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Chiller Plant Energy Optimization Modeling and Decision Analysis

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***Abstract**: The objective of this study was to identify a method that would enable a chiller plant to achieve the lowest possible operation energy consumption. Using mathematical programming, this study adopted the actual cooling capacity required by an air conditioning system as a basis for considering the operating performance and condition of each chiller plant component as well as the relationship among components to construct a decision analysis model for chiller plant energy optimization. The problem-solving performances of various algorithms were investigated. Finally, the model architecture and the algorithm that showed most satisfactory performance were employed to establish a decision analysis model for chiller plant energy optimization, which can serve as an objective reference for enabling chiller plant designers and operators to perform optimized equipment control.*

***Keywords:** central air conditioning system, chiller plant, energy optimization, mathematical programming, decision support system*

1. Introduction

The pursuit of a comfortable and convenient life has resulted in rapid technological development and increasing energy consumption. In addition to continually increasing energy costs due to energy overexploitation worldwide, the emphasis countries have placed on energy conservation and environmental protection because of global warming has also led to an inevitable increase in cost of electricity.

Taiwan is located in subtropical latitudes, characterized by hot and humid summers. Therefore, air conditioning (AC) systems (referred to as central AC systems consisting of a chiller, chilled water pump, condenser water pump, cooling tower, air handling unit, indoor air cooler, and related pipe lines and valves) are commonly used to maintain a comfortable environment in the indoor spaces of residential buildings. However, this results in large amount of energy consumption (primarily electric energy). The energy consumed by AC systems accounts for 40%–65% of the total energy consumption of an entire building. In particular, chillers are the primary source of power for refrigeration in central AC systems, and they require a large amount of electricity to produce cooled air for an entire building. Generally, the electricity required by a chiller is 50%–65% of the electricity consumed by an entire AC system. Therefore, studies on improving the energy efficiency of AC systems have primarily aimed to achieve optimal operating efficiency of chillers, chillers plus cooling towers, or chillers plus pumps. However, the optimal relationship among the chiller, chilled water pump, condenser water pump, and cooling tower has rarely been considered. Because of the mutual influence of these components, only optimizing the power consumption of certain components may cause increases in the power consumption of other components. Thus, such a method can only realize local optimization and is unable to achieve optimal operating efficiency of a chiller plant system.

Chiller plants (central AC waterside systems) are also referred to as central AC chilled water systems, which play the role of refrigeration, chilled water distribution, and heat removal. It consists of a chiller unit for refrigeration, a chilled water pump for chilled water delivery, a condenser water pump for heat transmission, and a cooling tower for heat removal. Its function is similar to that of the human heart. Because the chiller plant system is responsible for the cooling source (chilled water) for an entire building or factory, its power consumption is considerable and typically accounts for 60%–75% of the total power consumption of the AC system and 25%–45% of the total power consumption of a building. Thus, optimizing the operating efficiency of a chiller plant can effectively reduce its power consumption and thereby substantially reduce energy costs.

The operation of chiller plant components is typically set and modulated according to human experience or proportional–integral–derivative (PID) controllers based on pressure and temperature. However, these methods are not scientific and systematic and lack the logical basis of optimization, resulting in inaccurate chiller plant operation and excessive energy consumption. Therefore, the objective of this study was to investigate methods for effectively optimizing the operating models and parameters of the components of chiller plants, thereby enhancing overall operating efficiency and reducing energy cost.

2. Traditional Control of Chiller Plants

2.1 Judgment according to human experience

Experience-based control is generally inaccurate and unscientific. Specifically, the components of a chiller plant are set and modulated by on-site operators based on the weather, the use status of indoor space, and their personal experience. However, operators often tend to overly increase the operating capacity of the chiller plant to ensure sufficient cooling capacity for the building in question. In other words, the control of chiller plants depends solely on the subjective judgment of operators and lacks objective scientific control procedures. Thus, the operation of chiller plants is unreliable, unstable, and not energy efficient.

2.2 Control based on temperature and pressure

The control methods that have been most extensively applied to chiller plants are PID controllers and direct digital control that incorporates a PID controller. Both of these control methods use changes in temperature and pressure as the basis for setting and modulating the operating status of various components of a chiller plant.

However, neither PID control nor direct digital control are capable of achieving optimal chiller plant operation for two main reasons. First, the control models that use PID as the basic control logic adopt only independent control variables, such as temperature and pressure, to set and modulate the operating status of chiller plant components. However, independent control variables are not directly related to energy efficiency optimization. These models thus fail to consider the relationship among components from the perspective of energy efficiency optimization and are unable to effectively coordinate and integrate the operation of various components. Thus, chiller plants often have low-efficiency operation. Second, a typical PID feedback control uses the binary values of setpoint and feedback signal as well as proportional, integral, and derivative terms to calculate a proportional value before using the proportional value to reset and modulate the operating status of the controlled equipment. Because calculations of the proportional value do not consider the operating performance of the equipment in question, the optimal proportional value for the operating performance optimization of a chiller plant cannot be easily obtained. This may cause the chiller plant to operate under a nonoptimized state and lead to unnecessary energy consumption. Notably, the operating efficiency of the chiller plant may increase if the setpoints of all components are being continually adjusted (i.e., resetting the PID parameters), and this can lead to unstable operation.

3. Decision Analysis System for Chiller Plant Energy Optimization

Studies on the optimization of AC system operation have revealed two trends. One is using optimization methods, such as artificial neural networks, fuzzy reasoning, grey systems, operation research, system simulation, and dynamic programming, to explore and evaluate the optimal operation parameters for specific systems such as chiller, chilled water side, cooling water side, and airside systems. The other trend is investigating the performance of various optimization algorithms on determining optimal operation values. Both of these research approaches attempt to develop a method for realizing optimal AC system operation and thereby achieve the goal of energy conservation.

The operation of component equipment of chiller plants is typically set and modulated based on human experience or using PID controllers based on pressure and temperature. Because these methods are not scientific or systematic and lack the logical basis of optimization, chiller plants may operate ineffectively and consume excessive amounts of energy. Accordingly, this study referred to studies on AC system optimization to construct an optimization model for the decision-making of chiller plant operation and solve the optimization problem, thereby increasing operation efficiency and avoiding energy waste. Theoretically, if the operation of a chiller plant can be optimized, then resources can be optimally allocated and there will be no need for additional energy conservation. The steps and methods for establishing the decision analysis model for chiller plant energy optimization are as follows:

Step 1: A monitoring system (or related apparatus) is used to measure and collect the operation data of various component equipment of the chiller plant in question, and the data are compiled.

Step 2: A polynomial regression is performed to determine the operation performance function for each chiller plant component.

Step 3: Mathematical programming is conducted to establish decision analysis model for chiller plant energy optimization.

Step 4: Simulated annealing (SA), genetic algorithm (GA), particle swarm optimization (PSO), and harmony search (HS) are used to identify the decision variables for the decision analysis model for chiller plant energy optimization. The algorithms are then compared in terms of their performance.

Step 5: A decision support system is employed to establish the decision analysis model for chiller plant energy optimization.

In summary, this study developed a decision analysis (support) model for chiller plant energy optimization that enables rapid model construction and analysis and can serve as an objective basis for equipment designers and operation management personnel to perform optimized control of chiller plant components. The operation of chiller plant components can be optimized based on the optimization parameters, and the chiller plant operation can thus become both energy-saving and efficient. The main function of the developed system was to help users simulate the optimal start–stop model and operating load for all chiller plant components under various cold energy (unit: refrigeration ton [RT]) requirements and calculate the total power after optimization. The results can serve as an objective and reliable basis for users to improve the operation of chiller plants.

4. Case Test and Analysis

4.1 Specification of the case system

An actual chiller plant was used to test the performance of the energy optimization decision analysis system developed in this study. The case system was a small chiller plant, the capacity of which was 600 RT. It consisted of two centrifugal chillers, two centrifugal coupled primary chilled water pumps, two centrifugal coupled secondary chilled water pumps, two centrifugal coupled condenser water pumps, and two centrifugal cooling tower fans connected in parallel. The first and second chillers were separately provided with chilled water and cooled water by the first and second primary chilled water pump and condenser water pump, respectively. The temperature of the chilled water was 7ºC, and that of the cooled water was 30ºC. The equipment specifications and operating conditions are listed in Table 1.

4.2 Energy optimization decision analysis (support) system for the case system

Based on the collected operation data of the case system, a polynomial regression was performed to determine the operation performance function of each chiller plant component. Based on the previously established architecture and problem-solving method for the decision analysis model for chiller plant energy optimization, this study used the performance function and the actual specification and operating conditions (requirements) of the case system and employed Borland C++ Builder to write and edit the computing program and interface of the energy optimization decision analysis (support) system. Figure 1 shows the operating interface of the decision analysis (support) system developed in this study.

The area in red labeled “number 1” comprises operation buttons for users to start and stop calculations and save the results.

The area in red labeled “number 2” shows the parameters, including algorithm parameters and related requirements (constraints); values are input by users.

The area in red labeled “number 3” presents the constraints. The system calculates the constraint values according to the parameters. Subsequently, all results should satisfy the constraints.

The area in red labeled “number 4” indicates the record history, which lists all of the calculation results that can serve as a reference for subsequent problem solving.

The area in red labeled “number 5” is a convergence diagram produced from the system calculation. The horizontal axis is the number of calculations, and the vertical axis is the amount of energy consumed.

Table 1. Specification of the case chiller plant

	Device	Capacity	Water pressure	OLR Min.	OLR Max.
(I)	Chiller				
	CH_1	300(RT)	-	40(%)	100(%)
	CH_2	300(RT)	-	40(%)	100(%)
(II)	Primary Chilled Water Pump(Constant Speed Pump)				
	PCP_1	750(GPM)	3.5(KG/cm^2)	100(%)	100(%)
	PCP_2	750(GPM)	3.5(KG/cm^2)	100(%)	100(%)
(III)	Secondary Chilled Water Pump(Variable Speed Pump)				
	SCP_1	800(GPM)	6.0(KG/cm^2)	50(%)	50(%)
	SCP_2	800(GPM)	6.0(KG/cm^2)	50(%)	50(%)
(IV)	Condenser Water Pump(Constant Speed Pump)				
	CWP_1	1000(GPM)	4.0 KG/cm^2	100(%)	100(%)
	CWP_2	1000(GPM)	4.0 KG/cm^2	100(%)	100(%)
(V)	Cooling Tower Fan(Variable Speed Fan)				
	CTF_1	2200(CMM)	-	50(%)	50(%)
	CTF_2	2200(CMM)	-	50(%)	50(%)

Operating Condition of Chiller Plant (parameter)	Setting Value
(1) $C_{\text{Chilled Water}}$	1 (Kcal/Kg-℃)
(2) $\Delta T_{\text{Chilled Water}}$	5 (℃)
(3) $C_{\text{Condenser Water}}$	1 (Kcal/Kg-℃)
(4) $\Delta T_{\text{Condenser Water}}$	5 (℃)
(5) C_{Air}	0.24 (Kcal/Kg-℃)
(6) ΔT_{Air}	5 (℃)
(7) $P_{SCP,i}$	2.3 (Kg/KG/cm^2)
(8) $P_{SCP,i}$	3.8 (Kg/KG/cm^2)
(9) $P_{CWP,i}$	3.2 (Kg/KG/cm^2)
(10) Q_{max}	600 (RT)
(11) V	Depend on outside air condition(dry bulb temperature 、relative humidity)

The area in red labeled "number 6" records the optimal results, including the number of calculations, number of chillers that began operation, and the operating load of each chiller plant component.

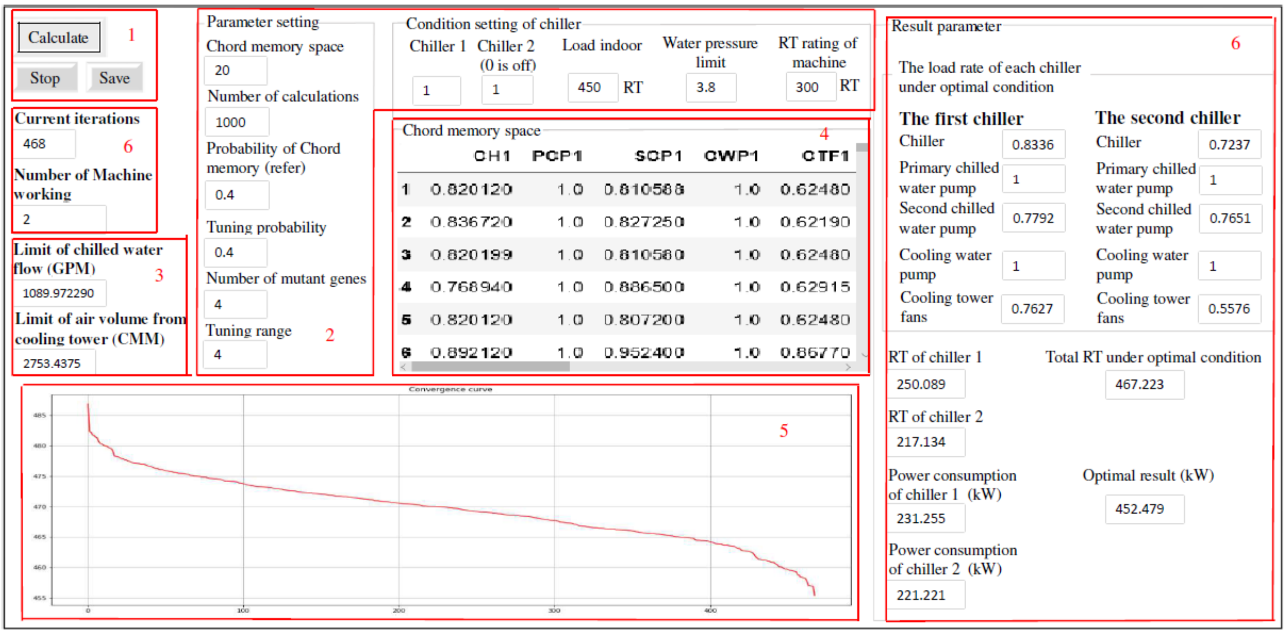

Figure 1. Operating interface of the decision analysis model for chiller plant energy optimization

4.3 Comparative analysis of efficiency (benefits)

Tables 2 and 3 present the power consumption and operating load of each component and the number of iterations calculated and performed using SA, GA, PSO, and HS when *Q* = 180 RT (30% total load), 210 RT(35% total load), 240 RT (40% total load), 270 RT (45% total load), 300 RT (50% total load), 330 RT (55% total load), 360 RT (60% total load), 390 RT (65% total load), 420 RT (70% total load), 450 RT (75% total load), and 480 RT (80% total load). The number of iterations denotes the solution convergence speed of each algorithm. A high number of iterations indicates short convergence time; that is, the optimal solution can be determined within a short time frame. According to the tables, HS demonstrated more satisfactory energy-saving performance and calculation speed when compared with SA, GA, and PSO. Although HS had more power than PSO when Q = 420, 450, and 480 RT, its calculation required fewer iterations. Therefore, HS was determined to be a cost-effective method that is advantageous for optimizing chiller plant operation. This study thus adopted HS as the problem-solving method for the decision analysis model for chiller plant energy optimization.

Table 2. Comparison of the solution results (power) of the four algorithms

	RT	CH1	PCP1	SCP1	CWP1	CTF1	CH2	PCP2	SCP2	CWP2	CTF2	Power(Kw)	Saving(Kw)	Saving(%)
Original	180.00	0.00%	0.00%	86.67%	0.00%	86.67%	60.00%	100.00%	86.67%	100.00%	86.67%	239.0500	-	-
SA	180.14	0.00%	0.00%	50.00%	0.00%	50.00%	60.05%	100.00%	75.09%	100.00%	56.40%	215.5851	23.4649	9.8159
GA	180.01	0.00%	0.00%	50.02%	0.00%	50.03%	60.00%	100.00%	73.34%	100.00%	50.04%	214.3441	24.7059	10.3350
PSO	180.00	0.00%	0.00%	50.00%	0.00%	50.09%	60.00%	100.00%	73.34%	100.00%	50.02%	214.3349	24.7151	10.3389
HS	180.00	0.00%	0.00%	50.00%	0.00%	50.00%	60.00%	100.00%	73.34%	100.00%	50.00%	214.3326	24.7174	10.3399
Original	210.00	0.00%	0.00%	86.67%	0.00%	86.67%	70.00%	100.00%	86.67%	100.00%	86.67%	262.7500	-	-
SA	210.64	0.00%	0.00%	50.00%	0.00%	56.50%	70.21%	100.00%	74.20%	100.00%	50.00%	224.5322	38.2178	14.5453
GA	210.00	0.00%	0.00%	50.13%	0.00%	50.05%	70.00%	100.00%	73.34%	100.00%	50.05%	223.6317	39.1183	14.8880
PSO	210.01	0.00%	0.00%	50.00%	0.00%	50.00%	70.00%	100.00%	73.35%	100.00%	50.01%	223.6105	39.1395	14.8961
HS	210.00	0.00%	0.00%	50.00%	0.00%	50.00%	70.00%	100.00%	73.34%	100.00%	50.00%	223.6056	39.1444	14.8979
Original	240.00	40.00%	100.00%	90.00%	100.00%	90.00%	40.00%	100.00%	90.00%	100.00%	90.00%	333.8500	-	-
SA	240.89	80.30%	100.00%	73.66%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	54.02%	231.1503	102.6997	30.7622
GA	240.02	80.01%	100.00%	73.52%	100.00%	50.03%	0.00%	0.00%	50.02%	0.00%	50.04%	230.6743	103.1757	30.9048
PSO	240.00	80.00%	100.00%	73.52%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.02%	230.6653	103.1847	30.9075
HS	240.00	80.00%	100.00%	73.52%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.00%	230.6608	103.1892	30.9088
Original	270.00	45.00%	100.00%	90.00%	100.00%	90.00%	45.00%	100.00%	90.00%	100.00%	90.00%	357.2500	-	-
SA	270.04	90.01%	100.00%	74.15%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	51.49%	244.5667	112.6833	31.5419
GA	270.01	90.00%	100.00%	73.51%	100.00%	50.16%	0.00%	0.00%	50.00%	0.00%	50.16%	244.2063	113.0437	31.6427
PSO	270.00	90.00%	100.00%	73.52%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.07%	244.1917	113.0583	31.6468
HS	270.00	90.00%	100.00%	73.52%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.00%	244.1853	113.0647	31.6486
Original	300.00	50.00%	100.00%	90.00%	100.00%	90.00%	50.00%	100.00%	90.00%	100.00%	90.00%	380.6500	-	-
SA	300.00	100.00%	100.00%	73.78%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.00%	275.4246	105.2254	27.6436
GA	300.07	40.01%	100.00%	73.51%	100.00%	50.05%	60.02%	100.00%	73.35%	100.00%	50.01%	368.0908	12.5592	3.2994
PSO	300.00	100.00%	100.00%	73.51%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.41%	275.3174	105.3326	27.6718
HS	300.00	100.00%	100.00%	73.52%	100.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.00%	275.3008	105.3492	27.6761
Original	330.00	55.00%	100.00%	93.33%	100.00%	93.33%	55.00%	100.00%	93.33%	100.00%	93.33%	411.3800	-	-
SA	334.97	40.00%	100.00%	75.37%	100.00%	67.42%	71.66%	100.00%	73.38%	100.00%	55.01%	381.1257	30.2543	7.3543
GA	330.00	40.00%	100.00%	73.51%	100.00%	50.03%	70.00%	100.00%	73.42%	100.00%	50.05%	377.3540	34.0260	8.2712
PSO	330.00	40.00%	100.00%	73.52%	100.00%	50.00%	70.00%	100.00%	73.34%	100.00%	50.22%	377.3229	34.0571	8.2787
HS	330.00	40.00%	100.00%	73.52%	100.00%	50.00%	70.00%	100.00%	73.34%	100.00%	50.00%	377.3113	34.0687	8.2816
Original	360.00	60.00%	100.00%	93.33%	100.00%	93.33%	60.00%	100.00%	93.33%	100.00%	93.33%	434.7800	-	-
SA	361.87	40.00%	100.00%	76.07%	100.00%	62.25%	80.62%	100.00%	74.61%	100.00%	50.00%	391.1307	43.6493	10.0394
GA	360.01	40.00%	100.00%	73.51%	100.00%	50.02%	80.00%	100.00%	73.36%	100.00%	50.05%	387.7723	47.0077	10.8118
PSO	360.00	40.00%	100.00%	73.51%	100.00%	50.00%	80.00%	100.00%	73.34%	100.00%	50.08%	387.7642	47.0158	10.8137
HS	360.00	40.00%	100.00%	73.51%	100.00%	50.00%	80.00%	100.00%	73.34%	100.00%	50.00%	387.7596	47.0204	10.8148
Original	390.00	65.00%	100.00%	93.33%	100.00%	93.33%	65.00%	100.00%	93.33%	100.00%	93.33%	458.1800	-	-
SA	390.42	40.00%	100.00%	74.93%	100.00%	60.46%	90.14%	100.00%	73.58%	100.00%	74.08%	407.9981	50.1819	10.9524
GA	390.01	40.00%	100.00%	73.59%	100.00%	56.16%	90.00%	100.00%	73.34%	100.00%	51.79%	404.8732	53.3068	11.6345
PSO	390.00	40.00%	100.00%	73.52%	100.00%	54.34%	90.00%	100.00%	73.34%	100.00%	53.61%	404.8197	53.3603	11.6461
HS	390.00	40.00%	100.00%	73.52%	100.00%	54.72%	90.00%	100.00%	73.34%	100.00%	53.21%	404.8157	53.3643	11.6470
Original	420.00	70.00%	100.00%	93.33%	100.00%	93.33%	70.00%	100.00%	93.33%	100.00%	93.33%	481.5800	-	-
SA	420.00	40.00%	100.00%	74.01%	100.00%	75.95%	100.00%	100.00%	76.55%	100.00%	54.49%	436.7230	44.8570	9.3145
GA	420.00	84.83%	100.00%	73.63%	100.00%	57.31%	55.17%	100.00%	73.36%	100.00%	58.95%	431.8244	49.7556	10.3317
PSO	420.01	84.64%	100.00%	73.52%	100.00%	58.03%	55.36%	100.00%	73.34%	100.00%	58.18%	431.7623	49.8177	10.3446
HS	420.00	84.34%	100.00%	73.52%	100.00%	57.27%	55.66%	100.00%	73.34%	100.00%	58.99%	431.7726	49.8074	10.3425
Original	450.00	75.00%	100.00%	93.33%	100.00%	93.33%	75.00%	100.00%	93.33%	100.00%	93.33%	504.9800	-	-
SA	454.55	86.08%	100.00%	75.18%	100.00%	80.58%	65.44%	100.00%	77.59%	100.00%	50.89%	449.2070	55.7730	11.0446
GA	450.01	81.35%	100.00%	77.60%	100.00%	63.98%	68.65%	100.00%	73.57%	100.00%	60.54%	444.3261	60.6539	12.0111
PSO	450.01	81.00%	100.00%	77.79%	100.00%	62.32%	69.01%	100.00%	73.35%	100.00%	62.18%	444.3008	60.6792	12.0162
HS	450.00	81.02%	100.00%	77.75%	100.00%	61.11%	68.98%	100.00%	73.40%	100.00%	63.38%	444.3011	60.6789	12.0161
Original	480.00	80.00%	100.00%	93.33%	100.00%	93.33%	80.00%	100.00%	93.33%	100.00%	93.33%	528.3800	-	-
SA	482.28	82.53%	100.00%	82.69%	100.00%	83.63%	78.23%	100.00%	80.23%	100.00%	50.00%	463.1750	65.2050	12.3406
GA	480.04	82.64%	100.00%	86.70%	100.00%	66.98%	77.37%	100.00%	73.39%	100.00%	65.84%	460.0867	68.2933	12.9250
PSO	480.00	83.33%	100.00%	86.64%	100.00%	66.22%	76.67%	100.00%	73.46%	100.00%	66.58%	460.0342	68.3458	12.9350
HS	480.00	83.44%	100.00%	83.44%	100.00%	66.73%	76.56%	100.00%	73.52%	100.00%	66.11%	460.0464	68.3336	12.9327

Table 3. Comparison of number of iterations of the four algorithms

	180(RT)	210(RT)	240(RT)	270(RT)	300(RT)	330(RT)	360(RT)	390(RT)	420(RT)	450(RT)	480(RT)	Total iterations
SA	202	199	197	191	188	190	198	168	170	161	201	2065
GA	172	161	201	108	109	222	118	99	98	128	210	1626
PSO	162	155	190	128	110	162	109	141	129	138	142	1566
HS	143	125	180	128	109	158	107	140	121	130	131	1472

5. Conclusion

This study used the developed operation optimization decision analysis (support) system to determine the optimal operation status (operating load) of the chiller plant component equipment and thus obtain the optimal operation energy consumption when no existing equipment was changed and the level of comfort provided by the AC system was not influenced. After comparing the solution quality and convergence time of the four algorithms, this study discovered that HS exhibited the most satisfactory performance (efficiency) and was the easiest method to understand and implement.

6. Acknowledgment

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