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Optimum Blending of Crude Oils Using Linear Programming

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Abstract

Crude oil blending is an important operation that provides flexibility for refineries with increasing operational complexity and constant change in feedstocks. Providing the same quality and quantity of the designed crude oil of an atmospheric distillation unit became a great challenge due to the depletion of the crude oil wells over time so, the crude oil blending is a very important operation nowadays that can provide a good match through the available crude oils.

Furthermore, the heavy crude oils are blended with lighter ones to meet the transportation specifications with lower required horse power. The challenge of such operation is the shrinkage loss in the volume of the blended crude oil so the value of shrinkage has to be calculated to assure it is in a reasonable range. The heavy conventional crude oils have a low price so some companies direct such crude oils to be blended with lighter ones with higher price to upgrade the overall price and improving the heavy crude oils marketing.

The focus of the present work is to optimize the crude oil blending strategy that feed the atmospheric distillation unit in an Egyptian refining plant that has to deliver a certain amount of long residue with some limitations on its quantity and quality. The plant has a fixed bed reformer that has to deliver certain amounts of gasolines either directly or through blending operation. The main target is to maximize the plant overall profit while fulfilling the plant commitments.

Linear programming model is used to achieve the proposed targets subject to the blended crude oil constrains affecting the required long residue. The model is a matrix of constrains describing the limitations on the variables of the optimization problem. Once the model got a feasible region of solutions, the equation of the objective function determines the optimal solution at one of the feasible region borders.

Two constrains are assigned to monitor the stability and the compatibility of the blended crude oil. The optimum crude oil blend was obtained according to different scenarios for domestic consumptions of petroleum products and for different availability of crude oils. For each scenario, the model is providing the maximum profit and fulfilling the required quantity and quality of the straight run fuel oil (long residue).

Keywords: Crude oil blending, Crude oil compatibility, production planning, optimization modelling

1. Introduction

Crude oil consists of complex and differing hydrocarbon groups. These groups include aromatic, naphthenic and paraffinic hydrocarbons; each with individual sub groupings. Configuration and length of the carbon-carbon structure of crude oils vary from country to country and even within the same country, from field to field. It is a complex mixture of different components consisting mainly of hydrocarbons and some heteroatoms such as sulfur, nitrogen, oxygen and metals. [1] [2] Crude oils vary widely in their physical and chemical properties. They are classified based on their individual API's gravities (light, medium and heavy) as well as their hydrocarbon groups. They are also classified based on sulfur content (Sweet, medium and Sour) and on the characterization factor (Paraffinic base, medium base and naphthenic base). [3]

Crude oil blending became an attractive solution for the refining plants that have the capability to blend

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different grades of crude oils in order to provide a consistent and optimal feedstock to refinery operations. To improve the refinery profitability, the proper selection of the purchased crude oils is an effective method. [4] Crude oils are often blended to increase refinery flexibility, enhance the flowability in pipelines or increase the sale price of a lower grade crude oil by blending it with a higher grade, higher price crude oil. The objective of such blending is to produce a blended crude oil with required specifications at the lowest cost using the minimum amount of the higher cost crude oil. [5] [6] [7] [8]

The production of the heavy and extra heavy crude oils is increasing with low selling prices due to the low API gravity, the high sulfur content, the high acidity and the high asphaltenes content. [9] [10] [11] Blending such heavy crude oils with other more valuable light crude oils can increase the overall selling price by upgrading the characteristics of the heavy crude oils to meet the contractual required qualities. Several factors have to be considered while optimizing the recipes of the blending; such as the prices of the two crude oils with and without penalties, the availability of the crude oils and the overall shrinkage in selling volume. [12] [13] [14]

The physical operation of blending the crude oils is simple, however the selection of proper crude oils to be blended and the blending recipes are difficult. Some crude oil properties can be calculated by simple linear addition method and these properties are called additive properties. On the other hand, some crude oil properties cannot be estimated by simple linear addition method and these properties are called non-additive properties. The non-additive properties bring difficulties in predicting the blended crude oil properties. Many researchers have proposed different empirical equations to estimate the non-additive properties of the blended crude oil; such as, the viscosity, the pour point and the smoke point. [15] [16]

The atmospheric distillation units were designed on some specific crude oils that were available in the past, but over time the production of these crude oils had declined. This decline in production forced refineries to search for alternatives. The crude oil blending is now the main alternative for providing an acceptable feedstock that is compatible with the design of these units. Crude oil blending also allows the utilization of the extra heavy crude oils with their low qualities through mixing with conventional crude oils with acceptable qualities. [17] [18]

The pure Nigerian crude oils are not suitable for lube base oil production, so a foreign imported crude oil (Arab light crude) was used for the lube base oil production. Enekwe C.B. et al, [3] developed a linear programming model to minimize the required quantity of imported crude oil, and at the same time meeting the feedstock limitations. M. K. Hassan et al, [19] developed a mathematical programming model in order to solve a crude oil blending problem with the objective of maximizing the naphtha productivity from a plant in Alexandria, Egypt.

Abdelmahmod Saad et al, [20] studied the blending of three different blends of crude oils are produced in the Sudan namely (Nile blend, Dar blend and Fulleblend) and the suitability of the resulted crude oil blend for the lube oil production. Geoffrey Gill, [21] addressed the linear programming model in New Zealand refining company (NZRP) and the contractual application of the LP model between New Zealand refining company (NZRP) and the four major oil companies in New Zealand (BP. Caltex, Mobil and Shell). The LP model provides the optimal solution of what crudes are allowed to feed each unit and in what order these crudes should be processed. The optimal solution enables the refinery users to purchase the suitable crudes and produce the desired quantities of products.

Present research work is focused on developing a model that can describe a refining plant with limitations on the capacities and the feedstock characteristics. The model is optimizing the recipes for feedstock, avoiding the crude oil incompatibility and maximizing the profitability margin for the refinery. An Egyptian case study was introduced and solved through this research work with different scenarios related to the availability of the crude oils and the variable demand for domestic consumption.

2. Model development for additive properties:

The additive properties of crude oil blends are predicted as shown below.

$$Property\ of\ blend = \sum_{i=1}^{n} property\ of\ crude * fraction\ of\ crude\ i\ in\ blend \quad (1)$$

Many properties of crude oil are mass additivity (Product yield, Salt content, Sulfur content, Acidity number, wax content) where on the other hand there are properties like the specific gravity are volume additivity.

For the mass additivity

$$Pb = \sum_{i=1}^{n} Pi * Xi \quad (2)$$

For the volume additivity

$$Pb = \sum_{i=1}^{n} Pi * Yi \quad (3)$$

Where Pb denotes the property of the blend, Xi and Yi are the mass and volume fractions of crude i in the blend, respectively. [3]

Specific gravity calculation (G)

$$API = \frac{141.5}{G} - 131.5 \quad (4)$$

API is not an additive property where (G) the specific gravity is an additive property, so the specific gravity for each crude oil participating in the blend should be calculated first using equation (5).

$$G = \frac{141.5}{API + 131.5} \quad (5)$$

Conversion factor calculation (F)

Most of crude oil handling (buying and selling) uses terms of volume in BBL where on the other side some refineries uses the terms of mass in Ton; this is the cause of presenting the conversion factor that providing an easy calculation for the conversion of volume of crude oil in BBL into mass of crude oil in Ton.

$$Volume\ in\ BBL = F * Mass\ in\ Tons \quad (6)$$

$$F = \frac{1000}{159 * G} \quad (7)$$

Calculations of kinematic viscosity for crude oils blend

The viscosity is a nonlinear property, so to calculate the viscosity of crude oils blend, the term of viscosity index, which is a linear property, will be used in this work. [22] [23] [24]

$$IND.\mu = ln(ln(\mu + 0.8)) \quad (8)$$

The viscosity index of the blend is calculated as follow:

$$(IND.\mu)_b = \sum_{i=1}^{n} (IND.\mu)_i * Xi \quad (9)$$

and then the viscosity of the crude oil blend can be calculated as follow:

$$\mu_b = e^{e^{(IND.\mu)_i}} - 0.8 \quad (10)$$

Calculations of compatibility index

To judge the compatibility of mixed oils expediently, greater numbers of parameters and indices were introduced. Asomaning, [25] presented a compatibility index (***CI***), which is the ratio of resin content to asphaltenes' in the oil. If the index was less than 0.35, then the crude oil blend is compatible, otherwise, the blend is incompatible. [4] [25]

$$CI = \frac{\sum_{i=1}^{n} (AS)i * Xi}{\sum_{i=1}^{n} (R)i * Xi} \quad (11)$$

Where the X_i is the mass fraction of crude i in the blend while the AS and R are the asphaltenes' and resins content in each of crudes participating in the blend.

Calculations of Colloidal Instability Index CII

In crude petroleum, asphaltenes are colloidally dispersed as micelles. Asphaltenes have a high affinity towards aggregation and as a result, precipitate and deposit in production and processing equipment. [26] [27]

Some of the older but most popular methods for determining the stability of asphaltenes are the Asphaltene–Resin ratio and the Oliensis Spot Test. Newer tests include solvent titration with solids detection and the Colloidal Instability Index (CII). [25] [28] [29]

The asphaltene–resin ratio, as the name implies, is the ratio of asphaltenes to resins calculated using weight percentages obtained from saturates, aromatics, resins, and asphaltenes (SARA) analysis [30]. The CII is defined as the mass ratio of the sum of asphaltenes and its flocculants (saturates) to the sum of its peptizers (resins and aromatics) in a crude oil. [31] [32]

$$CII = \frac{(Saturates + Asphaltenes)}{(Aromatics + Resins)} \quad (12)$$

Values of 0.9 and more indicate an oil with unstable asphaltenes, while values below 0.7 indicate an oil with stable asphaltenes; between 0.7 and 0.9, the stability of the asphaltenes falls in the uncertain region. [25]

Calculation of the shrinkage factor

As stated in the Dec. 1967 edition of API Publication 2509C regarding the result of blending two different hydrocarbons, "If the nature of the molecules of the components differ appreciably, then deviation from ideal behavior may be expected". This deviation may either be positive or negative; that is, the total volume may increase or decrease when components are blended. In liquid petroleum blending however, the result has always been shrinkage. [33] [34]

$$S = 4.86 * C * (100 - C)^{0.819} * \Delta G^{2.28} \quad (13)$$

Where: S = volumetric shrinkage, as a percentage of the total mixture ideal volume.

C = concentration, in liquid volume % of the lighter component in the mixture.

ΔG = gravity difference, in degrees API.

3. Methodology:

Linear Programming (LP) is a mathematical technique for finding the maximum or the minimum values of some equation subject to linear inequalities or equations (constraints). These inequalities or equations are compiled in a matrix of rows and columns, the columns representing the variables and the rows representing the relations between variables. The values in the matrix are simply the coefficients that apply to unknowns in each equation. A large number of solutions might satisfy all the problem parameters; however, the optimal solution must be chosen to satisfy constrains and at the same time maximize refinery profit or minimize operating cost. [35]

The proposed model of optimization has the ability to predict the optimum recipes of the available crude oils, so as to meet the required characteristics for the atmospheric distillation feedstock. The model considers the yield of products from each crude oil and adjusting the recipes to fulfill the demand of the domestic consumption. The compatibility and the stability factors are calculated within each run in the model to assure that the blended crude oil is stable and compatible with no probability for asphaltene precipitation. The economical driver for the optimization problem is the cost and the revenue. The cost includes utility cost, cost of transportation for crude oils and the cost of crude oils purchase, while the revenue includes the sales of the final products.

Python, as a high-level programming language, was utilized in our present work to solve the linear optimization problem.

3.1 Case Study:

The present case study is a plant with atmospheric distillation unit capacity of 150,000 BBL/d and a fixed bed reformer with a capacity of 5000 T/d. It has to deliver an atmospheric residue (Fuel oil) with a quantity of 10,600 T/d. The cost of utility (CU_i) for the distillation unit is 2 $/T of feed. The characteristics of the crude oil to be distilled should meet the specification limitations listed in table 1 while the fuel oil produced has to meet the specification limitations listed in table 2.

The fixed bed reformer receives naphtha produced from the atmospheric distillation unit and also receives naphtha from the OSBL (Out Side Battery Limit) (at most 5000 T/d) to produce reformate that meets the specifications of gasoline 92. Figure 1 is the block flow diagram for the optimization problem. The yields from the fixed bed reformer are 97% and 3% of reformate and LPG respectively, where the unit requires utility consumption with a cost of 1 $ per ton of feed. The imported gasoline 95 is available with at most 10000 T/d, the gasoline 80 is a blend of gasoline 95 and naphtha (RON 60) with 60% and 40% respectively. The minimum required amounts of gasoline 80 and 95 for domestic consumption are 4000 and 4500 T/d respectively.

Table 1 The Specification limitations on the required crude oil

Crude oil property	Limitation
Specific gravity	0.867
Salt content (ppm)	At most 30
Sulfur content (wt %)	At most 2.1
Acidity number (mg KOH/gm)	At most 12.1
Wax content (wt %)	At most 3.8
Kinematic viscosity @ 37.8 °c (cSt)	At most 30
Conradson Carbon Residue CCR (wt %)	At most 6.1

Table 2 The Specification limitations on the produced fuel oil

Fuel oil property	Limitation
Sulfur content (wt %)	At most 3
Wax content (wt %)	At most 7
Asphaltene content (wt %)	At most 5
Vanadium content in fuel oil (ppm)	At most 70
Nickel content in fuel oil (ppm)	At most 40

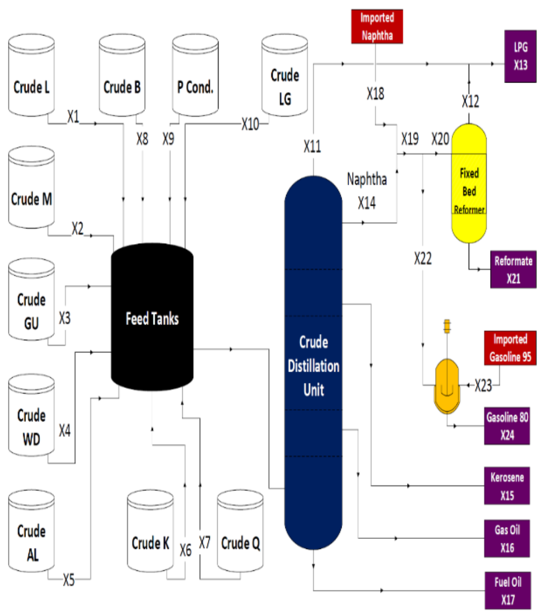

Figure 1 The BFD for The Optimization Problem

The objective is maximizing the profit while considering the following constrains: -

- Fulfilling the required amount of the fuel oil.
- Meeting the specification limitations on both crude oil and fuel oil.
- Fulfilling the required amounts of gasoline grades 80 and 92.

The cost of transportation for all crudes is 0.5 \$/Ton except for crude oils W.D and Q. The costs of transportation of crude oil W.D and Q are 1.5 \$/Ton and 0.8 \$/Ton respectively. The availability of crude oils and their prices are listed in table 3. The characteristics of the available crude oils are listed in tables 4 and 5.

Table 3 The Prices of crude oils and Availability

Crude Oil	**Price (\$/BBL)** (P_i)	**Availability in tons/d** (T_i)	**Conversion factor** (Ci)
L	58.858	3700	6.80
M	61.865	3800	7.16
Gu	60.914	11300	7.22
W. D	62.5	3200	7.75
A. L	58.589	13300	7.3
K	63.416	7100	7.22
Q	63.754	3700	7.29
B	59.795	6300	7.19
Cond.	58.752	1300	8.2
L. G	58.934	2600	7.12

Table 4 The Characteristics of The Available Crude Oils

Crude Oil	**Calculated specific gravity** (g_i)	**Salt content ppm** (Si)	**Sulfur content %** (SUi)	**Wax content %** (Wi)
L	0.925	42	2.85	3.72
M	0.878	33	2	2.92
Gu	0.871	28	1.61	3.8
W. D	0.812	18	0.3	6.1
A. L	0.862	15	1.85	3.5
K	0.872	38	2.8	1.8
Q	0.862	20	1.1	6.3
B	0.875	14	2.6	3.9
Cond.	0.767	9	0.5	6.2
L. G	0.883	12.8	1.63	2.2

Table 5 The Characteristics of The Available Crude Oils cont.

Crude Oil	**Acidity Number (mg KOH/gm)** (A_i)	**Conradson Carbon Residue CCR (wt %)** (CCR_i)	**Kinematic viscosity @ 37.8 °c (cSt)** (μ_i)
L	13	11.8	121
M	5.7	6.24	35
Gu	7	5.2	30
W. D	11	1.52	15
A. L	5	4	18
K	14	5.8	40
Q	16	4.04	32
B	11.2	6.33	29
Cond.	8	0.06	8
L. G	12	5.6	20

The products yield from the crude oils are fixed ratios while the same cut points are applied. Theses yields are listed in table 6. The study of the ratios of SARA is important to track the compatibility and the stability of the blended crude oil. The ratios of SARA (Saturates, Aromatics, Resins and Asphaltenes) for the available crude oils are listed in table 7.

Table 6 The Products Yield of The Available Crude Oils

Crude Oil	**LPG yield %** (L_i)	**Naphtha yield %** (NA_i)	**Kerosene yield %** (K_i)	**Gas oil yield %** (G_i)	**Fuel oil yield %** (F_i)
L	0.5	8	9	10	72
M	1.2	12.3	8	11	67
Gu	0.9	15.5	9	13.1	61
W. D	2.1	26.2	10	23.2	38
A. L	1.3	12	8.2	19	59
K	1.3	18	9	13	58.2
Q	1.8	16.2	11	19.5	51
B	1.1	12.4	10	18	58
Cond.	3	52	14	22	8.5
L. G	0.8	12	14.2	18	54.5

Table 7 The SARA Ratios for The Available Crude Oils

Oil	L	M	Gu	W.D	A.L
Saturates % (P_i)	30.9	36.7	39.3	43.1	38.7
Aromatics % (AR_i)	37.9	47.5	50.2	43.9	47.3
Resins % (R_i)	22.6	12.2	8.4	10.2	12.3
Asphaltenes % (AS_i)	8.6	3.6	2.1	2.8	1.7
Oil	**K**	**Q**	**B**	**Cond.**	**L.G**
Saturates % (P_i)	36.4	41.5	40.1	45.5	33.6
Aromatics % (AR_i)	47.7	46.5	44.5	50.5	46.2
Resins % (R_i)	12.9	8.8	11.8	3.9	17.5
Asphaltenes % (AS_i)	3.0	3.3	3.6	0.1	2.7

The produced fuel oil has to be delivered at a certain amount with other limitations on its specifications as well. The production of fuel oil is related to the yield of the crude oils that will be distilled where the specification is related to the property distribution for each crude oil when the same cut points are applied. The sulfur, wax, asphaltene, Vanadium and Nickel content in fuel oil of the available crude oils are listed in table 8.

Table 8 The Specifications of The Fuel Oil Produced from The Available Crude Oils

Crude Oil	L	M	Gu	W.D	A.L
Sulfur % (SUF_i)	3.77	3.1	2.4	0.8	2.5
Wax % (WF_i)	3.77	3.9	4.8	8.5	4.5
Asphaltenes % (ASFi)	14.7	4.9	2.9	1.6	1.5
Vanadium ppm (Vn_i)	152	100	76	20	43
Nickel ppm (N_i)	131	73	40	11	13.75
Crude Oil	**K**	**Q**	**B**	**Cond.**	**L. G**
Sulfur % (SUF_i)	3.45	3.4	3.2	0.2	2.57
Wax % (WF_i)	2.3	7.4	5.3	7.8	4.2
Asphaltenes % (ASFi)	2.5	1.9	5	0.5	5.1
Vanadium ppm (Vn_i)	62	11	66	9	100
Nickel ppm (N_i)	22	4	19	6	75

The prices of the LPG, naphtha, gasoline 80, gasoline 92, gasoline 95, kerosene, gas oil and fuel oil are 543, 510, 550, 580, 590, 512, 500 and 380 $/Ton respectively.
Linear programming is used as follow to get the optimum quantities from the available crude oils to be blended and distilled in the plant.

- Assume the quantities of crude oils to be blended in tons are X_1, X_2, …. X_{10}.
- Assume LPG yield from distillation to be X_{11}, LPG yield from fixed bed reformer to be X_{12} and total LPG yield to be X_{13}.
- Assume the product yields (naphtha, kerosene, gas oil, fuel oil) to be X_{14}, X_{15}, X_{16}, X_{17} respectively.
- Assume the imported naphtha to be X_{18} and the total naphtha to be X_{19}.
  - Assume the reformer capacity to be X_{20}, the yield of reformate to be X_{21}, the remaining available naphtha after feeding the fixed be reformer to be X_{22}, the gasoline 95 to be X_{23}

3.2 The Objective Function

The objective function is maximizing the profit: The profit = The revenue – The cost
The revenue = the sum of products yield multiplied by the price of each product

The revenue =
$$\sum_{i=1}^{10} 543 * Li * Xi + \sum_{i=1}^{10} 510 * NAi * Xi + \sum_{i=1}^{10} 512 * Ki * Xi + \sum_{i=1}^{10} 500 * Gi * Xi + \sum_{i=1}^{10} 380 * Fi * Xi + 0.03 * 543 * X20 + 0.97 * 580 * X20 + 550 * X24 \quad (14)$$

The cost = the amount of processed crude oil (Ton) multiplied by the price of each crude oil + the amount of processed crude oil (Ton) multiplied by the cost of transportation for Ton of crude oil + the amount of processed crude oil (Ton) multiplied by the cost of utility for Ton of crude oil + the naphtha price multiplied by the reformer feed + the utility of reformer multiplied by the reformer feed + the gasoline 95 price multiplied by the blended gasoline 95 in gasoline 80 + the naphtha price multiplied by the blended naphtha in gasoline 80

The cost $=\sum_{i=1}^{10} Pi * Xi + \sum_{i=1}^{10} CTi * Xi + \sum_{i=1}^{10} CUi * Xi + + 510 * X20 + 1 * X20 + 590 * X23 + 510 * X22$
(15)
So,
Z = 10.46 X_1 *– 25.842* X_2 *– 14.984* X_3 *– 31.159* X_4 *– 0.655* X_5 *– 29.013* X_6 *– 27.683* X_7 *– 1.708* X_8 *+ 11.433*

$X_9 + 13.210\,X_{10} + 67.89\,X_{20} - 510\,X_{22} - 590\,X_{23} + 550\,X_{24}$ (16)

3.3 The Constrains

Operating Capacity Constrain:

$$\sum_{i=1}^{10} Ci * Xi \leq 150{,}000 \quad (17)$$

Specific gravity constrain:

$$\sum_{i=1}^{10} Ci * Xi * gi = 0.867 * \sum_{i=1}^{10} Ci * Xi \quad (18)$$

Fuel oil production constrain:

$$\sum_{i=1}^{10} Fi * Xi \geq 10{,}600 \quad (19)$$

Salt content constrain:

$$\sum_{i=1}^{10} Si * Xi \leq 30 \sum_{i=1}^{10} Xi \quad (20)$$

Sulfur content constrain:

$$\sum_{i=1}^{10} SUi * Xi \leq 2.1 \sum_{i=1}^{10} Xi \quad (21)$$

Acidity number constrain:

$$\sum_{i=1}^{10} Ai * Xi \leq 12.1 \sum_{i=1}^{10} Xi \quad (22)$$

Wax content constrain:

$$\sum_{i=1}^{10} Wi * Xi \leq 3.8 \sum_{i=1}^{10} Xi \quad (23)$$

Kinematic viscosity constrain:
The kinematic viscosity of the crude oils blend should not exceed 30 cSt. As the kinematic viscosity cannot be linearly added so we use the viscosity index (VI) instead and after calculation of the viscosity index for the blend we can get the kinematic viscosity of the blend.

$$VI = Ln\,(Ln\,(\mu + 0.8)) \quad (24)$$

Therefore, the viscosity index of the blend should be at most 1.232.
From the previous equation and by knowing the kinematic viscosity for each crude oil the viscosity index is calculated and listed in table 9.

Table 9 The Calculated viscosity index for The Available Crude Oils

Crude Oil	X_i	Kinematic viscosity @ 37.8 °c (cSt) (μ_i)	VI
L	X_1	121	1.569
M	X_2	35	1.275
Gu	X_3	30	1.232
W. D	X_4	15	1.015
A. L	X_5	18	1.076
K	X_6	40	1.311
Q	X_7	32	1.25
B	X_8	29	1.222
Cond.	X_9	8	0.777
L.G	X_{10}	20	1.11

The viscosity index for the crude oils blend can be calculated as follow:

$$\sum_{i=1}^{10} VIi * Xi \leq 1.232 \sum_{i=1}^{10} Xi \quad (25)$$

Compatibility constrain:

$$Co = \frac{\sum_{i=1}^{10} ASi * Xi}{\sum_{i=1}^{10} Ri * Xi} \leq 0.35 \quad (26)$$

Colloidal instability index constrain:

$$CII = \frac{(Saturates + Asphaltenes)}{(Aromatics + Resins)} \leq 0.7 \quad (27)$$

Crude oils availability constrain:

$X1 \leq 3700$ (28)
$X2 \leq 3800$ (29)
$X3 \leq 11300$ (30)
$X4 \leq 3200$ (31)
$X5 \leq 13300$ (32)
$X6 \leq 7100$ (33)
$X7 \leq 3700$ (34)
$X8 \leq 6300$ (35)
$X9 \leq 1300$ (36)
$X10 \leq 2600$ (37)

Sulfur content in Fuel oil constrain:

$$\sum_{i=1}^{10} SUFi * Fi * Xi \leq 3 \sum_{i=1}^{10} Fi * Xi \quad (38)$$

Wax content in Fuel oil constrain:

$$\sum_{i=1}^{10} WFi * Fi * Xi \leq 7 \sum_{i=1}^{10} Fi * Xi \quad (39)$$

Asphaltene content in Fuel oil constrain:

$$\sum_{i=1}^{10} ASFi * Fi * Xi \leq 5 \sum_{i=1}^{10} Fi * Xi \qquad (40)$$

Vanadium content in Fuel oil constrain:

$$\sum_{i=1}^{10} Vni * Fi * Xi \leq 70 \sum_{i=1}^{10} Fi * Xi \qquad (41)$$

Nickel content in Fuel oil constrain:

$$\sum_{i=1}^{10} Ni * Fi * Xi \leq 40 \sum_{i=1}^{10} Fi * Xi \qquad (42)$$

LPG yield from distillation:

$$X11 = \sum_{i=1}^{10} Li * Xi \qquad (43)$$

LPG yield from reformer:

$$X12 - 0.03\, X20 = 0 \qquad (44)$$

Total LPG yield:

$$X13 - X11 - X12 = 0 \qquad (45)$$

Naphtha yield from distillation:

$$X14 = \sum_{i=1}^{10} NAi * Xi \qquad (46)$$

Kerosene yield from distillation:

$$X15 = \sum_{i=1}^{10} Ki * Xi \qquad (47)$$

Gas oil yield from distillation:

$$X16 = \sum_{i=1}^{10} Gi * Xi \qquad (48)$$

Fuel oil yield from distillation:

$$X17 = \sum_{i=1}^{10} Fi * Xi \qquad (49)$$

Total Naphtha available:

$$X19 - X14 - X18 = 0 \qquad (50)$$

Imported naphtha constrain:

$$X18 \leq 5000 \qquad (51)$$

Naphtha distribution:

$$X19 - X20 - X22 = 0 \qquad (52)$$

Fixed bed reformer capacity constrain:

$$\frac{X20}{0.71} \leq \frac{5000}{0.71} \qquad (53)$$

Reformate yield from reformer:

$$1.031\, X21 - X20 = 0 \qquad (54)$$

Gasoline 80 Blending:

$$\frac{X23}{X22} = \frac{0.6}{0.4} \qquad (55)$$

Gasoline 80 yield:

$$X24 - X22 - X23 = 0 \qquad (56)$$

Gasoline 80 Demand:

$$X24 \geq 4000 \qquad (57)$$

Gasoline 92 Demand:

$$X21 \geq 4500 \qquad (58)$$

Imported gasoline 95 constrain:

$$X23 \leq 10000 \qquad (59)$$

3.4 Cases with Different Scenarios

3.4.1 Case (1) Base Case: We can consider the previous case as the base case and from it different scenarios are generated with other optimal solutions according to different constrains.

3.4.2 Case (2) Demands on Other Products: In this case we will add three constrains -in addition to the previous ones- complying with the domestic consumptions as follow:

* LPG production has to be at least 400 T/d so,

$$X13 \geq 400 \qquad (60)$$

* Kerosene production has to be at least 1500 T/d so,

$$X15 \geq 1500 \qquad (61)$$

* Gas oil production has to be at least 3500 T/d so,

$$X16 \geq 3500 \qquad (62)$$

3.4.3 Case (3) Demands on Other products with crude oil AL limited: In this case we will change constrain of the crude oil AL availability (Equation 32) plus the already added constrains in case 2.

AL crude availability is limited to 10000 T/d so,

$$X5 \leq 10000 \qquad (63)$$

3.4.4 Case (4) Demands on other products with crude oil AL limited and Obligatory Delivery of 400 T/d, 2000 T/d from Crudes M and Gu respectively: In this case we will add two constrains to be assure that the obligatory delivery is taken into consideration plus the constrains of case 3.

* M crude obligatory delivery of 400 T/d so,

$$X2 \geq 400 \qquad (64)$$

* Gu crude obligatory delivery of 2000 T/d so,

$$X3 \geq 2000 \qquad (65)$$

4. Results and Discussion:

The Linear programming method to get an optimal solution is trying to get a feasible region that can comply with all constrains by drawing constrains graphically and get the intersection area. After getting the feasible region with multiple solutions, the line representing the equation of the objective function will hit this region at one of its edges. This edge (point) is the optimal solution that comply with the inequalities of constrains and at the same time provides the maximum profit or the minimum cost either the optimization problem is a maximization problem or a minimization one.

In our case study constrains of the capacity of units, the required characteristics for the crude oils blend, the compatibility of the blend and the required yield of the petroleum products are considered. After solving the previous inequalities, the results of the four cases are listed in table 10.

Table 10 The Results of The Four Cases, The Profit and The Shrinkage Loss

X_i (Ton)	Case 1	Case 2	Case 3	Case 4
X_1	2536	2586	1893	0
X_2	0	0	0	400
X_3	0	0	0	2000
X_4	0	0	0	354
X_5	13300	13300	10000	10000
X_6	658	864	4230	4460
X_7	0	0	0	631
X_8	0	89	902	227
X_9	1000	1039	1047	0
X_{10}	2600	2600	2600	2600
X_{11}	245	250	257	253
X_{12}	150	150	150	147
X_{13}	395	400	407	400
X_{14}	2749	2821	3078	2883
X_{15}	1887	1925	1977	1930
X_{16}	3554	3611	3500	3500
X_{17}	11556	11769	11754	11989
X_{18}	3851	3779	3522	3621
X_{19}	6600	6600	6600	6504
X_{20}	5000	5000	5000	4904
X_{21}	4850	4850	4850	4757
X_{22}	1600	1600	1600	1600
X_{23}	2400	2400	2400	2400
X_{24}	4000	4000	4000	4000
Profit ($/day)	352036	349275	245246	132569
Shrinkage Loss	1.42%	1.45%	1.45%	0.13%

Figure 2 illustrate the profit (The objective function) of the four cases relative to each other.

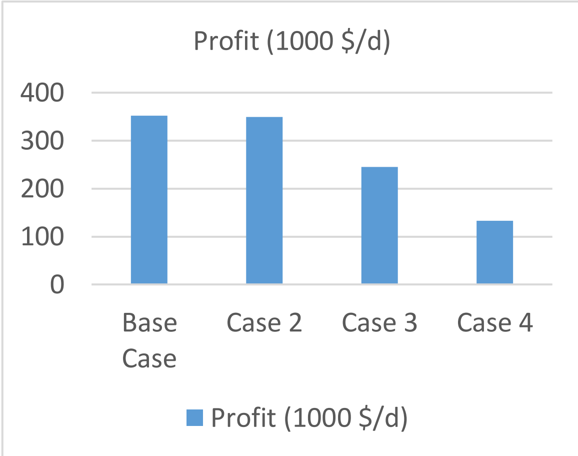

Figure 2 The Profit of the Four Cases

Figures 3, 4, 5 and 6 show the optimal quantities (in KT) of the ten crude oils in the four cases compared to the available quantity respectively.

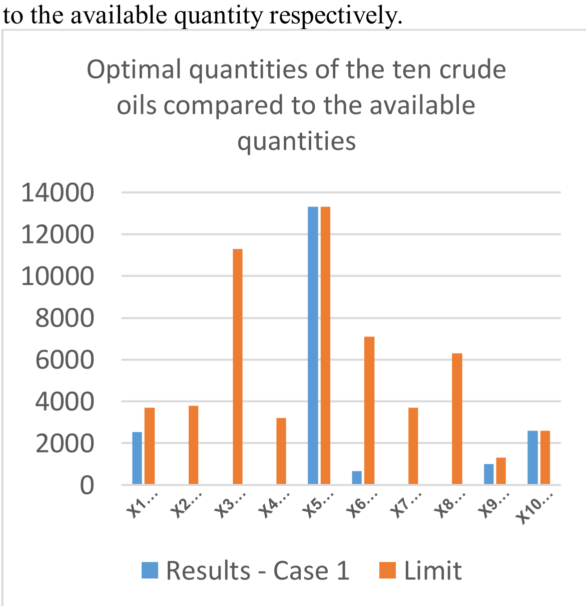

Figure 3 Optimal quantities of the ten crude oils in case 1 compared to the available quantities

<u>Case 1:</u>
The crude selection shows the following according to the profitability of each crude oil and at the same time meeting the required limits (constrains):

- Crudes AL and LG are preferred as the optimal quantity is hitting the maximum available quantity.

- P condensates are chosen with a reasonable quantity to improve the overall yield.
- Crude K is selected in small quantity due to its relative high price and sulfur content.
- Crudes WD and Q are not selected due to the high wax content and some problems related to the compatibility.

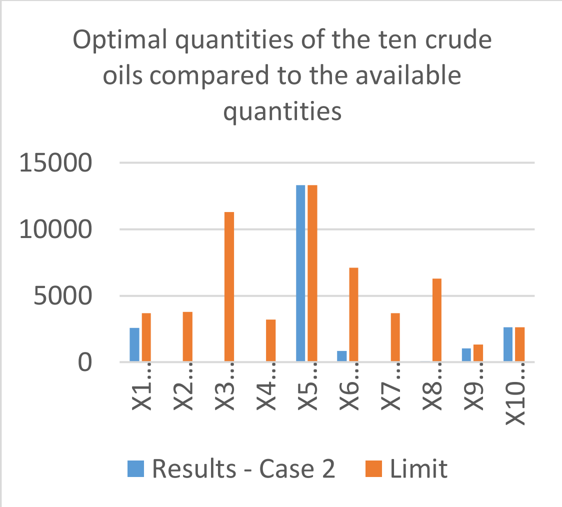

Figure 4 Optimal quantities of the ten crude oils in case 2 compared to the available quantities

Case 2:

- Case 2 is quite different from case 1 as three constrains related to minimum consumptions for the LPG, kerosene and gas oil are added. The impact of adding the three constrains is that it pushed the model to increase the selected amount of crude K and begins to select small quantity of crude B to improve the overall yield coping with the updated matrix of constrains.

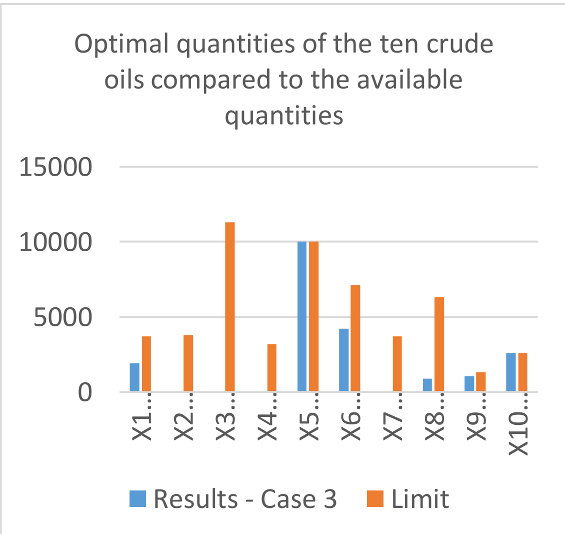

Figure 5 Optimal quantities of the ten crude oils in case 3 compared to the available quantities

Case 3:

The crude selection shows the following notes according to the profitability of each crude oil and at the same time meeting the required limits (constrains) with updated constrain related to the new available quantity of crude AL (10000 Ton)

- crudes AL and LG are preferred as the optimal quantity is hitting the maximum available quantity where the new limit for crude AL pushed the model to search for alternatives to meet the required yields.
- P condensates are chosen with a reasonable quantity to improve the overall yield.
- Crude K is selected in a greater quantity to compensate the shortage of crude AL, although it is still limited due to its relative high price and sulfur content.
- Crude B is selected as crude K to compensate the shortage of crude AL, although it is still limited due to its high acidity.
- Crudes WD and Q are not selected due to the high wax content and some problems related to the compatibility.

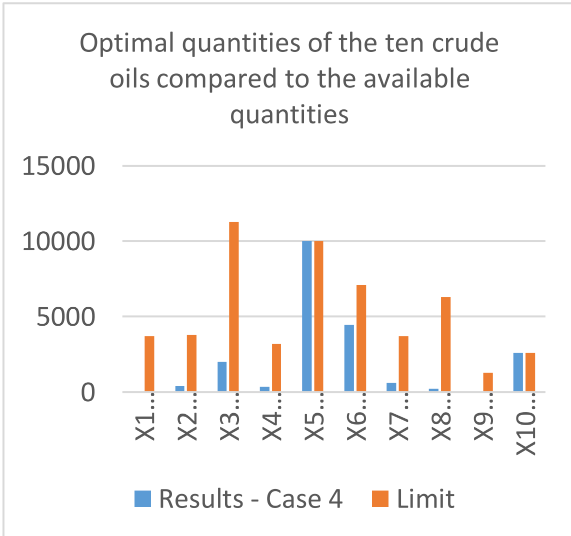

Figure 6 Optimal quantities of the ten crude oils in case 4 compared to the available quantities

Case 4:

The crude selection shows the following notes according to the profitability of each crude oil and at the same time meeting the required limits (constrains) with updated constrain related to obligations on selection minimum quantities of 400 ton and 2000 ton for crudes M and GU respectively. From the three cases it is obviously that the model does not prefer to select crudes M and GU, so we tried to force the model to choose the previous quantities and check the feasibility of this case.

- The model case is still feasible with the new obligations of receiving the quantities of crudes M and GU. The model chooses the minimum quantities of theses crude oils that is matching with the excluding of them from the previous cases.
- crudes AL and LG are preferred as the optimal quantity is hitting the maximum available quantity where the limit for crude AL pushed the model to search for alternatives to meet the required yields.
- P condensates are not chosen in this case as the capacity of the unit is already fully-utilized and the high yield of middle distillates of these condensates does not compensate their relative high price that is affecting the profitability according to the new matrix of constrains.
- Crude B is selected in a greater quantity to compensate to compensate the shortage of crude AL, although it is still limited due to its high acidity.
- Crude L is not chosen as the capacity of the unit is fully-utilized where other crude oils can handle the required amount of fuel oil in spite of its relative low price.
- Crudes WD are Q are selected by the model for the first time as the other selected crudes can handle the wax content so the blend is still meeting the required characteristics. The absence of crude L from the blend creates the opportunity for crudes WD and Q to be selected as crude L with a very high content of asphaltenes faces incompatibility and instability problems when blended with the crudes WD and Q with high saturates content and low resins content.

5. Conclusion

The model for prediction of crude oil blend property was found suitable for this study, with a linear programming problem, to obtain optimum quantities of the crude oils that when blended provide the suitable feed for the distillation unit with meeting the required characteristics of crude oil and fuel oil while fulfilling the requirements of the straight run fuel oil and crude oils compatibility with a reasonable shrinkage loss due to blending. The model also determines the required amounts of production that maximizing the profit of the base case study plant and fulfilling the domestic demands of gasoline grades 80 and 92.

Three other scenarios were studied with more constrains either on demand of the products or on the crude oil availability with their optimum solutions are obtained by using the appropriate inequalities that correctly defined constrains in the linear programming model.

The model validates -also after investigating the results of the studied scenarios- that the objective function (Profit) decreases with increasing the applied constrains as applying more constrains generate a smaller feasibility region with lower values for the optimal solutions.
The model is complying with updating the selection of the crude oils to be distilled with the optimal profitability (objective function) while any significant changes have to be updated on constrains of the availability and the new required demands for products.

The model helps also in checking the feasibility of the cases where there are obligations to receive specific amounts of undesirable crude oils. It updates the matrix of constrains by the new obligations and tries to find a feasible region of solutions that can meet all constrains together and then decides the optimal solution with highest profitability under the new conditions.

6. References

[1] Katta G. Murty, Models for Optimum Decision-Making Crude Oil Production and Refining, Operation Reasearch & Management Science, 2020.

[2] Chang Samuel Hsu and Paul R. Robinson, Petroleum Science and Technology, Springer, 2018.

[3] Enekwe C.B., Ibe E.C and Osoka E.C., “Optimization of Blends of Selected Foreign and Nigerian Crudes for Lubricant Production,” *International Journal of Science and Engineering Investigations,* 2012.

[4] Jialei Hou, Xingang Li and Hong Sui, “The optimization and prediction of properties for crude oil blending,” *Computers and Chemical Engineering,* 2015.

[5] Raheek I Ibrahim, Manal K Odah and Amna Al-Mufti, “An Overview on the Recent Techniques for Improving the Flowability of Crude Oil in Pipelines,” *1st International Conference on Petroleum Technology and Petrochemicals-IOP Publishing,* 2019.

[6] Rafael Martínez-Palou, María de Lourdes Mosqueira, Beatriz Zapata-Rendón, Elizabeth Mar-Juárez, César Bernal-Huicochea, Juan de la

Cruz Clavel-López and Jorge Aburto, "Transportation of heavy and extra-heavy crude oil by pipeline: A review.," *Journal of Petroleum Science and Engineering,* 2011.

[7] Jiaqiang Jing, Ran Yin, Ying Yuan, Yunliang Shi, Jie Sun and Ming Zhang, "Determination of the transportation limits of heavy crude oil using three combined methods of heating, water blending, and dilution.," *ACS Omega,* 2020.

[8] A. Saniere, I. Hénaut and J.F. Argillier, "Pipeline Transportation of Heavy Oils, a Strategic, Economic and Technological Challenge," *Oil & Gas Science and Technology – Rev. IFP,* 2004.

[9] José A. D. Muñoz, Jorge Ancheyta and Luis C. Castañe, "Selection of heavy oil upgrading technologies by proper estimation of petroleum prices," *Petroleum Science and Technology,* 2021.

[10] Scott Sayles and D Mark Routt, "Unconventional crude oil selection and compatibility," *Digital Refining,* 2011.

[11] Shadi W. Hasan, Mamdouh T. Ghannam and Nabil Esmail, "Heavy crude oil viscosity reduction and rheology for pipeline transportation," *Fuel Journal,* 2010.

[12] P. Gateau, I. Hénaut, L. Barré and J.F. Argillier, "Heavy Oil Dilution," *Oil & Gas Science and Technology – Rev. IFP,* 2004.

[13] Brian Betts, "Crude Oil Blending," 2010.

[14] Abarsi Hart, "A review of technologies for transporting heavy crude oil and bitumen via pipelines," *J. Pet. Explor. Prod. Technol,* 2013.

[15] H. Ganji, S. Zahedi, M. Ahmadi Marvast, S. Kananpanah and M. Sadi, S. Shokri, "Determination of Suitable Feedstock for Refineries Utilizing LP and NLP Models," *International Journal of Chemical Engineering and Applications,* 2010.

[16] Yang Huihua, Ma Wei, Zhang Xiaofeng, Li Hu and Tian Songbai, "A Method for Crude Oil Selection and Blending Optimization Based on Improved Cuckoo Search Algorithm," *China Petroleum Processing and Petrochemical Technology,* 2014.

[17] Xiaoou Li and Wen Yu, "Modeling of Crude Oil Blending via Discrete-Time Neural Networks," *International Journal of Mechanical and Mechatronics Engineering,* 2008.

[18] Rajeev Kumar, Ravi Kumar Voolapalli and Sreedevi Upadhyayula, "Prediction of crude oil blends compatibility and blend optimization for increasing heavy oil processing," *Fuel Processing Technology,* 2018.

[19] M.K. Hassan, A. Kandeil and A. Elkhayat, "Improving Oil Refinery Productivity through Enhanced Crude Blending using Linear Programming Modeling," *Asian Journal of Scientific Research,* 2011.

[20] Abdelmahmod Saad, Hana AbdElaziz Warag and Adam mosa, "Production of Base Oil From Sudanese Crude oil Based on the properties," *Red sea university Journal of Basic and Applied Science,* 2016.

[21] Geoffrey Gill, "Linear Programming as a tool for Refinery Planning," 2015.

[22] Han Shan-peng, Jiang Wen-xue and Zhang Jin-jun, "Approaches to predict viscosities of crude oil blends," *J. Cent. South Univ. Technol.,* 2007.

[23] Basma M. Yaghi and Ali Al-Bemani, "Heavy Crude Oil Viscosity," *Energy Sources,* 2010.

[24] Qian Jianhua, Zhang Jinjun, Li Hongying and Zhang Qiang, "Study evaluates viscosity prediction of crude blends," *Oil & Gas Journal,* 2006.

[25] Samuel Asomaning, "Test Methods for Determining Asphaltene Stability in Crude Oils," *Petroleum Science and Technology,* 2013.

[26] Krzysztof Bambinek, Andrzej Przyjazny and Grzegorz Boczkaj, "Compatibility Crude Oil Blends-Processing Issues Related to Asphaltene Precipitation, Methods of Instability Prediction-A Review," *Industrial & Engineering Chemistry Research,* 2023.

[27] Ivelina K. Shishkova, Dicho S. Stratiev, Mariana P. Tavlieva, Rosen K. Dinkov, Dobromir Yordanov, Sotir Sotirov, Evdokia Sotirova, Vassia Atanassova, Simeon Ribagin, Krassimir Atanassov, Danail D. Stratiev and Svetoslav Nenov, "Evaluation of the Different Compatibility Indices to Model and Predict Oil Colloidal Stability and Its Relation to Crude Oil Desalting," *Resources,* 2021.

[28] George Mushrush and James G. Speight, "Petroleum Products: Instability and Incompatibility," *Oil & Gas Journal,* 1996.

[29] I. N. Evdokimov, "The Importance of Asphaltene Content in Petroleum III—New Criteria for Prediction of Incompatibility in Crude Oil Blends," *Petroleum Science and Technology,* 2010.

[30] Hsienjen Lian, Jiuun-Ren Lin and Teh Fu Yen, "Peptization studies of asphaltene and solubility parameter spectra," *Fuel Journal,* 1993.

[31] Yousef Easa Al-Shamlan, "Mechanistic Investigation of Fouling of Heat Exchangers Caused by Asphaltene Deposition in Oil Refineries," *Rice University ProQuest Dissertations Publishing,* 2019.

[32] S. Asomaning and A. P. Watkinson, “Petroleum Stability and Heteroatom Species Effects in Fouling of Heat Exchangers by Asphaltenes,” *Heat Transfer Engineering,* 2000.

[33] Harry James, “Shrinkage Loses Resulting from Liquid Hydrocarbon Blending,” *IMEC Corporation,* 2015.

[34] Jabir Shanshool and Emad Talib, “Fitted Shrinkage Formula of Spiked Crude Oils,” *Petroleum Science and Technology,* 2007.

[35] Steven J. Miller, “An Introduction to Linear Programming,” 2007.