The evaluation method of HVAC system's operation performance based on exergy flow analysis and DEA method

Xing Fang, Xinqiao Jin, Yonghua Zhu, Bo Fan
Shanghai Jiao Tong University, China

Overview

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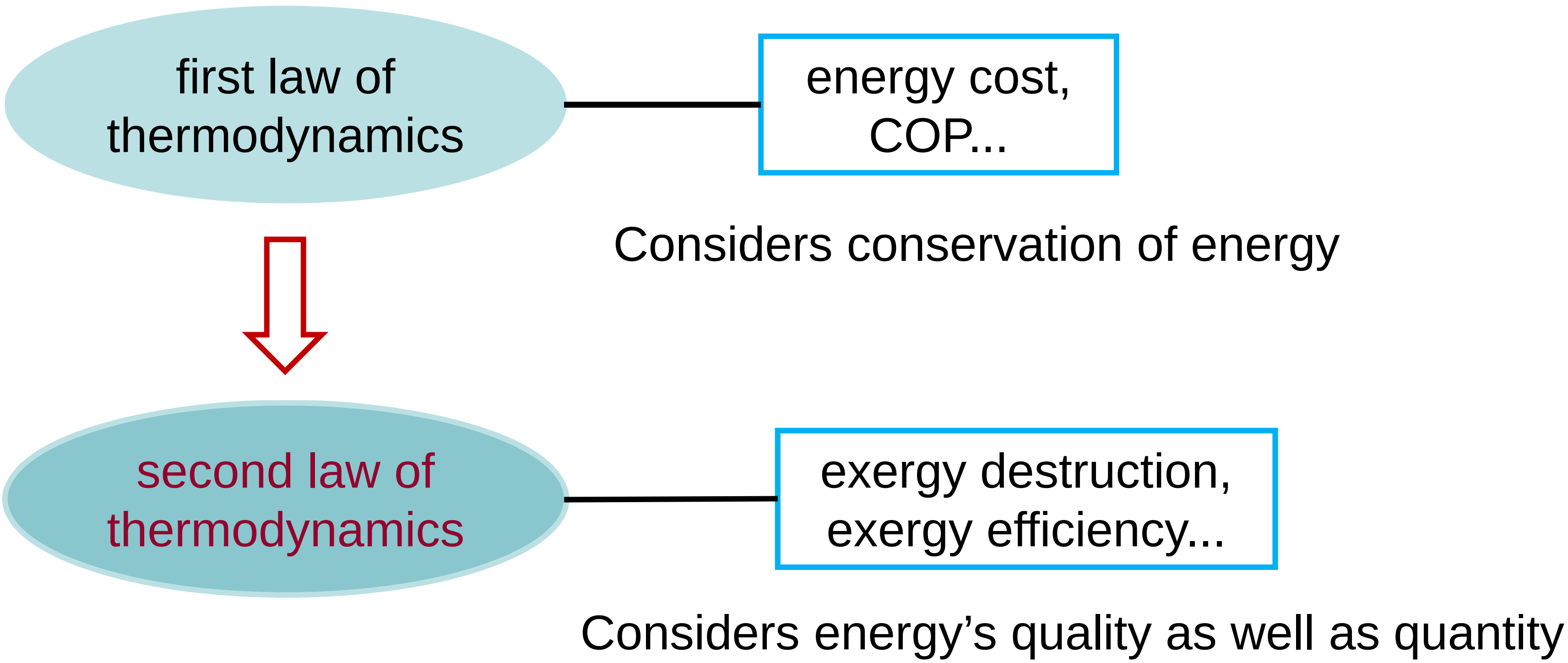
Introduction

In evaluation of operation performance of HVAC system, increasing attention is being given to thermodynamic analysis of HVAC systems.



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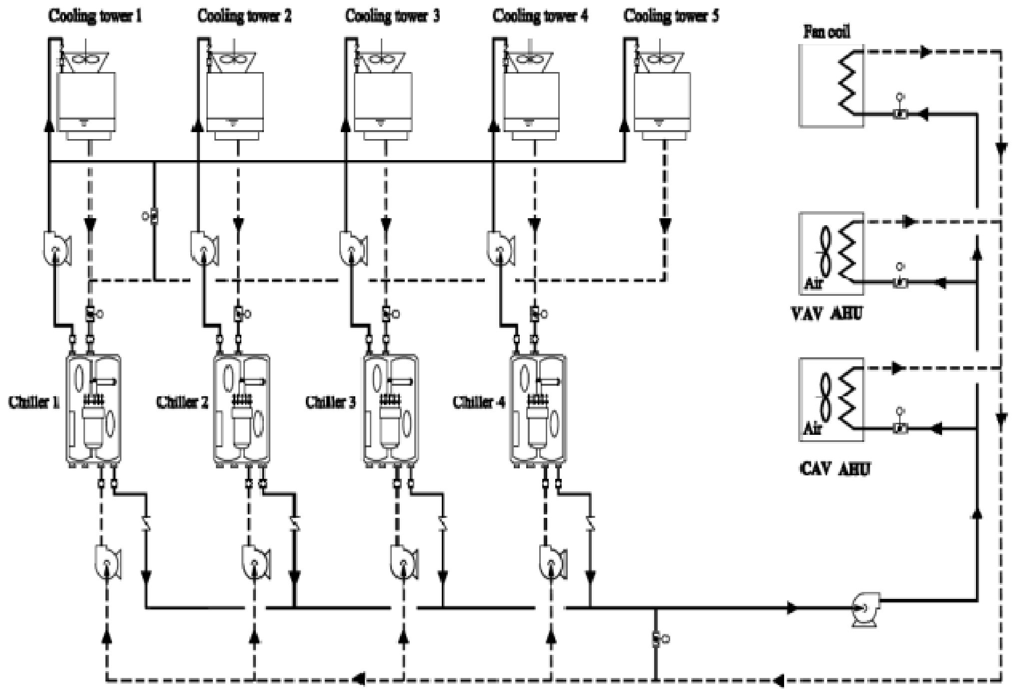
The aim of this study is to establish the benchmark of HVAC system based on exergy analysis, and propose the evaluation method of operation performance of system.

HVAC model	
↓	
Exergy flow analysis	exergy flow model
↓	
Ideal operation level	optimization techniques & DEA method
↓	
Evaluation index	control perfect index (*CPI*)
↓	
Evaluation results	control strategies

Description of HVAC system

An airport terminal's HVAC system is chosen as the studying object, which is located in Haikou, China.

The simulation model of HVAC system is build in TRNSYS.

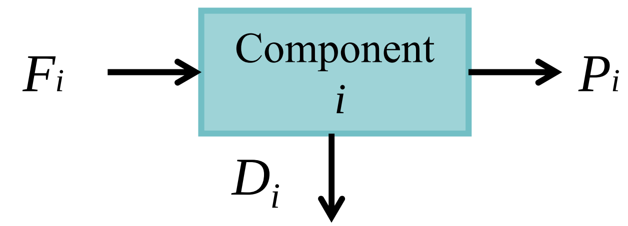


Configuration of HVAC system:

Building location	Haikou, China
Gross floor area	99,300m^2
Air-conditioned area	67,950m^2
Number of floor	4
Operating schedule	7:00 to 22:00
Cooling system	Water-cooled
Pump system	The primary pump, the secondary pump
Chillers	4 units rated capacity: T1,T2,T3:2461kW, Y4:4640kW input power: T1,T2,T3:470kW, Y4:836kW
Air handling system	40 AHUs, 202 FCUs
Design indoor dry bulb temperature and relative humidity	25□ , 55%
Design outdoor dry bulb temperature and relative humidity (summer)	34.5℃, 60%
Design outdoor dry bulb temperature and relative humidity (winter)	10℃, 85%

Evaluation method

3.1 Exergy analysis



$$D_i = F_i - P_i$$

The *exergy efficiency*, *exergy destruction ratio* and *exergy cost distribution ratio* are calculated as:

$$\eta_i = \frac{P_i}{F_i} \times 100\% = \frac{1}{k_i} \times 100\%$$

$$E_{d,i} = \frac{F_i - P_i}{\sum_{i=1}^{n} F_i - \sum_{i=1}^{n} P_i} \times 100\%$$

$$E_{dis,i} = \frac{P_i \times k^*{}_{p,i}}{\sum_{i=1}^{n} P_i \times k^*{}_{p,i}} \times 100\%$$

F_i : fuel flow of the i_{th} component;

P_i : product flow of the i_{th} component;

3.2 Control perfect index (*CPI*)

CPI is used to measure the gap between actual operation performance and ideal operation performance.

$$CPI_{sys,j} = \frac{1/D^{c}_{sys,i}}{1/D^{0}_{sys,i}}$$

$CPI_{sys,j}$: the *CPI* of HVAC system under j_{th} operation condition;

$D^{C}_{sys,j}$: actual exergy destruction of HVAC system under j_{th} operation condition;

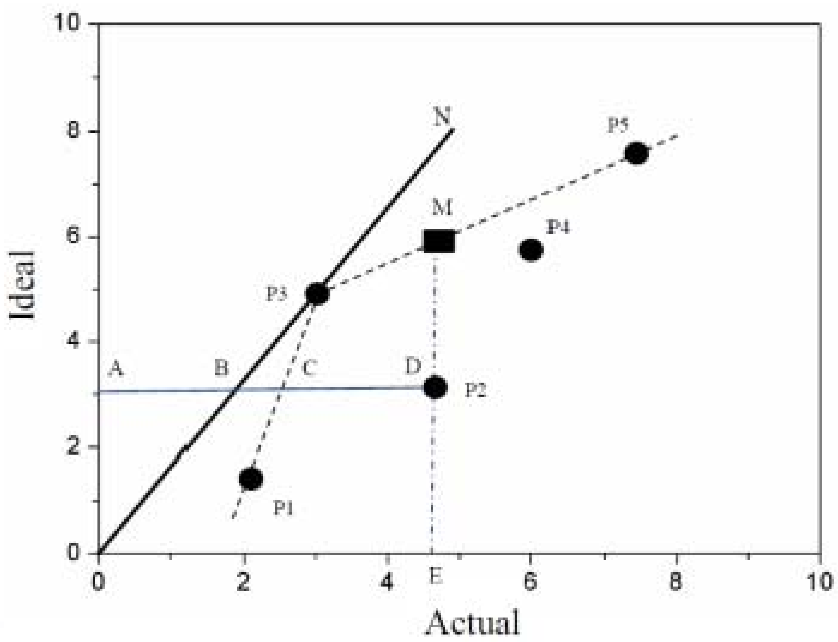
$D^{0}_{sys,j}$: ideal exergy destruction of HVAC system (the lowest exergy loss) under j_{th} operation condition.

3.3 DEA method

In this paper, we use DEA method to obtain the benchmark of HVAC system's operation performance, the ideal operation performance.

DEA is a non-parametric technique used to measure the relative efficiency of decision making units (DMU) with the same general objectives.

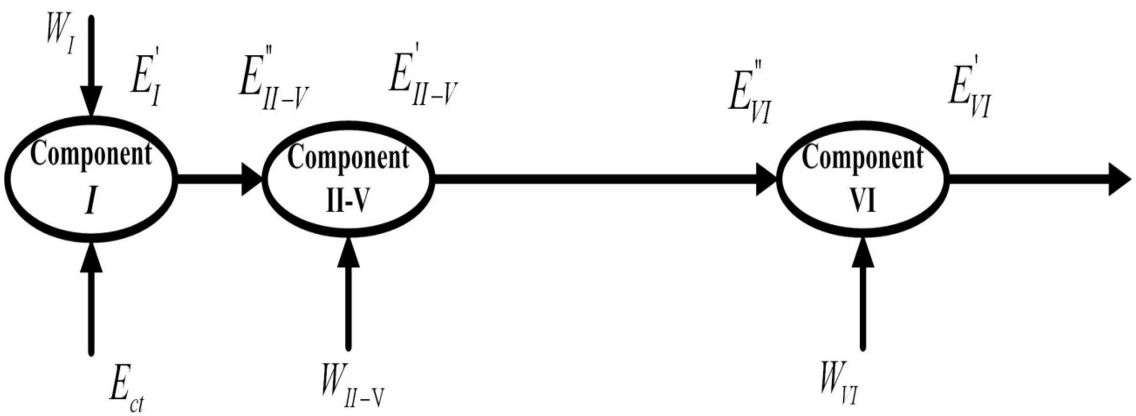
DMU
actual operation performance
v.s.
optimal operation performance
under j_{th} operation condition.



Ideal operation level of HVAC system based on DEA

4.1 Global optimization of HVAC for lowest exergy destruction

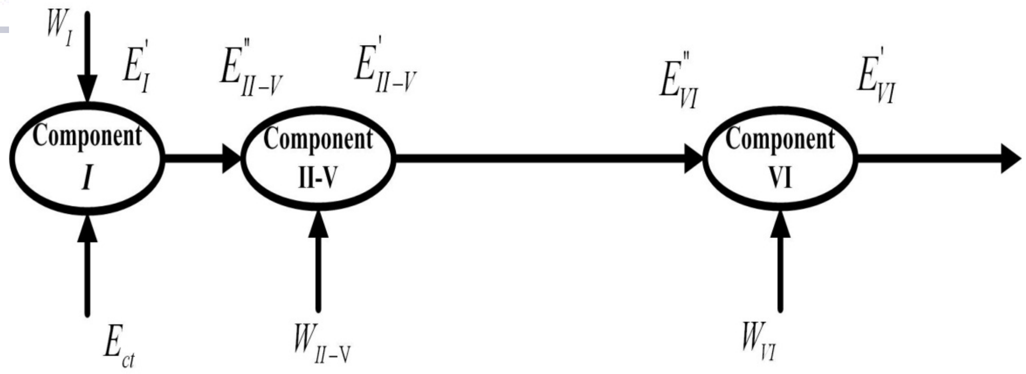
The exergy flow model of the HVAC system:



Component I : cooling towers and cooling water pumps;

Component II~V : four chillers and chilled water pumps;

Component VI : AHUs and secondary pumps.



Exergy balance equations of the HVAC system:

$$Y_{tot} = W_I + E_{ct} - E_I^{'} + W_{II-V} + E_{II-V}^{''} - E_{II-V}^{'} + W_{VI} + E_{VI}^{''} - E_{VI}^{'}$$

$$E_I^{'} = E^{''}_{II-V}$$

$$E^{'}_{II-V} = E^{''}_{VI}$$

$$Y_{tot} = W_I + E_{ct} + W_{II-V} + W_{VI} - E_{VI}^{'}$$

Y_{tot} : total exergy destruction of HVAC system;
W_i : input power of component *i* ;
E'_i : outflow exergy of component *i* ;
E''_i : inflow exergy of components *i*

The objective of global optimization

T_{ct} : outlet water temperature set-point of the cooling tower;

$\triangle T_{ctwD\_min}$: minimum temperature difference between T_{chw_out} and T_{chw_out} ;

T_{chw_out} : outlet chilled water temperature set-point of the chiller;

T_{sa} : supply air temperature set-point of AHU;

PLR : part load ratio of chiller

Q_{ch_sum} : total cooling load of chillers;

$Q_{ch\_des,i}$: rated refrigerating capacity of the i_{th} chiller;

PSO algorithm

destruction of the HVAC system under certain operation conditions

$$MinY_{tot} = f(T_{ctw\_out\_set}, PLR_i, T_{chw\_out\_set\_i}, T_{sa\_set})$$

$$T_{chw\_out\min} \le T_{chw\_out} \le T_{chw\_out\max}$$

$$T_{ctw\_out\min} \le T_{ctw\_out} \le T_{ctw\_out\max}$$

$$T_{ctw\_out\min} = T_{wb\_out} + \Delta T_{ctwD\_\min}$$

$$if\ T_{ctw\_out\min} < T_{wb\_out} + \Delta T_{ctwD\_\min}$$

$$T_{sa\min} \le T_{sa} \le T_{sa\max}$$

$$PLR_{\min} \le PLR \le 1$$

$$Q_{ch\_sum} = \sum_{i=1}^{N} PLR_i \times Q_{ch\_des,i}$$

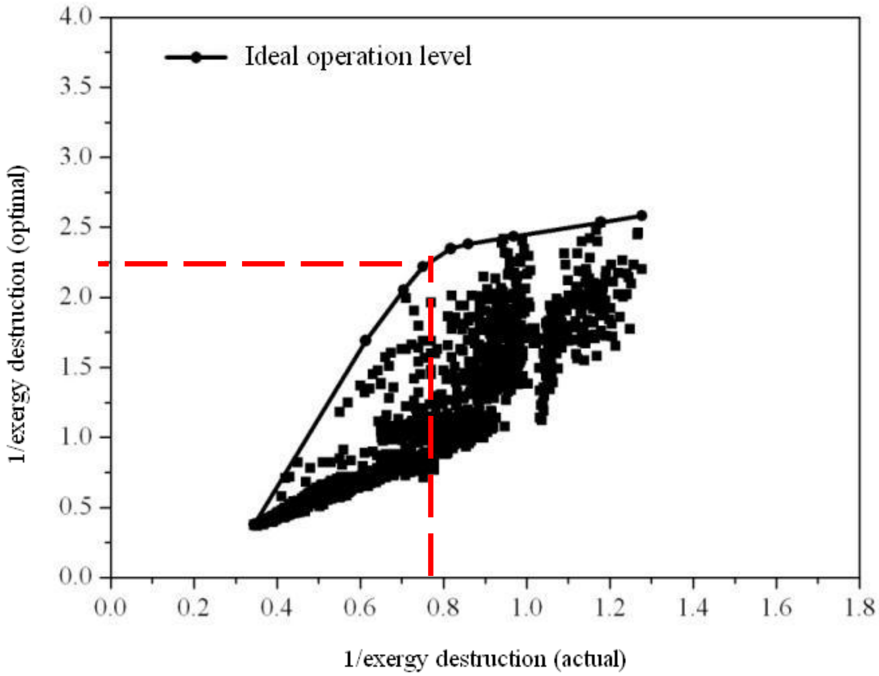
4.2 *Ideal operation level* of HVAC system

The lowest exergy destruction of the HVAC system under different operation conditions

DEA method →

The lowest exergy destruction of the HVAC system under all operation conditions

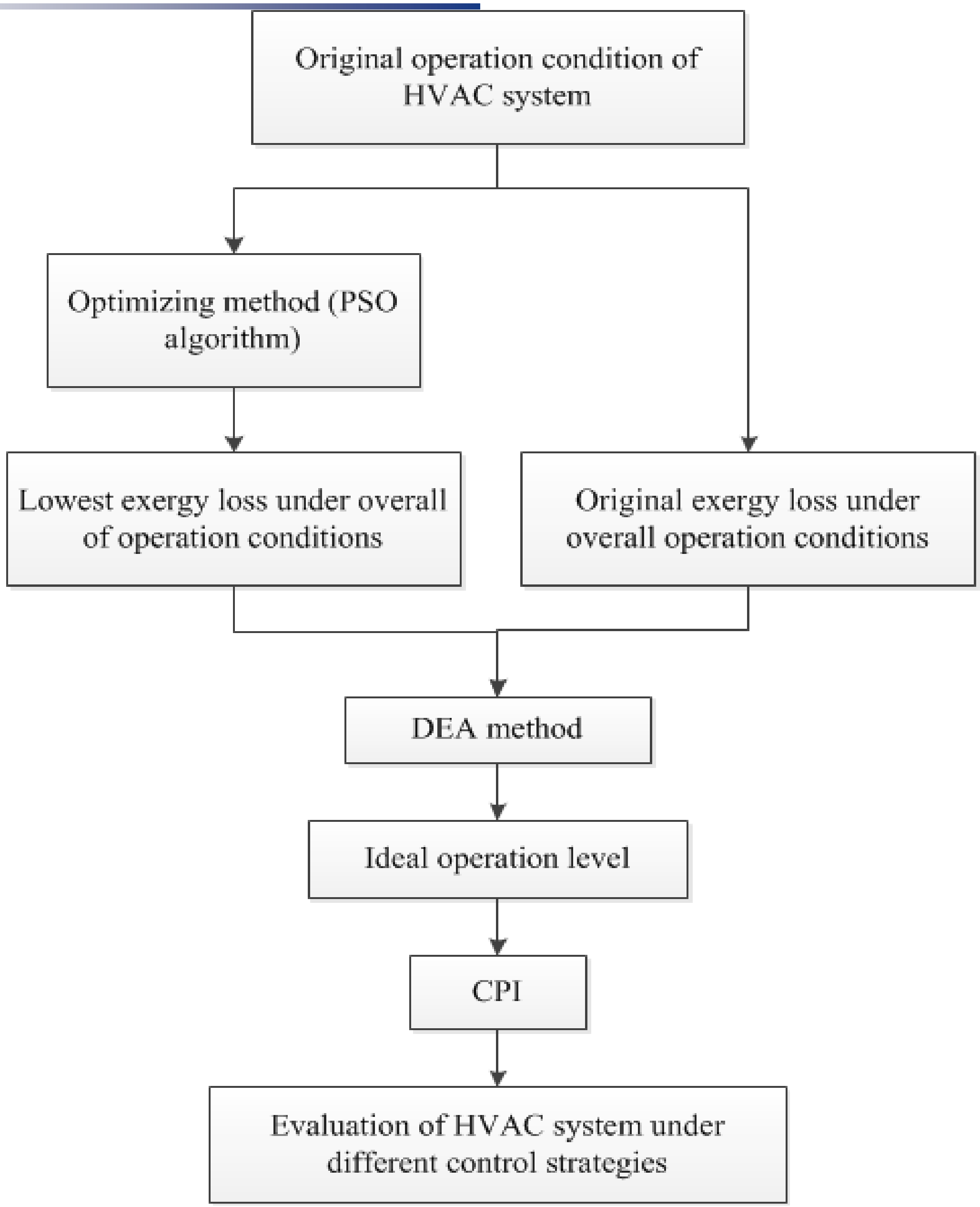
Ideal operation level



$$CPI_{sys,i} = \frac{1/D^{c}_{sys,i}}{1/D^{0}_{sys,i}}$$

CPI can evaluate HVAC system's operation performance under any operation condition.

Evaluation of control strategies for HVAC



5.1 Optimal control strategies for HVAC system

Original control strategy:

(1) fixed set-points: T_{ct} =30℃, T_{chw_out} =7℃, T_{sa}=14℃

(2) turns on chillers in a fixed sequence according to total cooling load.

Optimal control strategies:

(1) optimal supply chilled water temperature reset strategy (*CHW* strategy)

$$MinJ = function(T_{chw,set})$$

$$7℃ \le T_{chw,set} \le 12℃$$

The objective function is used to obtain the minimum total power consumption of HVAC system.

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(2) optimal load allocation control strategy

(*Load Allocation Strategy*)

The problem of *Load Allocation Strategy* for HVAC is a nonlinear programming problem with hybrid constraints.

$$Minimize\ P = \sum_{i=1}^{N} \frac{CAP_i \cdot PLR_i \cdot X_i}{COP_i}$$

$$\begin{cases} \sum_{i=1}^{N} \frac{CAP_i \cdot PLR_i \cdot X_i}{Q} = 1 \\ 0 \le \frac{CAP_i \cdot PLR_i \cdot X_i}{Q} \le 1 \\ PLR_{\min} \le PLR_i \le 1 \\ 0 \le PLR \cdot X_i \le 1 \end{cases}$$

CAP_i : refrigerating capacity of the i_{th} chiller;

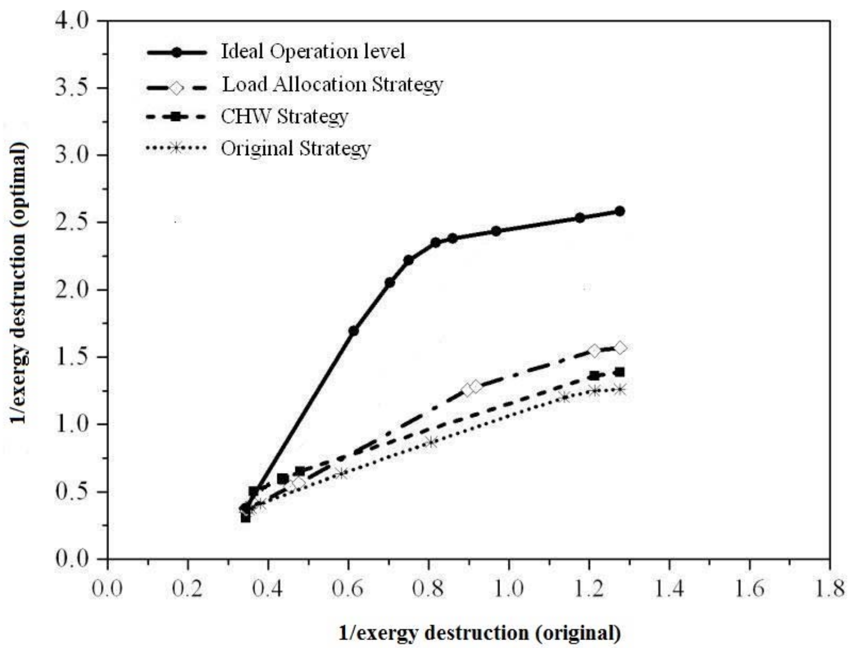
X_i : the on/off state of the i_{th} chiller, "0"means off and "1"means on;

PLR_i : PLR of the i_{th} chiller; PLR_{min}=0.25;

CL : the total cooling load of systems.

5.2 Results and discussion

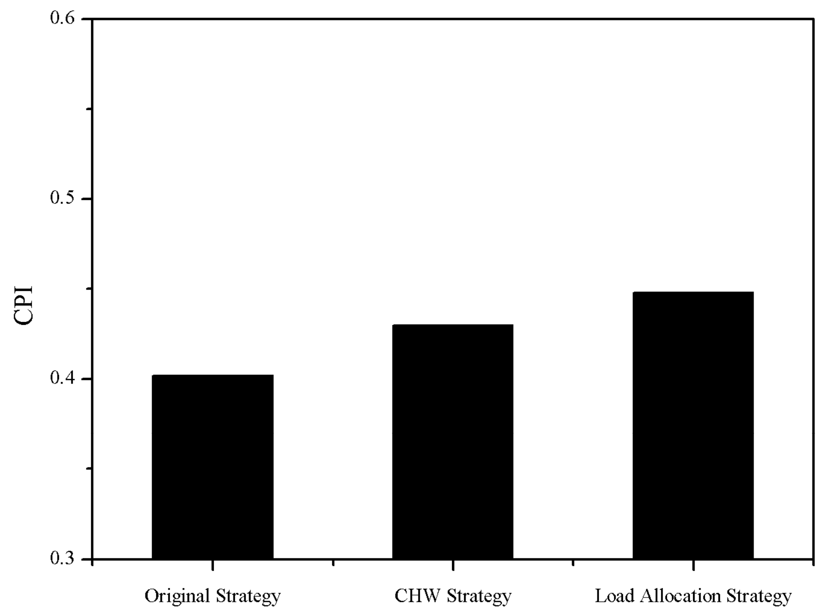
Figure shows the *ideal operation level* and three frontier lines of HVAC system under *Original strategy*, *CHW strategy* and *Load Allocation Strategy* based on annual operating data.



the frontier line of *Load Allocation Strategy* is the highest; the frontier line of *Original strategy* is the lowest ; the frontier line of *CHW strategy* is in the middle.

According to the *ideal operation level* and three frontier lines of HVAC system, the average value of *CPI* of each control strategy can be calculated.

$$CPI_{ave}^{stra,i} = \sum_{j=1}^{n} CPI_{j}^{stra,i} / n$$



comparing to *Original Strategy*, *CHW Strategy* improves the *CPI* of the total system from 0.77 to 0.78; *Load Allocation Strategy* improves the *CPI* of HVAC system from 0.77 to 0.82.

Load Allocation Strategy > CHW Strategy > Original Strategy

Conclusions

a) Exergy analysis is applied in the simulation model of HVAC system;

b) Define the evaluation index of *CPI* to measure the gap between actual operation performance and ideal operation performance;

c) Global optimization is used to obtain the lowest exergy destruction of HVAC under different operation conditions, DEA method then helps to ascertain the ideal operation level;

d) Apply optimal control strategies (*CHW strategy* and *Load Allocation Strategy*) in HVAC system, the average value of *CPI* of each strategy will give reasonable assessments: *Load Allocation Strategy* is better than *CHW strategy* and *Original strategy.*

Thank you ！