MULTIPERIOD PLANNING OF REFINERY OPERATIONS UNDER MARKET UNCERTAINTY

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Abstract

A novel approach is developed for the multiperiod planning of refinery operations under market uncertainty. Planning of refinery operations under uncertainty is important in light of the ever changing market conditions. Thus, the consideration of uncertainty is interesting as it may create flexibility and avoid crisis in the management decisions by exploiting short term opportunities. In this multiperiod planning problem, aim is to consider variation in product distribution during time horizon while considering uncertainty in product prices and to provide appropriate operating strategies at different time points. The objective is to maximize the overall profit and set optimal targets for the scheduling level. For uncertainty in the product prices, normal distribution is assumed with given mean and standard deviation. An oil refinery project has been evaluated when the prices of the product are uncertain and management has the flexibility to switch operating process units.

Introduction

A multiperiod planning model for refinery operation with uncertainty in product prices is presented based on discrete time formulation and crude oil purchase decisions along with refinery unit operations are optimized such that overall profit for refinery is maximized. In this multiperiod planning problem, aim is to consider variation in product distribution during time horizon while considering the uncertainty in product prices and to provide appropriate operating strategy at different time points.

To convert crude oils to more valuable products, involve many processes such as crude oil distillation, catalytic reforming, catalytic cracking, hydrotreating, and hydrocracking etc. Each process is very complex in its own right in terms of model building and optimization. Crude oil can be blended with broad range of other crude oils and it can be processed differently depending upon the refinery configuration for a given product demand. Also different units in a refinery can be operated at a corresponding operating mode to suit with maximum profit and raw material availability. With smart supply chain systems time dependent decisions such as which crude oil to buy, which product to produce and how much, can be optimized to improve refinery profitability. The state of the art for overall refinery optimization is linear programming, which assumes complete segregation between defined elements. To date, few researchers have studied oil supply chain under uncertainty. Yet, refineries are vital components of national economies, and the fluctuations in the prices and demands of crude oil, gasoline, and diesel oil are highly uncertain in reality, arising from uncertain global and national economic situations and indeterminate factors such as outbreaks of war, strikes, cyclones, and diseases.

Most of the current plant planning/scheduling models are based on deterministic programming. However, because of volatile raw material prices, fluctuating products demand, and other changing market conditions, many parameters in a planning/scheduling model are uncertain. Failure to account for significance demand fluctuations could lead to either unsatisfied customer demand fluctuations could lead to either unsatisfied customer demand, translating into loss of market share, or excessively high inventory holding costs. Thus, the consideration of uncertainty is critical in oil supply chain models and is now attracting the attention of increasing number of researchers. Stochastic programming deals with problems in which some parameters incorporated into the objective or constraints are uncertain. These uncertain parameters are usually described by probability distributions or by possible scenarios in stochastic programming. Stochastic programming mainly consists of recourse models (Clay et al., 1997; Liu et al., 1996) and chance-constrained programming (Kall et al., 1994; Li et al., 2003), distinguished by the methods used to describe the uncertain parameters and the algorithm used to solve the model. Recently, Li et al. (2004) proposed an approximation based approach for refinery planning under uncertainty. Their approach is good in agreement, compared to the methods available in the literature, with a better solution speed.

In this paper, a case study has been evaluated for the overall refinery plant optimization, which includes an atmospheric and vacuum distillation unit (AVU), a catalytic reforming unit (CRU), a residue fluid catalytic cracking unit (RFCCU), a delayed coking unit (DCU), several hydrotreating units, product blending units and auxiliary units. The results of the case study demonstrate that the flexibility model helps the optimizer to find better optimum.

Refinery Planning

Figure 1 illustrates the flow diagram of a typical refinery which processes crude oil into sellable products. Crude oil can either be imported through oil vessels or in packets through pipeline. Oil terminals are connected with refinery tank farms through pipeline network. The decisions, which blend to charge and how much to process everyday, are taken by refinery processing department. The department also decides various operating conditions for the refining processes. The products from different units are blended to meet certain specifications and stored in product tank farm. From the product tank farm the products are delivered to customers before predefined quantity and due date.

A multiperiod planning model can be stated as follows given:

i. crude oil quality, availability and delivery procedure
ii. present inventory of raw material and final products
iii. unit connectivity and capacity
iv. crude oil cost and product selling price
v. product specification, demand and due dates over the planning time horizon
vi. time horizon of interest and the number of discrete time points

Determine:

i. crude oil purchase decisions – optimum quantity, optimum purchase date
ii. the optimal allocation of raw material to different plants
iii. the optimal operating mode and capacity utilization of different plants
iv. the optimal production of products and delivery time to customers
v. the optimal blend of intermediate products to form final products
vi. the amount of intermediate products produced at any particular time point within the scheduling time horizon

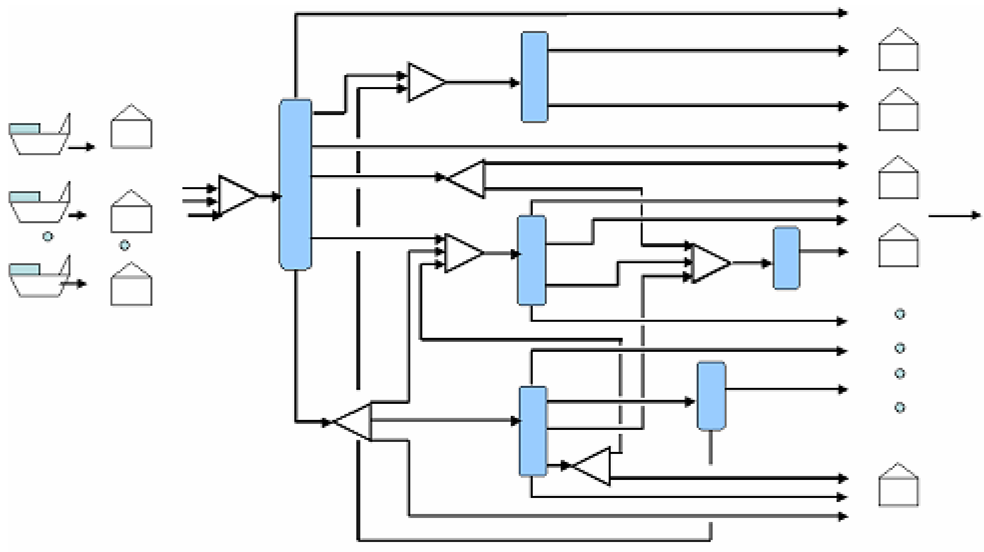


Figure 1: Refinery flow sheet

Overall refinery is very complicated and has several intermediate storage tanks, vessels and operating routes. However, in the present case for the planning level intermediate storage tanks are not considered. The objective of multiperiod planning level optimization is to provide good quality targets to corporate decision makers and to the scheduling level. At this stage the detailed flow diagram may cause difficulty to obtain results due to highly nonlinear nature of the problem and may not have large impact on overall profitability, so we have considered site level modeling for the refinery optimization problem

Site Level Modeling

At the site level, crude oil vessels (OV), crude oil storage tanks (ST), mixers (M), splitters (S), and processes (PR) together with their connections and corresponding inlet (PI) and outlet physical properties (PO) are considered. The modeling involve individual process flows (PF), which consists of feeds (CF), intermediate (CI) and product flows (PF), together with their components (CC), in conjunction with distribution of resources (RS) (e.g. raw material, utilities and catalyst). The following gives discussions of different modeling aspects.

Modeling of Process Streams

Crude oil is composed of millions of kinds of hydrocarbons. The most common approach to describe crude oils is to use true boiling point (TBP) distillation curves and gravity mid percent curves. Based on TBP curves, crudes can be separated into several distillates obtained from operation of atmospheric and vacuum distillation. In the present work, the atmospheric and vacuum distillation (AVU) feed is lumped into dry gas (DG), liquid petroleum gas (LPG), 80-130, 130-180, 180-230, 230-350 and 350-550 ^{o}C distillates (vacuum gas oil, VGO) and the fraction heavier than 550 ^{o}C boiling point (vacuum residue, VR). The different lumps used for various other refining processes are mentioned in Table 1. These lumps are interconnected with each other through different processes. It should be noted that number of lumps for different processes can be varied and it will affect optimization results and computational time.

Table 1: Lumps used for modelling process streams

Process	Lumps used
AVU	DG, LPG, 80-130 °C, 130-180 °C, 180-230 °C, 230-350 °C, 350-550 °C, 550 °C+
CCR	H_2, DG, LPG, CR_PET
FCC	DG, LPG, F_PET, LCO, SLURRY, COKE1
DC	DG, LPG, DC_NAP, LGO, HGO, COKE2
DHT	H_2, GAS, HD_NAP, HD
LGOHT	H_2, GAS, LGO_NAP, HLGO
LCOHT	H_2, GAS, LCO_NAP, HLCO
CNHT	H_2, GAS, COK_NAP

Modeling of Time

Most of the refinery unit operations are continuous in nature, which makes refinery optimization a dynamic optimization problem. In order to simplify the optimization problem, the time horizon is divided in finite number of uniform discrete time intervals.

Modeling of Plant Configuration

The modeling is based on the flow diagram shown in Figure 1 and the notations for the equations are given in nomenclature. The overall plant model consists of objective function, crude oil purchase decisions, mixer model, splitter model, process model, product demand, and throughput constraints.

Objective Function

The objective of the site level optimization is to maximize the profit, which can be expressed as product sale minus the cost of raw material, utilities, major inventories and raw material transport.

$$\text{Profit} = \sum_t \sum_k \sum_n \sum_j F_{j,n,k,t} C_{j,k} - \sum_t \sum_k \sum_n \sum_i F_{i,n,k,t} C_{i,k} - \sum_t \sum_n \sum_k Q_{n,k,t} C_n - \sum_t \sum_{ist} V_{ist,t} C_{ist} - \sum_t \sum_i \sum_{isize} Xsize_{i,isize} C_{i,isize} \quad (1)$$

The first term represents the summation over the multiplication of the price of the product j coming from process k and flow rate of outlet streams j coming from process k in t time interval by processing of n crude oils. The second term represents the summation over the multiplication of the price of the inlet process flows i, which is being processed in process k and flow rate of inlet process streams i, processing in process k in t time interval by processing n crude oils. The third term represents the summation over the multiplication of consumption of resource n in process k and the price of resource n. The fourth term represents the summation over the multiplication of volume of storage tank i at time t and the inventory cost of storage tank i per unit time per unit volume.

Crude Oil Purchase Decisions

It is assumed that crude oil is purchased from overseas manufacturer and it is transported to refinery tank farm through standard oil vessels. These vessels are available in discrete size, hence binary variable $X\_AV_{i,isize,t}$ is defined to determine the size of vessel $isize$ and type of crude oil i to be selected.

$$Q\_PURCHASE_{i,t} = \sum_{isize} X\_AV_{i,isize,t} VSIZE_{isize} \quad (2)$$

Crude Oil Inventory Balance

Crude oil inventory balance equation is given as

$$V\_AV_{i,t1} = V\_AV_o + Q\_PURCHASE_{i,t1} - F\_AV_{i,t1} \quad (3)$$

$$V\_AV_{i,t} = V\_AV_{i,t-1} + Q\_PURCHASE_{i,t1} - F\_AV_{i,t1} \quad (4)$$

Crude oil inventory should satisfy the storage availability. Furthermore, the feed flow must satisfy the CDU operating capacity.

$$L\_Inv_i \le V\_AV_{i,t} \le U\_Inv_i \quad (5)$$

In order to minimize crude oil cost, optimization results converges at the minimum inventories at the last time slice. This feature can cause an infeasible schedule at the next cycle. To overcome this problem, a constraint is added to make sure at the final time slice crude oil inventory for next 5 days of operation is available.

$$V\_AV_{i,t30} \ge \sum \sum F\_AV_{i,t} / 6 \quad (6)$$

Modeling of Mixers

Mixers are modeled in two different ways. For feed mixers that provide input streams for other processes and for other mixers that produce final products, are treated as individual processes.

Modeling of Splitters

Mass balance equation for splitters is given as

$$\sum_j FO_{j,n,s,t} = FS_{n,s,t} \quad (7)$$

Since all the flow rates are decomposed according to the origin of their crude oils, the decomposition has to be precisely maintained in splitter operations. In other words, the composition of inlet streams of a splitter should be the same as that of its outlet streams. It is given as

$$\frac{FO_{j,n,s,t}}{\sum_n FO_{j,n,s,t}} = \frac{FS_{n,s,t}}{\sum_n FS_{n,s,t}} \quad (8)$$

The composition of components in the outlet streams of a splitter is the same as that of the inlet stream.

$$x_{l,j,n,s,t} = x_{l,n,s,t} \quad (9)$$

For splitters, the properties of outlet streams should be the same as those of the inlet stream.

$$PRO_{q,j,n,s,t} = PRO_{p,i,n,s,t} \quad (10)$$

Modeling of Processes

In the site level, the product yields of processes are modeled as linear functions of their feeds.

$$FO_{j,n,k,t} = \sum_i \alpha_{j,i,n,k,t} Fl_{i,n,k,t} \quad (11)$$

This linear function in provided by process simulation using finite difference approximation and continuously updated with iterations.

All the compositions and properties of products, together with the consumption of resources, are also treated in the same way as the product yields, given as linear function of feed.

$$x_{l,j,n,k,t} = \sum_i \zeta_{l,j,n,k,t} Fl_{i,n,k,t} \quad (12)$$

$$Q_{r,k,t} = \sum_n \sum_i \beta_{r,i,n,k,t} Fl_{i,n,k,t} \quad (13)$$

Modeling of Process Connections

If product j from process k is sent as feed i to process k', then

$$Fl_{i,n,k',t} = FO_{j,n,k,t} \quad (14)$$

The composition of components and properties of the two streams should be kept the same with the following equations.

$$x_{l,i,n,k',t} = x_{l,j,n,k,t} \quad (15)$$

If the product j from process k is sent to splitter s, then

$$FS_{n,s,t} = FO_{j,n,k,t} \quad (16)$$

If product j from splitter s is sent as feed i to process k, then

$$Fl_{i,n,k,t} = FO_{j,n,s,t} \quad (17)$$

$$x_{l,i,n,k} = x_{l,j,n,s} \quad (18)$$

Modeling of Product Delivery

In the present framework, it is assumed that contracts for the products p are available and the scheduling optimization determines the recipe of product delivery via shipment or via pipeline. Predetermined amount of products with its specifications must be delivered to the customers before the due date of delivery. This situation is modeled using the following example equation:

$$\sum_{t=t1}^{tdue} Fp_{j,t} = Qdemand_j \quad (19)$$

Other Constraints

In overall refinery operations, process capacity limits, market demands, product specifications, emission control, etc. need to be satisfied. These properties are calculated by setting the lower bound and the upper bound.

Composition of l in inlet flow i to process k:

$$x_{l,i,k,t}^{L} \le \sum_n x_{l,i,n,k,t} \le x_{l,i,k,t}^{U} \quad (20)$$

Composition of l in outlet flow j from process k:

$$x_{l,j,k,t}^{L} \le \sum_n x_{l,j,n,k,t} \le x_{l,j,k,t}^{U} \quad (21)$$

Throughput of process k:

$$F_k^L \le \sum_n \sum_l Fl_{i,n,k,t} \le F_k^U \quad (22)$$

Consumption of resource r:

$$Q_r^L \le \sum_k Q_{r,k,t} \le Q_r^U \quad (23)$$

In the site level modeling, individual process performances are only represented by product yields and properties, which are updated by process optimization. Therefore, size of the master model is greatly reduced.

Process Simulation in Site Level

To improve the feasibility of overall solution, simulation is introduced in the site level. The simulation, which provides linear yield correlations in the form of equations (12-15) for each process, is based on detailed process models.

Rigorous models are preferred for the process simulation. Since they are not available in public domain, for the purpose of explanation, simplified nonlinear correlations published by HPI Consultants Inc. (1987) are used. In the present approach to increase the solution space for the NLP problem, flexibility is introduced in the product prices. A case study is carried out in the next section which shows the comparison of multiperiod planning optimization with and without consideration of flexibility model.

Uncertain Parameter Calculation

For the calculation of uncertain parameters like demand or price two approaches are available in the literature: a) two stage stochastic programming approach for process planning under uncertainty in which the uncertain parameters are usually described by the possible scenarios, b) chance constrained programming approach in that seeks to satisfy the constraints at a predetermined confidence level using the known probability density distribution of uncertain parameters. In our work we have used chance constrained programming approach for the uncertain parameter calculation (Li et al, 2004).

Case Study – Maximize Overall Refinery Profit

This case study is used to illustrate how the consideration of uncertainty can be applied to the problem of overall refinery multiperiod planning optimization. The flow sheet of an overall refinery plant is shown in Figure 2, which includes an Atmospheric and Vacuum Distillation Unit (AVU), a Catalytic Reforming Unit (CRU), a Residue Fluid Catalytic Cracking Unit (RFCCU), a Delayed Coking Unit (DCU), several hydrotreating units, product blending units and auxiliary units. The refinery can process the three crude in which crude 1 is light and sweet compare to crude oil 2 and 3. Crude cost and product price information are provided in Table 2. For multiperiod optimization, it is assumed that the due dates for all the products are at the end of time horizon. The current refinery operation is optimized with multiperiod planning optimization and compared with the proposed model, which shows an increase in the overall profit by 0.5%.

The multiperiod optimization with uncertainty consideration increases the search space for the optimization problem by giving flexibility in the product prices and helps to find better optima. In the present case multiperiod optimization is performed for one month planning. The time period is divided in discrete length of 1 day, hence total 30 time periods have been used. In the results we can see that when uncertainty is not considered the crude 1, crude 2, and crude 3 consumptions are 140048.3, 15361.38, and 143754.9 respectively. While with the consideration of uncertainty the consumptions are 140048.3, 11951.68, and 147536.7 for the crude 1, crude 2, and crude 3 respectively. We can see that the crude 1 consumption is same for both the cases while there is trade-off for the consumption of crude 2 and crude 3.

Table 2: Cost and price information

Cost/Price List, $/ton	
Crude 1	123
Crude 2	120
Crude 3	126
Gasoline 90#	185
Gasoline 93#	190
Gasoline 95#	195
Gasoline 97#	200
Diesel	180

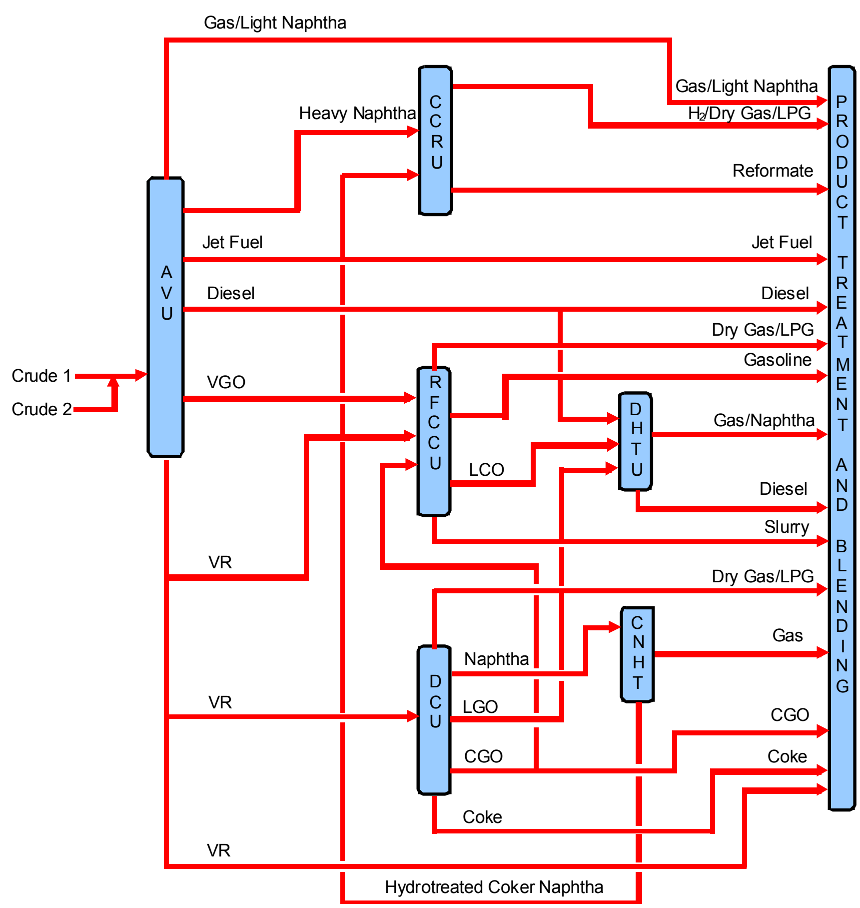
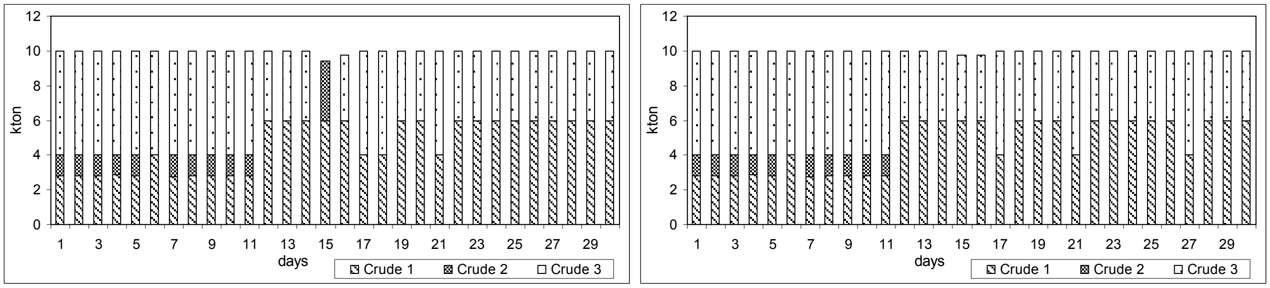


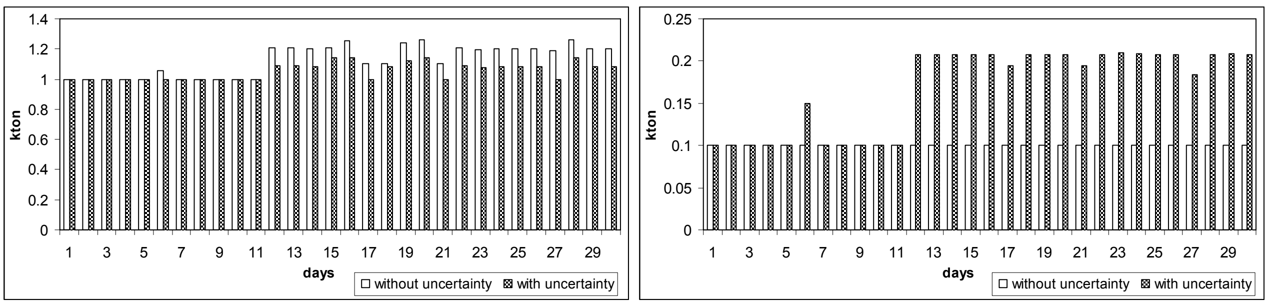
Figure 2: Refinery processes connectivity for case study

The optimization process satisfies all the constraints, hence due dates, quantities and product specifications are satisfied through out the time horizon. The final products are the blend of different intermediate products. The blending rate of Gasoline90, Gasoline97, and Diesel are shown in Figure 3 and Figure 4. Figure 3 indicates that the production of Gasoline90 is lower while considering the uncertainty in the Gasoline prices (without uncertainty: 33812.07, with uncertainty: 31610), whereas we can see that the production of Gasoline97 is higher in case of uncertainty (without uncertainty: 3000, with uncertainty: 5052.59). The consideration of uncertainty takes the benefit of higher Gasoline97 price and aim to produce more Gasoline97 for higher profit. So, by this case study we can say that consideration of the uncertainty model widen the search space for the optimization problem and may able to produce better optimum point.



(a) (b)

Figure 3: Blend for crude distillation unit a) without uncertainty consideration b) with uncertainty consideration



(a) (b)

Figure 4: Production of a) Gasoline90 with and without uncertainty b) Gasoline97 with and without uncertainty

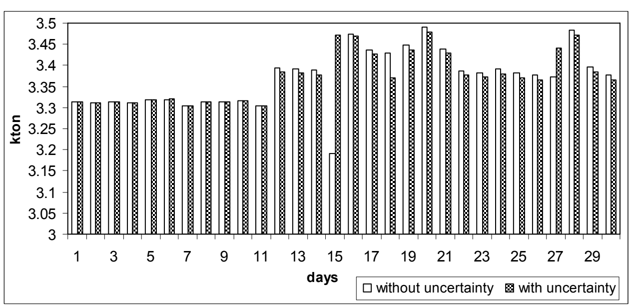


Figure 5: Production of Diesel with and without uncertainty

Conclusions

In this paper the effect of uncertainty consideration is evaluated for multiperiod planning of refinery operations. Multiperiod planning problem is an NLP formulation and results may stick in a local optimum. The consideration of flexibility model increases the search direction and result in providing a better optimum point for the problem. The proposed approach is applied to a refinery problem. In the problem the trade off between different types of crude buying decision has been captured. The effect of multiperiod uncertainty in product demand can be evaluated in future.

Nomenclature

Indices

c = key component
i = inlet process flows
ist = storage tanks
$isize$ = size of vessel (packet)
j = outlet process flows
k = processes
n = crude oils
t = time point

Parameters

$\alpha_{i,j,n,k,t}$ = Yield of product *j* from feed *i* contributed by crude *n* in process *k* at time *t*
$\beta_{i,n,k,t}$ = Consumption of resource *r* from feed *i* contributed by crude *n* in process *k* at time *t*
C_n = Cost of resource *n*
F_k^L = Lower bound for throughput of process *k*
F_k^U = Upper bound for throughput of process *k*
$F_{i,n,k}^L$ = Lower bound for usage of raw material *i* in process *k* having crude oil *n*
$F_{i,n,k}^U$ = Upper bound for usage of raw material *i* in process *k* having crude oil *n*
Q_n^L = Lower bound for usage of crude oil *n*
Q_n^U = Upper bound for usage of crude oil *n*
$Vis\max_i$ = Maximum allowable volume of raw material in *i* in the refinery
$Vis\min_i$ = Minimum allowable volume of raw material *i* in the refinery
$x_{l,i,k}^L$ = Lower bound of the composition of *l* in inlet flow *i* to process *k*
$x_{l,i,k}^U$ = Upper bound of the composition of *l* in inlet flow *i* to process *k*

Variables

$F_{i,n,k,t}$ = Flow of raw material *i* from to unit *k* and using resources *n* at time *t*
$F_{j,n,k,t}$ = Flow of product *j* from unit *k* and using resources *n* at time *t*
$FI_{i,n,k,t}$ = Flow of inlet flow *i* contributed by crude *n* to process *k* at time *t*
$Fp_{j,t}$ = Flow of product *j* at time *t*
$FO_{j,n,k,t}$ = Flow rate of outlet flow *j* contributed by crude *n* from process *k*
$FO_{j,n,s,t}$ = Flow of product *j* from resources *n* to splitter *s* at time *t*
$FS_{n,s,t}$ = Flow coming out of splitter *s* at time *t* for resources *n*
$Q_{n,k,t}$ = Amount of resource *n* used in process *k* at time *t*
$V_{ist,t}$ = Volume of storage tank *ist* at time *t*
$Xsize_{i,isize,t}$ = 1, if vessel of size *isize* and raw material *i* is selected at time *t*

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