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Operation Optimisation of Combined Cooling, Heating and Power Systems

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Improving the overall performance of combined cooling, heating, and power (CCHP) systems have received great attention from both industry and academia. Due to the high amount of nonlinearities involved in detailed CCHP operations, it has to be formulated as a complex nonlinear programming (NLP) model. The existing work usually uses stochastic algorithms, such as the Genetic Algorithm (GA), which in general have difficulty obeying equality constraints for solving large-scale NLP problems. This paper presents an effective deterministic algorithm to satisfy all equality constraints and find optimal solutions in acceptable computation time. A case study has been carried out to compare our method with GA. The solution given by GA has large deviations in the constraints of cooling. Our optimal solution based on the deterministic algorithm can achieve the same energy-saving but satisfies all operational constraints, which demonstrated the validity and efficiency of our proposed method.

1. Introduction

A typical combined cooling, heating, and power (CCHP) system consist of a power generator unit (PGU), cooling components, and heating components. PUG consumes fuel to produce electric energy and the heat from exhaust gas (Orre et al., 2018). This exhaust heat splits into two parts, one provides heat to a heating system, and another is utilised to drive chillers (cooling system), converting around 75 % of the fuel source into useful energy. The efficiency of a CCHP system depends on its operations greatly. Operation optimisation has been widely studied for improving CCHP performances. Due to the nonlinearities required for formulating detailed CCHP operations, including the nonlinear coefficients of PGU efficiency and cooling unit efficiency, CCHP operations have to be modelled as a nonlinear programming (NLP) or mixed-integer nonlinear programming (MINLP) problems, namely nonconvex optimisation. Stochastic and deterministic methods constitute two classes of methods for nonconvex global optimisation (Cho et al., 2014).

The stochastic methods such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are often recommended for solving complex nonlinear problems. Ebrahimi et al. (2012) used GA to optimise a CCHP cycle to provide energy to a residential building. They stated that the energy-saving ratios could achieve more than 69 % in summer and 25 % in winter. Wang et al. (2010) employed GA to optimise a building cooling heating and power (BCHP) system to maximise energy saving and environmental impact reduction, where the optimal ratio of electric cooling to cool load balances the relationship between the waste heat and the generated electricity from the PGU. Even many stochastic methods have been reported for optimising CCHP operations, and their main drawback is the difficulty to handle constrained problems as the stochastic search operators frequently produce infeasible solutions. Deterministic approaches generate a sequence of points that converge to a globally optimal solution based on the analytical properties of the problem. Hashemi (2009) proposed an offline (MINLP) model for optimal operation of CCHP systems, and also used LINGO to find optimal energy flow regarding both the amounts of electric, thermal and cooling loads in each time interval and the prices of electricity and utilities. Lu et al. (2015) used the MINLP approach to solve the optimal scheduling

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problems of energy systems in building integrated with energy generation and thermal energy storage. Their results showed that the strategy could reduce operational energy costs greatly (about 25 %) compared with a rule-based strategy.
Based on the above discussion, compared with deterministic methods, stochastic methods are less mathematically complicated, contain randomness in the search procedure, but converge to a solution much slower. This paper presents a deterministic approach for optimising an industrial CCHP problem and compares our method with the most popular stochastic method, namely GA.

2. Problem statement

The problem addressed for comparing the GA method and the deterministic method is an industrial problem (Li et al., 2018). It is a CCHP-CHR system composed of a power generator unit (PGU), a PGU heat recovery unit (PGUHRU), a heat pump (HP), a hot water unit (HWU), exchangers, an absorption chiller (AC), and a condensation heat recovery unit (CHRU). As presented in Figure 1, both the electric grid (E_{grid}) and PGU (E_{pgu}) provide the electricity to the building. The cooling system generates cool air with the use of the HP (Q_{hp}) driven by electricity (E_{hp}) and the absorption chiller (Q_{ab}) driven by the heat from the PGUHRU ($Q_{hre,ab}$). The heating provided to the building are mainly from the hot water unit (Q_{hwu}) driven by electricity (E_{hwu}), the heat (Q_{hwe}) exchanged from the PGU heat recovery unit ($Q_{hre,hwe}$), and the heat (Q_{ch}) from the condensation heat recovery unit. The PGUHRU collects the waste heat from PGU jacket water and exhaust gas. CHRU includes two heat exchangers since the energy equality of HP and AC is different, and some low-grade heat ($Q_{ex,ch}$) from AC should be abandoned. The temperatures of CHRU are shown in Table 1. This CCHP-CHR system performs much better than the traditional CCHP system as it utilises the condensation heat from the heat pump and absorption chiller.

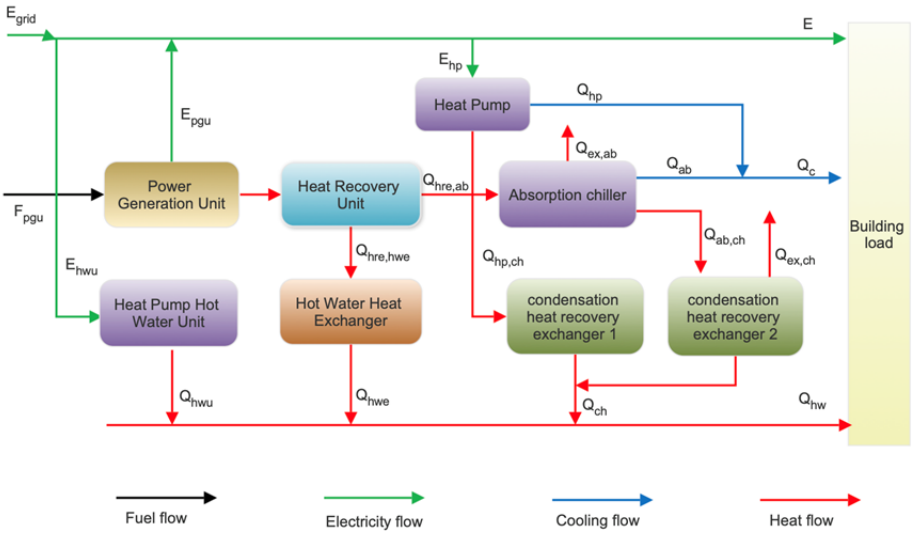

Figure 1: A CCHP-CHR structure

3. Modelling of the CCHP-CHR system

Modelling the CCHP-CHR system includes formulating the energy balance and efficiency in each unit, the relationships among the units, and the satisfactions of energy requirements. The whole system is divided into three sub-systems, an electricity system, a cooling system, and a heating system. And the system planning period consists of several independent time intervals (t).

3.1 Modelling of the electricity system

In each operating time interval (t), the electricity from the electric grid ($E_{grid}(t)$) and power generation unit ($E_{pgu}(t)$) provides the electricity to the building ($E_{load}(t)$), heat pump ($E_{hp}(t)$) and hot water unit ($E_{hwu}(t)$), as shown in Figure 1.

$$E_{pgu}(t) + E_{grid}(t) = E_{load}(t) + E_{hp}(t) + E_{hwu}(t) \tag{1}$$

Eq(2) describes that the electricity produced by the power generation unit (*$E_{pgu}(t)$*) is affected by the fuel consumption (*$F_{pgu}(t)$*), electricity efficiency (*η_{el}*) and thermal efficiency (*η_{th}*) of the power generator. Thermal efficiency is the energy efficiency of an internal combustion engine, and electricity efficiency is the mechanical efficiency of the generator.

$$E_{pgu}(t) = F_{pgu}(t) \cdot \eta_{el} \cdot \eta_{th} \tag{2}$$

This electricity efficiency (*η_{el}*) and thermal efficiency (*η_{th}*) of the power generator are obtained by polynomial fitting of statistic data from American Society of Heating, Refrigerating and Air-Conditioning Engineers(Wu et al., 2016), shown as Eq(3) and (4).

$$\eta_{el} = a_0 + a_1 PLR_{pgu} + a_2 PLR_{pgu}{}^2 \tag{3}$$

$$\eta_{th} = b_0 + b_1 PLR_{pgu} + b_2 PLR_{pgu}{}^2 \tag{4}$$

PLR_{pgu} is the part-load ratio of the power generator, which is defined in Eq(5), where *$E_{pgu,\ rated}$* (*t*) is the rated capacity of the power generator.

$$PLR_{pgu} = \frac{E_{pgu}(t)}{E_{pgu,rated}(t)} \tag{5}$$

Similar to the power generation unit, the electricity bought from the electric grid (*E_{grid}* (*t*)) is constrained as follows:

$$E_{grid}(t) = F_{grid}(t) \cdot \eta_{pg,grid} \cdot \eta_{pt,grid} \tag{6}$$

where *F_{grid}* (*t*) is the fuel consumed by the grid, *$\eta_{pg,grid}$* and *$\eta_{pt,grid}$* are the power generation efficiency and transmission efficiency of the grid. Since the range of *$\eta_{pg,grid}$* and *$\eta_{pt,\ the\ grid}$* is not very large, they are taken as constant here.

As shown in Eq(1), the heat pump and hot water unit also require electric energy. The electricity consumed by the heat pump (*E_{hp}* (*t*)) and hot water unit (*E_{hwu}* (*t*)) is related to their supplying thermal energy (*Q_{hp}* (*t*) or *Q_{hwu}* (*t*)) and the relevant coefficients (*COP_{hp}* or *COP_{hwu}*), as expressed in Eq(7) and Eq(8).

$$E_{hp}(t) = \frac{Q_{hp}(t)}{COP_{hp}} \tag{7}$$

$$E_{hwu} = \frac{Q_{hwu}(t)}{COP_{hwu}} \tag{8}$$

3.2 Modelling of the cooling system

As presented in Figure 1, the cooling load of the building (*$Q_{load,c}$* (*t*)) is the sum of the cooling from the absorption chiller (*Q_{ab}* (*t*)) and heat pump (*Q_{hp}* (*t*)).

$$Q_{ab}(t) + Q_{hp}(t) = Q_{load,c}(t) \tag{9}$$

Eq(10) and Eq(11) describe the cooling from the absorption chiller (*Q_{ab}* (*t*)), where *$Q_{hre,ab}$* (*t*) is a part of the heat recovered from the power generator and used to drive the absorption chiller, *COP_{ab}* is the cooling coefficient of the absorption chiller simulated by polynomial fitting, *c* is the coefficient of the formulation of *COP_{ab}*, and *PLR_{ab}* is the part-load ratio of the absorption chiller similar to Eq(5).

$$Q_{ab}(t) = Q_{hre,ab}(t) \cdot COP_{ab} \tag{10}$$

$$COP_{ab} = c_0 + c_1 PLR_{ab} + c_2 PLR_{ab}{}^2 + c_3 PLR_{ab}{}^3 \tag{11}$$

In order to determine the heat recovered from the power generator to drive the absorption chiller (*$Q_{hre,ab}$* (*t*)), the heat recovered from the power generator (*Q_{hre}* (*t*)) must be calculated as follows:

$$Q_{hre}(t) = F_{pgu}(t) \cdot (1 - \eta_{th}) \cdot \eta_{hre} \tag{12}$$

where *η_{hre}* is the efficiency of the heat recovery unit which represents the heat loss of the recovered heat from PGU, *F_{grid}* (*t*)·(1- *η_{th}*) means the waste heat recovered from the power generator.

The part of recovered heat of power generator used to drive the absorption chiller (*$Q_{hre,ab}$* (*t*) in Eq(10) can be expressed in Eq(13). *α*(*t*) is the ratio of recovered heat from the power generator sent to the absorption chiller.

$$Q_{hre,ab}(t) = \alpha(t) \cdot Q_{hre}(t) \tag{13}$$

3.3 Modelling of the heating system

The energy balance of the heating system in Figure 1 shows that the sum of the hot water load of the building ($Q_{load,hw}(t)$) and the waste heat from the condensation heat recovery unit ($Q_{ex,ch}(t)$) is equal to the summation of a part of heat recovered from the power generator to produce hot water ($Q_{hwe}(t)$), the heat from hot water unit (Q_{hwu}), and the heat recovered from the condensation heat recovery unit ($Q_{ch}(t)$). $Q_{ex,ab}(t)$ is not included since it is represented in the energy balance of absorption chiller. $Q_{ex,ch}(t)$ means part of low-grade condensation heat($Q_{ch}(t)$) is abandoned.

$$Q_{hwe}(t)+Q_{hwu}(t)+Q_{ch}(t)=Q_{load,hw}(t)+Q_{ex,ch}(t) \tag{14}$$

First, the heat recovered from a power generator to produce hot water ($Q_{hwe}(t)$) can be presented as:

$$Q_{hwe}(t) = (1-\alpha(t)) \cdot Q_{hre}(t) \cdot \eta_{hwe} \tag{15}$$

where $(1-\alpha(t))\cdot Q_{hre}(t)$ means the heat from the power generator which is sent to the hot water heat exchanger, and η_{hwe} is the efficiency of the hot water heat exchanger.
Second, the heat recovered from the condensation heat recovery unit ($Q_{ch}(t)$) is from the condensation heat from heat pump ($Q_{hp,ch}(t)$) and the condensation heat from absorption chiller ($Q_{ab,ch}(t)$). η_{chr} is the efficiency of the condensation heat recovery unit.

$$Q_{ch}(t)=\eta_{chr}\cdot(Q_{hp,ch}(t)+Q_{ab,ch}(t)) \tag{16}$$

Since the energy produced by refrigerant condensation and evaporation are similar, the cooling produced by heat pump ($Q_{ch}(t)$) is equal to the heat it generates ($Q_{hp,ch}(t)$), as shown in Eq(17).

$$Q_{hp,ch}(t)=Q_{hp}(t) \tag{17}$$

The condensation heat from the absorption chiller ($Q_{ab,ch}(t)$) is calculated in Eq(18), where $Q_{ab}(t)$ is the cooling from the absorption chiller, $Q_{hre,ab}(t)$ is the heat recovered from the power generator to drive the absorption chiller, and $Q_{ex,ab}(t)$ is the waste heat disposed of by the absorption chiller. $Q_{ab}(t)$ and $Q_{hre,ab}(t)$ represent the external heat supply while $Q_{ab,ch}(t)$ and $Q_{ex,ab}(t)$ represent where the heat going.

$$Q_{ab,ch}(t)=Q_{ab}(t)+Q_{hre,ab}(t)-Q_{ex,ab}(t) \tag{18}$$

In the condensation heat recovery unit, cool water is preheated by the low grade heat recovered from the absorption chiller ($Q_{ab,ch}(t)\cdot\eta_{chr}$) in the first condensation heat exchanger, and then enters the second condensation heat exchanger to exchange energy with the high grade energy recovered from the PGU ($Qhwe(t)$) and heat pump ($Q_{hp,ch}(t)\cdot\eta_{chr}$). Since the heat exchanged capacity of high-grade energy is stronger than that of the low grade, Eq(19) is given:

$$\frac{Q_{ab,ch}(t)\cdot\eta_{chr}}{T_{ab,ch}-T_w}\le\frac{Q_{hp,ch}(t)\cdot\eta_{chr}+Q_{hwe}(t)}{T_{hw}-T_{ab,ch}} \tag{19}$$

where $T_{ab,ch}$ is the temperature of condensation water from absorption chiller, T_w is the environmental water temperature, and T_{hw} is the hot water temperature in the building.

3.4 Objective function

The objective of the optimal operation of CCHP-CHR systems is to minimise the total energy consumption, as shown in Eq(20).

$$Min \quad F_{pgu}(t) + F_{grid}(t) \tag{20}$$

The deterministic model for optimising CCHP-CHR operation consists of the objective function given in Eq(20) and the constraints given from Eqs(1) - (19). It can be noted that the CCHP-CHR operation addressed is featured by many nonlinearities, such as Eqs(2) - (4), Eq(6), Eqs(10) - (13), Eq(15) and Eq(19).

4. Case study

In case studies, the stochastic method (GA) and the deterministic method are used to find the optimal operational solutions of the CCHP-CHR. GA is based on biological evolution and uses three basic operators (selection, crossover, and mutation) to search for the global optimal solution. GA will search the optimal setpoint of the PGU and cooling ratio, while the other variables are calculated through energy balance until the convergent condition is reached or the maximum number of iteration is achieved. GA usually uses penalty function to solve the problem with constraints. Even the value of the penalty function is small, and the error could be intolerable in this case since the errors are enlarged after calculation. The number of evolutionary generations here was 500, and the population size was 50. Our method employs branch-and-cut methods to break an NLP model down into a list of subproblems. Each subproblem is analysed and either a) is shown to not have a feasible or optimal solution, or b) an optimal solution to the subproblem is found, e.g., because the subproblem is shown to be convex, or c) the subproblem is further split into two or more subproblems which are then placed on the list. Given appropriate tolerances, after a finite, though a possibly large number of steps a solution provably global optimal to tolerances is returned. The CCHP-CHR parameters are shown in Table 1.

Table 1: The CCHP-CHR parameters

Parameters	Symbol	Value	Parameters	Symbol	Value
Coefficients of electrical efficiency	a_0	0.03998	Cool water temperature	T_w	15 ^oC
	a_1	0.7597	The temperature of condensation water from the absorption chiller	$T_{ab,ch}$	31 ^oC
	a_2	-0.5147	Hot water temperature	T_{hw}	45 ^oC
Coefficients of thermal efficiency	b_0	0.7361	The efficiency of power generation	$\eta_{pg,grid}$	0.35
	b_1	0.3016	The efficiency of power transmission	$\eta_{pt,grid}$	0.92
	b_2	-0.1193	Peak value Electricity price /¥/(kWh) (8:00 - 10:00, 18:00 - 23:00)		1.346
Coefficients of absorption chiller	c_0	0.425	Flat value Electricity price /¥/(kWh) (7:00 - 8:00, 11:00 - 17:00)		0.9
	c_1	1.683	Valley value Electricity price /¥/(kWh) (1:00 - 6:00, 23:00 - 24:00)		0.475
	c_2	-2.419	Gas price /¥/(kWh)		0.315
	c_3	1.108	Rate capacity of the grid (kW)	$E_{grid,rc}$	50
COP of heat pump	COP_{hwu}	4.43	Rate capacity of PGU (kW)	$E_{pgu,rc}$	100
Waste heat recovery unit efficiency	η_{hre}	0.8	Rate capacity of absorption chiller (kW)	$Q_{ab,rc}$	104
Condensation heat recovery efficiency	η_{chr}	0.96	Rate capacity of a heat pump (kW)	$Q_{hp,rc}$	115
Heat exchanger efficiency	η_{hex}	0.96	Rate capacity of hot water unit (kW)	$Q_{hwu,rc}$	92

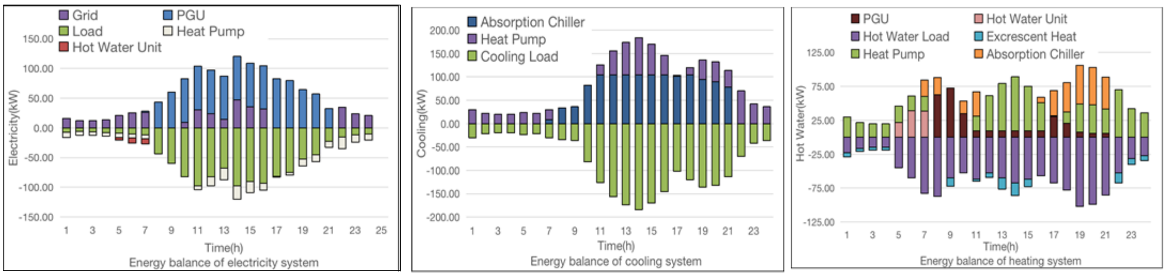

Figure 2: Optimal results of CCHP-CHR obtained by our method

Table 2 presents a comparison of the optimal solutions obtained by GA and our method. It can be found that GA gives a solution with minor errors, as $Q_{hre,hwe}(t)+Q_{hre,ab}(t)$ is larger than $Q_{hre}(t)$ in the time intervals 9, 15, 17 - 21, which does not satisfy the constraint that the waste heat recovered from the PGU is the only heat source providing to the absorption chiller and hot water heat exchanger (Figure 1). The solution obtained by the proposed method is under all operational constraints in the CCHP-CHR system, and achieves the same objective values as the GA. Worth to be mentioned, the solve time of the proposed method is no more than 3 seconds while GA spends much more time than it. Figure 2 expresses our optimal results of the energy balances between the suppliers and consumers in electricity dispatching, cooling dispatching, and hot water dispatching. In electricity dispatching, electricity from grid and PGU is supplied to a heat pump, hot water unit and the electricity load of the building. The cooling load of the building is supported by the absorption chiller and heat pump in cooling balance. The energy balance in a heating system is that the recovered heat from

PGU, heat produced by hot water unit, the condensation heat from absorption chiller and heat pump is equal to the heat load of the building and excrescent heat. The CCHP-CHR uses the condensation heat from the heat pump and absorption chiller to provide building hot water in most of the time intervals (Figure 1), and reduces the overall energy saving and cost-efficiently.

Table 2: Comparison of GA and our method

	Genetic Algorithm (GA) method				Our method			
Energy-saving (%)	21.44				21.40			
Time t (hour)	$Q_{hre,hwe}(t)$	$Q_{hre,ab}(t)$	$Q_{hre,hwe}(t)+Q_{hre,ab}(t)$	$Q_{hre}(t)$	$Q_{hre,hwe}(t)$	$Q_{hre,ab}(t)$	$Q_{hre,hwe}(t)+Q_{hre,ab}(t)$	$Q_{hre}(t)$
9	83.47	47.14	130.61	122.57	75.43	47.14	122.57	122.57
15	18.73	130.49	149.22	146.03	9.57	130.49	140.06	140.06
17	35.16	108.19	163.61	155.77	31.83	127.41	159.24	159.24
18	25.15	95.99	155.64	151.91	21.73	130.30	152.03	152.03
19	11.68	57.84	133.63	126.73	7.82	119.57	127.39	127.39
20	9.51	57.46	125.82	119.28	5.87	113.89	119.75	119.75
21	9.23	58.26	110.32	104.89	6.11	98.97	105.08	105.08

5. Conclusions

Due to the strongly nonlinear nature of the combined cooling, heating, and power (CCHP) operations, their optimisation problems are usually formulated as a nonlinear programming (NLP) or mixed-integer nonlinear programming (MINLP). Many stochastic methods based on Genetic Algorithm (GA) have been reported for optimising the CCHP operations. However, the stochastic methods use stochastic search operators and may fail to find feasible solutions for large scale problems as the searching space of the stochastic algorithm increases significantly. Taking advantage of the recent development of the deterministic method, this paper presents a rigours nonlinear programming model for CCHP-CHR. A detailed comparison of GA and our deterministic method has been carried out in an industrial case, where GA solutions showed some deviations from the system operations, while our solutions can obey all operational constraints completely. The two methods can achieve the same level of energy-saving ratio, which are 21.44 % and 21.40 %, while our method can find the optimal solution in a relatively computing time (no more than 3 s).

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References

Cho H., Smith A.D., Mago P., 2014, Combined cooling, heating and power: A review of performance improvement and optimization, Apply Energy, 136,168-185.

Ebrahimi M., Keshavarz A., Jamali A., 2012, Energy and exergy analyses of a microsteam CCHP cycle for a residential building, Energy Build, 45, 202-210.

Hashemi R., 2009, A developed offline model for optimal operation of combined heating and cooling and power systems, IEEE Transaction Energy Conversion, 24, 222-229.

Li F., Sun B., Zhang C., Zhang L., 2018, Operation optimization for combined cooling, heating, and power system with condensation heat recovery, Apply Energy, 230, 305-316.

Lu Y., Wang S., Sun Y., Yan C., 2015, Optimal scheduling of buildings with energy generation and thermal energy storage under dynamic electricity pricing using mixed-integer nonlinear programming, Apply Energy,147, 49-58.

Orre J., Bellqvist D., Nilsson L., Alstrom L., Wiklund S., 2018, Optimised integrated steel plant operation dependent on seasonal ombined heat and power plant energy demand, Chemical Engineering Transaction, 70, 1117–1122.

Wang J., Zhai Z., Jing Y., Zhang C., 2010, Optimisation design of BCHP system to maximise to save energy and reduce environmental impact, Energy, 35, 3388-3398.

Wu J., Wang J., Li S., Wang R., 2014, Experimental and simulative investigation of a micro-CCHP (micro combined cooling, heating and power) system with thermal management controller, Energy, 68, 444-453.