. For process 2, it is observed that two different local minimum exists, one with a higher capital investment and one with a higher operating cost. While these extremums are all candidates for being the absolute minimum, it is not clear that the absolute minimum has been reached by any of these algorithms. The optimization may be conducted by utilizing different algorithms to obtain even better results.

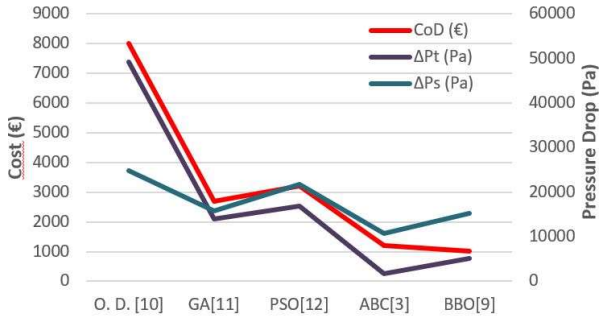

Figure 6: Resulted pressure drop and discounted operating cost values of optimization methods for process 2.

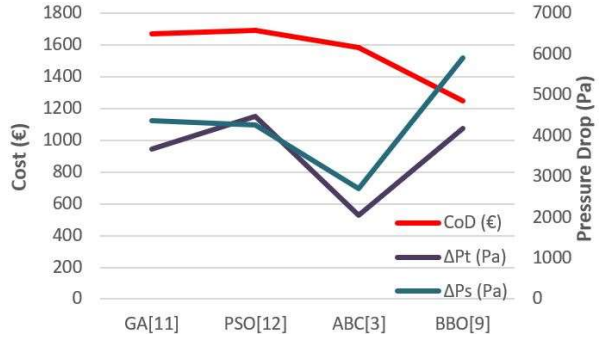

Figure 7: Resulted pressure drop and discounted operating cost values of optimization methods for process 3.

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