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IMPACT OF SO_2 EMISSION LIMITS ON PETROLEUM REFINERY OPERATIONS III: UNCERTAINTIES IN PROFIT AND EMISSIONS ESTIMATES

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ABSTRACT

The previous two parts of this article developed the linear programming (LP) model, applied it to an existing refinery, and presented a methodology for minimizing SO_2 emissions. In this article, the issue of uncertainties in percent sulfur in different feed and blending streams, which lead to uncertainties in estimates of SO_2 emission and refinery profitability, is discussed. It is also based on the linear programming model of the same refinery discussed in first part of this study. A stochastic method is used to generate inputs to the LP model to simulate the randomness of real-life operations. The results show that for the typical refinery considered, the SO_2 emission estimate has a standard deviation of 8.4 kg/hr at the mean SO_2 emission rate of 520 kg/hr. The refinery profit for the same refinery shows a standard deviation of 3.1 million Rs/month on a mean value of 283.7 million Rs/month.

INTRODUCTION

A linear programming (LP) model was formulated in the first part of this article to estimate the impact of emissions on operation and profitability of a petroleum refinery [1]. The model was validated and tested against a real world situation by applying it to an existing refinery in India. The model's output provides an optimized operating plan of the refinery with details on the process unit throughputs, feed and product blend composition, and properties of streams produced from the process units. In the second part of the article, a two-step solution methodology was suggested to minimize the SO_2 emission rate while preserving refinery profit [2]. The proposed two-step procedure identified an alternate solution of the LP model, leading to an operating plan with maximized profit and minimized SO_2 emission rate.

Formulating a linear programming model of a refinery requires knowledge of the refinery's configuration, process unit throughput limits, yields and properties of streams from process units, selling price, and other factors. All these parameters are best estimates, often based on averaged data. The effect of uncertainties in input data is expected to show up as a probabilistic distribution for the maximized profit value and total SO_2 emission. The most expected (most probable) profit and its distribution metrics should be evaluated for economic comparison of different scenarios of operation of the refinery. Similarly, information on the most probable minimum total SO_2 emission rate and its probabilistic spread around that value ought to support an assessment of the legitimacy of the SO_2 emission limits imposed on the refiners. The present research work evaluates and investigates such optimized profit, and its spread, along with the probabilistic distribution of SO_2 emissions for the refinery studied in the first part of this article.

THE EXAMPLE REFINERY

The full details of the configuration of this existing Indian petroleum refinery were provided in the first part of this article [1]. The refinery can process two types of crude oil, low-sulfur (LS) and high-sulfur (HS), and produces fuel products for sale to markets. Some special "cuts" from its vacuum distillation unit are transferred to the adjoining lubricating-oil base-stock refining complex. The six process units in the refinery are: crude distillation unit I (CDU-I), crude distillation unit II (CDU-II), naphtha pretreater and catalytic reformer (CRU), kerosene hydro-desulphurisation unit (K-HDS), visbreaking unit (VBU), and vacuum distillation unit (VDU). Streams from the CDU and other secondary processing units are blended as required to produce the products: liquefied petroleum gases (LP), straight run naphtha (NP), motor spirit (MS), aviation turbine fuel (AF), kerosene (SK), high speed diesel (DL), Jute batching oil-C (JC), Jute batching oil-P (JP), fuel oil (FO), and lube oil base-stock raw cuts: spindle oil (SO), light oil (LO), intermediate oil (IO), heavy oil (HO), and short residue (SR). Fuel gas (FG) produced in different process units is washed with amine solution to remove the accompanying H_2S, and the sweetened gas (free of H_2S) is consumed in different furnaces of the process units. Some specific heavier liquid hydrocarbon streams, such as reduced crude oil (RCO) and SR, are blended to meet the liquid fuel requirement of the furnaces in the process unit and of the captive power plant of the refinery. This stream is called the refinery fuel oil (RFO). The amine solution stream picking up the H_2S from the fuel gas is regenerated. H_2S released during the regeneration is fed to a sulfur recovery unit (SRU), which converts about 94% of this H_2S to elemental sulfur. The SO_2 emissions from the refinery are due to the unrecovered sulfur in the SRU stack and the burning of the sulfur compounds bearing RFO in the various furnaces and captive power plant boilers of the refinery.

Streams produced from each unit are shown schematically in Figure 1. Destinations of these streams (to various process unit feed, fuel gas, and refinery fuel oil pools) are shown in Figure 2. Figure 3 shows the blending of various streams into final products.

The scope of present work is limited to the effect of variation of percent sulfur in process streams for the above-mentioned refinery. The effect of uncertainties has been quantified in terms of impact on the refinery profit and the total SO_2 emission.

EFFECT OF VARIATION IN PERCENT SULFUR OF PROCESS STREAMS ON REFINERY PROFIT FOR DIFFERENT CRUDE MIXES

Case of Free Crude Mix

There are twenty-eight steams in the LP model that are blended to process unit feed or product pools where percent sulfur limits exist. The percent sulfur in these streams is tested according to procedure ASTM D1552-00 [3]. Repeatability and reproducibility standards are shown in Tables 1 and 2. The mean values of percent sulfur data for different streams, used in formulating the LP model, are obtained from the routine laboratory tests at the refinery. A normal distribution of sulfur test results around its reported mean value is assumed. The sulfur percentages then are expected to remain within $\pm 3\sigma$ of the mean values with 99.5% probability. Accordingly, an assumption is made that the standard deviation of percent sulfur results is about one-third of the repeatability reported in the standard test procedure.

To simulate the refinery operation with free crude mix under randomly varying values of sulfur content in different streams, a stochastic method has been used. A large number (1000) of values of percent sulfur of all twenty-eight streams is randomly generated using MATLAB [4] such that the mean of their random population is same as the mean value reported by refinery laboratory (used in the LP formulation), and such that the standard deviation matches closely the test

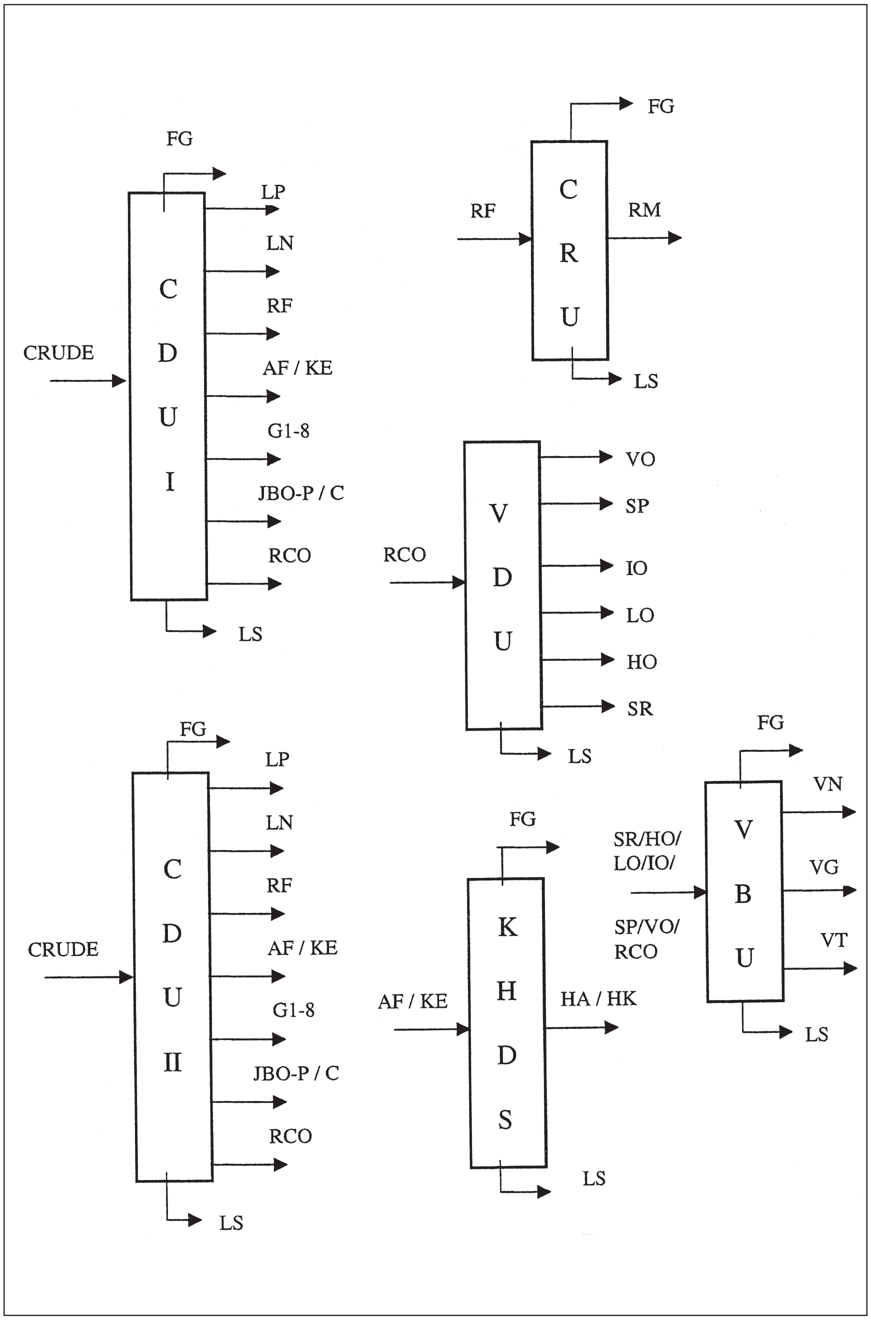

Figure 1. Streams produced in different process units.

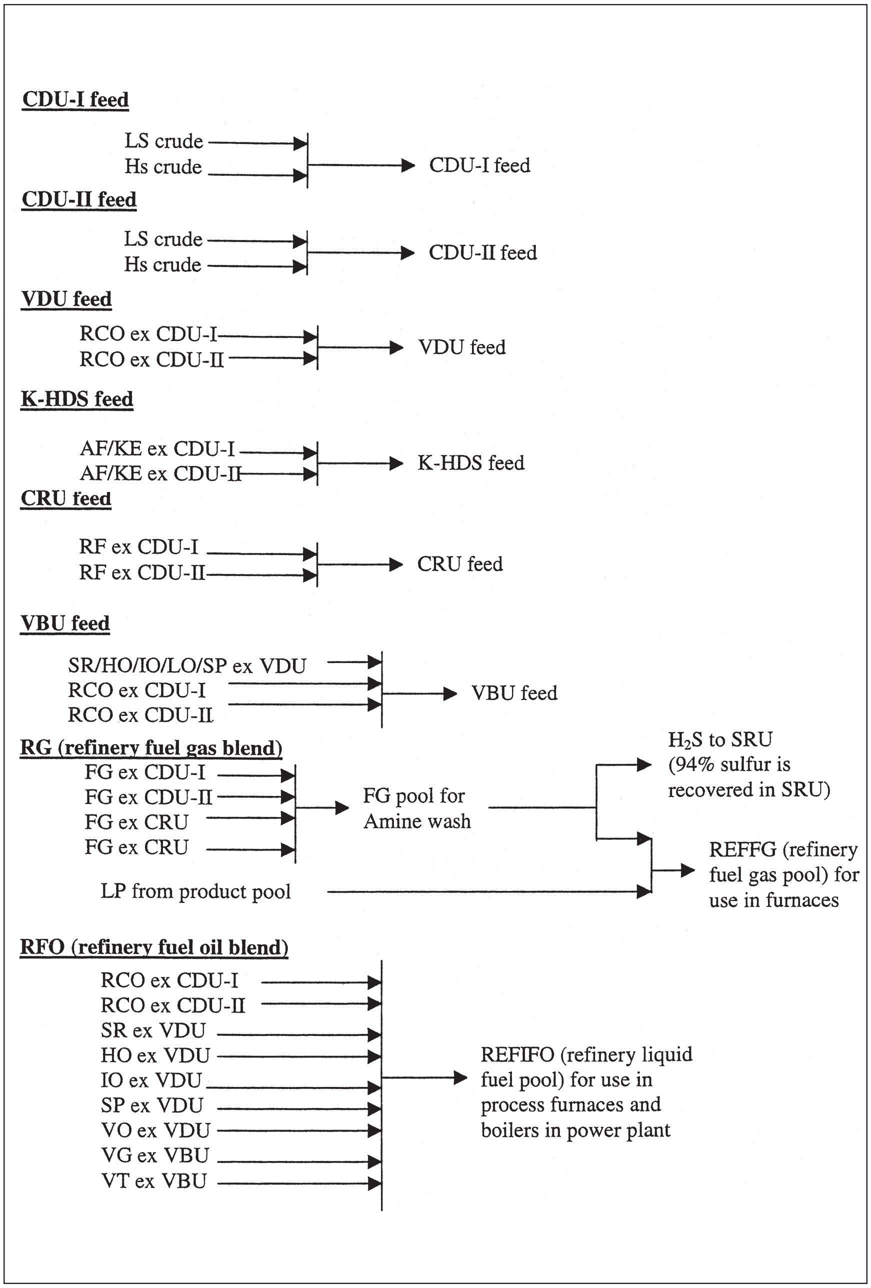

Figure 2. Destination of streams to process unit feed and fuel blend pools.

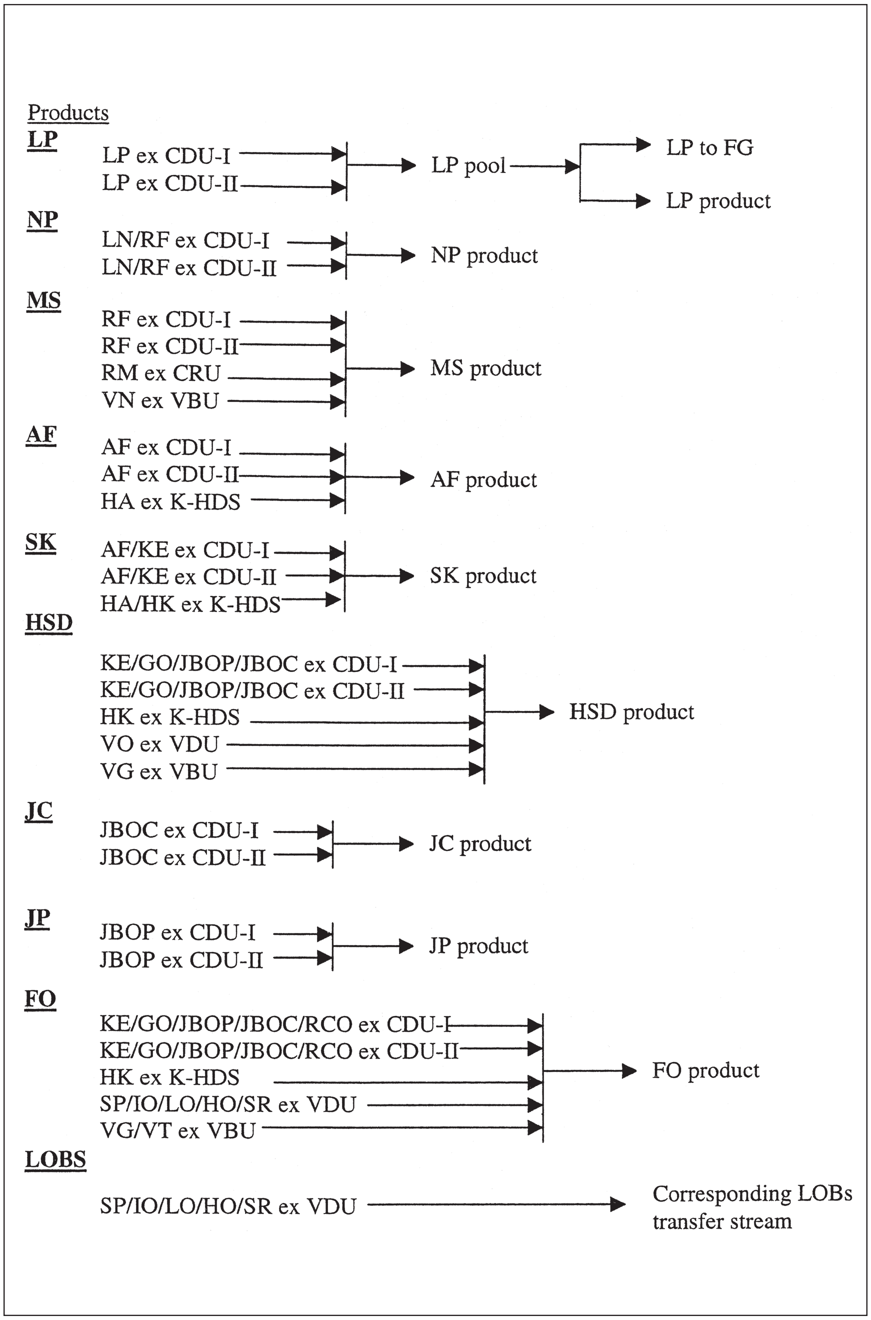

Figure 3. Destination of streams to product blends.

Table 1. Repeatability and Reproducibility of Method of Analysis of Sulfur (ASTM D1552-00)[a]

Percent sulfur by wt.	Repeatability	Reproducibility	Sulfur bearing streams in the LP model
0–0.5	0.05	0.08	AE, KE, HA, HK
0.5–1.0	0.07	0.11	G1, G2, G3, G5, J1
1.0–2.0	0.10	0.17	G4, G6, G7, G8, J2, J3, J4, R1, R2, VO, VG
2.0–3.0	0.16	0.26	SP, LO, IO
3.0–4.0	0.22	0.40	R3, R4, HO, SR, VT
4.0–5.0	0.24	0.54	

[a]This method is applicable to samples boiling above 350°F and containing not less than 0.06% sulfur.

Table 2. Repeatability of Method of Analysis of H_2S in Refinery Fuel Gas

Method of analysis	Repeatability
H_2S in refinery fuel gas to be analyzed using ORSAT apparatus with 30% KOH solution as absorbent	$\pm$ 0.2% v/v

procedure mentioned above. For each maximum SO_2 emission limit, a set of data for percent sulfur in the streams was chosen randomly and the LP formulation was solved to obtain the maximized profit in this case. This step was repeated a large number of times (1000), and the frequency distribution of the maximized profit was plotted. It follows a normal distribution. The mean of the maximized profit values obtained is the most probable profit of the refinery under expected normal variation of the percent sulfur in the streams from the process units. The standard deviation portrays the likely spread of the profit around its mean value. The mean and its corresponding standard deviation values were found by following the procedure outlined for different maximum total SO_2 emission limits from the refinery. The distribution of maximized profit considering uncertainty in the percent sulfur variation in different sulfur-bearing streams for maximum SO_2 emission limits is shown in Figure 4.

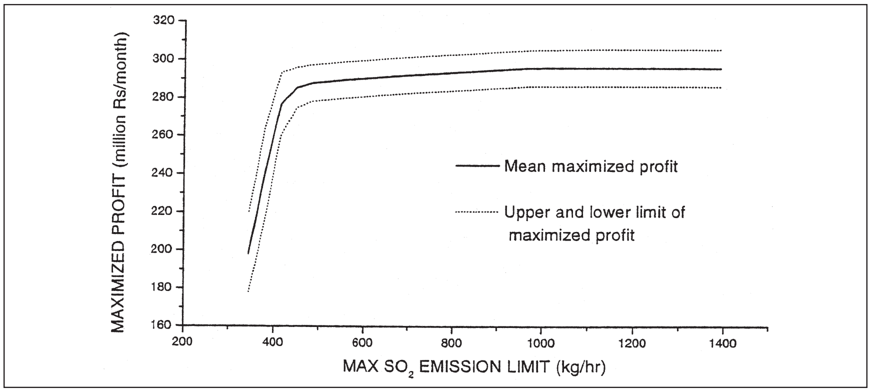

Figure 4. Limits and mean value of maximized profit at different levels of maximum SO_2 emission limits for free crude mix case.

The LP model was also run with average values of percent sulfur for different streams and different maximum total SO_2 emission limits. The comparison of the results with average percent sulfur in streams and those with stochastic data for percent sulfur in streams at different maximum total SO_2 emission limits is given in Table 3. The mean profits reported in the two cases are close (~ 0.2%) at all maximum total SO_2 emission limits. A slight increase in the standard deviation is observed at lower maximum limits. This is probably due to increased number of infeasible LP solutions (out of the 1000 random formulations) under severely constrained conditions of maximum SO_2 emissions when the percent sulfur in several streams is on the higher side. For the same reason, the percent differences predicted in most cases are positive.

It can be concluded from the above discussion that the optimum operation plan of the refinery can be generated using the average percent sulfur in the streams.

Case of Fixed Crude Mix (5% Low Sulfur Crude)

In this particular case, 5% LS crude processing along with HS crude is considered. The maximum SO_2 constraint level is set to 520 kg/hr, a value at which the refinery profit is constrained by the maximum SO_2 emission limit. The same stochastic procedure for the random formulation of the LP problem was conducted a large number of times (1000). The frequency distribution of the maximum profit

Table 3. Comparison of Refinery Profit Obtained Using (1) Average Percent Sulfur for Streams and (2) Stochastic Simulation for Free Crude Mix Case

Maximum total SO_2 emission limit (kg/hr)	Total crude (thousand MT/month)	% LS crude	Case 1— Maximized profit considering average percent sulfur in streams (million Rs/month)	Case 2— Mean and standard deviation of maximized profit considering uncertainties in percent sulfur in streams (million Rs/month)		% difference in maximized profit in two cases
1390	450	0	295.80	296.35	3.2354	0.18
1180	450	0	295.80	296.35	3.2354	0.18
1110	450	0	295.80	296.35	3.2354	0.18
970	450	0	295.68	296.19	3.1659	0.17
695	450	0	291.49	292.16	3.1497	0.23
555	450	0	288.90	289.55	3.1676	0.22
485	450	0	287.32	287.94	3.1883	0.22
450	450	1.04	284.49	285.38	3.5534	0.31
415	450	3.69	277.38	276.80	5.4965	–0.21
380	384.4	3.92	240.56	240.67	8.0908	0.05
345	305.18	4.41	197.74	198.07	6.9758	0.17

obtained from the runs is shown in Figure 5. This shows the mean profit as 283.7 million Rs/month and standard deviation of 3.1 million Rs/month. The LP model was also run with average value of the percent sulfur of the streams, which showed a maximized profit of 283.2 million Rs/month.

The mean profit is close (~ 0.2% deviation) to that obtained with average percent sulfur in the respective streams. This suggests that the refinery operation plan for maximum profit may be obtained by solving the LP formulation using average percent sulfur in the respective streams with any significant risk.

EFFECT OF VARIATION IN PERCENT SULFUR OF PROCESS STREAMS ON TOTAL SO_2 EMISSIONS

In an operational plan, the fuel gas and refinery fuel oil compositions are specified. The maximum profit/minimum SO_2 emissions plan based on mean

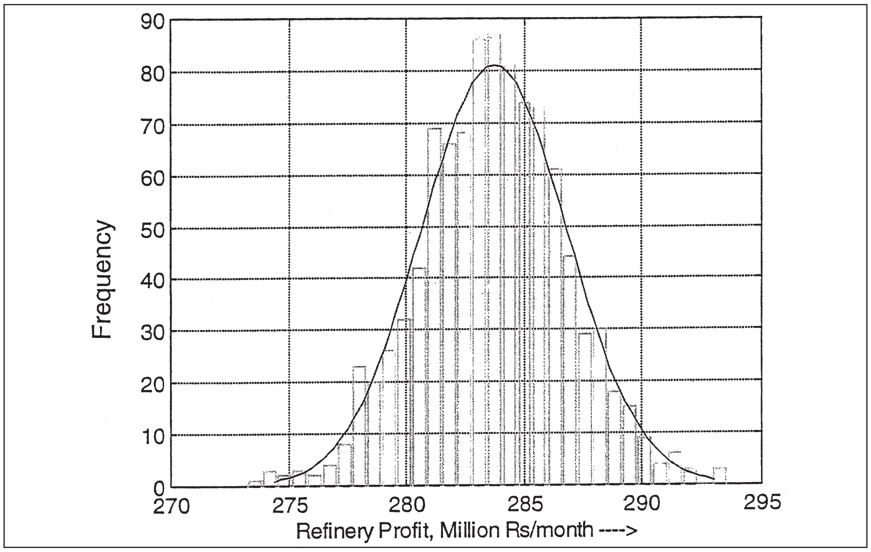

Figure 5. Frequency plot of refinery profit from stochastic simulations of random variation of percent sulfur in different streams for 5% LS crude mix case.

percent sulfur for the streams will therefore have a corresponding mix of refinery fuel oil and fuel gas. The refinery would attempt to blend for these targeted compositions. The probability distribution of SO_2 emissions for the maximized profit plan can be obtained using the uncertainties of percent sulfur in each stream of the fuel gas and fuel oil at the planned compositions.

To study this scenario, a base case LP solution with 5% low-sulfur crude in crude mix and a maximum 520 kg/hr SO_2 emissions limit is chosen. The input percent sulfur data for the process streams were the average values as mentioned earlier. The refinery is expected to adhere to this composition of the refinery fuels as obtained in the optimum operation plan. Hence the uncertainty of the percent sulfur in the refinery fuel streams will contribute directly to the uncertainty of the total SO_2 emission from the refinery.

The total SO_2 emission from the refinery is the sum of SO_2 contributed by the fuel gas and fuel oil streams. The uncertainties for a normal distribution of percent sulfur around the mean values can be estimated from the respective percent sulfur standard test procedure repeatability values. Based on this estimate, standard deviations of each component of SO_2 emission contribution are calculated. Due to the linear relationship of all these contributions to the total emissions of the refinery, the variance of total SO_2 emissions can be written as sum of the variance of each contributing component's contribution. The contribution of SO_2 from fuel gas and its effect on the variations in the total SO_2 from the refinery is small. At this typical operating situation of the refinery, the mean SO_2 emission is estimated as 520 kg/hr and the standard deviation is 8.4 kg/hr following normal distribution. Hence one may roughly say the SO_2 emission (with 99.5% probability) is correct to the extent of around ±25 kg/hr.

CONCLUSIONS

The effect of the variation of percent sulfur in process streams on the refinery's profit and its total SO_2 emissions has been estimated using stochastic simulation 1,000 trials. The frequency distribution of maximized profit is found to follow a normal distribution. The mean of the frequency distribution of maximized profit, considering uncertainties in percent sulfur in different streams, is very close (~ 0.2%) to that considering average percent sulfur in respective streams. Hence, the operation of the refinery for maximum profit may be decided by considering average percent sulfur in the respective streams. It is also found that the variation of percent sulfur in the fuel streams is the prime contributor to the variation in total refinery SO_2 emissions. For the refinery under study, the SO_2 emission estimate has a standard deviation of 8.4 kg/hr at the mean value of SO_2 emission rate of 520 kg/hr.

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