Modeling of Co-Generation System Using Mixed Integer Linear Programming

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ABSTRACT

With the development in Computer technology, interest in computer aided process analyses has increased among the decision-makers. Applications of Operations Research techniques for management decision making in complex situations are widely known in the paper industry. Mathematical programming techniques have their capabilities to combine the technical and economic factors effectively to arrive at optimum solutions. In this article, a co-generation system is modeled using Mixed-Integer Linear Programming technique to decide on optimum operational strategies to keep cost of energy at minimum level. The model has been developed for the co-generation system an integrated pulp and paper mill. The appropriateness of the model is demonstrated, in the form of a case study with real data taken from M/s Seshasayee Paper and Boards Limited, Erode.

INTRODUCTION

Mathematical programming techniques have been widely used in the paper industry for providing solutions to practical problems involving optimal utilisation of energy resources (1-7). The major objective in the above applications is to determine the operating conditions of boilers (fuel mix and steam generation mix) and turbo-generators and purchased power (power mix) so that the total energy cost is optimum. Some of the techniques used are linear programming, non-linear programming and mixed integer linear programming. In this paper an attempt has been made to develop a mixed integer linear programming model for the co-generation system of an integrated pulp and paper mill to determine ideal mix of purchased power and generated power. The capability of the model is demonstrated using the data from a case study mill and further the model is modified for evaluating alternate co-generation system.

Development of the Model

The configuration of a co-generation system of an integrated pulp and paper mill for which the model is developed is shown in Fig 1. The time horizon for the model is assumed as a day. The unit of measurement for steam flow is in tonnes/day while the unit for power is MW and that for electrical energy is MWH. The notations for parameters used in the development of the model with defination, the decision variables of the model and the mathematical form of the MILP model are not shown here. The objective function and the constraints are described below.

Objective Function

The objective function is to minimize the sum of costs of purchased fuels used in power boilers and cost of purchased electrical energy per day at 100% production capacity. This can be expressed as follows.

Minimize

(Cost of steam) x (Steam Generated in) + (Cost of Purchased) x (Purchased
RS/t power boilers -t/day Power RS/MWH) Power
-tonnes/day) MWH/day) MWH/day)

Constraints

These are briefly described below:

(i) Mass balance in High-pressure steam header
(ii) Limitation on total steam generated by power boilers
(iii) Process fuel boiler capacity
(iv) Upper limit on the steam flow into each turbo-generator
(v) Mass balance across each turbo-generators
(vi) Steam to Electrical conversion in turbo-generators
(vii) Upper limit on the extraction/condensing steam flows
(viii)Minimum condensation in turbo-generators
(ix) Medium pressure desuper heater
(x) Mass balance in medium pressure steam header

(xi) Low Pressure Desuper heater

(xii) Mass balance in the low pressure steam header

(xiii) Deaerator steam consumption

(xiv) Electrical energy flow balance

(xv) Upper limit on power from different sources

(xvi) Relationship between power and energy

(xvii) Integer variable restriction

(xviii) Non-negativity constraints

Case Study

The suitability of the above model was examined through real data from Seshasayee Paper & Boards Ltd (SPB). SPB's present installed capacity is 1,15,000 tonnes per annum. The mill manufactures super, fine, graphic, copier, writing and printing paper, pulp board, posters and kraft papers. The mill uses wood, bagasse and waste paper as raw material and also imports pulp. The mill has 4 stationary digesters for cooking wood and two continuous digesters for cooking bagasse. It has a complete chemical recovery section with two streets of evaporators, two recovery boilers and recausticing plant. It has 5 paper machines. It normally uses two power boilers and three turbo-generators of capacities 5 MW, 3 MW and 2.5 MW.

The conversion coefficients, namely, average specific power generation for steam flows, of the turbo-generators are determined using regression analysis. The power generated by steam at two different pressure levels is equal to {Steam flow x (isentropic heat drop) x (Conversion efficiency)}.

The total power generated by the turbo-generator is given by the following formula:

$$P=(E) \times (1000)\times(430/3600)\times(ee) + (C)\times(1000)\times(1030/3600)\times(ec)$$

where P is the total power generated in kwh/day,

E is the extraction steam flow at low pressure in tonnes/day,

C is the condensation flow in tonnes/day

ee is the conversion efficiency of extraction stage and

ec is the conversion efficiency of condensation stage

From daily operational data, all the parameters in the above equation except the two efficiencies are available. Using the daily data in a spreadsheet package the regression analysis is carried out and the two unknown conversion efficiencies are determined. From these efficiencies, the parameters aij (average specific power generation for steam flows) are computed and used in the Mixed Integer Linear Programming (MILP) model.

Milp Model for the Case Study

The MILP model formulated for the case study mill is as follows:

```
MIN      400 TBHS + 4120 GPD
Subject to
2   TBHS + HPRBS - TGS1 - TGS2 - TGS3 - PRS
    =50
3   TBHS <=   2160
4   HPRBS <=   500
5   MPRBS <=   340
6   1860 ITG1 + TGS1 <=   0
7   874 ITG2 + TGS2 <=   0
8   750 ITG3 + TGS3 <=   0
9   TGS1 - TGE12 - TGE13 =    0
10  TGS2 - TGE21 - TGE23 =    0
11  TGS3 - TGE32 =    0
12  64 TGE12 + 115 TGE13 - 1000 TGPD1 =    0
13  35 TGE21 + 196 TGE23 - 1000 TGPD2 =    0
14  71 TGE32 - 1000 TGPD3 =    0
15  700 ITG1 + TGE12 <=   0
16  288 ITG1 + TGE13 <=   0
17  480 ITG2 + TGE21 <=   0
18  216 ITG2 + TGE23 <=   0
19  120 ITG1 + TGE13 >=   0
20  100 ITG2 + TGE23 >=   0
21  750 ITG3 + TGE32 <=   0
22  108 PRS - 108 TGE21 + 100 MPDS =    0
23  MPRBS + MPDS - PRS12 =    650
24  105 TGE32 - 105 PRS12 + 100 LPDS =    0
25  TGE12 + LPDS - DAS =    1150
26  85 TBHS - 85 HPRBS - 85 MPRBS + 1000 DAS
    =   0
27  GPD + TGPD1 + TGPD2 + TGPD3 =    432
28  GP <=   15
29  5 ITG1 - TGP1 >=   0
30   2.5 ITG2 - TGP2 >=   0
31  3 ITG3 - TGP3 >=   0
32  TGPD1 - 24 TGP1 =    0
33  TGPD2 - 24 TGP2 =    0
34  TGPD3 - 24 TGP3 =    0
35  GPD - 24 GP =    0
INTEGER  ITG1
INTEGER ITG2
INTEGER ITG3
```

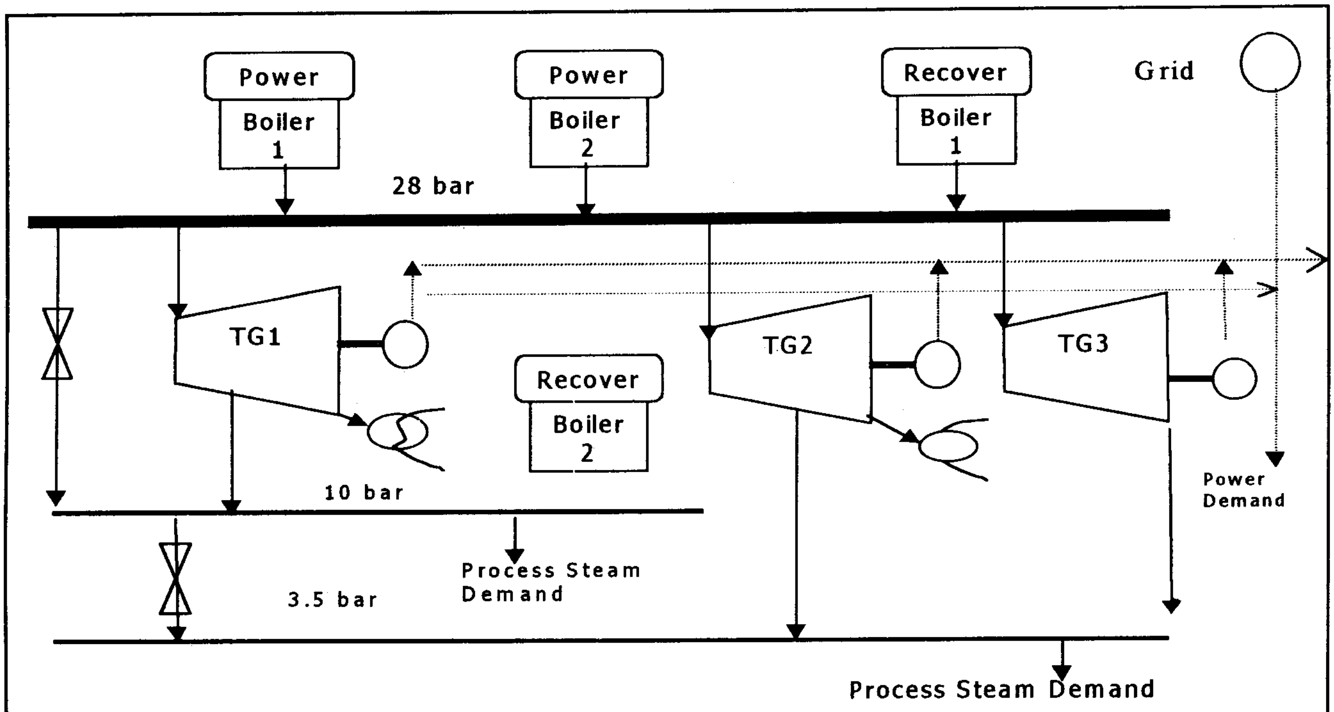

Fig. 1 Typical Cogeneration System

RESULTS AND DISCUSSION

The optimal solution for the case study mill is as follows:

Optimum value of objective function = 1723056

Variable	Optimum value	Variable	Optimum value
ITG1	1.00	TGE32	750.00
ITG2	1.00	TGPD1	69.95
ITG3	1.00	TGPD2	52.38
TBHS	1666.59	TGPD3	53.25
GPD	256.41	MPDS	310.00
HPRBS	500.00	PRS12	0.00
TGS1	863.56	LPDS	787.50
TGS2	503.03	DAS	213.06
TGS3	750.00	GP	10.68
PRS	0.00	TGP1	2.92
MPRBS	340.00	TGP2	2.18
TGE12	575.56.00	TGP3	2.22
TGE13	288.00		
TGE21	287.03		
TGE23	216.00		

An analysis of the results indicate the followings:

- The minimum (optimum) purchased energy cost is Rs 17,20,516.00 per day.
- This can be achieved by drawing 10.68 MW of power from NEB grid and generating 2.92 MW, 2.18 MW & 2.22. MW of power in turbo-generator-1, turbo-generator-2 and turbo-generator-3 so as to meet the total power demand of 18 MW.
- Generation of 1666 tonnes of high pressure steam in the power boilers and 500 tonnes of steam in high pressure recovery boiler and 340 tons of steam in medium pressure process boiler in order to meet process steam demand for 100% production including condensation.

Evaluation of alternate Co-generation System for the case study

The mathematical programming model can be used for evaluating the effectiveness of alternative configuration of the co-generation system. The alternative configuration of energy system consists of a new single power boiler and new single recovery boiler both at very high pressure of 120 bar with single new double extraction cum condensing turbo-generator. The arrangement of the configuration is shown in Fig. 2. The modified MILP model is as follows:

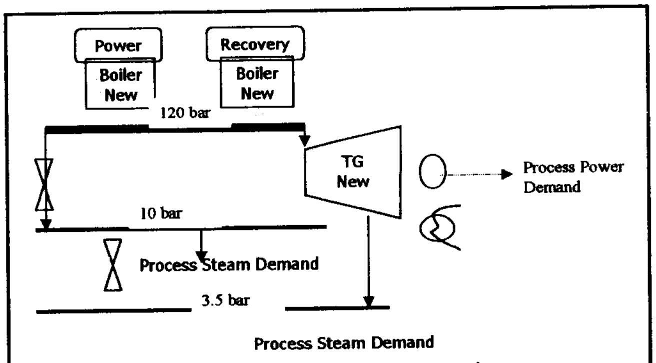

Fig. 2 Alternative Co-generation system

MIN $400\ TBHS + 4120\ GPD$

Subject to

2 $TBHS - TGS4 - PRS + HPRBSN = 15$

3 $TBHS \le 2160$

4 $HPRBSN \le 840$

5 $TGS4 \le 3000$

6 $TGS4 - TGE41 - TGE42 - TGE43 = 0$

7 $154\ TGE41 + 218\ TGE42 + 270\ TGE43 - 1000\ TGPD4 = 0$

8 $TGE43 \ge 300$

9 $112\ PRS - 112\ TGE41 + 100\ MPDS = 0$

10 $MPDS - PRS12 = 650$

11 $108\ TGE42 - 108\ PRS12 + 100\ LPDS = 0$

12 $LPDS - DAS = 1150$

13 $85\ TBHS - 85\ HPRBSN + 1000\ DAS = 0$

14 $GPD + TGPD4 = 432$

15 $GP \le 15$

16 $TGPD4 - 24\ TGP4 = 0$

17 $GPD - 24\ GP = 0$

This optimal solution obtained is as follows:

Optimum value of objective function = 511097.20

Variable	Optimum value	Variable	Optimum value
TBHS	1277.74	TGPD4	432.00
GPD	0.00	MPDS	734.96.00
TGS4	2102.74	PRS12	84.96.00
PRS	0.00	LPDS	1330.00
HPRBSN	840.00	DAS	180.08
TGE41	656.21	GP	0.00
TGE42	1146.52	TGP4	18.00
TGE43	300.00		

The results indicate the following:

- The optimum energy cost for the modified model is Rs. 5,11,097.20 with the generation of full 18 MW of power in the new single turbo-generator.
- The economic advantage of such new configuration results in a saving of nearly Rs. 12,11,959 per day.
- This works out to Rs 40 crores per year.
- The total project cost will be of the order of Rs 160 crores and
- The simple payback period is 4 years.

CONCLUSION

A co-generation system has been modeled using Mixed Integer Linear Programming (MILP). The model determines optimum steam generation from power boilers and optimum power from steam turbines and purchased power source. The model was demonstrated using data from M/s Seshasayee Paper & Boards Limited and further used for evaluating alternative configuration of the co-generation system. The model has the capability for finding answers to various "What if "questions? For example, how the total purchased energy cost will change when there is a change in process steam or power demand, change in the major energy generating equipment in the co-generation system. While reduction in power will result in reducing purchased power cost or fuel cost depending up on the source, reduction in process steam will reduce purchased fuel cost but increase the purchased power cost. Hence an optimum condition needs to be determined. The mathematical model of the co-generation system aids the decision-maker for taking optimal decisions.

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