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Optimal chiller loading solution for energy conservation using Barnacles Mating Optimizer algorithm

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ABSTRACT

This paper proposes an application of evolutionary optimization algorithm, Barnacles Mating Optimizer (BMO) to solve the optimal chiller loading (OCL) problem for minimization of the power consumption in the multi chiller system. BMO mimics the mating behaviour of barnacles in nature. To generate new off-springs, the concept of Hardy–Weinberg principle is adopted for exploitation process and the sperm-cast process is treated as exploration behaviour of BMO. OCL on the other hand is the problem of finding the combination of partial load ratio of each chiller to obtain the minimum energy consumption in air-conditioning system. To demonstrate the effectiveness of proposed BMO, it is tested on three different chiller systems. The obtained results from BMO are compared with other well-known optimization algorithms in the literature. The obtained comparison results indicate that proposed BMO is effective to reach minimum energy consumption for solving the OCL problem.

1. Introduction

The multiple chiller system is widely used in air conditioning system in the world. It can be said that chiller consume about 20 to 40% of the total electricity utilization in commercial building [1]. It also can be categorized as one of the components in multi-energy system (MES) which have attracted attention worldwide recently [2]. To save the energy utilization in the building, it is necessary to improve the energy efficiency for the multi chiller system. Since the system consist of chillers with varying performance of characteristics and capacities, the optimal chiller loading (OCL) problem need to be assessed wisely and optimally [3]. Each unit of chillers need to be set and run with the highest efficiency as possible so that the minimum energy utilization for the various cooling load demand can be achieved. An analysis of the energy efficiency of air-cooled multiple-chiller plant in buildings has been reported in [4] where the load-frequency and weather-load profiles are constructed. In this study, to solve the OCL problem, partial load ratios (PLRs) of the chillers are used as the variables to be optimized and the energy consumption of the chiller is considered as the fitness function.

To date, there are various algorithms have been proposed to solve OCL problem especially by using metaheuristic approach. Metaheuristic approach becoming the selection of many researchers due to their efficiency in addressing various kind of problems and can be classified into four groups: evolutionary based, swarm based, physics-based and human-based algorithms [5,6]. Evolutionary based mimics the evolutionary process by producing new offspring that inherited from their parent and one of the well-known algorithms that has been applied to solve OCL problem is Genetic Algorithm (GA) [7,8]. Similar approach of GA also has been used to study the optimum sizing of cogeneration plants in [9]. Other than GA, the implementation of Evolutionary Strategy (ES) to solve OCL has been proposed in [10], which is fall under this category too. The implementation of Grass Fibrous

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Root Optimization in finding the optimal combination of sustainable resources (SERs) for building energy performance that has been proposed in [11] is also fall under evolutionary based technique.

Swarm based algorithms on the other hand, mimic the social behaviour of groups of animals such as Particle Swarm Optimization (PSO) [12], Differential Search Algorithm (DSA) [13], Enhanced Differential Bat Algorithm (DBA) [14], Improved Invasive Weed Optimization (EIWO) [1], Improve Cuckoo Search Algorithm (ICSA) [15], Augmented Group Search Optimization (AGSO) [16], Improved Firefly Algorithm (IFA) [17], Emperor Penguin Optimization with Quantum theory (QEPO) [18] and hybrid Whale Optimization Algorithm and Sequential Quadratic Programming (WOA-SQP) [19] are amongst that have been applied to solve OCL problem.

For the third category, the physical based algorithm is inspired by the nature and physic law such as Harmony Search Algorithm (HSA) [20] and Equilibrium optimization (EO) [21], which have been implemented in performance optimization of HVAC system and OCL solution, respectively. Finally, the human based algorithm that mimic the human behaviour such as socializing, competition and etc. such as Imperialistic Competitive Algorithm (ICA) [22], Robust Optimization [23], improved Teaching–Learning Based Optimization (TLBO) [24] and Exchange Market Algorithm (EMA) [25] that have been proposed in solving the OCL problem. In spite of the variety of optimization algorithms that all groups provide, they mostly share some common characteristics such as the use of stochastic components and there are some parameters need to be tuned [26].

To enhance the searching behaviouror to improve the performance of a single algorithm, there are effort to hybrid the algorithms for the sake of obtaining better results, whether within the same metaheuristic category or from different category, especially in solving OCL problem. The hybrid of GA with Artificial Neural network (ANN) to optimize the chiller loading and determine the minimum power consumption has been proposed in [27] and hybrid exchange market and genetic algorithm (EMGA) has been proposed in [28]. It can be noted that the proposed GA-ANN in [27] is the hybrid from evolutionary based with the machine learning approach and EMGA is hybrid from evolutionary based and human based metaheuristic. Another ANN approach to solve the absorption chiller network plant (ACNP) has been proposed in [29].

Another recent approach to solve OCL has been proposed in [30] where the Gordon-Ng simplified model suggested by ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) Guideline 14 is adopted to estimate the chiller efficiency. The consideration of dual-temperature chiller plants has been initiated in [31] where two optimal control strategies for dual-temperature chilled water plants are proposed. Due to dynamic behaviourof multi chiller system, the solution of OCL with dynamic effects due to transients arising from switching on and off of units are proposed in [32]. Risk-based robust chiller sequencing control strategy for energy-efficient operation has been proposed in [33] and Robust Optimization (RO) algorithm that considering the measurement, control and threshold uncertainties has been discussed in [34].

In this work, a recent algorithm namely Barnacle Mating Optimizer (BMO) based on the barnacles' mating behaviour [6,35,36] has been proposed to solve OCL problem. BMO can be categorized as group of evolutionary based algorithms since it produces the new offspring to achieve the objective that has been set. As far as the knowledge of the authors, it can be confirmed that BMO is the new algorithm proposed in the literature as well as in the implementation into the OCL problem. In this paper, it is worth to highlight that the on/off status of the chillers is being considered to obtain minimum energy utilization which will be presented in the later section. The cooling load production and the electricity consumption for all selected algorithms to be compared will be further investigated to verify the optimization results. Thus, the solution given by the respected researchers can be confirmed. The contributions of this paper are as follow:

a. The development of original BMO algorithm application to solve OCL problem by minimizing total energy consumption subject to satisfy some constraints in the multiple chiller system.
b. The implementation of BMO into the three well known case systems compared with various state-of-the-art algorithms available in literature.
c. The simulation results prove the effectiveness of proposed BMO compared to others.

The rest of the paper is organized as follows: Section 2 discusses the formulation of the OCL problem. It is followed by the concept and development of BMO in Section 3 and BMO application into OCL problem in Section 4. Section 5 presents the results and discussion and finally, Section 6 states the conclusion of this paper.

2. Problem formulation

A multi chiller system consists of more than one chiller connected by series or parallel piping to a distribution system as depicted in Fig. 1. In the primary cycle, the electrical power is consumed by the pump i to increase the pressure of water flowing in the chiller i resulting the efficiency improvement of the refrigeration cycle. The pressure of chilled water flow is controlled by the secondary cycle pump. The chilled water then enters the cooling coils, and the heat is absorbed before returning to the primary cycle pumps. In multiple chiller system, the best performance of the chiller system can be obtained by the minimum sum of energy consumption by the chiller which is fulfilling all the load demand. In this paper, the objective function to be minimized is the total energy consumption for supplying the cooling load at hour t for N chillers as follows:

$$OF = \min P_{total}^{t} = \sum_{i=1}^{N} P_i^t \tag{1}$$

where P_i^t is the electrical power consumption of the chiller i at hour t that can be calculated as follows [22]:

$$P_i^t = a_i + b_i PLR_i^t + c_i \left(PLR_i^t\right)^2 + d_i \left(PLR_i^t\right)^3 \tag{2}$$

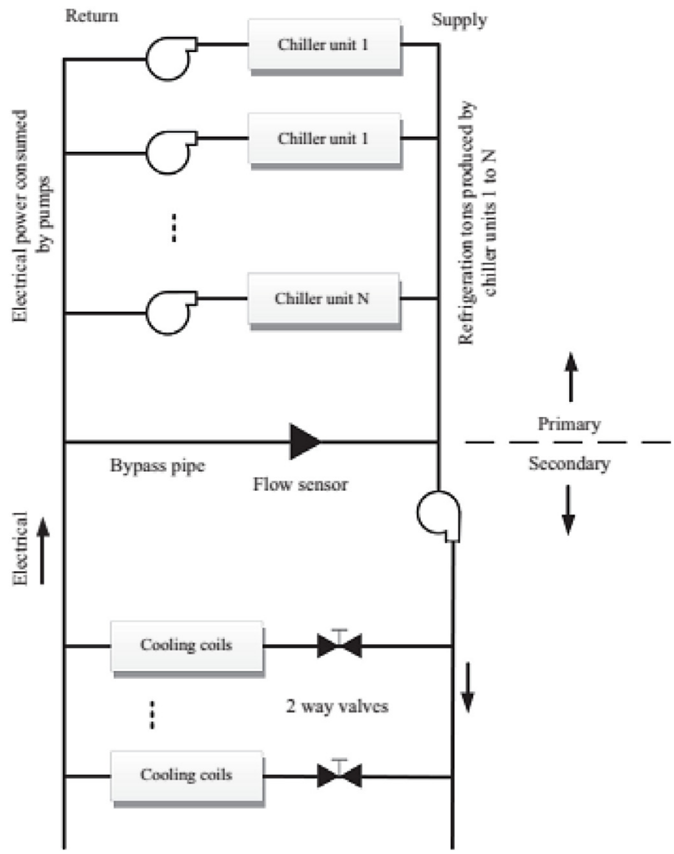

Fig. 1. Illustration of typical water-cooled multi-chiller system [16].

where a_i, b_i, c_i and d_i are the coefficients of respected chiller i and PLR_i^t is the partial load ratio (variables to be optimized) that can be defined as:

$$P_i^t = u_i^t \times \frac{\text{Cooling load of chiller } i \text{ at hour } t}{\text{Refrigeration capacity of chiller } i} \tag{3}$$

And u_i^t can be explained as:

$$u_i^t = \begin{cases} 0 & \text{if the chiller } i \text{ is off} \\ 1 & \text{if the chiller } i \text{ is on} \end{cases} \tag{4}$$

The sum of cooling load of each chiller must satisfy with the system load, CL^t which gives the equality constraint as follows:

$$\sum_{i=1}^{N} \left(PLR_i^t \times RT_i \right) = CL^t \tag{5}$$

where RT_i is the cooling capacity of chiller at hour t. The inequality constraints for OCL problem are that PLR_i^t of each operating chiller must be operating between 0.3 and 1 if the chiller is ON which can be described as follows [1]:

$$= \begin{cases} 0.3 \le PLR_i^t \le 1 & \text{if chiller } i \text{ is ON} \\ 0 & \text{if chiller } i \text{ is OFF} \end{cases} \tag{6}$$

3. Barnacles mating optimizer

Barnacles commonly found attached permanently to solid substance such as rocks, ships, corals and even to the sea turtles. They are hermaphroditic organisms which have both male and female reproduction system and one of the unique features of barnacles is their penis size can stretch to multiple times compared to the length of their body (up to seven to eight times). The mating behaviour of barnacles happened in two ways: by the normal copulation and sperm-cast. For normal copulation, the male barnacle will knock the female barnacle and the mating process is happened naturally. Meanwhile, sperm-cast will take place for mating of

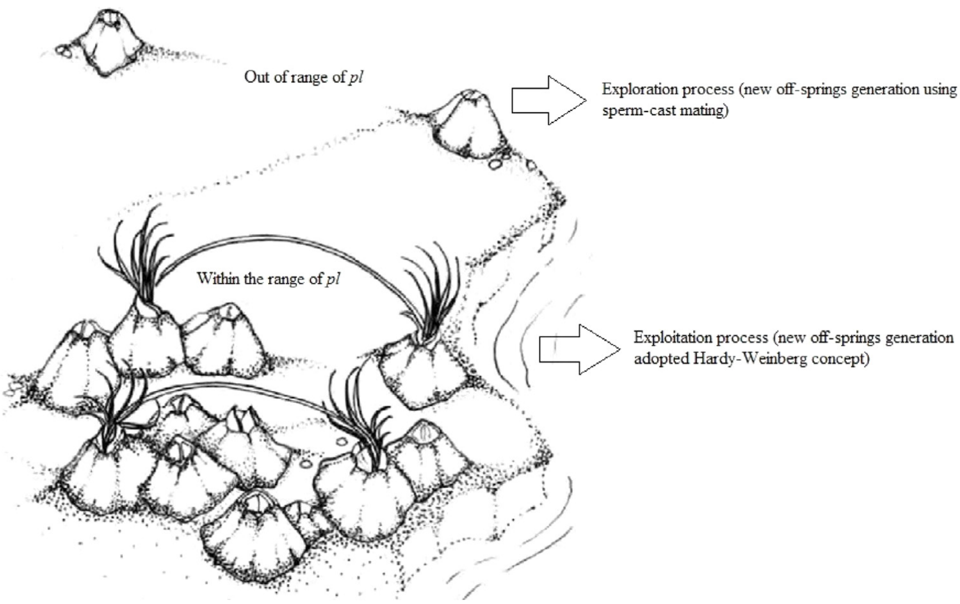

Fig. 2. Exploitation and exploration concept of BMO.
Source: Adopted from [39].

the isolated barnacles. This is done by releasing the fertilized eggs into the water. This exclusive behaviour of barnacles in producing new offspring becoming an insight in the introduction of BMO for solving optimization problems.

3.1. Selection process of Barnacles' Parents to Be Mated

Similar with other evolutionary algorithms such as GA, BMO also uses the similar approach to have the selection process of parents to be mated to produce new offspring. However, the technique of solution is different compared to GA which is without using any well-known selection such as roulette wheels, tournament or etc. The selection process of barnacle's parents to be mated is made based on the following rules for simplification:

- Even though barnacles are known as hermaphroditic organism and by referring to [37] that female barnacles able to be fertilized by more than one male barnacle, it is assumed each barnacle can only be mated by one other barnacle only. This is to avoid the algorithm's complexity.
- The value of pl need to be set initially by the user and the selection of barnacles' parents is done randomly. The value of *pl* is the only control parameter in this algorithm which user can tune to obtain good optimization results aside of number of barnacles and maximum iterations.
- The concept of Hardy-Weinberg [38] is used if the selection of barnacles' parents is within the range of *pl*. Otherwise the sperm-cast process will impose to obtain new off-springs.

3.2. Barnacles' new off-springs generation

The generation of new off-springs is guided by the principle of Hardy–Weinberg concept. The definition is as in (7) and (8):

$$x_i^{N\_new} = px^N_{barnacle\_m} + qx^N_{barnacle\_d} \quad for \quad k \leq pl \tag{7}$$

$$x_i^{N\_new} = rand() \times x^N_{barnacle\_m} \quad for \quad k > pl \tag{8}$$

where $k = |barnacle\_m\text{-}barncle\_d|$, p is the normally distributed pseudo random number, $q = (1 - p)$, $x^N_{barnacle\_m}$ and $x^N_{barnacle\_d}$ are the randomly chosen variables for barnacle's parents (Mum and Dad) respectively. Meanwhile, rand() denotes the random number range between zero to one (0∼1). By referring to these equations, p and q represent the inheritance percentage from the respective barnacles' parents. For example, let say p is generated to 0.80. It indicates that the new off-spring inherits 80% of the Mum's feature or behaviour and 20% (100%–80%) of Dad's feature. Eq. (7) basically can be treated as the exploitation process of optimization while Eq. (8) can be treated as the exploration process of developed BMO. It is also worth to mention here that the exploration process (sperm-cast) is associated with Mum's barnacle only since the Mum's barnacle received the sperm released from the other barnacles elsewhere. The concept of exploitation and exploration proposed in BMO are adopted from [39] and visualized in Fig. 2.

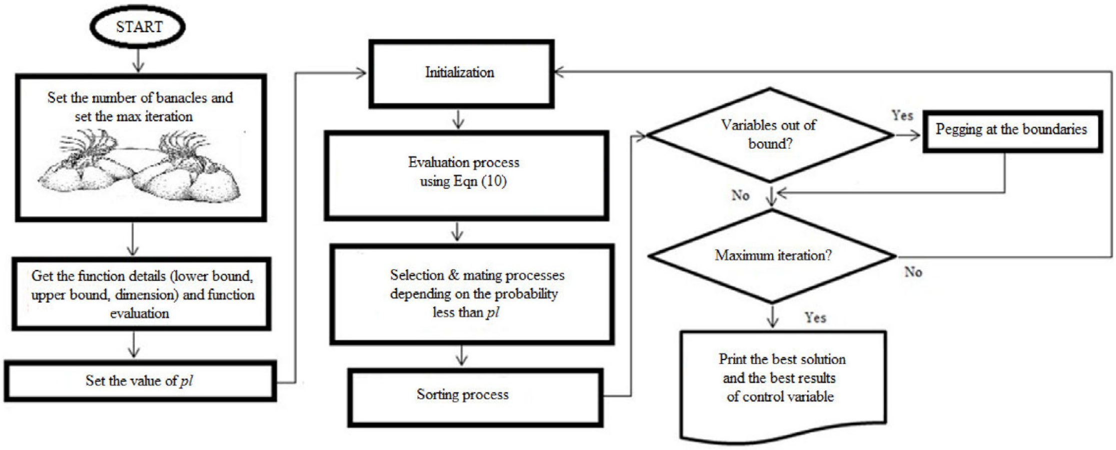

Fig. 3. The flow of BMO to OCL problem.

3.3. Sorting the best barnacles

When the barnacles breed, the number of populations will be doubled from the initial population. To control this expansion, something must be done. Similar with GA, the sorting process is needed in BMO where the best result for a certain iteration will be located at the top half of the doubled population. Only the best top half of the sorting population will be considered for the next generation and the bottom half are deceased.

4. BMO for solving OCL problem

To solve the OCL problem using BMO, firstly, the initialization is conducted. This comprises the population randomization is obtained, and the initial evaluation is performed. The population variables consist of random values PLR_i^t quoted in terms of X, as follows:

$$X = \begin{bmatrix} x_1^1 & \cdots & x_N^1 \\ \vdots & \ddots & \vdots \\ x_1^{pop} & \cdots & x_N^{pop} \end{bmatrix} \tag{9}$$

where pop is the number of population and N is the number of chillers in the multi chiller system. In order to obtain the optimal results, the equality and inequality constraints need to be handled wisely. To handle the inequality constraint, when the searching process of x or PLR_i^t is less than 30%, BMO will decide it is OFF state. For equality constraint in Eq. (5), the penalty factor (PF) approach has been used. The penalty value is reflected by the summation mismatch and embedded in the objective function in (1) as follows:

$$OF = (OF) + PF \times abs\left[\sum_{i=1}^{N}\left(PLR_i^t \times RT_i\right) - CL^t\right] \tag{10}$$

The implementation of BMO in solving OCL problem is shown in Fig. 3.

5. Results and discussion

All simulations to obtain the optimal results of OCL which bring the minimization of energy consumption using BMO are implemented in MATLAB. The implementation of BMO has been tested on the three standard systems with 6, 4 and 3 unit of chillers and the results are compared with various state-of-the-art algorithms available in literature. The parameters of BMO and selected algorithms are summarized in Table 1. It is worth to highlight that the parameters for selected algorithms are extracted from the respective works.

5.1. Case 1: 6-unit chiller system

The coefficients data to run the simulation are obtained from [1,16,22]. This system is based on the real semiconductor factory in Hsinchu Scientific Garden, Taiwan with 6 chillers. Table 2 shows the data of this system that consist of coefficients and capacity of respected chillers.

Table 1
Parameters of investigated algorithms for solving OCL problem.

Algorithms	Parameters
PSO [12]	50 populations, 400 maximum iterations, inertial weight maximum = 0.9, inertial weight minimum = 0.4, and an acceleration constant value (C1 and C2) = 2
ICA [22]	Number of countries = 75, decades = 200, number of initial imperialists = 10, assimilation coefficient = 2 and assimilation angle coefficient = 0.5
AGSO [16]	Not Available.
BMO	30 populations, $pl = 21$, maximum iteration = 300 (case 1), 500 (cases 1 and 2)

Table 2
Test system of 6-chillers system.

Chiller	a_i	b_i	c_i	Capacity (RT)
1	399.345	–122.12	770.46	1280
2	287.116	80.04	700.48	1280
3	–120.505	1525.99	–502.14	1280
4	–19.121	898.76	–98.15	1280
5	–95.029	1202.39	–352.16	1250
6	191.750	224.86	524.04	1250

For this case, different cooling load levels are considered for simulations. The results of optimal values of PLRs, building cooling load required and total power utilization of the chillers by BMO together with PSO [12], ICA [22] and AGSO [16] are tabulated in Table 3. In Table 3, the first column represents the different levels of cooling loads followed by the six chillers for this system in column 2. For each algorithm, the results of PLRs for each chiller are presented where the exact total cooling loads is shown at the next of it. The next column is the actual calculation of energy consumption from each chiller and finally the total energy consumption which is the objective function (*OF*) is exhibited at the next column.

The results for compared algorithms are obtained by referring to the published results and verification is made using the respected equations used. It can be seen that BMO is outperformed those selected algorithms in terms of the minimum energy consumption. From this table, it can be noted that the results obtained by BMO is better compared to PSO in terms if *OF* (total kW) for all cooling loads (70%–90% RT). It is worth to highlight that even though AGSO and ICA produce minimum energy consumption compared to BMO, the results presented by them were violating the inequality constraint in Eq. (6). This resulted discrepancy cooling load summation obtained by ICA and AGSO for PLRs as highlighted in bold and italic fonts in Table 3. In addition, results of total energy consumption for 70% and 75% RT are miscalculated and the correct results are highlighted in bold and brackets. This is because the negative result of kW is included since the PLRs at the respected chillers should be zero or can be treated as OFF as mentioned in Eq. (6).

From this table also shows that BMO contributes the best results for 70% and 75% RT compared to PSO. For 5717 RT, the improvement of energy consumption obtained by BMO and PSO is 3921.07 kW–3865.67 kW = 235.4 kW saving which is about 6% energy reduction and for 5334 RT, the saving is 3642.55 kW–3544.33 kW = 98.22 kW which is about 2.7% energy reduction. This is due to chiller 4 should be shut down to comply the cooling load proposed by BMO compared to PSO that give minimum PLR value (0.3). The energy saving for these cases are for daily basis and if the differences hold for each hour of the year, the annual energy saving can be calculated as 235.4 kW/h × 8760 h = 2,062,104 kW and 98.22 kW/h × 8760 h =860,407.2 kW, respectively which can be considered as massive energy consumption reduction. As been mentioned in introduction section, the multi-chiller system consumed about 20 to 40% of the total electricity utilization in commercial building. Thus, the impact of achieving energy reduction may provide occupants with a comfortable, safe, and attractive living and work environment.

Fig. 4 shows the convergence performance of BMO in obtaining the optimal PLRs for all cooling loads. It can be noted that BMO able to converge less than 50 iterations to obtain the results for all levels of cooling loads.

5.2. Case 2: 4-unit chiller system

The coefficients data to run the simulation for this case are also obtained from [1,12,16,22]. The specification of this system is tabulated in Table 4. The best results of PLRs as well as power utilization by the chillers obtained by PSO, AGSO, ICA and BMO are reported in Table 5. It is demonstrated that BMO reaches similar solution with PSO, AGSO and ICA for cooling load of 70%, 80% and 90% RT respectively. For 50% and 60% RT, BMO outperformed PSO which is less 13.04 kW and 13.1075 kW improvement respectively, which are about 1.59% and 1.53% of energy reductions. It is worth to mention that the *OF* for PSO is extracted from [16] and the results for individual kW obtained might be slightly different due to PLR value up to two decimal points only. Again, the energy reduction is calculated for daily basis and if the differences hold for each hour of the year, the annual energy saving can be calculated as 13.04 kW/h × 8760 h = 114,230.40 kW and 13.1075 kW/h x 8760 h =114,821.70 kW, respectively. For these cooling load also show that IGSA and ICA reported discrepancy results as shown in bold and italic fonts. This is because of they included the negative results of chiller 2 since the coefficient a_i is –67.15 if the PLRs is zero. As stated in Eq. (6), if the PLRs is less than 0.3, it is assumed shut down. Thus, the effect of coefficient a_i should be excluded and the true power utilization for AGSO and ICA are highlighted in bold and brackets. This issue is also occurred for 40% RT. Nevertheless, for 40% RT, PSO outperformed

Table 3
Optimal results obtained by BMO and other algorithms for 6-unit chillers system.

CLt	Chiller	PSO				ICA				AGSO				BMO			
	i	PLRt	CLt from PLRt	kW	OF (kW)	PLRt	CLt from PLRt	kW	OF (kW)	PLRt	CLt from PLRt	kW	OF (kW)	PLRt	CLt from PLRt	kW	OF (kW)
	1	0.8026		797.6362		0.7594		750.88675		0.7935		7.875569		0.81265		808.9184	
	2	0.7799		775.6019		0.7497		740.86526		0.7286		7.172885		0.749537		740.6431	
6858 (90%)	3	0.9996	6857.6	903.1362	4739.53	1	***6802.5284***	903.345	4691.965	1	***6802.9***	9.03345	4690.546	1	6857.7	903.345	4738.282
	4	0.9998		781.3485		0.9997		781.29441		1		7.81489		1		781.489	
	5	0.9999		755.1511		1		755.201		1		7.55201		1		755.201	
	6	0.8183		726.6579		0.8489		760.37132		0.8357		7.456522		0.838452		748.6856	
	1	0.7606		752.1812		0.7012		692.54971		0.7102		701.2231		0.727591		718.3647	
	2	0.6555		640.5646		0.6429		628.10718		0.6396		624.8677		0.655979		641.0428	
6477 (85%)	3	1	6477	903.345	4423.0396	1	***6425.4889***	903.345	4382.373	1	***6425.7***	903.345	4382.031	1	6476.3	903.345	4421.1606
	4	1		781.489		0.9991		780.84687		1		781.489		1		781.489	
	5	1		755.201		1		755.201		1		755.201		1		755.201	
	6	0.6835		590.2588		0.7169		622.32119		0.7104		615.9568		0.716324		621.7182	
	1	0.6591		653.5534		0.6284		626.82624		0.6269		625.5815		0.643283		639.6139	
	2	0.5798		569.0022		0.5466		540.11299		0.545		538.7979		0.562418		553.7037	
6096 (80%)	3	0.9991	6095.8	902.8751	4147.69	1	***6048.3717***	903.345	4111.764	1	***6048.3***	903.345	4111.756	1	6096	903.345	4143.6569
	4	0.9979		780.0134		1		781.489		1		781.489		1		781.489	
	5	0.9921		751.2443		1		755.201		1		755.201		1		755.201	
	6	0.571		491.0036		0.5876		504.78893		0.5906		507.3418		0.5941		510.3042	
	1	0.7713		763.5033		0.8421		842.87648		0.8236		821.3831		0.8204		817.6948	
	2	0.7177		705.3733		0.7285		717.18616		0.7622		755.065		0.758		750.2963	
5717 (75%)	3	0.3	5717.1	292.0994	3921.07	0.0001	***5660.1286***	−120.2455	***3789.997***	0	***5660.4***	−120.505	***3788.77***	0	5716.1	0	3865.672
	4	0.9991		780.8567		1		781.489	(3910.2404)	1		781.489	(3909.1557)	1		781.489	
	5	1		755.201		1		755.201		1		755.201		1		755.201	
	6	0.7187		624.0391		0.8956		813.4877		0.8805		796.017		0.8495		760.9912	
	1	0.6418		638.3264		0.7258		716.5766		0.7399		730.77829		0.7369		727.744	
	2	0.6621		647.1844		0.6877		673.4405		0.6701		655.29015		0.6624		647.4459	
5334 (70%)	3	0.3301	5334	328.5081	3642.55	0.0024	***5281.461***	−116.7709	***3466.355***	0	***5281.3***	−120.505	***3463.714***	0	5334	0	3544.3336
	4	0.9906		774.8772		1		781.4890	(3583.1249)	1		781.489	(3585.2317)	1		781.489	
	5	0.999		754.7026		1		755.2010		1		755.201		1		755.201	
	6	0.5806		498.9557		0.7512		656.4178		0.7572		662.47329		0.7273		632.4537	

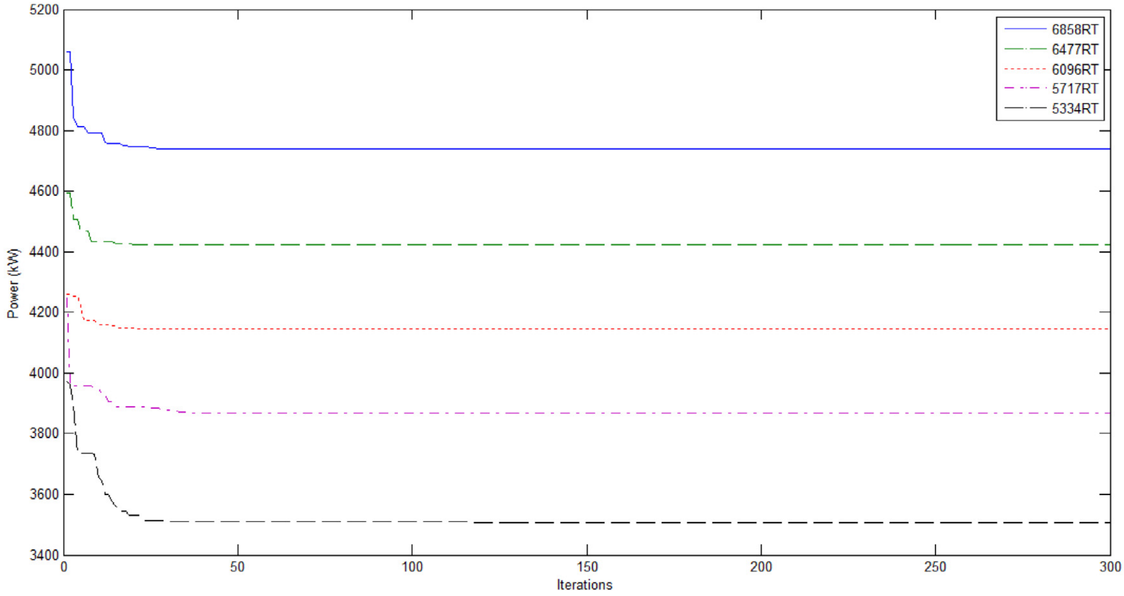

Fig. 4. Convergence graph for OCL problem for 6-unit chillers system using BMO.

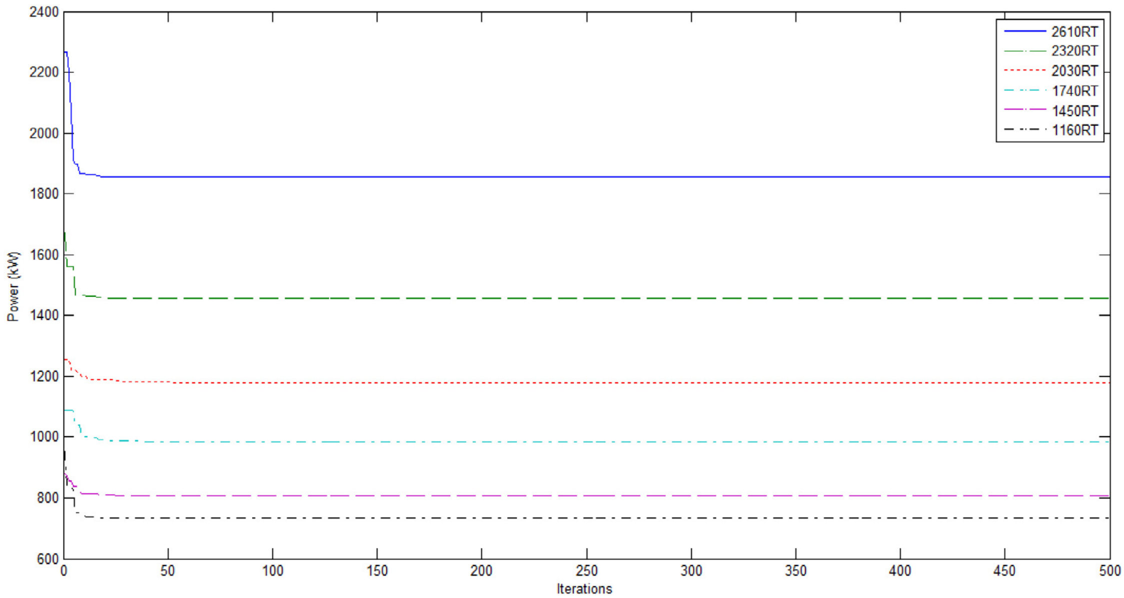

Fig. 5. Convergence graph for OCL problem for 4-unit chillers system using BMO.

Table 4
Test system of 4-chillers system.

Chiller	a_i	b_i	c_i	d_i	RT_i
1	104.09	166.57	–430.13	512.53	450
2	–67.15	1177.79	–2174.53	1456.53	450
3	384.71	–779.13	1151.42	–63.2	1000
4	541.63	413.48	–3626.5	4021.41	1000

BMO since PSO able to obtain 651.07 kW power utilization compared to 732.71 kW obtained by BMO. Fig. 5 shows the convergence performance of BMO in obtaining the optimal PLRs for all cooling loads fort this case study. The results are converged less than 30 iterations to obtain the results for all levels of cooling loads.

Table 5
Optimal results obtained by BMO and other algorithms for 4-unit chillers system.

CL_t	Chiller	PSO				ICA				AGSO				BMO			
	i	PLR^t	CLt from PLRt	kW	OF (kW)	PLR^t	CLt from PLRt	kW	OF (kW)	PLR^t	CLt from PLRt	kW	OF (kW)	PLR^t	CLt from PLRt	kW	OF (kW)
2610 (90%)	1	0.99	2615.00	344.73	1857.3	0.9930	2610	347.2391	1857.3	0.991	2610	345.5542	1857.29	0.9907	2610	345.33187	1857.0342
	2	0.91		301.51		0.9051		297.4564		0.9061		298.2661		0.9058		298.00856	
	3	1		694		1.0000		693.8000		1		693.8		1.0000		693.8	
	4	0.76		526.51		0.7558		518.8093		0.7563		519.6694		0.7564		519.89376	
2320 (80%)	1	0.83	2328.00	239.08	1455.66	0.8295	2320.0	238.8355	1455.665	0.8289	2320.05	238.5226	1455.66	0.8288	2320.00	238.49505	1455.6647
	2	0.81		234.21		0.8054		231.8154		0.8061		232.1956		0.8055		231.90346	
	3	0.90		570.07		0.8964		565.9910		0.8966		566.2063		0.8966		566.2397	
	4	0.69		421.42		0.6879		419.0228		0.6877		418.7975		0.6879		419.0265	
2030 (70%)	1	0.73	2031.50	195.85	1178.14	0.7257	2030.0	194.3421	1178.137	0.7261	2029.99	194.4672	1178.13	0.7265	2030	194.62513	1178.1371
	2	0.74		203.86		0.7399		203.8185		0.7401		203.8981		0.7400		203.87453	
	3	0.72		397.04		0.7218		398.4203		0.7217		398.3733		0.7215		398.21439	
	4	0.65		382.58		0.6487		381.5562		0.6485		381.3907		0.6485		381.4231	
1740 (60%)	1	0.60	1737.00	159.89	998.53	0.7442	1740.0	201.0885	***942.070*** (1009.1983)	0.7501	1740.75	203.3316	***942.006*** (1009.87)	0.7322	1740	196.65158	985.42247
	2	0.66		181.71		0.0000		−67.1288		0		−67.15		0.0000		0	
	3	0.56		298.38		0.7503		421.5884		0.747		418.8588		0.7308		405.598	
	4	0.61		357.22		0.6548		386.5214		0.6562		387.6747		0.6507		383.17289	
1450 (50%)	1	0.61	1454.50	161.98	820.07	0.6077	1450.0	161.4837	***752.9270*** (820.0749)	0.6071	1450.00	161.3647	***752.919*** (820.07)	0.5906	1450	158.00955	807.02972
	2	0		−67		0.0000		−67.1476		0		−67.15		0.0000		0	
	3	0.57		303.00		0.5672		301.7017		0.5681		302.1052		0.5514		294.59788	
	4	0.61		357.22		0.6093		356.8895		0.6087		356.6004		0.6039		354.42229	
1160 (40%)	1	0	1160	0	651.07	0.0000	1160	0.0000	***583.9230*** (651.0716)	0	***886.1***	0	***627.919*** (590.981)	0.3981	1160	134.57263	732.7116
	2	0		0		0.0000		−67.1488		0		−67.15		0.0000		0	
	3	0.56		298.38		0.5550		296.1763		0.3487		250.3509		0.4183		255.64089	
	4	0.6		352.8		0.6050		354.8953		0.5374		340.6301		0.5626		342.49809	

Table 6
Test system of 3-chillers system.

Chiller	a_i	b_i	c_i	d_i	RT_i
1	100.95	818.61	–973.43	788.55	800
2	66.598	606.34	–380.58	275.95	800
3	130.09	304.5	14.377	99.8	800

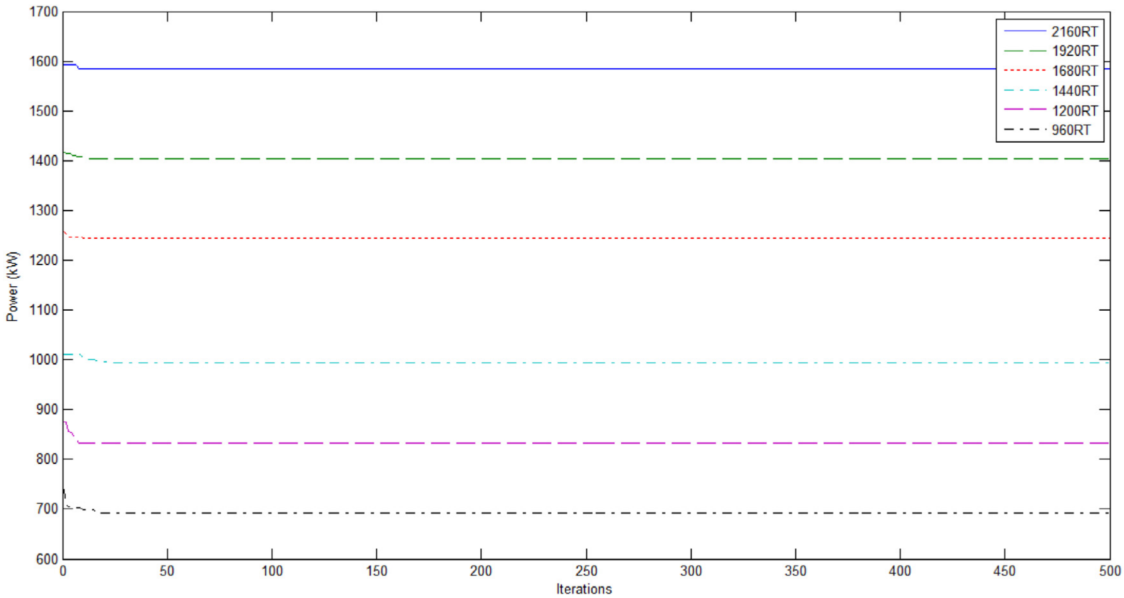

Fig. 6. Convergence graph for OCL problem for 3-unit chiller systems using BMO.

5.3. Case 3: 3-unit chiller system

The coefficients data to run the simulation for this case is using a semiconductor plant in Hsin Tsu Sience-based Park with 800RT capacity chillers [1,16,22]. The specification of this system is tabulated in Table 6. The simulations have been conducted for six different cooling loads such as 2160 (90% RT), 1920 (80% RT), 1680 (70% RT), 1440 (60% RT), 1200 (50% RT) and 960 (40% RT) as presented in Table 7. It can be observed that all algorithms obtained similar results in terms of power utilization even the value of PLRs are slightly different among all algorithms. This can be expected since the small unit system is used. It is also can be seen that there are no violations of inequality constraints, such have been discussed in previous two case studies. It can be concluded that all algorithms are able to obtain quite similar optimal results that contribute the similar *OF* for all levels of cooling loads. The convergence performance of BMO for this case study is depicted in Fig. 6 where it can be seen that BMO is able to converge less than 50 iterations to obtain the results for all levels of cooling loads.

6. Conclusion

This paper proposed an evolutionary optimization algorithm inspired by barnacles's life which has been implemented in solving the energy utilization of optimal chiller loading (OCL) problem. The results showed that BMO was able to provide very competitive results compared to selected recent algorithms in obtaining the optimal value of partial load ratios (PLRs) for minimizing the energy utilization through three case studies viz. 6-units, 4-units and 3-units chiller systems. For example, the energy reductions obtained by BMO compared to PSO for 6-units chiller system are 235.4 kW or 6% energy saving for 5717 RT and 98.22 kW or 2.7% energy reduction for 5334 RT. This is massive energy saving when the annual calculation is considered which are 2,062,104 kW and 9860,407.2 kW, respectively. BMO also performs well by not violating the inequality constraints that has been set such have been occurred in results obtained by ICA and AGSO. In addition, it is worth to highlight that BMO only has one parameter to be tuned which is value of *pl* apart from number of population and iterations. This is major advantage in solving real application of optimization problems. However, the limitation of proposed BMO in solving OCL is that the algorithm needs more computation time due to extra sorting process in the algorithm's development if dynamic loading conditions are considered. This issue becomes our motivation to implement the parallel computing concept, which also open the chances and challenges for BMO to be improved in the future. The MATLAB code for BMO is available at https://www.mathworks.com/matlabcentral/fileexchange/74730-barnacles-mating-optimizer-bmo?s_tid=srchtitle_barnacles%20mating_1.

Table 7
Optimal results obtained by BMO and other algorithms for 3-unit chillers system.

CLt	Chiller	PSO				ICA				AGSO				BMO			
	i	PLR^t	CLt from PLRt	kW	OF (kW)	PLR^t	CLt from PLRt	kW	OF (kW)	PLR^t	CLt from PLRt	kW	OF (kW)	PLR^t	CLt from PLRt	kW	OF (kW)
	1	0.73		486.55		0.725093		483.3396		0.7252		483.40925		0.72525		483.43934	
2160 (90%)	2	0.97	2160.00	548.51	1583.81	0.974906	2160	551.6963	1583.806	0.9747	2160	551.56217	1583.81	0.97475	2160	551.59717	1583.804
	3	1		549		1		548.767		1		548.767		1		548.767	
	1	0.66		443.91		0.658172		442.8795		0.6589		443.28899		0.65993		443.87084	
1920 (80%)	2	0.86	1920.00	482.09	1403.2	0.858771	1920	481.4004	1403.196	0.8586	1920	481.30411	1403.2	0.85744	1920	480.65138	1403.194
	3	0.88		477.19		0.883057		478.914		0.8825		478.60034		0.88263		478.67204	
	1	0.6		412.0		0.597557		410.7818		0.598		411.00338		0.5961		410.05342	
1680 (70%)	2	0.74	1680.0	418.71	1244.32	0.745451	1680	421.4184	1244.327	0.7431	1680.32	420.24667	1244.31	0.7452	1679.99999	421.29488	1244.323
	3	0.76		413.62		0.756992		412.1243		0.7593		413.27458		0.7587		412.97451	
	1	0		0		0		0		0		0		0		0	
1440 (60%)	2	0.89	1440	499.32	993.6	0.885634	1440	496.7736	993.602	0.8853	1440.24	496.57937	993.602	0.88525	1440	496.55044	993.6021
	3	0.91		494.30		0.914366		496.8286		0.915		497.19716		0.91475		497.05168	
	1	0				0		0		0		0		0		0	
1200 (50%)	2	0.74	1200	420.22	832.33	0.743055	1200	420.2243	832.325	0.743	1199.92	420.19689	832.326	0.74304	1200	420.21767	832.3252
	3	0.76		412.10		0.756945		412.1009		0.7569		412.07849		0.75696		412.1075	
	1	0		0		0		0		0		0		0			
960 (40%)	2	0.57	960	339.67	692.25	0.570018	60	339.6733	692.251	0.57	961.68	339.66537	692.25	0.57029	960	339.79546	692.2513
	3	0.63		352.59		0.629982		352.578		0.6321		353.51386		0.62971		352.45585	

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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