J. ENVIRONMENTAL SYSTEMS, Vol. 29(1) 15-38, 2002-2003

IMPACT OF SO_2 EMISSION LIMITS ON PETROLEUM REFINERY OPERATIONS I: A LINEAR PROGRAMMING MODEL

AMIT DUTTA

A. K. DIKSHIT

S. RAY

M. BANDYOPADHYAY

Indian Institute of Technology, Kharagpur, India

ABSTRACT

This is the first part of the three-part article. This article discusses the development of a general-purpose linear programming model to evaluate the impact of imposed maximum SO_2 emission limits on the operation and the profitability of a petroleum refinery satisfying all relevant constraints due to the refinery configuration and operational limitations. The proposed model has been applied to an existing petroleum refinery in India. The model generates the tradeoff curve for profit as a function of maximum SO_2 emission limits, which helps in identifying opportunities for source reduction of SO_2. The case study clearly demonstrates that the model can be used for any refinery as a tool to schedule the optimal monthly operation satisfying the SO_2 emission standard.

INTRODUCTION

Petroleum extraction and refining and use of petroleum products and by-products have become keystones of modern civilization. Petroleum refineries are strong contributors to the global and local economy, and supply a major part of the world's energy. A refinery is a large, multi-unit plant that, as such, generates many pollutants. Among them SO_2 emission is a matter of global concern owing to its several environmental impacts [1, 2]. Global and local pollution control authorities impose a maximum emission limit for SO_2 from specific petroleum refineries [3-6]. The treatment of the gaseous emissions from a refinery is not common. The present study helps to address this gap by investigating the relationship between SO_2 emission reduction at the source and refinery profit.

Linear programming (LP) of refineries is well-studied and reported in research literature [7-12]. Typical refinery LP models have an economic objective function (say maximization of profit) and various constraints on refinery configuration and operational limitations, such as unit capacities, crude availability, product demands, product quality, and (property) specification limits. These models traditionally have been used to plan the operations of crude and process units and the blending of streams to produce optimum product mixes for maximum profitability in a refinery. Hartmann [13] has presented a critical review of the limitations and capabilities of different linear programming models of refineries. The use of LP for waste minimization and pollution control in refineries is relatively recent. Chen and Pike [14] developed an on-line optimization system using GAMS (General Algebraic Modeling Systems) and reported that it can be used for waste minimization of petroleum refineries. High & Watt Associates, Ltd. [15] has recently upgraded their LP based Refinery Modeling System to allow refinery emissions to be calculated.

In this first part of a three-part article, a general-purpose linear programming model is developed to evaluate the impact of incorporating environmental constraints on SO_2 emission rates on profitability and operation of a petroleum refinery. The LP model is applied to a typical refinery situated in eastern India. In the second part, a new methodology is presented to obtain the best operating plan, intended to maximize the profit and simultaneously minimize SO_2 emissions. The third and final part addresses the issues of uncertainties in SO_2 emission rates and profits.

LP MODEL FORMULATION

Fundamental Assumptions of the Proposed Model

The following assumptions have been made to formulate the present model:

1. Each process unit operates only in one or more of its possible modes of operation. The corresponding stream yields and properties used are the average values based on the past operating experiences of the refinery.

2. The pooled streams and the product blend pools have uniform composition and their blend properties are computed from the contribution of its components.

3. Calorific values for the fuel gas (FG) and refinery fuel oil (RFO) pools are considered to be average values, not significantly affected by composition variation.

4. The entire sweet FG is used in furnaces and no option of flaring of FG is considered. The FG and RFO consumption ratio has an upper bound as well as a lower bound; the values of these ratios are derived from the operating experience of the refinery furnaces for stable operation.

5. The operating cost of each process unit is assumed to be proportional only to its throughput in the operating zone of 60 to 100 percent capacity.

6. The direct fuel (fired in the process unit furnace) and the indirect fuel (consumed in the captive power plant of the refinery, on account of the power and utilities consumption) in each process unit are assumed to be proportional to the throughput in the operating zone of 60 to 100 percent capacity.

7. Operating cost and revenue from the sale of sulfur produced from SRU are neglected in computation of refinery profit, as these figures in reality are very small (the net amount is of the order of 0.1 percent of the total refinery profit as shown by past data of the refinery). The cost of the effluent treatment plant considering capital, operation, and maintenance cost [16] is also neglected in computing the refinery profit for the same reason.

8. Adequate storage and blending facilities are considered to be available in the refinery for crude, process unit feed, and products.

The data pertain to the details of several entities involved in the refinery. These entities are crude(s), product(s), process unit(s), mode(s) of operation for each of the process units, properties (qualities) of the products, and special streams like Refinery Fuel Gas (FG) and Refinery Fuel Oil (RFO). Apart from these, there are flows of crudes and streams that are treated as variables.

Model Formulation Parameters

Indices

The following indices are used for the model:

R	Total number of crude oils	c = index for crude (1 .. R)
S	Total number of streams	*i* = index for a stream (1 .. S)
T	Total number of products	*j* = index for process unit (1 .. U)
U	Total number of process units	*k* = index for process unit (1 .. U)
V	Total number of property (quality) of different products	*m* = index for mode in a unit k (1 .. n_k)
		p = index for a product (1 .. T)
W	Maximum number of modes	*q* = index for a quality (1 .. V)

Input Data in the Form of Matrices

$CRFM_{ckm}$ Routing of crude *c* going to process unit *k* in its mode *m* (R × U × W matrix)

$STPM_{ijp}$ Routing of stream *i* produced in process unit *j* going to product *p* (S × U × T matrix)

$SFGM_{ij}$	Routing of stream *i* produced in process unit *j* going to fuel gas pool (S × U matrix)
$SRFOM_{ij}$	Routing of stream *i* produced in process unit *j* going to fuel oil pool (S × U matrix)
$STUM_{ijkm}$	Routing of stream *i* produced in process unit *j* going to process unit *k* in its mode *m* as feed (S × U × U × W matrix)
$SSRUM_{ij}$	Routing of stream *i* produced in process unit *j* going to SRU (S × U matrix)
$CAPX_k$	Maximum capacity limit of process unit *k* (U × 1 matrix)
$CAPN_k$	Minimum capacity limit of process unit *k* (U × 1 matrix)
Y_{ijm}	Yield of stream *i* produced in process unit *j* in its mode *m* (S × U × W matrix)
CP_p	Price of product *p* (T × 1 matrix)
CC_c	Cost of crude *c* (R × 1 matrix)
CR_k	Running cost of process unit *k* (U × 1 matrix)
AVX_c	Maximum availability of crude *c* (R × 1 matrix)
AVN_c	Minimum availability of crude *c* (R × 1 matrix)
DXP_p	Maximum demand of product *p* (T × 1 matrix)
DNP_p	Minimum demand of product *p* (T × 1 matrix)
$PRST_{qi}$	Property *q* of stream *i* (V × S matrix)
$PRXP_{qp}$	Maximum limit of property *q* of product *p* (V × T matrix)
$PRNP_{qp}$	Minimum limit of property *q* of product p (V × T matrix)
$PRXF_{qkm}$	Maximum limit of property *q* for processing in unit *k* in its mode *m* (V × U × W matrix)
$PRNF_{qkm}$	Minimum limit of property *q* for processing in unit *k* in its mode *m* (V × U × W matrix)
$PRXRF_q$	Maximum limit of property *q* of refinery fuel (V × 1 matrix)
$PRNRF_q$	Minimum limit of property *q* of refinery fuel (V × 1 matrix)
PRC_{qc}	Property *q* of crude *c* (V × R matrix)
$SRFC_k$	Percentage standard refinery fuel (SRF) consumption in unit *k* (U × 1 matrix)
α	Maximum permissible limit of FG (refinery fuel gas) to RFO (refinery fuel oil) ratio
β	Minimum permissible limit of FG (refinery fuel gas) to RFO (refinery fuel oil) ratio
ϕ	FG to SRF conversion factor considering fuel value
φ	RFO to SRF conversion factor considering fuel value
γ	Stoichiometric conversion factor for H_2S to SO_2
δ	Stoichiometric conversion factor for S to SO_2
SEL	Maximum permissible SO_2 emission limit

Variables

CRF_{ckm}	Quantity of crude *c* going to process unit *k* in its mode *m* as feed
STU_{ijkm}	Quantity of stream *i* produced in process unit *j* going to process unit *k* in its mode *m* as feed
STP_{ijp}	Quantity of stream *i* produced in process unit *j* going to product *p* as product
SFG_{ij}	Quantity of stream *i* produced in process unit *j* going to fuel gas pool as refinery fuel
$SRFO_{ij}$	Quantity of stream *i* produced in process unit *j* going to fuel oil pool as refinery fuel
$SSRU_{ij}$	Quantity of stream *i* produced in process unit *j* going to SRU (H_2S absorbed in SRU)
TP_p	Total quantity of product *p*
FG	Total quantity of refinery fuel gas
RFO	Total quantity of refinery fuel oil
H2S	Total quantity of refinery H_2S gas
RF	Total quantity of total refinery (FG + RFO) fuel
SO2	Total quantity of total refinery SO_2

The Objective Function and the Constraints

Objective Function

The objective function of this LP model is maximization of refinery profit.

Refinery profit = [(revenue from sales of all products) – (cost of crude processed) – (operating cost of crude distillation units and other process units)]

$$= \Sigma_p [CP_p TP_p] - \Sigma_c [CC_c (\Sigma_k \Sigma_m CR_{ckm})] - \Sigma_k CR_k [\Sigma_i \Sigma_j \Sigma_m STU_{ijkm} + \Sigma_c \Sigma_m CRF_{ckm}] \quad (1)$$

Constraints

Various constraints of the model are as follows:

1. The quantity of a crude processed can not exceed the maximum availability limit for that crude type and cannot be less than the minimum availability limit for that crude type

$$\Sigma_k \Sigma_m CRF_{ckm} \leq AVX_c \qquad \forall_c = 1 .. \mathrm{R} \quad (2)$$

$$\Sigma_k \Sigma_m CRF_{ckm} \geq AVN_c \qquad \forall_c = 1 .. \mathrm{R} \quad (3)$$

2. The total quantity of a product is the sum of all streams routed to that product

$$\Sigma_i \Sigma_j STP_{ijp} - TP_{\mathrm{p}} = 0 \qquad \forall_p = 1 \,..\, \mathrm{T} \tag{4}$$

3. The total quantity of fuel gas (FG) produced is the sum of the fuel gas produced in all process units

$$\Sigma_i \Sigma_j SFG_{ij} - FG = 0 \tag{5}$$

4. The total quantity of refinery fuel oil (RFO) produced is the sum of the refinery fuel oil produced in all process units

$$\Sigma_i \Sigma_j SRFO_{ij} - RFO = 0 \tag{6}$$

5. Maximum and minimum permissible ratio of FG to RFO should be maintained

$$\Sigma_i \Sigma_j SFG_{ij} - \alpha\Sigma_i \Sigma_j SRFO_{ij} \leq 0 \tag{7}$$

$$\Sigma_i \Sigma_j SFG_{ij} - \beta\Sigma_i \Sigma_j SRFO_{ij} \geq 0 \tag{8}$$

6. Material balance for each specific stream should be fulfilled

$$\begin{aligned} &\Sigma_k \Sigma_m [Y_{ikm} \{\Sigma_l \Sigma_j STU_{ljkm}\}] + \Sigma_k \Sigma_m [Y_{ikm} \{\Sigma_c CRF_{ckm}\}] \\ &\quad - \Sigma_k [\Sigma_f \Sigma_m STU_{ikfm} + \Sigma_p STP_{ikp} + SFG_{ik} + SRFO_{ik} + SSRU_{ik}] = 0 \\ &\qquad \forall_i = 1 \,..\, \mathrm{S}\ (l = 1 \,..\, \mathrm{S}, f = 1 \,..\, \mathrm{U}) \end{aligned} \tag{9}$$

7. The total quantity processed by a unit should be within its maximum and minimum capacity limits

$$\Sigma_i \Sigma_j \Sigma_m STU_{ijkm} + \Sigma_c \Sigma_m CRF_{ckm} \leq CAPX_k \qquad \forall_k = 1 \,..\, \mathrm{U} \tag{10}$$

$$\Sigma_i \Sigma_j \Sigma_m STU_{ijkm} + \Sigma_c \Sigma_m CRF_{ckm} \geq CAPN_k \qquad \forall_k = 1 \,..\, \mathrm{U} \tag{11}$$

8. Product property value should be within its acceptable maximum and minimum limits

$$\Sigma_i \Sigma_j [STP_{ijp} (PRST_{qi} - PRXP_{qp})] \leq 0 \qquad \forall_q = 1 \,..\, \mathrm{V}, p = 1 \,..\, \mathrm{T} \tag{12}$$

$$\Sigma_i \Sigma_j [STP_{ijp} (PRST_{qi} - PRNP_{qp})] \geq 0 \qquad \forall_q = 1 \,..\, \mathrm{V}, p = 1 \,..\, \mathrm{T} \tag{13}$$

9. The total fuel (calorific value) required for the refinery operation is exactly met by FG and RFO

$$\begin{aligned} &\Sigma_k [SRFC_k \{\Sigma_i \Sigma_j \Sigma_m STU_{ijkm}\}] + \Sigma_k [SRFC_k \{\Sigma_c \Sigma_m CRF_{ckm}\}] \\ &\quad - \phi\, \mathrm{FG} - \varphi\, \mathrm{RFO} = 0 \end{aligned} \tag{14}$$

10. The total quantity of each product produced should be within its maximum and minimum production limits

$$\Sigma_i \Sigma_j STP_{ijp} \leq DXP_p \qquad \forall_p = 1 \,..\, \mathrm{T} \tag{15}$$

$$\Sigma_i \Sigma_j STP_{ijp} \geq DNP_p \qquad \forall_p = 1 \,..\, \mathrm{T} \tag{16}$$

11. The viscosity of visbreaking units (VBU) feed should be within its maximum and minimum limits

$$\Sigma_i \Sigma_j [(PRST_{qi} - PRXF_{qkm}) (\Sigma_m STU_{ijkm})] \leq 0 \qquad \forall_q = 1 \,..\, \mathrm{V}, k = \mathrm{VBU} \tag{17}$$

$$\Sigma_i \Sigma_j [(PRST_{qi} - PRNF_{qkm}) (\Sigma_m STU_{ijkm})] \geq 0 \qquad \forall_q = 1 \,..\, \mathrm{V}, k = \mathrm{VBU} \tag{18}$$

12. The total SO_2 emission from the refinery should not exceed the maximum permissible emission limit

$$\gamma \Sigma_i \Sigma_j SSRU_{ij} + \delta \Sigma_i [PRST_{1i} \Sigma_j SRFO_{ij}] - SO2 = 0 \qquad \forall_q = 1 \text{ for weight fraction of sulfur} \tag{19}$$

$$SO2 \leq SEL \tag{20}$$

MODEL IMPLEMENTATION

The model was implemented using LINDO software [17]. The model can be run for any given refinery for any time scale ranging from daily to yearly. However, most refineries plan their activities on monthly basis. The solution of the LP model generates an optimum-operating plan for the refinery, which maximizes the profit for the month. The output (optimum plan) details:

1. crude and other process units feed quantities and their compositions,
2. operating modes of each of the process units,
3. streams produced from the crude and other processing units and their blending routes,
4. total production of each product, their blend compositions and properties, and
5. SO_2 emission details.

CASE STUDY

Description of the Refinery Under Study

The configuration of the fuel processing section of an Indian refinery was modeled using the LP model. The refinery consists of six process units, viz., Crude Distillation Unit-I (CDU-I), Crude Distillation Unit-II (CDU-II), Vacuum Distillation Unit (VDU), Visbreaking Unit (VBU), Catalytic Reforming Unit

(CRU), and Kero-Hydro Desulfurization (K-HDS) Unit. The capacities and the operating costs of various process units are given in Table 1. The refinery can process low sulfur (LS) and high sulfur (HS) crudes in both CDUs. Prices for these crudes are Rs 5282 per metric ton and Rs 4706 per metric ton, respectively. Each process unit has its specific number of modes of operation—CDUs have eight modes, VDU four modes, VBU and CRU one mode each and K-HDS two modes. In each mode of operation, operating conditions are different and a specific set of streams is produced. For example, the CDUs in the refinery can produce: (i) kerosene/aviation turbine fuel and (ii) jute batching oil-C/jute batching oil-P in blocked out operations. Accordingly, for each type of crude (LS and HS) there are four possible modes (m) of operation in each CDU. The production of aviation turbine fuel and jute batching oil-C from LS crude is one such specific mode of operation in a CDU.

There are 35 streams emanating from various process units (Table 2), which are blended to produce 14 final products. The typical configuration of the refinery along with 35 streams has been shown in Figure 1. The products, their prices, and demands are given in Table 3 (as of the year 1999-2000). The streams and products are characterized by one or more of the following four properties: percentage sulfur (by weight), viscosity index, flash point index, and research octane number.

The refinery fuel gas (FG) produced in CDUs, VBU, K-HDS, and CRU process units is pooled up and is washed with amine solution to remove H_2S. This amine solution is regenerated for reuse, releasing the absorbed H_2S. The H_2S is fed to a Sulfur Recovery Unit (SRU) based on the Claus process to convert H_2S to elemental sulfur having efficiency of 94 percent [6, 18]. Various heavy streams are blended together to form the refinery fuel oil (RFO).

Table 1. Process Units of the Refinery and Their Operating Costs and Capacities

Unit no.	Names of process units	Unit operating cost (Rs/MT of throughput)	Capacity (thousand MT/month)	
			Maximum	Minimum
1	Crude Distillation Unit-I (CDU-I)	65.58	250	150
2	Crude Distillation Unit-II (CDU-II)	65.58	200	120
3	Vacuum Distillation Unit (VDU)	146.50	142	85.2
4	Visbreaking Unit (VBU)	91.50	49.4	29.64
5	Catalytic Reforming Unit (CRU)	1278.88	14.5	8.7
6	Kero-Hydro Desulfurization (K-HDS) Unit	93.78	37	22.2

Table 2. Various Streams in the Refinery

Stream no.	Stream name
1	Fuel Gas (FG)
2	H_2S Gas (H2S)
3	Liquefied Petroleum Gas (LP)
4	C5/90 Naphtha cut (LN)
5	90/140 Reformer Feed (RF)
6	Aviation Turbine Fuel (AF)
7	Kerosene (KE)
8	Gas Oil in AF/Jute Batching Oil-C (JBOC) run — LS crude (G1)
9	Gas Oil in KE/JBOC run — LS crude (G2)
10	Gas Oil in AF/Jute Batching Oil-P (JBOP) run — LS crude (G3)
11	Gas Oil in KE/JOBP run — LS crude (G4)
12	Gas Oil in AF/JBOC run — HS crude (G5)
13	Gas Oil in KE/JBOC run — HS crude (G6)
14	Gas Oil in AF/JBOP run — HS crude (G7)
15	Gas Oil in KE/JBOP run — HS crude (G8)
16	Jute Batching Oil-C (JBOC) from LS crude run (J1)
17	Jute Batching Oil-P (JBOP) from LS crude run (J2)
18	JBOC from HS crude run (J3)
19	JBOP from HS crude run (J4)
20	Reduced Crude Oil (RCO) JBOC run — LS crude (R1)
21	RCO JBOP run — LS crude (R2)
22	RCO JBOC run — HS crude (R3)
23	RCO JBOP run — HS crude (R4)
24	Gas Oil from VDU (VO)
25	Spindle Oil from VDU (SP)
26	Light Oil from VDU (LO)
27	Intermediate Oil from VDU (IO)
28	Heavy Oil from VDU (HO)
29	Short Residue from VDU (SR)
30	VBU Gas Oil (VG)
31	VBU Naphtha (VN)
32	VBU Tar (VT)
33	Reformate (RM)
34	Hydrotreated Aviation Turbine Fuel (HA)
35	Hydrotreated Kerosene (HK)
—	Loss (LS)

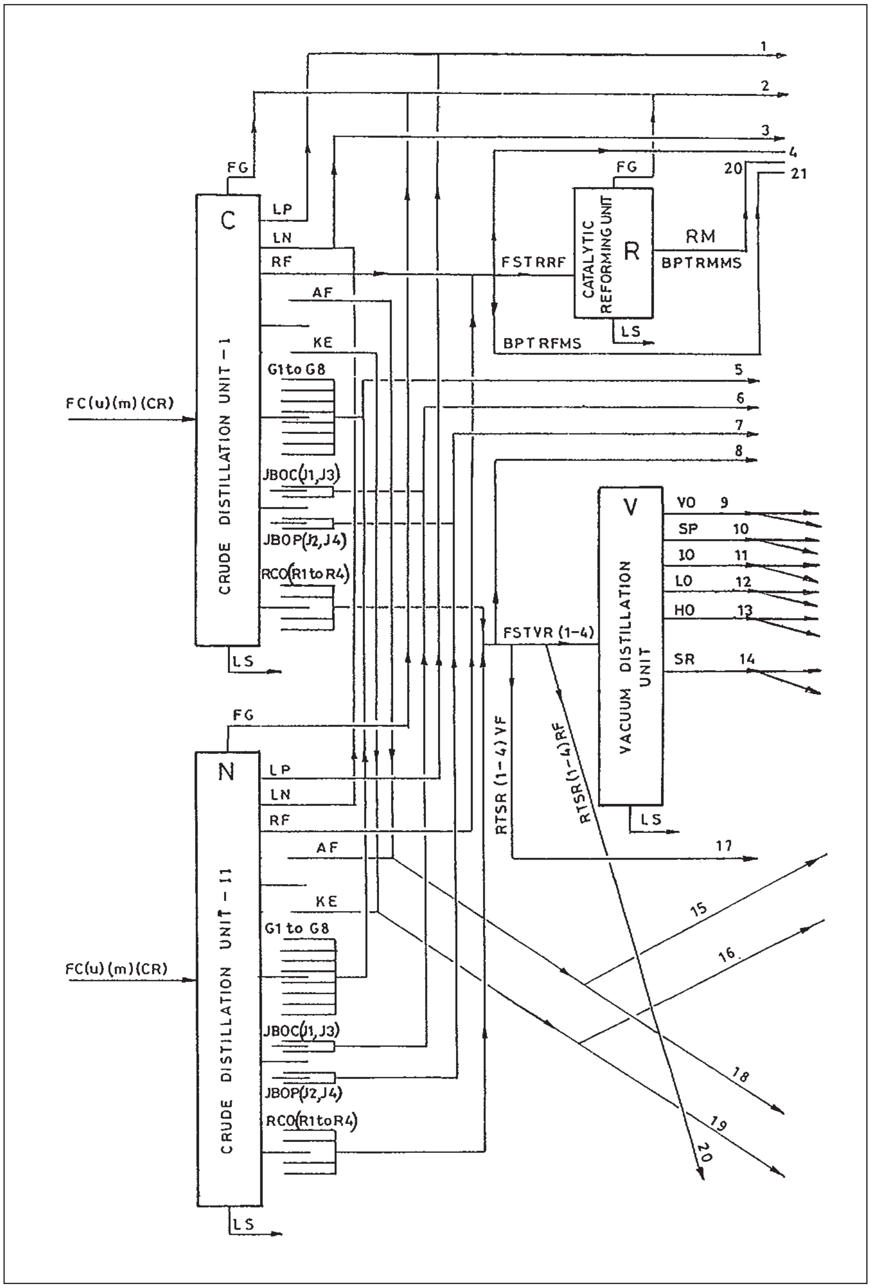

Figure 1. Schematic diagram of various units and streams of the refinery under study (cont'd.).

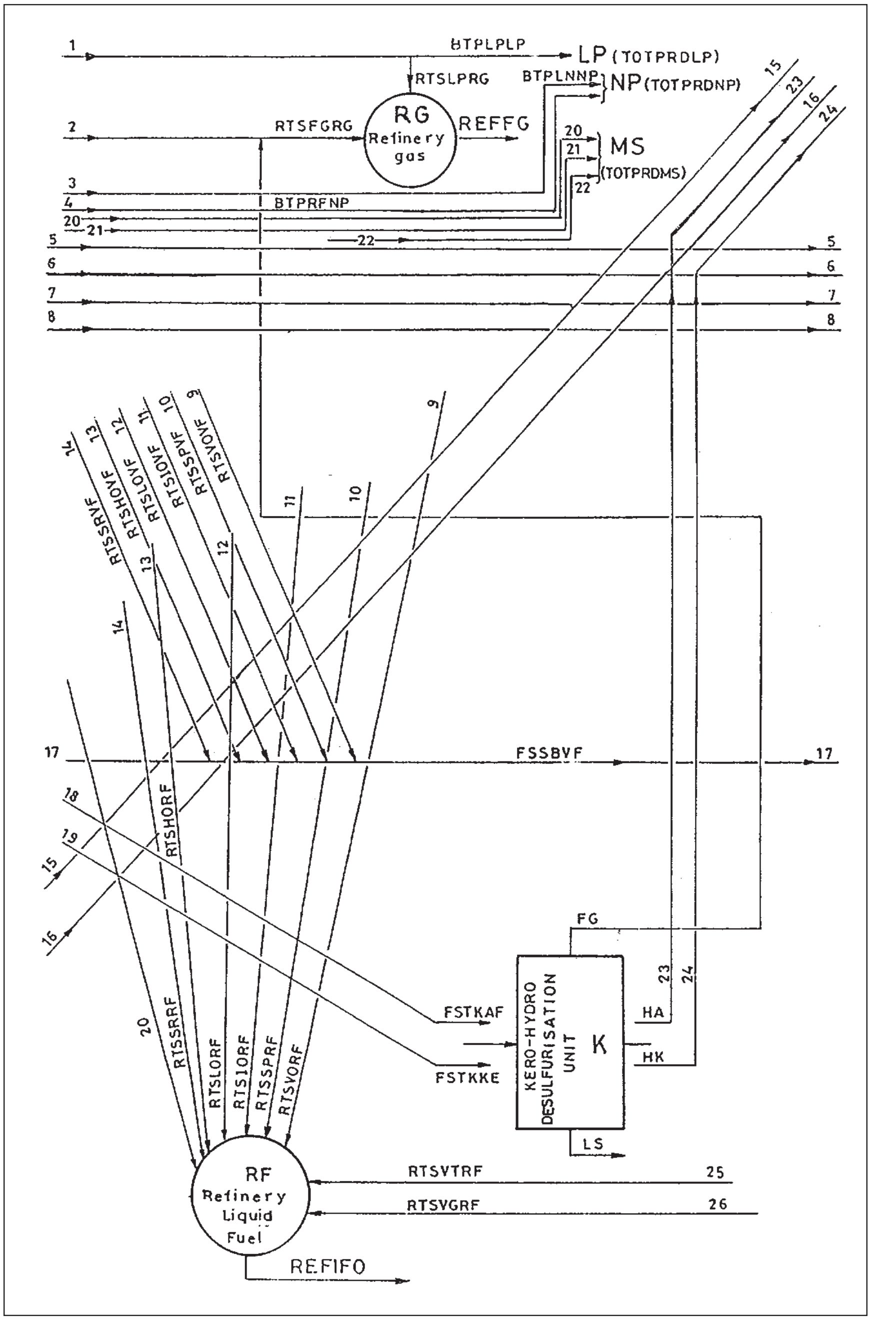

Figure 1. (Cont'd.).

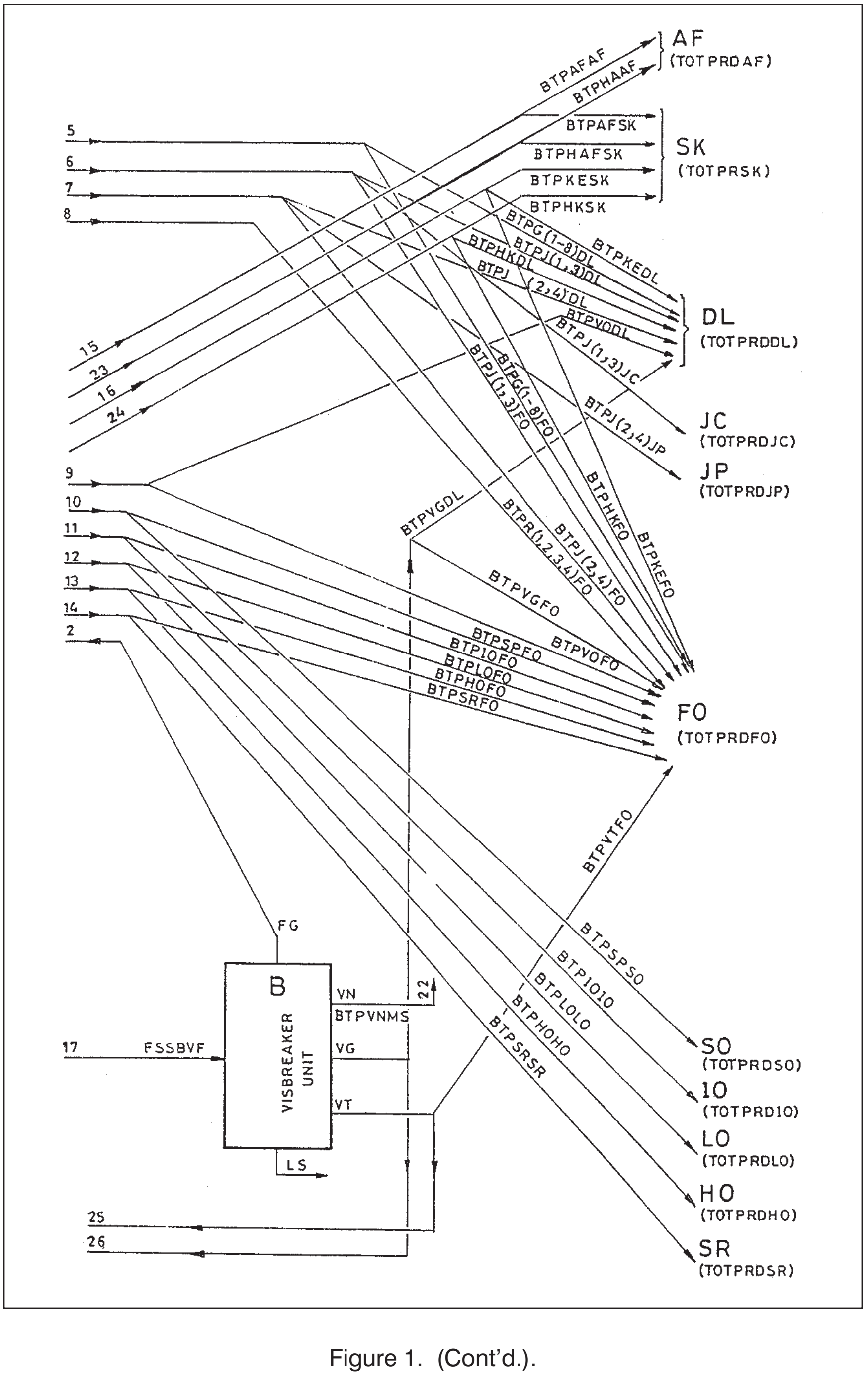

Figure 1. (Cont'd.).

Table 3. Products from the Refinery, Their Prices and Demands

Sl. no.	Product	Price (Rs/MT)	Demand (thousand MT/month)	
			Maximum	Minimum
1	LPG (LP)	6728	no limit	no limit
2	Naphtha (NP)	5808	no limit	no limit
3	Motor Spirit (MS)	8834	no limit	no limit
4	Aviation Turbine Fuel (AF)	7248	no limit	no limit
5	Kerosene (SK)	5502	no limit	no limit
6	Jute Batching OIl-C (JC)	8575	2.7	no limit
7	Jute Batching Oil-P (JP)	8575	4.3	no limit
8	High Speed Diesel (DL)	5987	no limit	no limit
9	Fuel Oil (FO)	4396	no limit	no limit
	Raw Lube Cuts			
10	Spindle Oil (SO)	5487	0.4	no limit
11	Light Oil (LO)	5886	0.6	no limit
12	Inter Oil (IO)	5886	26.0	no limit
13	Heavy Oil (HO)	5886	5.9	no limit
14	Short Residue (SR)	3300	40.0	no limit

The refinery meets all its internal fuel requirements in various process unit furnaces and the captive power plant boilers from the sweetened fuel gas (FG) and refinery fuel oil (RFO). The entire refinery fuel gas pool is consumed in the furnaces. The remaining fuel requirement is met by the refinery fuel oil pool. As per industry practice, the consumption of total fuel quantity per unit throughput is used in the model to estimate refinery's own (internal) fuel consumption.

The raw lube cuts are sent to the lube oil processing section of the refinery, which is not included in this model. The prices for these transfers are the product transfer prices.

SO_2 emissions in the refinery are from burning of sulfur-containing RFO in process furnaces and captive power plant boilers and un-recovered sulfur leaving the SRU incinerator stack as SO_2. The present maximum total SO_2 emission limit for the entire refinery, set by the West Bengal Pollution Control Board, is approximately 1500 kg/hr.

The data for the year 1999-2000 has been used for running the model [19].

Methodology of Automating the Formulation and Solution of the LP Problem

A program “LPGEN” written in FORTRAN 90 reads the input data items in a specific tabular format from an ASCII input file (.INP). The output of the program is the LP formulation in the IBM MPSX LP input file format readable by the commercially available LP solver ‘LINDO.’ The flow chart is shown in Figure 2. The above flow sheet steps were repeated for every run of the LP problem to generate various studies presented in this article.

Validation of Model

Exact verification of the SO_2 emission predicted by a model for a real refinery is difficult due to non-availability of data and the lack of systematic measurements and record keeping. However, an attempt to assess the quality of SO_2 estimate obtained from the model is presented below.

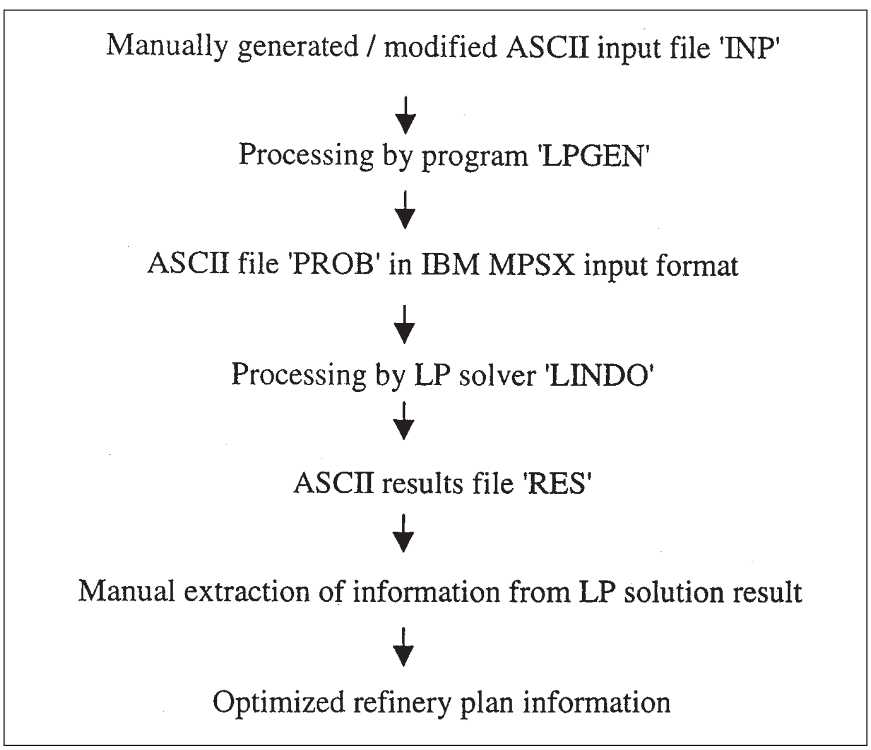

Figure 2. Flowchart for formulating and solving the LP model.

A summary of refinery operations during the year 1996-97 was made available for the entire configuration of the refinery. This included the details on fuel (gas and liquid fuel) consumption in the refinery. The data was analyzed and FG and RFO quantities were apportioned for all the refinery process units (CDU, VDU, CRU, KHDS, VBU process units). Typical H_2S content in FG before amine wash was noted to be around 9 percent w/w. The %S in RFO varied from 1.5 to 2.2 percent w/w, depending on the composition of blend. The total SO_2 emission has been reported to be in the range of 486 to 700 kg/hr.

The above-mentioned data was used to run the LP model at the same process unit throughputs (for the modeled section of refinery) as in 1996-97. The total SO_2 emission was predicted to vary from 514 to 658 kg/hr. This compares well with the reported refinery data.

In addition to the foregoing validation, another run was made with 1991 EIA data for the refinery. During 1991, the refinery processed primarily a variety of high sulphur crudes. The Environmental Impact Assessment Report of the refinery gives the monthly and average stack-wise SO_2 emission data. This SO_2 emission data has been adjusted for the addition of new CDU (CDU-II, included in the model) in recent times. This adjusted emission figure is 1207 kg/hr and it is of the same order of 1050 to 1180 kg/hr, which are the model predictions of SO_2 emission with processing of only HS crude.

The above two validation studies argue that the model estimations of SO_2 emission rates are realistic estimates (within ± 5-10 percent). Further studies may be carried out using this LP model.

Effect of Maximum SO_2 Emission Limit on Refinery Profit and Operation

The LP model maximizing the profit was run at different maximum limits of total SO_2 emission from the refinery. Two cases were considered. First, the maximum LS and HS crude availability constraints in the model were set at high values, so that the LP model solution was free to choose its optimum proportion of LS and HS crude. Second, the LS crude availability was set to “zero.” This correspond to processing of only HS crude in the refinery. The variation of profit in these cases has been discussed in following sections.

Processing Optimal Proportion of Low Sulfur and High Sulfur Crude

The total refinery profit, LS crude throughput, total crude throughput, and percent sulfur in RFO were plotted against the maximum SO_2 emission limits as shown in Figure 3.

The plot in Figure 3a has five zones. Boundaries of the zones are A, B, C, D, E, and F. The same zone boundaries are marked on Figure 3b and 3c as well. The features of the zones are:

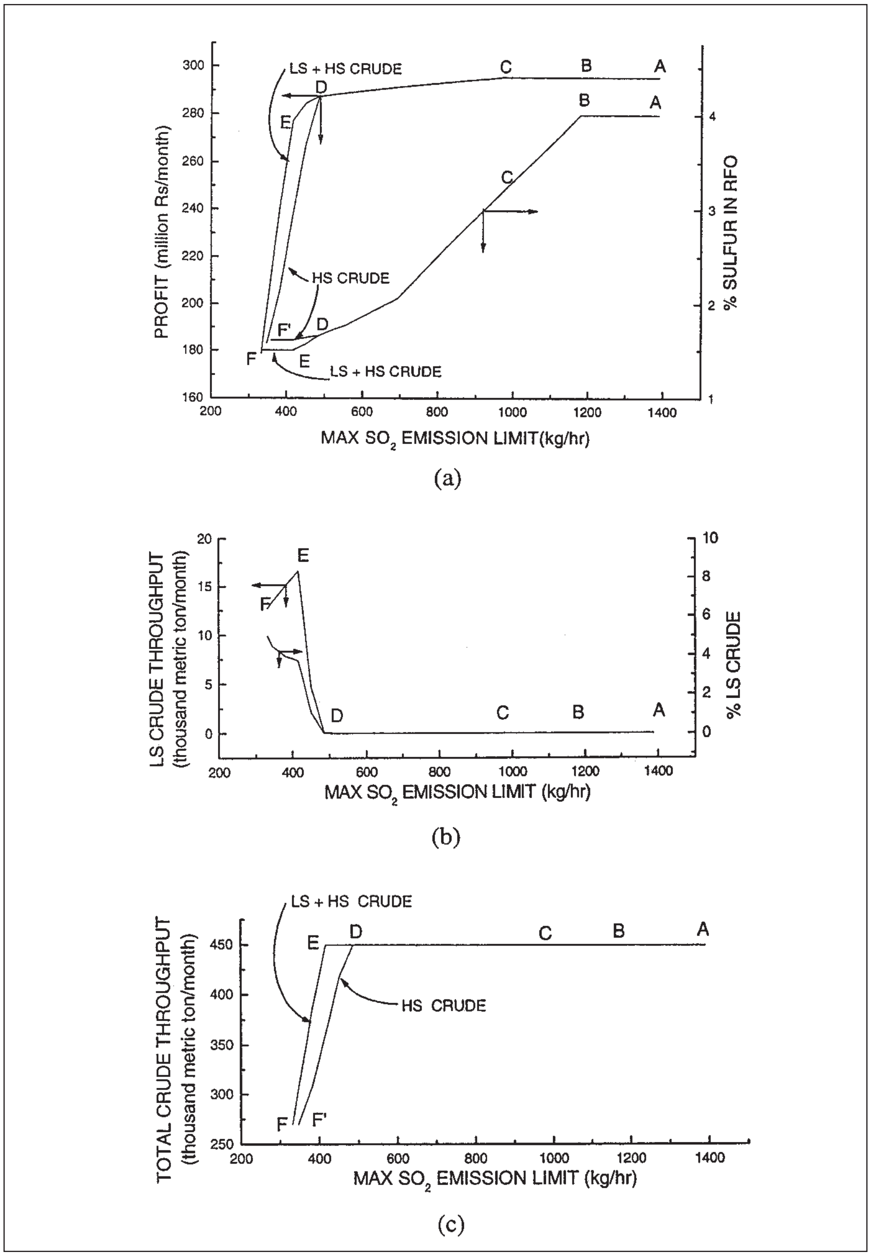

Figure 3. Variations of profit, % sulfur in RFO, LS crude throughput, and total crude throughput with maximum SO_2 emission limit with free crude mix and only HS crude processing.

Zone 1 (A-B) — Here the profit-maximum SO_2 emission limit relationship is horizontal, signifying that the refinery makes the same profit (295.8 million Rs/month) at different possible levels of SO_2 emission (1180 kg/hr and above). Hence, increasing or relaxing SO_2 emission levels above 1180 kg/hr (point B) does not constrain the refinery operation for maximum profitability. The refinery operates at maximum throughput with only HS crude being processed as the optimum choice in this zone; at maximized profit, 1180 kg/hr is the minimum SO_2 emission rate from the refinery.

Zone 2 (B-C) — The refinery profit in this zone is same as in zone 1 (295.8 million Rs/month) even though the maximum SO_2 emission limit is lowered from 1180 kg/hr (point B) to 985 kg/hr (point C). The SO_2 emission rate is lowered by altering the blends of refinery fuel oil (RFO), VBU feed and some heavy products, so that the resulting blend of RFO has lower percent sulfur compared to the same in zone 1. Since the crude processing and the different products produced are the same, the refinery profit in zones 1 and 2 remains the same. The minimum SO_2 emission at maximized profit of the refinery is therefore 985 kg/hr.

Zone 3 (C-D) — The refinery profit shows a slow decline (from 295.8 to 287.3 million Rs/month), with lowering of the maximum SO_2 emission limit in this zone from 985 kg/hr to 485 kg/hr (point D). In this zone a reduction of 50.8 percent in SO_2 emission lowers the profit of the refinery by 2.9 percent. This suggests that, if environmental reasons force a reduction in the maximum total SO_2 emission limit, then reduction up to a level of 485 kg/hr (point D) will probably be accepted by the refinery, as its profit may fall at the most only by ~3 percent. With a tighter SO_2 emission limit, the RFO blend chosen has lower percent sulfur. It is observed from the LP solutions that the CRU throughput, a major contributor to SO_2 emission, is also lowered. Hence the SO_2 emission is lowered but at the cost of valuable products like motor spirit (MS) produced by CRU, on the whole, the profit declines from C to D.

Zone 4 (D-E) — The refinery profit shows a sharper fall (287.3 to 277.4 million Rs/month) as the maximum SO_2 emission limit in this zone is lowered (from 485 to 415 kg/hr). Over the zone, most of the secondary processing unit throughputs fall to their minimum to reduce fuel consumption and SO_2 emission. Also, the refinery starts processing more and more higher priced LS crude in lieu of the same amount of HS crude as shown in Figure 3b and 3c. The low sulfur streams from LS crude processing going to RFO increase in this zone for reducing percent sulfur in RFO. Thus, the emission reduction comes from lowered secondary throughputs and fuel consumption, as well as from use of larger proportions of low sulfur components in RFO. The fall in profit is due to the lower secondary process unit throughputs as well as the use of higher cost LS crude. If forced to operate in this range of maximum SO_2 emission limit, the refinery will probably be forced to consider additional investment to alter the refinery configuration to retain its profitability level.

Zone 5 (E-F) — The refinery profit shows its steepest fall (from 277.4 to 178.6 million Rs/month) with reduction of the maximum SO_2 emission limit in this zone (from 415 to 332 kg/hr). As the maximum SO_2 emission limit is lowered, the refinery has no option but to reduce crude (Figure 3c) and all secondary processing unit throughputs. Below the maximum SO_2 emission limit 332 kg/hr (point F), the refinery cannot operate without the crude or at least one secondary processing unit throughput falling below the minimum "turn-down" throughput (violating the constraint of minimum throughput). Therefore, the zone of SO_2 emission below 332 kg/hr becomes infeasible and is not investigated.

Secondary Processing Units Throughputs

The throughputs of the secondary processing units for different maximum limits on total SO_2 emission from the refinery are shown in Figure 4 and are discussed below.

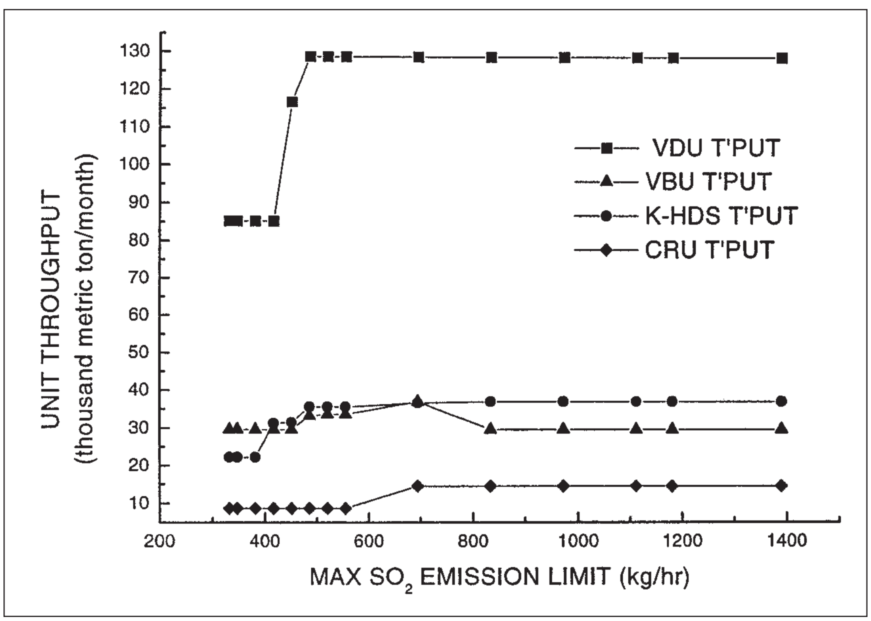

Figure 4. Variations of throughputs of secondary processing units with maximum SO_2 emission limit with free crude mix.

VDU — The maximum throughput of VDU is 128.7 thousand metric ton/month, which is ~91 percent of its maximum capacity. Full capacity utilization is never achieved due to limited demand of the heavy products (SO/IO/HO/SR). This unit's throughput is the same over the range of maximum total SO_2 emission levels of 485 kg/hr and higher. Below this emission limit, the throughput sharply falls to the minimum turndown ratio of the plant (85.2 thousand metric ton/month). This is explained by the sharp fall in crude processing in this zone for reasons already explained, with consequent lower generation of feed (RCO) to VDU.

K-HDS — This unit runs at its maximum capacity (100 percent) of 37 thousand metric ton/month over the range of maximum total SO_2 emission above 835 kg/hr. ATF, the high priced product from this unit, with free demand keeps the unit throughput high. Below an emission limit of 415 kg/hr, the unit throughput falls sharply as the crude throughput is reduced due to reasons already explained.

VBU — At high limits of total SO_2 emission from the refinery, the unit runs at its minimum throughput. VB tar, the major product from this unit, is the prime component for the low valued product FO. Production of VB tar for FO is minimized for maximizing profits, and hence the unit runs at lower capacity.

When the total SO_2 emission limit from the refinery is lowered from 835 to 485 kg/hr, the VBU throughput increases and more VB gas oil (with lower percent sulfur) is diverted to RFO pool to reduce its percent sulfur. Lower-percent sulfur in RFO leads to lower SO_2 emission. Reducing the total SO_2 emission limit below 485 kg/hr reduces VBU throughput due to increased processing of LS crude for generating low sulfur RCO components for RFO. As the RCO yield from the LS crude is lower, the VBU throughput falls with increasing LS crude processing.

Below an SO_2 emission limit of 415 kg/hr, the crude processing falls sharply, leading to lower heavy ends availability, and forcing the VBU to run at its minimum capacity.

CRU—Reformer units produce high octane reformate, which is the major component of gasoline. It is the highest value product from the refinery. To keep profitability high by producing more gasoline, the reformer unit runs at its maximum throughput whenever possible. This is seen in the range of maximum limit of SO_2 emission from 695 kg/hr and higher. This unit consumes a large amount of fuel, which contributes to total refinery SO_2 emissions. On reducing maximum SO_2 emission limit below 555 kg/hr, the reformer throughput is cut down to lower fuel consumption to meet emission limits.

SO_2 Emission from FG and RFO

Over the entire range of maximum total SO_2 emission limits studied, the total SO_2 emissions and their components from FG and RFO firing are plotted in Figure 5. The SO_2 from fuel gas is primarily due to its H_2S component. This SO_2

is emitted from the SRU stack due to the unrecovered sulfur from H_2S. It can be observed from the figure that FG does not significantly contribute to the SO_2 emission, as the SO_2 emission from the FG varies over a small range of 100 to 150 kg/hr (total SO_2 emission level varies from 332 to 1180 kg/hr). The average value of the SO_2 emission from FG is only ~125 kg/hr. RFO turns out to be the major contributor to total SO_2 emissions. This is further corroborated by the fact that the reduction in SO_2 emissions is associated with the reduction of percent sulfur in RFO pool, as has been presented in Figure 3a. The percent sulfur in RFO continuously falls to meet the maximum SO_2 emission limits until it attains its lowest feasible value of 1.5 percent at the SO_2 emission limit of 415 kg/hr and lower.

Processing of Only High Sulfur Crude in the Refinery

Operation of the refinery was also studied with only low-priced HS crude being available. These results were obtained from another set of LP formulations. In these, the maximum LS crude availability constraint in the model was set to "zero," so that the LP model solution chose processing of only HS crude. The profits at different maximum SO_2 emission levels are also plotted in the Figure 3a, to draw a comparison between the case when the refinery is forced to use only HS

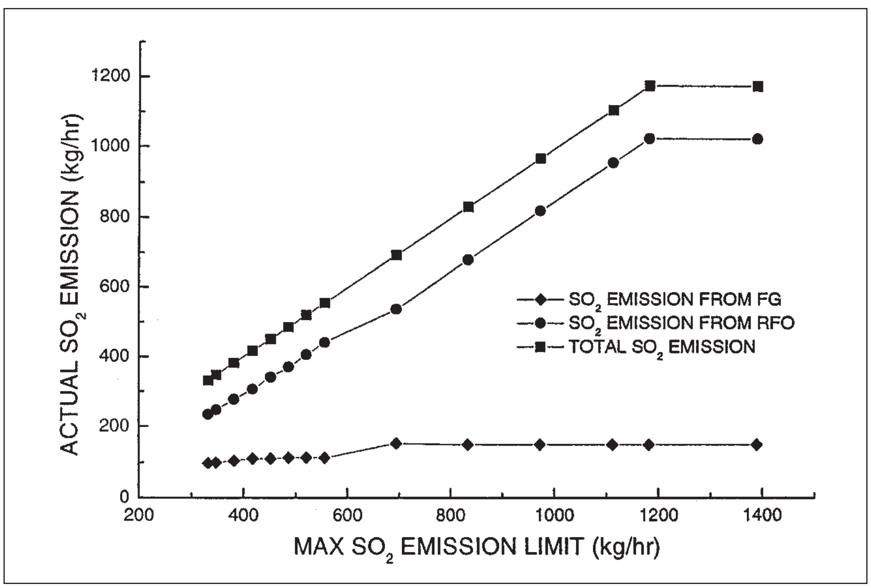

Figure 5. Contributions of SO_2 emissions from fuel gas and refinery fuel oil with free crude mix.

crude and that when the refinery can process LS and HS crude freely. The plot shows that the profits are higher in spite of processing LS crude bought at a higher price. Thus, the processing of LS crude to avoid reduction in refinery profitability is an attractive option in this emission-limiting zone. The optimal free choice of crude as long as the maximum SO_2 emission limit for the refinery is above 485 kg/hr is 100 percent HS crude. This makes the lines (in Figure 3a, b, and c) for only HS crude processing coincide with the other option for all SO_2 emission limits above 485 kg/hr (point D). As emission limit is lowered below point D (485 kg/hr), the refinery with option of processing only HS crude has no option but to reduce emission through sharp reductions in secondary unit and total crude throughput. This causes the sharp fall in the profit with reduction of SO_2 emission limit as was observed in zone 5 of the former case of free choice of crude blend.

Feasibility of Setting a Maximum Percent Sulfur Limit in RFO to Control Total SO_2 Emission

CONCAWE reports that there is a direct relation between the sulfur content of the fuel and the amount of SO_2 emitted [18]. Since some refineries use this common idea for reducing SO_2 emission by enforcing a maximum limit on percent sulfur in RFO, the effect of this myth of *enforcing a maximum %S in RFO to control maximum SO_2 emission from the refinery* is further investigated.

The model is first formulated with a constraint on the maximum SO_2 emission from the refinery set at 520 kg/hr, an arbitrary value in the Zone 3. The model is free to choose an optimum mix of LS and HS crude for maximizing the refinery profit. The solution of this problem provides the maximized profit, percent sulfur in RFO and other details of the refinery operation with total refinery SO_2 emission limited to 520 kg/hr.

A second formulation of the LP model is made by replacing the constraint on the maximum SO_2 emission (equation 20) by the following constraint on the maximum percent sulfur in RFO.

$$\Sigma_i \Sigma_j \, [(PRST_{\mathrm{qi}} - PRXRF_{\mathrm{q}}) \, SRFO_{\mathrm{ij}}] \leq 0 \qquad \forall \, q = \text{i.e. sulfur} \qquad (21)$$

A limit of 1.5 percent was chosen as an arbitrary value lower than the percent sulfur value obtained from the first LP solution. In this case also, the model has free choice for the crude mix. The solution of this problem generates the maximized profit, total refinery SO_2 emission and other details of the refinery operation with the maximum percent sulfur in RFO limited to 1.5 percent w/w. The pertinent operating details for the refinery for both the cases are presented in Table 4.

The comparison of the refinery operation, SO_2 emissions, percent sulfur in RFO and profit from table reveal that the plan with lower percent sulfur in RFO has lower profit as well as higher SO_2 emission.

Table 4. Comparison of Effect of Total SO_2 Emission as a Constraint and Percent Sulfur Limit in RFO as a Constraint on Refinery Operating Plans

Description		Total SO_2 emission as constraint	Maximum percent sulfur in RFO as constraint
Maximum SO_2 emission limit (kg/hr)		520	—
Actual SO_2 emission rate (kg/hr)		520	537
Profit (million Rs/month)		288.13	284.33
Crude throughput	HS	450	429
(thousand MT/month)	LS	0	21
%LS crude		0	4.67
Throughput	CDU	450	450
(thousand MT/month)	CRU	8.7	14.5
	K-HDS	35.6	37
	VDU	128.7	128.7
	VBU	33.7	29.6
Refinery fuel requirement	FG	2.29	2.45
(thousand MT/month)	RFO	8.52	9.26
Emission of SO_2 from	FG	114	151
(kg/hr)	RFO	406	386
%S in RFO		1.72	1.5

The model chose processing of cheaper HS crude alone, when only the maximum SO_2 emission from the refinery was constrained. In the other case, some portion of the costlier LS crude is also processed. Constraining the maximum percent sulfur limit for RFO requires the RFO components to be low in sulfur, which is possible from LS crude processing. Processing of more expensive LS crude brings down the refinery profit. Also, to make up for the reduction in profit due to LS crude processing through the value addition from secondary processing units, their throughputs are readjusted and the total RFO consumption increases. Increase of fuel consumption increases SO_2 emission level as there is no restriction on SO_2 emission, though the %S of RFO is low (1.5 percent). The additional SO_2 (537 kg/hr against 520 kg/hr) is primarily contributed by this additional fuel firing.

It is, therefore, seen that using a maximum limit on percent sulfur in RFO as the constraint to restrict total SO_2 emission from the refinery may lead to lower profit at higher SO_2 emission. Hence, to restrict total refinery SO_2 emission, the limit should be placed directly on the total maximum SO_2 emission rate but not on maximum percent sulfur in RFO.

CONCLUSIONS

The general-purpose LP model developed in this study was applied to an existing refinery in India to evolve monthly operation plans at maximum possible profit conforming to maximum SO_2 emission limit. Detailed studies performed yielded very useful results on refinery profit and associated operations. There was a lot of scope in measures for reducing SO_2 emissions from the refinery without having to reduce profit. It was found that the main contribution of SO_2 emission from refinery is from RFO firing. The model was also used to evaluate the use of maximum percent sulfur in RFO as a constraint parameter to limit maximum SO_2 emission. It is concluded that this may be inadequate and may result in lower profits, higher SO_2 emission operating plans. This measure should serve only as a broad operating guideline and not as an emission-limiting control parameter. The success of the LP model illustrates that it can be used as a tool for any refinery to study the impact of maximum SO_2 emission limit on refinery profit and to generate monthly operation plans. In the second part of this article, a new methodology will be presented for deriving the best operating plan that maximizes profit and minimizes SO_2 emissions.

ACKNOWLEDGMENTS

The authors would like to thank the management and staff of the petroleum refinery, which provided all the data used to undertake the research outlined in this research article.

REFERENCES

1. EPA (U.S. Environmental Protection Agency), *Profile of the Petroleum Refining Industry, Office of Compliance Sector Notebook Project, EPA 310-R-95-013, September 1995,* US EPA, Washington, D.C., 1995.
2. CPCB (Central Pollution Control Board, India), *Comprehensive Industry Document Oil Refineries, COINDS/3/1980-81,* Central Board for the Prevention and Control of Water Pollution, New Delhi, India, 1981.
3. EPA (U.S. Environmental Protection Agency), *Code of Federal Regulations, 40 CFR Part 60, Standards of Performance for New Stationary Sources,* U.S. Environmental Protection Agency, Federal Office Building, New York, 1997.
4. World Bank, *Pollution Prevention and Abatement Handbook: Petroleum Refining,* Environment Department, Washington, D.C., 1998.

5. Ministry of Environment and Forests, *The Gazette of India Extraordinary Notification, Part II, Sec. 3(i),* New Delhi, 19th May, 1993.
6. CPCB (Central Pollution Control Board, India), *Comprehensive Industry Document Series: Emission Regulations, Part II, COINDS/18/1984-85,* Central Board for the Prevention and Control of Water Pollution, New Delhi, India, 1985.
7. K. Magoulas and D. Marinos-Kouris, Instructions are Given for Building Gasoline-Blending LP, *Oil and Gas Journal, 86*:27, pp. 32-37, 1988.
8. P. J. Kennedy, Real-Time Refinery Optimization, *Hydrocarbon Processing, 68*:4, pp. 57-61, 1989.
9. K. D. Bartholomew and A. Soudek, LP Accuracy is Improved by Incorporating FCC Simulation Data, *Oil and Gas Journal, 87*:44, pp. 57-62, 1989.
10. J. H. Jenkins, LP Modeling Pieces Together Reformulation Puzzle, *Oil and Gas Journal, 90*:46, pp. 41-44, 1992.
11. P. Grosdidier, Economics of Blend Giveaway, *Hydrocarbon Processing, 76*:11, pp. 55-60, 1997.
12. M. C. Hu, R. T. Powell, and N. F. Kidd, Develop LP Models Using A Steady-State Simulator, *Hydrocarbon Processing, 76*:6, pp. 81-86, 1997.
13. J. C. M. Hartmann, Decision-Making and Modeling in Petroleum Refining, *Hydrocarbon Processing, 76*:11, pp. 77-81, 1997.
14. X. Chen and R. W. Pike, *Interactive On-Line Optimization System, User's Manual,* Minerals Processing Research Institute, Louisiana State University, 1998.
15. High & Watt Associates Ltd., *Refinery Modelling System,* High & Watt Associates Ltd., London, http://www.highandwatt.com/hwmodel.htm, 2001.
16. CPCB (Central Pollution Control Board, India), *Minimal National Standards: Oil Refineries. COINDS/4/1980-81,* Central Board for the Prevention and Control of Water Pollution, New Delhi, India, 1981.
17. L. Schrage, *User's Manual for Linear, Integer and Quadratic Programming with LINDO,* LINDO Systems, Inc., Chicago, Illinois, 1984.
18. CONCAWE, *Best Available Techniques to Reduce Emission from Refineries,* CONCAWE Air and Water Quality Management Groups, Brussels, 1999.
19. A. Dutta, *Assessment and Minimization of the Environmental Impact of Petroleum Refinery Operations,* Ph.D. dissertation, Department of Civil Engineering, Indian Institute of Technology, Kharagpur, 2002.

Direct reprint request to:

Dr. A. K. Dikshit
Associate Professor
Department of Civil Engineering
Indian Institute of Technology, Kharagpur
Kharagpur (W.B.) 721 302
India
e-mail: anil@civil.iitkgp.ernet.in