Multi-Objective Optimal Operation for Steam Power Scheduling Based on Economic and Exergetic Analysis

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Abstract: Steam supply scheduling (SSS) plays an important role in providing uninterrupted reliable energy to meet the heat and electricity demand in both the industrial and residential sectors. However, the system complexity makes it challenging to operate efficiently. Besides, the operational objectives in terms of economic cost and thermodynamic efficiency are usually contradictory, making the online scheduling even more intractable. To this end, the thermodynamic efficiency is evaluated based on exergetic analysis in this paper, and an economic-exergetic optimal scheduling model is formulated into a mixed-integer linear programming (MILP) problem. Moreover, the ε-constraint method is used to obtain the Pareto front of the multi-objective optimization model, and fuzzy satisfying approach is introduced to decide the unique operation strategy of the SSS. In the single-period case results, compared with the optimal scheduling which only takes the economic index as the objective function, the operation cost of the multi-objective optimization is increased by 4.59%, and the exergy efficiency is increased by 9.3%. Compared with the optimal scheduling which only takes the exergetic index as the objective function, the operation cost of the multi-objective optimization is decreased by 19.83%, and the exergy efficiency is decreased by 2.39%. Furthermore, results of single-period and multi-period multi-objective optimal scheduling verify the effectiveness of the model and the solution proposed in this study.

Keywords: steam supply scheduling; exergetic analysis; multi-objective; ε-constraint method

1. Introduction

As the material basis of human survival and development, energy plays an increasingly important role in promoting social and economic development as well as in improving people's living standards [1]. The energy situation and environmental problems have recently attracted worldwide attention. Steam supply scheduling (SSS) consumes primary energy to provide energy for an enterprise and simultaneously produces a substantial number of pollutants. This paper focuses on optimizing operation of the SSS to reduce the operation cost and improve the thermodynamic efficiency, thus the economic–exergetic operation of the system can be realized [2,3].

Scholars have conducted in-depth studies on the operation optimization of SSS and have made some achievements. Grossman proposed a mixed-integer linear programming (MILP) model framework for utility systems [4], and a mixed-integer nonlinear programming (MINLP) problem based on a successive MILP approach was solved [5]. Based on utility systems modeling, numerous

scholars have focused on optimal operation strategy so as to achieve cost minimization and energy distribution. In order to reduce operation cost, a model was established which integrated the start and stop of utility operating units under different process requirements [6]. In [7], the multi-period with different electricity or steam demand was introduced into the operation strategy of the utility system, and the optimal choice of units for each period was determined by using the two-stage approach. Based on the linear single-device models in public utility systems, the influence of the change of external electricity price on the system operation scheduling was studied by taking into account the steam equilibrium, fuel supply and devices operation constraints [8]. A multi-period MILP model for byproduct gases, steam and power distribution optimization was proposed in steam power plants, and the experimental results showed that the proposed model could effectively reduce system cost [9]. Given the uncertainty of device efficiency and process demand, a data-driven method was proposed to achieve the tradeoff between optimality and robustness of operational decisions in utility system optimization, and the experiments demonstrated the effectiveness of the method [10,11]. Besides, a method for the simultaneous synthesis of heat exchanger networks and utility systems was presented, and the two-stage algorithm was used to identify the best tradeoff between utility systems and heat exchanger networks costs [12,13]. Due to the escalating environmental crisis, several scholars have conducted extensive researches on the environmental issue. Central utility systems with adjoining waste-to-energy networks were integrated to form an ecological friendly energy management system, and the feasibility of the combination of the two networks was demonstrated from environmental and economic perspectives through experiments [14]. By taking into account the impact of pollutants on environment, the utility system consisting of boilers, gas turbines with heat recovery steam generators, ST and CT has been developed [15]. Considering the environmental performance of the entire site utility system, the structural design was optimized to minimize the total annual cost [16]. In addition, the multimodal genetic algorithm was used in the exergoenvironmental analysis of a combined heat and power plant [17]. In general, most studies have focused on the economic and environmental operation that consider energy quantity saving in the SSS, without considering the quality distinction between different energy resources.

In 1953, Rant put forward the concept of exergy, which is a physical quantity that synthesizes the first and the second law of thermodynamics to measure working ability. This concept can focus on the quality and quantity of energy [18–20], which provides a highly efficient method to evaluate the energy efficiency of the system [21–23]. Certain scholars have recently studied the energy system by means of the exergetic analysis. A kind of solid oxide fuel cell integrated with gas and steam trigeneration systems was optimized, and the energy, exergy and economy of the system were analysed in [24]. In addition, the influence of parameter changes on system performance was further studied. An existing CHP system was analysed in terms of energy, exergy and environmental (3E) aspects [25]. In order to analyse the performance and optimize parameter of the geothermal power plant, a system optimization model was formulated to maximize the exergy efficiency, which was solved through the gravitational search algorithm [26]. A study was conducted to examine the energy and exergy performance as well as multi-objective optimization of an exhaust air heat recovery system, which could provide reference for system planning [27]. In [28], considering the total cost, carbon dioxide emission and exergetic destruction, a multi-objective optimization of district heating system was carried out and the Pareto front was obtained with the weighting method. By means of exergy, exergoeconomic and exergoenvironmental analysis, the optimal integration of steam and power system with a steam power plant as the source and a utility system as the sink was investigated, and the experimental results reflected that the integration of steam power plant and utility system is a favorable option [29]. However, most studies have applied exergetic analysis to the performance evaluation and parameter optimization of the energy system, while there are relatively few quality studies on the energy such as heat and electricity in the SSS.

In this paper, exergy is introduced into the operation optimization of SSS. Firstly, the multi-objective mixed-integer linear programming (MOMILP) model of SSS is established by using the exergetic

analysis method to reduce the operation cost and exergy input for SSS. At the same time, the Pareto front of the multi-objective optimization model is obtained with the ε-constraint approach, and the compromise solution on the Pareto front was acquired with the fuzzy satisfying approach. Finally, the effectiveness of the proposed model and solution method was verified by the results of single-period and multi-period multi-objective optimal scheduling.

This paper is organized as follows: the MOMILP model of SSS is developed in Section 2. In Section 3, the multi-objective operation strategy of SSS is presented to obtain the Pareto front, and a tradeoff is conducted between these different objectives. Case studies are analysed in Section 4, and the conclusion is summarised in Section 5.

2. Problem Formulation of Multi-objective Optimal Operation of SSS

The SSS converts primary energy (fuel coal, fuel gas, fuel oil) into secondary energy (electricity, steam and hot water) to provide enterprises with the required process steam, thermal energy and electricity, and its typical structure is illustrated in Figure 1. To realize the economic and efficient operation of the SSS, the mathematical model of each equipment is built and the concept of exergy is adopted to evaluate all types of energy. Subsequently, the MOMILP optimal model of the SSS is formulated.
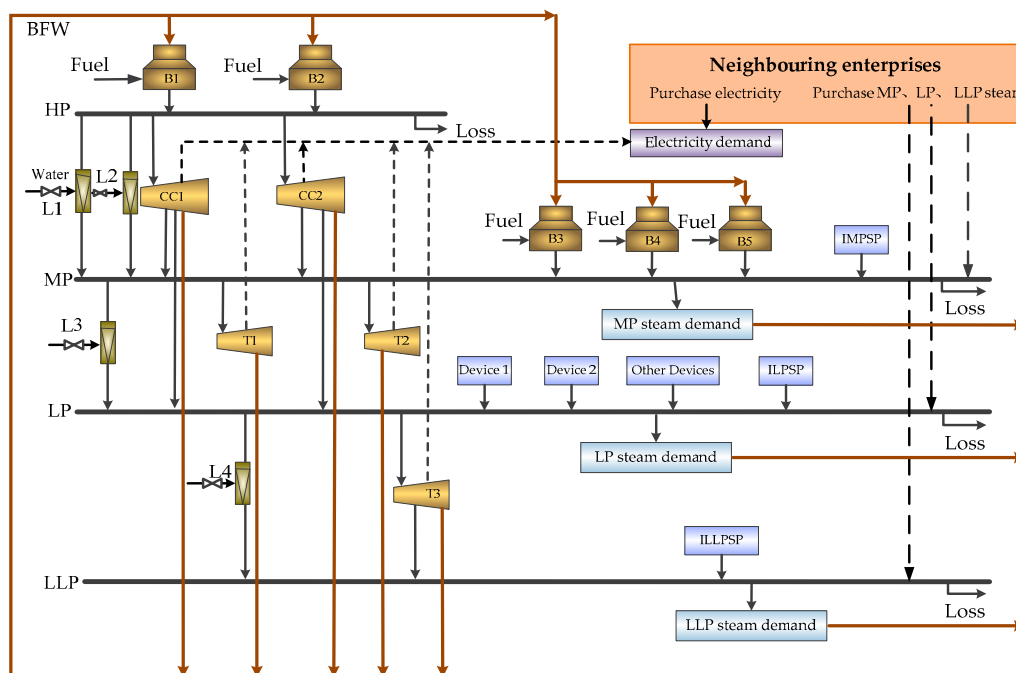

Figure 1. Steam supply scheduling (SSS) of a petrochemical enterprise.

2.1. Objectives

2.1.1. Economic Objective

Generally, the economic objective of SSS operation is to minimize the total cost of the entire period, including fuel consumption cost, electricity or steam purchase cost, equipment operation and maintenance cost, depreciation cost and equipment start/stop cost. The specific expression is as follows:

$$
\begin{aligned}
f_1 = {} & \sum_{Bn}\sum_{i}\sum_{t} F_{Bn,t,i}p_i + \sum_{r}\sum_{t} PS_{r,t}p_r + \sum_{t} PE_t p_e \\
& + \sum_{n}\sum_{t} CM_n Y_{n,t} + \sum_{n}\sum_{t} CST_n Z_{n,t} + \sum_{n}\sum_{t} CSP_n ZS_{n,t}
\end{aligned}
\tag{1}
$$

2.1.2. Exergetic Objective

Exergy represents the maximum amount of useful work that can be obtained from a given form of energy, that is, the quality of energy. For different kinds of energy, the quality of the same quantity of energy is not necessarily the same. Hence, the quality of different energy of the SSS is evaluated with the exergetic analysis method, and then the maximum exergy efficiency can be achieved. Among them, exergy efficiency can be defined as the ratio of the total output exergy to the total input exergy [21], and the formula is as follows:

$$\psi = \frac{\sum_t \dot{Ex}_{out,t}}{\sum_t \dot{Ex}_{in,t}} \tag{2}$$

Figure 1 shows that the energy types on the load side include electric energy and heat energy, and the input energy includes fossil energy (fuel coal, fuel oil, fuel gas), purchased steam and electricity. Therefore, the load demand exergy and the input exergy of the SSS are expressed as follows:

$$\begin{cases} \dot{Ex}_{out,t} = \dot{Ex}^e_{out,t} + \dot{Ex}^h_{out,t} \\ \dot{Ex}_{in,t} = \dot{Ex}^{coal}_{in,t} + \dot{Ex}^{oil}_{in,t} + \dot{Ex}^{gas}_{in,t} + \dot{Ex}^e_{in,t} + \dot{Ex}^h_{in,t} \end{cases} \tag{3}$$

Fuel coal, fuel oil and fuel gas are all chemical fuels, and their specific exergy is generally expressed by a lower heating value (LHV) and an exergy factor [30,31]. The exergy factors of different types of fuels are slightly different, but basically the same [32]. The exergy in chemical fuels can be expressed by the following formula:

$$\begin{cases} \alpha_i = \gamma_{i,LHV}\zeta_i \\ \dot{Ex}^i_{in,t} = \alpha_i F_{Bn,t,i}/3.6 \end{cases} \tag{4}$$

The exergy of electricity is equal to electricity because it can be completely converted into work. However, the work done by heat energy is limited by the Carnot factor, and its heat exergy is equal to the work done by the Carnot cycle. Therefore, the heat and electricity exergy of SSS are described as follows:

$$\dot{Ex}^h_{out,t} = \sum_r \left(1 - \frac{T_a}{T^h_r}\right) DS_{r,t} h_r / 3.6 \tag{5}$$

$$\dot{Ex}^h_{in,t} = \sum_r \left(1 - \frac{T_a}{T^h_r}\right) PS_{r,t} h_r / 3.6 \tag{6}$$

$$\dot{Ex}^e_{out,t} = DE_t \tag{7}$$

$$\dot{Ex}^e_{in,t} = PE_t \tag{8}$$

The energy demand of SSS is predictable, that is, the total output exergy can be calculated. Therefore, the exergetic objective could be converted from maximum exergy efficiency to minimum exergy input of the SSS. The formula is as follows:

$$f_2 = \sum_t \dot{Ex}_{in,t} \tag{9}$$

2.2. Constraints

2.2.1. Device Constraints

Industrial boilers generally convert the chemical energy in fuel into heat energy, and then transfer this heat energy to water through different heating surfaces, and finally produce the high-pressure (HP)

or medium-pressure (MP) steam required by the system. The model is represented by Equation (10). Equation (11) indicates that the boiler load should be placed within a certain safety range:

$$F_{Bn,t,i}\gamma_{i,LHV} = a_{Bn}Y_{Bn,t} + b_{Bn}G_{Bn,t} \tag{10}$$

$$G_{Bn}^{L}Y_{Bn,t} \leq G_{Bn,t} \leq G_{Bn}^{U}Y_{Bn,t} \tag{11}$$

The operation characteristics of a simple ST, including backpressure and CT, can be expressed by the linear relationship between steam intake and power output, and the steam intake and output power of ST should be placed within a certain safety range. The general constraints are detailed as follows:

$$P_{Tn,t} = d_{Tn}Y_{Tn,t} + e_{Tn}G_{Tn,in,t} \tag{12}$$

$$P_{Tn}^{L}Y_{Tn,t} \leq P_{Tn,t} \leq P_{Tn}^{U}Y_{Tn,t} \tag{13}$$

$$G_{Tn,in}^{L}Y_{Tn,t} \leq G_{Tn,in,t} \leq G_{Tn,in}^{U}Y_{Tn,t} \tag{14}$$

The double extraction CT generates steam with different pressure, and at the same time it can generate the power required to meet the external electricity load. Its output power is related to steam intake, industrial sectors or heating steam extractions. The model generally uses a linear function to represent the relationship among steam intake, adjustable extraction and power of the double extraction CT. It can be described as follows:

$$P_{cn,t} = g_{cn}G_{cn,in,t} - \sum_{oj} h_{cn,oj}G_{cn,oj,t}^{out} - f_{cn}Y_{cn,t} \tag{15}$$

$$P_{cn}^{L}Y_{cn,t} \leq P_{cn,t} \leq P_{cn}^{U}Y_{cn,t} \tag{16}$$

$$G_{cn,in}^{L}Y_{cn,t} \leq G_{cn,in,t} \leq G_{cn,in}^{U}Y_{cn,t} \tag{17}$$

$$G_{cn,oj}^{out,L}Y_{cn,t} \leq G_{cn,oj,t}^{out} \leq G_{cn,oj}^{out,U}Y_{cn,t} \tag{18}$$

The main function of the pressure reducer and attemperator is to adjust the steam from high temperature and high pressure to the relatively low temperature and low pressure required by the system. The general form of the model is shown in Equation (19) [10,33]. For a given steam system, once the steam pressure and temperature of each level steam are specified, the enthalpy $h_{Ln,out}$, $h_{Ln,in}$, and $h_{Ln,w}$ are constant. By defining a parameter $\eta_{Ln,}$ the expression is shown in Equation (20):

$$G_{Ln,in,t} = \frac{h_{Ln,out,t} - h_{Ln,w,t}}{h_{Ln,in,t} - h_{Ln,w,t}}G_{Ln,out,t} \tag{19}$$

$$G_{Ln,in,t} = \eta_{Ln}G_{Ln,out,t} \tag{20}$$

2.2.2. Balance Constraints

Electricity balance and steam balance should be considered to meet the energy demand and energy distribution among various energy devices in the SSS should also be considered. Therefore, the steam and electricity balance model are expressed as follows:

$$DS_{r,t} = PS_{r,t} + \sum_{n} G_{Bn,t}Y_{Bn,t} + \sum_{n} G_{cn,oj,t}^{out}Y_{cn,t} + \sum_{n} G_{Ln,out,t}Y_{Ln,t} - \sum_{n} G_{Tn,in,t}Y_{Tn,t} - \sum_{n} G_{Ln,in,t}Y_{Ln,t} - Loss_r \tag{21}$$

$$DE_t = PE_t + \sum_{n} P_{Tn,t}Y_{Tn,t} + \sum_{n} P_{cn,t}Y_{cn,t} \tag{22}$$

2.2.3. Logical Constraints on Device Start and Stop

Due to the different demand for steam and power in different periods, the equipment is easy to start and stop in the adjacent two periods, thus resulting in the start and stop cost of the equipment. In this study, Equations (23) and (24) are used to represent the start and stop logic of the equipment:

$$Z_{n,t} = Y_{n,t} - Y_{n,t-1}, Y_{n,0} = 0 \tag{23}$$

$$ZS_{n,t} = Y_{n,t} - Y_{n,t+1}, Y_{n,t+1} = 0 \tag{24}$$

In summary, the MOMILP optimal model of SSS can be represented as follows:

$$\begin{aligned} &\min \text{obj}_1 = f_1(x_t, y_t) \\ &\min \text{obj}_2 = f_2(x_t, y_t) \\ &\text{subject to} \begin{cases} g(x_t, y_t) \leq 0 \\ h(x_t, y_t) = 0 \\ x_t \in (x^L, x^U) \\ y_t \in (0, 1) \end{cases} \end{aligned} \tag{25}$$

3. Solution and Decision of the Optimal Condition

In order to achieve optimal operation of the economy and exergetics of the SSS, this section uses the ε-constraint method to solve the proposed multi-objective problem, so as to obtain the Pareto front. The Pareto curve is used to determine the optimal solution with the fuzzy satisfying approach.

3.1. ε-Constraint Based Solution

In the optimization problem of SSS, the two objectives of reducing the operation cost and exergy input are considered to affect each other, that is, it is difficult for both sides to reach the optimal simultaneously. Therefore, the ε-constraint method is used to solve this multi-objective optimal problem. The ε-constraint method preserves one of the objectives in the objective function and transforms the rest of the objective functions into constraints. Thereby the multi-objective optimization problem is transformed into a series of single-objective optimization problems, which can be solved by modifying the value range of the constraints condition step by step. The details are presented as follows:

$$\begin{cases} \min f_1 \\ \text{subject to } f_2 \leq \varepsilon \\ \text{Equations } (1) - (24) \end{cases} \tag{26}$$

where the value of ε is considered to be expressed by the following equation:

$$\varepsilon = f_{2,\max} - (f_{2,\max} - f_{2,\min})(a - 1)/(a_{\max} - 1) \tag{27}$$

where $a = 1, 2, \ldots, a_{max}$, a_{max} is the maximum number of cycles; $f_{2,\min}$ and $f_{2,\max}$ are the maximum and minimum values of f_2 obtained when f_2 and f_1 are considered as a single-objective function, respectively. Furthermore, the economic objective is taken as f_1 as shown in Equation (1) and the exergetic objective as f_2 as shown in Equation (9) in this paper.

3.2. Decision based on Fuzzy Satisfying Approach

To achieve the coordination and unification of the multi-objective of SSS, the fuzzy satisfying approach [34] is introduced to help the operator establish a trade-off between the economic objective and the exergetic objective. The target values of each operation strategy are normalized according to

(28). Subsequently, the membership function value of each operation strategy is calculated according to (29), and the best operation strategy is selected according to Equation (30):

$$\mu_k^a = \begin{cases} 1 & f_k^a \leq f_{k,\min} \\ \frac{f_{k,\max} - f_k^a}{f_{k,\max} - f_{k,\min}} & f_{k,\min} \leq f_k^a \leq f_{k,\max} \\ 0 & f_k^a \geq f_{k,\max} \end{cases} \tag{28}$$

$$\mu^a = \min(\mu_1^a, \mu_2^a) \tag{29}$$

$$\mu^{\max} = \max(\mu^1, \mu^2, \dots \mu^{a_{\max}}) \tag{30}$$

To make the fuzzy satisfying approach clearer, a small example is given in Table 1, and the multi-objective optimization strategy selected is scheme 7, which is the bold part of Table 1. In addition, Figure 2 summarizes the specific process of the multi-objective operation optimization.

Table 1. An example of the fuzzy satisfying approach.

a	f_1	f_2	μ_1	μ_2	$\mu^{\max}$
1	57883.09281	575814.554	1	0	0
2	58242.90797	560822.484	0.956601	0.105264	0.105264
3	58697.95742	545830.368	0.901716	0.210528	0.210528
4	59153.00687	530838.253	0.846831	0.315792	0.315792
5	59608.05632	515846.137	0.791946	0.421056	0.421056
6	60063.10577	500854.021	0.73706	0.52632	0.52632
7	**60566.37947**	**485861.905**	**0.676359**	**0.631584**	**0.631584**
8	61116.28338	470869.789	0.610033	0.736848	0.610033
9	61666.18728	455877.674	0.543707	0.842112	0.543707
10	66174.01862	433390.6	0	1	0
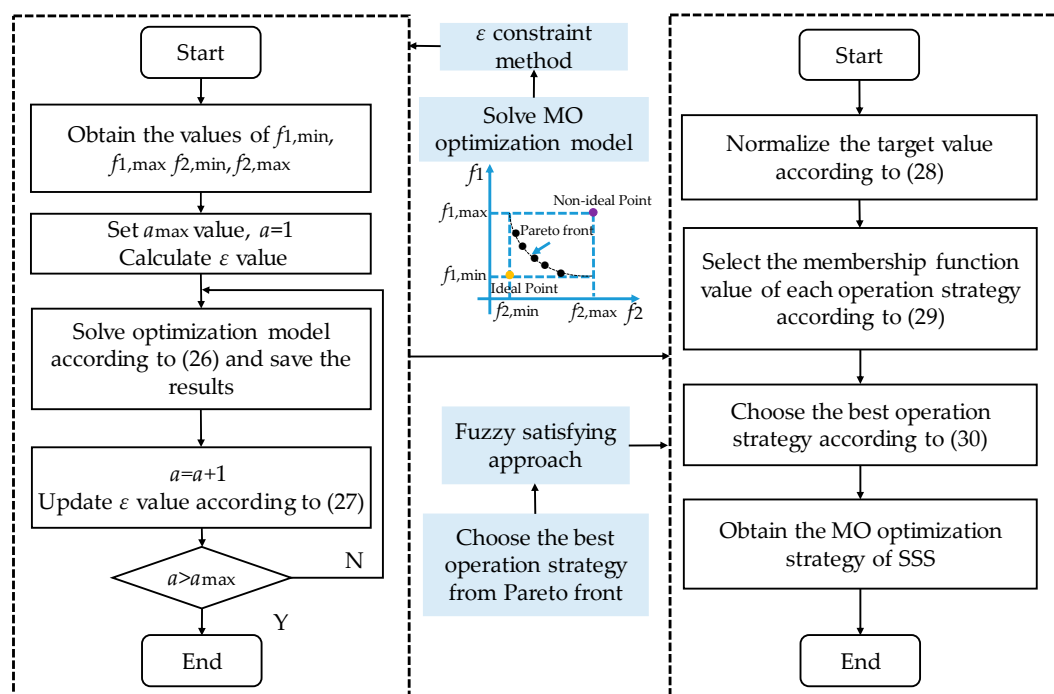
Figure 2. Flowchart of the multi-objective optimization solution.

4. Case Study

To verify the effectiveness of the MILP model of SSS with economic and exergetic objectives, the optimal model of single-period and multi-period of SSS are solved and results are analysed in

this section. Moreover, it is necessary to declare the case studied in this paper does not consider optimization situation of neighbouring enterprises, which is a partial optimization.

4.1. Case Description

This study takes the SSS of petrochemical enterprises as an example (Figure 1), which includes four different levels of steam, namely, high-pressure steam (HP, 9.5 MPa and 535 °C), medium pressure steam (MP, 3.5 MPa and 425 °C), low-pressure steam (LP, 1 MPa and 300 °C) and low and low-pressure steam (LLP, 0.3 MPa and 200 °C). B1–B2 are coal-fired boilers that produce HP steam with a blowdown rate of 8%; B3–B5 are dual fuel boilers, which burn oil and gas to produce MP steam. The amount of gas is determined by the processing unit, and the maximum available gas import capacity is 12 t/h. Double extraction CT (CC1, CC2) produces MP and LP steam as well as electric energy. T1 and T2 steam turbines generate power, and T3 produces LLP steam and electric energy. As can be seen from Figure 1, the condensate is recycled and converted into boiler feed water. Furthermore, the minimum value of condensing steam amount of steam turbine is 63 t/h, the maximum value of condensing steam amount is 142 t/h, and the condensing pressure is 5.9 kPa. Pressure reducer and attemperator (L1, L2, L3 and L4) can convert high-temperature and high-pressure steam into relatively low-level steam. The study allows the maximum electricity import capacity from neighbouring enterprises of 50,000 kW. The maximum MP steam, LP steam and LLP steam import capacity from neighbouring enterprises of 100, 50 and 50 t/h. The effects of device 1, device 2 and other devices on the system are not considered in this study, and the loss of the system is neither considered, that is, $loss_r = 0$. Table 2 indicates the model parameters of boiler and steam turbine. Tables 3 and 4 list the equipment parameters, start/stop costs and equipment operation costs of boilers and ST. Table 5 indicates the unit price of resources. Table 6 shows the parameters of the resource, and Table 7 lists the start and stop time of the equipment.

Table 2. Model parameters of boiler and steam turbine (ST).

Parameter	Value	Parameter	Value
a_{B1}	95.8	f_{c1}	−179
a_{B2}	95.8	f_{c2}	−179
a_{B3}	19.47	g_{T3}	73.37
a_{B4}	5.818	g_{c1}	252
a_{B5}	5.159	g_{c2}	252
b_{B1}	0.8488	$h_{c1,o1}$	−235
b_{B2}	0.8488	$h_{c1,o2}$	−102
b_{B3}	0.931	$h_{c2,o1}$	−235
b_{B4}	1.021	h_{c2o2}	−102
b_{B5}	1.032	h_{T3}	−23.3
d_{T1}	−1459	η_{L1}	0.933
d_{T2}	−1650	η_{L2}	0.933
e_{T1}	86.2	η_{L3}	0.913
e_{T2}	88.6	η_{L4}	0.923
f_{T3}	−116.7		

Table 3. Boiler equipment information.

Boiler	B1	B2	B3	B4	B5
Rated evaporation (t/h)	320	320	140	75	65
Minimum evaporation (t/h)	160	160	80	35	50
Start and stop cost (¥)	10,000	10,000	13,000	13,000	13,000
Equipment operation cost (¥/h)	100	100	200	185	170
Steam temperature (°C)	535	535	425	425	425
Steam pressure (MPa)	9.5	9.5	3.5	3.5	3.5
Feedwater temperature (°C)	211.23	211.23	163	163	163
Feedwater pressure (MPa)	15.08	15.08	3.5	3.5	3.5

Table 4. Steam turbine equipment information.

| Equipment | Start and Stop Cost (¥) | Equipment Operation Cost (¥/h) | Power Rating (kW) | | Maximum Steam Intake (t/h) | Maximum First Extraction Steam (t/h) | Maximum Second Extraction Steam (t/h) |
			Maximum	Minimum			
CC1	12,000	200	50,000	20,000	380	190	180
CC2	12,000	200	50,000	20,000	380	190	180
T1	6000	160	6500	1500	85	—	—
T2	6000	140	6500	1500	85	—	—
T3	6000	110	6000	3500	100	—	—

Table 5. The unit price of resources.

Fuel Coal (¥/t)	Fuel Gas (¥/t)	Fuel Oil (¥/t)	Electricity (¥/kWh)	MP Steam (¥/t)	LP Steam (¥/t)	LP Steam (¥/t)
750	1200	3500	0.45	180	135	80

Table 6. Parameters of the resource.

Fuel	Lower Heating Value (kJ/kg)	Exergy Factor	/	Enthalpy (kJ/kg)	Industrial Steam Production	Value (t/h)
Coal	24,440	1.08	MP	3280.7	IMPSP	57
Gas	32,503	1	LP	3051.7	ILPSP	76.8
Oil	40,245	1.06	LLP	2865.9	ILLPSP	34.9
			Water of Ln	632.2		

Table 7. Start and stop time of equipment.

Equipment	B1	B2	B3	B4	B5	CC1	CC2	T1	T2	T3
Start time (h)	10	10	7.5	7.5	7.5	3.3	3.3	3.3	3.3	3.3
Stop time (h)	10	10	7.5	7.5	7.5	3.3	3.3	3.3	3.3	3.3

4.2. Single-Period Case

Table 8 reports the demand for steam and electricity over a single period time, without considering the start and stop costs of the equipment in the economic objective. During the solution process, the maximum number of cycles n in the ε-constraint method is set to 20.

Table 8. Single-period steam and electricity demands.

| Steam (t/h) | | | Electricity (kW) |
MP	LP	LLP	
180	125	150	64,400

Figure 3 shows the single-period Pareto front for the SSS, the points on it are all optimal values, which can provide different operation strategies for operators. Furthermore, the multi-objective optimal operation strategy can be obtained with the fuzzy satisfying approach, which is the point marked on the Pareto curve in Figure 3. Tables 9 and 10 show the optimal scheduling results of boilers load and purchased resources for SSS.
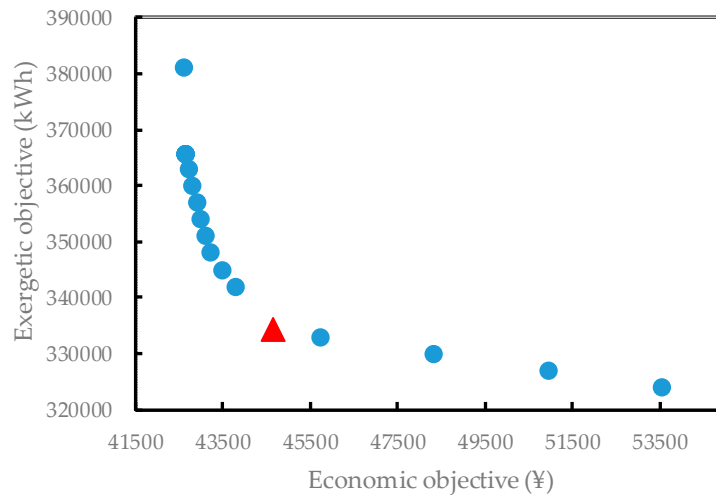
Figure 3. Pareto front of single- period for SSS.

Table 9. Optimal scheduling results of boilers load for SSS.

Boilers Load (t/h)/Situation	Multi-Objective Operation (Standard)	Economic Operation	Exergetic Operation
B1 steam production	320	0	0
B1 coal consumption	41.33	0	0
B2 steam production	0	320	247.03
B2 coal consumption	0	41.33	34.36
B3 steam production	0	103.00	0
B3 oil consumption	0	0	0
B3 gas consumption	0	8.55	0
B4 steam production	0	0	0
B4 oil consumption	0	0	0
B4 gas consumption	0	0	0
B5 steam production	0	0	0
B5 oil consumption	0	0	0
B5 gas consumption	0	0	0

Table 10. Optimal scheduling results of purchased resources for SSS.

Purchased Resources/Situation	Multi-Objective Operation (Standard)	Economic Operation	Exergetic Operation
PMP steam (t/h)	21.74	0	100
PLP steam (t/h)	0	0	0
PLLP steam (t/h)	0	0	0
PE (kW)	19,838.62	743.04	19,838.62

Evidently, compared with the multi-objective operation, the energy conversion equipment such as boilers and ST meets the demand for steam and most electricity in the economic operation. Consequently, less steam and electricity are purchased. By contrast, exergetic operation purchases more steam from the neighbouring enterprises. The multi-objective operation establishes a tradeoff between the economic objective and exergetic objective to satisfy the multi-objective optimal operation by coordinating the consumption of different types of energy (fossil energy, heat energy and electric energy).

Table 11 indicates the operation cost, input exergy and exergy efficiency in multi-objective optimization and single-objective optimization. Based on the results of multi-objective optimization, the growth rate of operation cost, input exergy and exergy efficiency in economic operation and exergetic operation are calculated. Results reveal that compared with the multi-objective optimal operation, the operation cost of the economic operation is decreased by 4.59%, while the input exergy

is increased by 13.97%. On the contrary, for the exergetic operation, its input exergy is decreased by 3.06%, while its operation cost is increased by 19.83%.

Table 11. Comparison of multi-objective optimization results with single-objective optimization results.

Situation	Indicator	Value	Growth Rates
Multi-objective operation (standard)	Operation cost/¥	44,667.83	0
	Input exergy/kW	334,216	0
	Exergy efficiency/%	75.83%	0
Economic operation	Operation cost/¥	42,615.71	−4.59%
	Input exergy/kW	380,921.40	13.97%
	Exergy efficiency/%	66.53%	−9.3%
Exergetic operation	Operation cost/¥	53,526.94	19.83%
	Input exergy/kW	323,989.8	−3.06%
	Exergy efficiency/%	78.22%	2.39%

Compared with SSS optimal scheduling which only takes economic or exergetic as the objective function, from the above calculated data, it can see that the multi-objective operation can comprehensively consider energy efficiency from the point of view of economic and exergetic, make a tradeoff between the economic index and exergetic index, and pay attention to the quality and quantity of energy simultaneously, so as to achieve the purpose of reducing cost and increasing efficiency. Furthermore, this paper is in line with the sustainable energy development strategy of the world today.

4.3. Multi-Period Case

A multi-period case is established in this section to further verify the effectiveness of the proposed multi-objective model and solution method. The multi-period model includes six periods, each with a duration of 720 h, which is consistent with the solution method and the ε-constraint parameter setting in Section 4.2. Table 12 indicates the steam and electricity demands of the six periods. The optimal scheduling results are detailed as follows.

Table 12. Multi-period steam and electricity demands.

Period	Steam (t/h)			Electricity (kW)
	MP	LP	LLP	
1	180	125	150	64,400
2	350	165	75	73,700
3	320	185	60	85,700
4	250	200	95	58,700
5	200	175	105	67,600
6	335	300	120	78,300

Figure 4 depicts the steam distribution among the equipment. It can be seen that under the premise of fully considering the steam purchase, the boiler and ST jointly produce steam, and the system supplements the regulation of pressure reducer and attemperator, thus the integrated operation of steam production and supply at all levels can be realized.
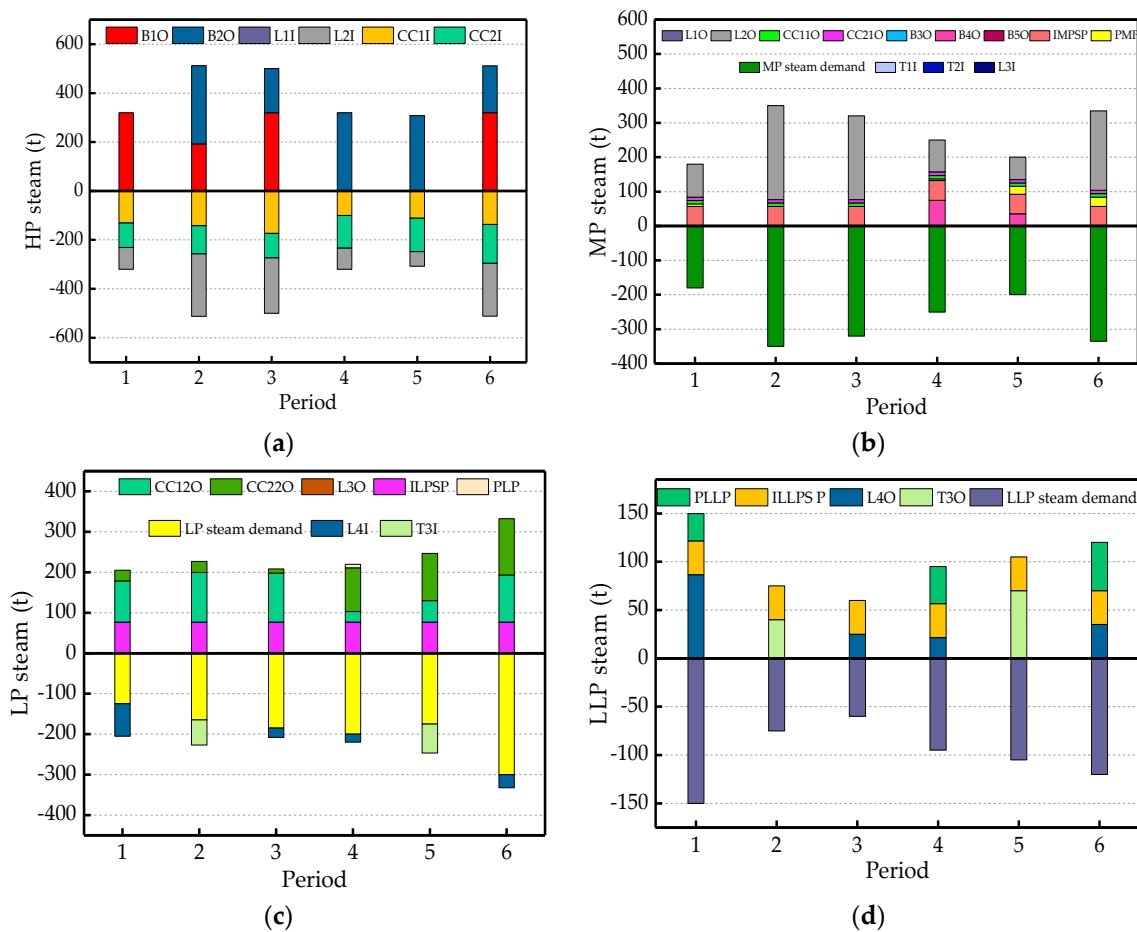
Figure 4. Optimal scheduling results for steam: (**a**) high-pressure steam; (**b**) medium pressure steam; (**c**) low-pressure steam; (**d**) low and low-pressure steam. (I, O indicate input and output of equipment, respectively.).

Table 13 shows the optimal scheduling results of the start and stop of multi-period operation equipment. Figure 5 describes the optimal scheduling results of fuel consumed in the system. Evidently, changes in steam and electricity demand lead to the inevitably start and stop of equipment, thus changing fuel consumption. Due to the relative high steam and electricity demand compared with other periods, the B1 and B2 are in operation in periods 2, 3 and 6. Furthermore, since the MP steam demand of period 1 is lower than that of periods 4 and 5, boilers producing MP steam are closed in period 1. Moreover, considering that the energy of the system is converted from the HP steam generated by B1 and B2, a large amount of coal is consumed.

Table 13. Optimal scheduling results of start/stop of multi-period operation equipment.

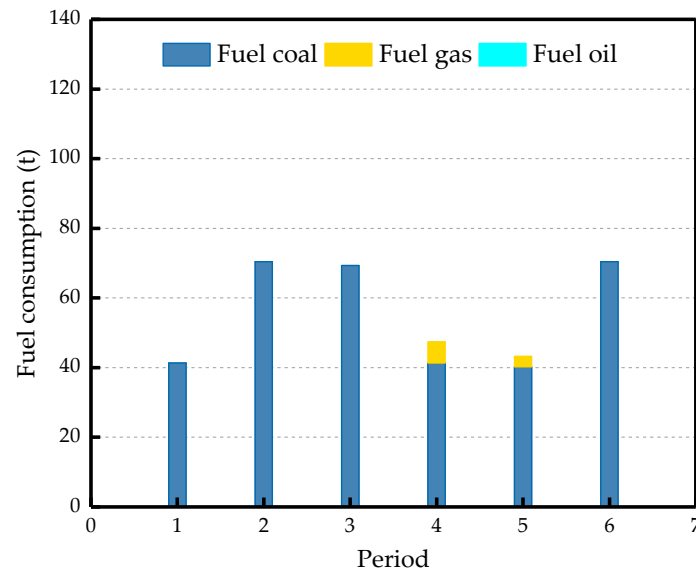| Equipment/Period	1	2	3	4	5	6
B1	1	1	1	0	0	1
B2	0	1	1	1	1	1
B3	0	0	0	0	0	0
B4	0	0	0	1	1	0
B5	0	0	0	0	0	0
CC1	1	1	1	1	1	1
CC2	1	1	1	1	1	1
T1	0	0	0	0	0	0
T2	0	0	0	0	0	0
T3	0	1	0	0	1	0

Figure 5. Optimal scheduling results for fuel.

Figure 6 shows the optimal scheduling results of electricity. Under the premise of purchasing electricity (Figure 6 PE), it can be observed that the coordinated operation of T1, T2, T3, CC1 and CC2 can meet the electricity demand. Besides, T1 and T2 are stopped in each period and double extraction CT is used more frequently during the operation process. On the one hand, this is because CC1 and CC2 can satisfy most of the electricity demand. Moreover, CC1 and CC2 can generate electricity and produce both MP and LP steam to meet the steam demand by consuming HP steam. On the other, T1 and T2 only generate electricity. In order to save operation costs, it is not necessary to maintain the operation of all units. In addition, T3 is used more frequently than T1 and T2, partly because T3 can generate electricity and LLP steam simultaneously. On the other hand, it can be seen from Table 4 that the operation cost of T3 is lower than that of T1 and T2. Accordingly, this operation strategy can save economic costs. Furthermore, in order to balance both economic and exergetic objectives, the system neither over purchases energy, nor blindly consumes chemical fuel to meet the electricity demand, thus realizing the primary energy saving and improving the thermodynamic efficiency of the system in multi-period operation.
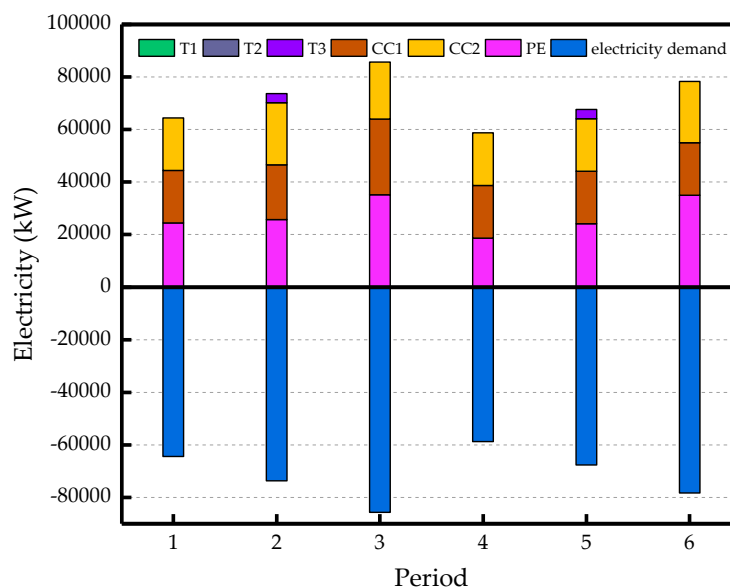

Figure 6. Optimal scheduling results for electricity.

Therefore, the multi-period case study in this section can provide guiding significance for the actual operating system, and the corresponding unit output plan can be made from the two aspects of system economy and thermodynamic efficiency. Furthermore, this study can help reduce greenhouse gas emissions and improve the thermodynamic efficiency under the premise of meeting the power and thermal demand of enterprises.

5. Conclusions

In order to achieve a good balance between enhancing energy efficiency and reducing system cost, this paper adopts the exergetic analysis method in thermodynamics to evaluate the effective energy contained in different kinds of energy. At the same time, the exergetic objective function is built. Considering the cost of electricity and steam, combined with the mathematical model of each equipment, an SSS optimal model based on economic index and exergetic index is further built. Utilizing the ε-constraint method to obtain the Pareto front of multi-objective optimization problems, the fuzzy satisfying approach is introduced to determine the optimal operation strategy. Taking the single-period operation as an example, it can be seen that the multi-objective optimization operation strategy can consider the economic and exergetic of the system by comparing with the single-objective optimization results. Meanwhile, the single-objective optimization only takes the economic or exergetic index as the objective function. Moreover, it can be verified by the results of multi-period scheduling that the multi-objective model and solution is effective. In addition, to deal with the multi-objective problem, the fuzzy satisfying approach is introduced to obtain the optimal results. However, the optimal results may rely on the fuzzy satisfying approach. Therefore, to get better multi-objective optimal results, our future work will focus on the effectiveness of various multi-objective optimal methods.

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Nomenclature

a_{Bn}, b_{Bn}	model comodel coefficients of Bn
CM_n	operation and maintenance of equipment (¥)
CST_n	start cost of equipment (¥)
CSP_n	stop cost of equipment (¥)
DE_t	demand electricity of the SSS (kW)
$DS_{r,t}$	demand steam of the SSS (t/h)
d_{Tn}, e_{Tn}	model coefficients of Tn
$\dot{Ex}_{out,t}$	exergy output of SSS (kW)
$\dot{Ex}_{in,t}$	exergy input of SSS (kW)
$\dot{Ex}_{out,t}^{e}$	electricity exergy output (kW)
$\dot{Ex}_{out,t}^{h}$	heat exergy output (kW)
$\dot{Ex}_{in,t}^{coal}$	fuel coal exergy input (kW)
$\dot{Ex}_{in,t}^{oil}$	fuel oil exergy input (kW)
$\dot{Ex}_{in,t}^{gas}$	fuel gas exergy input (kW)
$\dot{Ex}_{in,t}^{e}$	electricity exergy input (kW)
$\dot{Ex}_{in,t}^{h}$	heat exergy input (kW)
$F_{Bn,t,i}$	fuel consumed by the boiler (t/h)

f_{cn}, g_{cn}, $h_{cn,oj}$	model coefficients of *cn*
f_1	economic objective
f_2	exergetic objective
$G_{Bn,t}$	generated steam by *Bn* (t/h)
$G_{Tn,in,t}$	flow rates of the inlet for *Tn* (t/h)
$G_{cn,in,t}$	flow rates of the inlet for *cn* (t/h)
$G_{Ln,in,t}$, $G_{Ln,out,t}$	flow rates of the inlet and outlet steam for *Ln* (t/h)
$G^{out}_{cn,oj,t}$	adjustable steam extraction of *cn* (t/h)
G^L_{Bn}, G^U_{Bn}	upper and lower limits of the steam generated by *Bn* (t/h)
$G^U_{Tn,in}$, $G^L_{Tn,in}$	upper and lower limits of flow rates of the inlet for *Tn* (t/h)
$G^{out,U}_{cn,oj}$, $G^{out,L}_{cn,oj}$	upper and lower limits of adjustable steam extraction of *cn* (t/h)
$G^U_{cn,in}$, $G^L_{cn,in}$	upper and lower limits of flow rates of the inlet for *Tn* *cn* (t/h)
$g(x_t,y_t)$	inequality constraint equation
h_r	steam enthalpy (kJ/kg)
$h(x_t,y_t)$	equality constraint equation
$h_{Ln,out,t}$	enthalpy of outlet steam for *Ln* (kJ/kg)
$h_{Ln,in,t}$	enthalpy of inlet steam for *Ln* (kJ/kg)
$h_{Ln,w,t}$	enthalpy of water for *Ln* (kJ/kg)
$Loss_r$	loss stream at all levels
p_i	price of fuel (¥/t)
p_r	price of purchased steam (¥/t)
p_e	price of purchased electricity (¥/kW)
$PS_{r,t}$	purchased steam of the SSS (t/h)
PE_t	purchased electricity of the SSS (kW)
$P_{cn,t}$	generated electricity by *cn* (kW)
$P_{Tn,t}$	generated electricity by *Tn* (kW)
P_{Tn}^U, P_{Tn}^L	upper and lower limits of electricity generated by *Tn* (kW)
P^U_{cn}, P^L_{cn}	upper and lower limits of electricity generated by *cn* (kW)
T_a	ambient temperature (K)
T_r^h	steam temperature (K)
x_t	continuous variable
x^U, x^L	upper and lower limits of *x*
y_t	binary variables of the running state of the equipment
$Y_{n,t}$	binary variables of the running state of the equipment
$Z_{n,t}$	binary variables
$ZS_{n,t}$	binary variables
Subscripts	
a_{max}	maximum number of cycles
Bn	boiler equipment
cn	double extraction condensing turbines equipment
i	fuel type
k	the number of objective functions
Ln	pressure reducer and attemperator equipment
n	equipment
r	level for steam
Tn	simple steam turbine equipment
Symbols	
α_i	specific exergy of fuel (kJ/kg)
ψ	exergy efficiency (%)
$\gamma_{i,LHV}$	lower heating value of fuel (kJ/kg)
ζ_i	exergy factor of fuel
η_{Ln}	conversion efficiency (%)

Abbreviations

B1~ B5	boiler 1~5
BFW	boiler feed water
CC1, CC2	double extraction condensing turbines 1~2
CC11	flow rates of first extraction steam for CC1
CC12	flow rates of second extraction steam for CC1
CC21	flow rates of first extraction steam for CC2
CC22	flow rates of second extraction steam for CC2
CT	condensing turbines
HP	high pressure
IMPSP	medium pressure produced in industrial
ILPSP	low pressure produced in industrial
ILLPSP	low and low-pressure steam produced in industrial
L1~ L4	pressure reducer and attemperator 1~4
LP	low pressure
LLP	low and low-pressure steam
LHV	lower heating value
MP	medium pressure
MILP	mixed-integer linear programming
MINLP	mixed-integer nonlinear programming
PMP	medium pressure purchased from neighbouring enterprises
PLP	low pressure purchased from neighbouring enterprises
PLLP	low and low-pressure steam purchased from neighbouring enterprises
ST	steam turbines
T1~T3	simple steam turbine 1~3

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