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AN ENERGY MANAGEMENT COMPUTER PROGRAM FOR PROCESS PLANTS

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Abstract—An energy management program has been developed which can be customized for any typical plant which uses optional steam turbines and electric motors. The plant energy cost can be minimized by using the optimum combination of optional equipment. A huge sum of energy cost can be saved even during the period with lower energy cost as present.

INTRODUCTION

In a typical plant, more than one equipment are available for a specific service. For example, there are three cooling water pumps in Unit 1. One has an electric motor, another one has a turbine using 600 psig steam and discharging to the 160 psig steam header, and the third one has a turbine using 160 psig steam and discharging to the 15 psig header. Depending on the plant steam balance, there exists an optimum choice which can minimize the plant energy cost. If there are many optional equipment in a complex plant, selecting a set of optional equipment which will minimize the energy cost is not a trivial task.

This paper describes an energy management computer program which has been developed and implemented in chemical plants since 1982. This resulted in a significant reduction of plant energy cost. This program selects ten best options out of all possible combinations of the optional turbines and electric drivers which can satisfy the current plant energy demand and constraints.

The program output shows the boiler load, the steam vent flow, steam breakdown flows and up/down status of the optional equipment both for the current mode of operation and for the ten best options. It also shows the savings to be achieved by changing the mode of operation from the current to the ten best modes and the necessary changes.

PLANT STEAM SYSTEM

Figure 1 shows a typical plant steam system. Plant boilers generate high pressure steam and feed to the 650 psig steam header. The 650 psig steam is used in turbines for compressors and pumps. The 650 psig steam can also be used in heat exchangers or reboilers requiring high temperature. Back pressure turbines use the 650 psig steam as their power source and discharge the used steam to any one of 160, 60 and 15 psig steam headers. Some turbines use the 160 psig steam and discharge to the 60 or to the 15 psig header. The steam from these lower pressure headers is normally used in preheaters and reboilers for purification columns in different processes.

The 650 psig steam header pressure is controlled by manipulating the fuel gas flow to boilers. The pressure of each one of the 160, 60 and 15 psig steam headers is controlled by manipulating the makeup

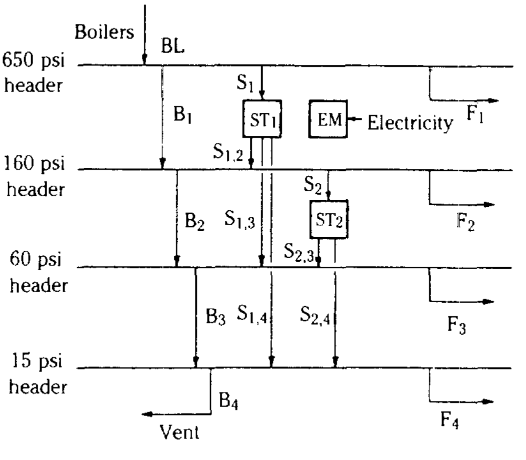

Fig. 1. A typical steam system.

flow from its next higher level pressure header and the breakdown flow to the lower pressure header. The excess steam at the 160 or 60 psig header is sent to its next lower level steam header. The excess steam at the 15 psig header is vented to the atmosphere.

The material balance for the steam system in Figure 1 can be expressed as follow:

$$\begin{aligned} BL &= B_1 + S_1 + F_1 \\ B_1 &= B_2 + S_2 - S_{1,2} + F_2 \\ B_2 &= B_3 - S_{1,3} - S_{2,3} + F_3 \\ B_3 &= B_4 - S_{1,4} - S_{2,4} + F_4 \end{aligned} \tag{1}$$

The header pressure control scheme maintains

$$\mathrm{Min}(B_1,\ B_2,\ B_3,\ B_4) = 0. \tag{2}$$

Equation (2) means that B_1, B_2, B_3, and B_4 are greater or equal to zero and at least one of them is zero. BL, B_1, B_2, B_3 and B_4 are measured and S_1, S_2, $S_{1,2}$, $S_{1,3}$, $S_{1,4}$, $S_{2,3}$ and $S_{2,4}$ can be determined if the equipment status are known. Fixed net demand of each pressure level steam (F_1, F_2, F_3, F_4) can be defined as the amount of necessary steam which is independent from the use of optional equipment. It usually depends on the up/down status and production rate of each unit in the plant.

Steam header pressures can be affected by either equipment status changes or fixed net demand changes. As the equipment up/down status changes, electric demand, S_1, S_2, $S_{1,2}$, $S_{1,3}$, $S_{1,4}$, $S_{2,3}$, and $S_{2,4}$ will change causing changes in steam header pressures. The steam header pressure control scheme will take control action which may eventually change BL, B_1, B_2, B_3, and B_4. Changes in electric demand and boiler load affect the total energy cost.

COST SAVINGS OPPORTUNITIES

In the steam system described above, there exist cost savings opportunities as follows:

1. When the steam vent flow is significant, it can be decreased by bringing up electric motors and turning off steam turbines.

2. When there are significant breakdown flows, electricity usage can be reduced by bringing up steam turbines and turning off electric motors.

3. When efficiencies of equipment are different, the most efficient equipment available should be used to satisfy the plant energy requirement.

The most energy efficient plant operation can be maintained by using the optimum combination of optional equipment which satisfies both the plant operation demand and the maintenance needs.

OPTIMIZATION PROBLEM FORMULATION

The objective function used in this program is the sum of the fuel gas cost necessary to meet the plant boiler load, the electricity cost and treated water cost. The optimization problem minimizing the objective function can be formulated as a nonlinear integer programming problem.

Minimize

$$F(x) = \text{Steam cost} + \text{Electricity cost for optional electric motors} + \text{Treated water cost} \tag{3}$$

where $x = [x_1, x_2, \ldots, x_i, \ldots, x_N]^T$ Each element of x is an integer.

x_i indicates the status of i^{th} equipment. A "0" means it is down and an "1" means up. A "2" means two of the same kind are up.

Subject to

Plant operation demand

$$\mathbf{A}x = b \tag{4}$$

Maintenance need and availability of equipment

$$0 \leqq x_i \leqq x_{i,max} \quad i = 1, \cdots, N \tag{5}$$

Necessary data to evaluate the objective function are as follows:

1. The current boiler load and electric demand
2. Steam vent and breakdown flows
3. Up and down status of all optional turbines and electric motors
4. Electric and steam demand of each optional equipment
5. Cost data for fuel gas, electricity and treated water

Constraints for the optimization problem originate from the following considerations:

1. Operations' philosophy of running optional equipment affects the constraints of the optimization problem. For example, to prevent freezing when the weather is cold, all boiler feed water pump turbines are slow rolled. This is not necessary under normal weather conditions.

2. Also for reliability reasons operations may want to run one electric and one turbine when they need two pumps and more than two pumps are available. Thus, when they lose electricity they still have a steam turbine. In case they lose steam they still have an electric pump to prevent total plant shutdown.

3. Another example is that a unit may need an extra pump on line when the rate exceeds a certain rate.

4. When a pump or a compressor is down for maintenance, to prevent the program from asking for

bringing it up, this information has to constitute a new constraint for the optimization problem.

Given the above objective function and constraints the computer program determines how to best minimize the total energy cost for the plant. The program output suggests ten best options from which operations personnel can select.

Ten best options are suggested because the optimum is relative. By that I mean that often a less than absolute optimum is trivially different, in terms of dollars saved, from the absolute optimum solution. Further it may require significantly fewer changes to achieve most of the possible savings. Or it may require changes which are easier to make. These considerations can be very difficult to be translated into the objective function model. Table 1 and 2 show an exam-

Table 1. Energy management computer program output

	CURRENT	1	2	3	4	5	6	7	8	9	10
OBJ. FUNCT., $/HR	2474.97	2306.85	2306.85	2307.31	2307.31	2316.55	2316.55	2317.01	2317.01	2319.01	2319.01
BOILER LOAD, MPPH	409.00	375.00	375.00	375.00	375.00	378.00	378.00	378.00	378.00	375.00	375.00
15# STEAM VENT	70.00	36.00	36.00	36.00	36.00	39.00	39.00	39.00	39.00	36.00	36.00
60# STEAM VENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
160# STEAM VENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60# BREAKDOWN	44.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00
160# BREAKDOWN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
600# BREAKDOWN	45.00	0.00	3.60	4.00	7.60	0.00	3.60	4.00	7.60	14.00	17.60
OPT. ELE. DEMAND, KWH	1689.00	2440.00	2440.80	2450.00	2271.80	2450.00	2271.80	2281.80	2281.80	2684.80	2684.80
1. UN1 CWP P59 E	1	1	1	1	1	1	1	1	1	1	1
2. UN1 CWP P115	0	1	1	1	1	1	1	1	1	1	1
3. UN1 CWP P58	1	0	0	0	0	0	0	0	0	0	0
4. UTI SER AIR C36 E	1	0	0	1	1	0	0	1	1	1	1
5. UTI SER AIR C37	0	1	1	0	0	1	1	0	0	0	0
6. UTI BFW P132 E	0	0	0	0	0	0	0	0	0	0	0
7. UTI BFW P970	1	1	0	1	0	1	0	1	1	1	0
8. UTI BFW P123/124	1	1	2	1	2	1	2	1	1	1	2
9. SB BFW P970	0	0	1	0	1	0	1	0	0	0	1
10. SB BFW P123/124	1	1	0	1	0	1	0	1	1	1	0
11. UTI DEM P72	1	1	2	1	1	1	1	1	1	1	1
12. UTI DEM P73	0	0	0	0	0	0	0	0	0	0	0
13. UN2 CWP P388/979 E	1	1	1	2	2	1	1	2	2	1	1
14. UN2 CWP P386/387	2	2	2	1	1	2	2	1	1	2	2
15. UN2 CON P392 E	0	1	1	1	1	1	1	1	1	1	1
16. UN2 CON P1240	1	0	0	0	0	0	0	0	0	0	0
17. UN2 CHI P1112 E	0	1	1	1	1	1	1	1	1	1	1
18. UN2 CHI P1113	1	0	0	0	0	0	0	0	0	0	0
19. UN3 CWP 2E	0	1	1	0	0	1	1	0	0	1	1
20. UN3 CWP 3S	3	2	2	3	3	2	2	3	3	2	2
21. UN3 CON P719 E	1	1	1	1	1	1	1	1	1	1	1
22. UN3 CON P720	0	0	0	0	0	1	0	0	0	0	0
23. UN4 RCY P814 E	1	1	1	1	1	0	1	1	1	1	1
24. UN4 RCY P873	0	0	0	0	0	1	0	0	0	0	0
25. UN4 QCH P899 E	1	1	1	1	1	0	0	0	0	1	1
26. UN4 QCH P900/901	1	1	1	1	1	0	2	2	2	1	1
27. UN4 VAC C70 E	0	1	1	1	1	2	1	1	1	1	1
28. UN4 VAC C69	1	0	0	0	0	1	0	0	0	0	0
29. UN5 CHI P907 E	1	1	1	1	1	1	1	1	1	1	1
30. UN5 CHI P908/909	2	2	2	2	2	2	2	2	2	2	2
31. UN6 CWP P283 E	0	0	0	0	0	0	0	0	0	0	0
32. UN6 CWP P281/282	0	0	0	0	0	0	0	0	0	0	0
33. UN6 CHI P298 E	0	0	0	0	0	0	0	0	0	0	0
34. UN6 CHI P299	0	0	0	0	0	0	0	0	0	0	0
35. UN6 KRS P296 E	0	0	0	0	0	0	0	0	0	0	0
36. UN6 KRS P295	0	0	0	0	0	0	0	0	0	0	0

Optimum Strategy for Turbine-Electric Motor Sparing on 11/17/83

Fuel Gas Cost = $3.905 per MMBTU ($5.740 per MLB of 600 psig Steam)

Variable Electricity Cost = $0.050 per KWH ($0.037 per HPH)

Treated Water Cost = $0.310 per MLB

Table 2. Program output for changes from the current to best options

		Change from the Current to Best Options									
	CURRENT	1	2	3	4	5	6	7	8	9	10
OBJ. FUNCT., $/HR	2474.97	-168.12	-168.12	-167.66	-167.66	-158.42	-158.42	-157.96	-157.96	-157/96	-155.96
BOILER LOAD, MPPH	490.00	-34.00	-34.00	-34.00	-34.00	-31.00	-31.00	-31.00	-31.00	-34.00	-34.00
15$ STEAM VENT	70.00	-34.00	-34.00	-34.00	-34.00	-31.00	-31.00	-31.00	-31.00	-34.00	-34.00
60$ STEAM VENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
160$ STEAM VENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60$ BREAKDOWN	44.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
160$ BREKDOWN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
600$ BREAKDOWN	45.00	-45.00	-41.40	-41.00	-37.40	-45.00	-41.40	-41.00	-37.40	-31.00	-27.40
OPT. ELE. DEMAND, KWH	1689.00	751.80	751.80	761.00	761.00	582.80	582.80	592.00	592.00	996.00	995.00
1. UN1 CWP P59 E	1	0	0	0	0	0	0	0	0	0	0
2. UN1 CWP P115	0	1	1	1	1	1	1	1	1	1	1
3. UN1 CWP P58	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
4. UTI SER AIR C36 E	1	-1	-1	0	0	-1	-1	0	0	0	0
5. UTI SER AIR C37	0	1	1	0	0	1	1	0	0	0	0
6. UTI BEW P132 E	0	0	0	0	0	0	0	0	0	0	0
7. UTI BFW P970	1	0	-1	0	-1	0	-1	0	-1	0	-1
8. UTI BFW P123/124	1	0	1	0	1	0	1	0	1	0	1
9. SB BFW P970	0	0	1	0	1	0	1	0	1	0	1
10. SB BFW P123/124	1	0	-1	0	-1	0	-1	0	-1	0	-1
11. UTI DEM P72	1	0	0	0	0	0	0	0	0	0	0
12. UTI DEM P73	0	0	0	0	0	0	0	0	0	0	0
13. UN2 CWP P388/979 E	1	0	0	1	1	0	0	1	1	0	0
14. UN2 CWP P386/387	2	0	0	-1	-1	0	0	-1	-1	0	0
15. UN2 CON P392 E	0	1	1	1	1	1	1	1	1	1	1
16. UN2 CON P1240	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
17. UN2 CHI P1112 E	0	1	1	1	1	1	1	1	1	1	1
18. UN2 CHI P1113	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
19. UN3 CWP 2E	0	1	1	0	0	1	1	0	0	1	1
20. UN3 CWP 3S	3	-1	-1	0	0	-1	-1	0	0	-1	-1
21. UN3 CON P719 E	1	0	0	0	0	0	0	0	0	0	0
22. UN3 CON P720	0	0	0	0	0	0	0	0	0	0	0
23. UN4 RCY P814 E	1	0	0	0	0	0	0	0	0	0	0
24. UN4 RCY P873	0	0	0	0	0	0	0	0	0	0	0
25. UN4 QCH P899 E	1	0	0	0	0	-1	-1	-1	-1	0	0
26. UN4 QCH P900/901	1	0	0	0	0	1	1	1	1	0	0
27. UN4 VAC C70 E	0	1	1	1	1	1	1	1	1	1	1
28. UN4 VAC C69	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
29. UN5 CHI P907 E	1	0	0	0	0	0	0	0	0	0	0
30. UN5 CHI P908/909	2	0	0	0	0	0	0	0	0	0	0
31. UN6 CWP P283 E	0	0	0	0	0	0	0	0	0	0	0
32. UN6 CWP P281/282	0	0	0	0	0	0	0	0	0	0	0
33. UN6 CHI P298 E	0	0	0	0	0	0	0	0	0	0	0
34. UN6 CHI P299	0	0	0	0	0	0	0	0	0	0	0
35. UN6 KRS P296 E	0	0	0	0	0	0	0	0	0	0	0
36. UN6 KRS P295	0	0	0	0	0	0	0	0	0	0	0
**NO. OF CHANGINGES NEEDED		12	16	10	14	14	18	12	16	10	14

1 MEANS BRING UP
-1 MEANS SHUTDOWN
0 MEANS NO CHANGE

Total no. of iteration is 23040

ple output of the program. The final selection of which option to implement is left to the operations personnel.

OPTIMIZATION TECHNIQUE

As we are interested in finding ten best solutions rather than an absolute minimum, evaluating all possible options is required. The backtrack enumerization technique [1] is best suited for this application. Enumerative approaches to integer programming take advantage of the fact that in a bounded integer programming, the set of values of the integer variables is finite.

The basic idea of enumerative methods can be ex-

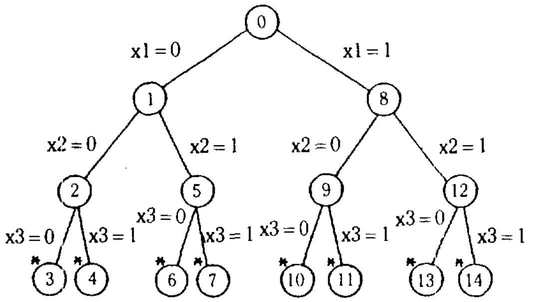

Fig. 2. Basic idea of enumerative methods.

plained using a tree shown in Figure 2. The solutions are given by the unique paths from vertex 0 to each of the vertices marked by an asterisk in Figure 2.

A typical algorithm is listed in Appendix. Every time a new option is evaluated, it is compared with the ten best solutions found so far. If the new option is better than any one of the ten best options they are updated with the new one.

As the number of decision variables increases, the number of function evaluations required by the enumerization technique increases drastically. For example if there are 30 decision variables and each decision has two options, the total number of possible options is 1,073,741,824. Intelligently taking advantage of existing constraints for the steam system is necessary to reduce the total number of objective function calculations.

IMPLEMENTATION

Variations of the above basic approach can be adapted for different plant situations. A plant steam system may have different structure from the system shown in Figure 1. In many cases, each steam header pressure is controlled by venting steam when the pressure is higher than its setpoint and by making it up with the next higher pressure level steam when it is lower than its setpoint. Steam system material balances have to be modified accordingly to fit the actual steam system structure.

Some plants may use both the imported steam from the cogeneration unit and the steam from the plant boilers. The steam from the cogeneration unit is usually cheaper than the steam generated from plant boilers. For reliability reasons plant boilers are kept running at the minimum load. Thus when cogeneration unit goes down by any réasons, boiler load can be increased to keep the plant running without causing plantwide shutdowns. Usually the cogen steam has a different price structure depending on the cogen steam usuage. This pricing curve has to be incorporated in the objective function calculation.

In case for a plant where the amount of low level steam quite often exceeds the flexibility the existing optional equipment can allow to reduce steam ven-

Table 3. Operator interface for data input

Description	Value	Input	_ _ Page 1 of 5
11/17/83		[ ]	
BOILER LOAD(MPPH)	409	[ ]	_ _
600 TO 160# BREAKDOWN(MPPH)	45.0	[ ]	_ _
160# STEAM VENT(MPPH)	0.0	[ ]	_ _
60# STEAM VENT(MPPH)	44.0	[ ]	_ _ USEFUL KEYS
15# STEAM VENT(MPPH)	0.0	[ ]	_ _
**NO. OF UN1 CWPS NEEDED (0,1,2)	70	[ ]	_ _ Up Arrow
1. UN1 CWP P59 E 55 401.	2	[ ]	_ _ Down Arrow
2. UN1 CWP P115 12 33.	1	[ ]	_ _ Right Arrow
3. UN1 CWP P58 24 15.	0	[ ]	_ _ Left Arrow
**NO. OF UTI. SER AIR COMP. NEEDED(0,1,2)	1	[ ]	_ _ Help
4. UTI SER AIR C36 E 55 243.2	1	[ ]	_ _
5. UTI SER AIR C37 12 14	1	[ ]	_ _
			_ _

Instructions. Use the up and down arrows to select the data to be modified, then press⟨RET⟩. Enter the new data and press⟨RET⟩. Use the right arrow to go to the next input page or the left arrow to go to a previous page or use the Find key. Press E to exit.
Messages ⟹

ting, installing a turbine which can use both the high and the low pressure level steam will eliminate unnecessary steam venting. The steam balance equations in objective function calculation can be modified to reflect this modification.

If the plant is a medium scale and the plant operation is comparatively steady, the energy management program can be run once a day or once a shift to see where the current condition is compared to the optimum condition and to make a necessary change to save energy cost. The data necessary to run the program can be entered by a process engineer of an operator through the user friendly interface as shown in Table 3.

In a larger and more dynamic plant the steam balance may fluctuate more rapidly. In this case, more frequent program run is necessary to capture the potential savings opportunity during the transient period. This can be done by scheduling the program run once an hour or once every two hours. This may require automating equipment up/down status inputs and steam breakdown and vent flows.

RESULTS

The result of the program implementation has been impressive. In one plant, since we implemented this program we could have a significant manpower reduction in energy conservation area and still have been saving ~$300 M per year. In another plant we could justify the plantwide computer communication network and replace the outmoded computers with state-of-art computer systems. Not only the benefit of saving energy could be achieved but also the improved productivity of plant personnel could be realized due to plantwide computer literacy, better communication through electronic mail, better coordination among different units, total integration of plant database, and ultimate plantwide management.

APPENDIX

Backtrack Enumeration Algorithm Coding

```
C***  INITIALIZATION
C     W(J) IS AN ASSIGNMENT VECTOR. W(J)=-1 IF
      J IS FREE, OTHERWISE J IS NOT
C     FREE. W(J) CAN BE 0,1,...,WMAX(J). WMAX
      (J) IS THE UPPER LIMIT OF W(J).
C     SET ALL VARIABLES FREE.
       L=0
       DO 10 J=1,N
   10  W(J)=-1
C
C***  FATHOM
  100  CONTINUE
       DO 20 J=1,N
       IF(W(J).NE.-1) GO TO 20
       JS=J
       GO TO 40
   20  CONTINUE
C
C***  EVALUATE OBJECTIVE FUNCTION
       CALL OBJ(W,ZL)
       IF(ZL.LT.ZBEST) GO TO 999
       ZBEST=ZL
       DO 21 J=1,N
   21  XBEST(J)=W(J)
  999  CONTINUE
       GO TO 200
C
C***  SEPARATE
   40  CONTINUE
       W(JS)=0
       U(L+1)=0
C     U(L)=0 MEANS LEVEL L TO BE FATHOMED.
C         =1                HAS BEEN FATHOM-
      ED.
       P(L+1)=JS
C     P(L) IS THE SEPARATION VARIABLE.
       L=L+1
       GO TO 100
C
C***  BACKTRACK
  200  CONTINUE
       IF(U(L).EQ.O) GO TO 210
       J=P(L)
       W(J)=-1
       L=L-1
  210  J=P(L)
       W(J)=W(J)+1
       IF(W(J).EQ.WMAX(J)) U(L)=1
       GO TO 100
 1000  CONTINUE
       IF(L.EQ.O) GO TO 100
       GO TO 200
```

NOMENCLATURE

A : A matrix which defines the number of equipment in each specific service for the plant operation

b : A vector which defines the number of equipment needed in each service for the plant operation

BL : Boiler load, MPPH

B_1 : Breakdown flow from 650 to 160 psig header, MPPH

B_2 : Breakdown flow from 160 to 60 psig header, MPPH

B_3 : Breakdown flow from 60 to 15 psig header, MPPH

B_4 : 15 psig steam vent flow, MPPH

EM : Electric motors

F_1 : Net steam demand at 650 psig header, MPPH

F_2 : Net steam demand at 160 psig header, MPPH

F_3 : Net steam demand at 60 psig header, MPPH

F_4 : Net steam demand at 15 psig header, MPPH

N : Number of optional equipment

S_1 : 600 psig steam flow for optional equipment, MPPH

S_2 : 160 psig steam flow for optional equipment, MPPH

$S_{i,j}$: Steam flow for optional equipment, MPPH (Used from i^{th} level and discharged to j^{th} level)

ST_1 : Steam turbines using 600 psig steam

ST_2 : Steam turbines using 160 psig steam

x : An equipment status vector

REFERENCE

1. Garfinkel, R.S. and Nemhauser, G.L.: "Integer Programming", John Wiley & Sons, New York, NY (1972).