CARITAS UNIVERSITY AMORJI-NIKE, EMENE, ENUGU STATE

Caritas Journal of Engineering Technology

CJET, Volume 4, Issue 2 (2025)

Article History: ***Received: 20th January, 2025 Revised: 4th March, 2025 Accepted:2nd April, 2025***

Application of Mathematical Model for Optimal Blending of Crude Oils

Princewill W. Igbagara
Department of Chemical Engineering,
Federal University Otuoke, Bayelsa State, Nigeria
E-mail: igbagarapw@fuotuoke.edu.ng

Abstract

Crude oil blending as a unit operation in the transportation and refining processes is critical for process optimization. This is because crude oils vary in properties based on their source of production. Meanwhile, distillation equipment (crude distillation unit) is designed based on the specific properties of crude oil. Product yield, therefore, is dependent on the proximity of the crude properties to be distilled to the design parameters of the crude distillation unit (CDU). Processing of crude oil with a wide disparity in properties gives a poor yield. Crude oil blending addresses this problem by mixing crude oils with different properties to give approximate values to the desired design properties. The present work developed mixing criteria for crude oils to achieve the properties that give optimum distillation output based on select crude parameters. The models were tested with simulation data from three Sudanese Crude oils and gave good predictive quality.

Keywords: ***Crude Oil; Model; Distillation, Blending; Design parameters***

1.0 Introduction

The blending of crude oil as well as its products has become a major activity in crude oil refining and general midstream and downstream Petroleum operations. Frequently, crude oil products such as lubricating oils, gasoline and fuel oils are blended with appropriate chemical additives to enhance their quality for the desired purpose (Igbagara et al., 2019). Eneckwe et al (2012) posited that Arab light crude oil was used as a blend to produce lube base oil since the pure Nigerian crude oils were not suitable for its production. Nevertheless, they developed a linear programming model to minimize the required quantity of imported crude oil while meeting the feedstock limitations. Earlier refineries used tetraethyllead as an additive to enhance the anti–knock properties of gasoline. However, this practice was shortly abandoned due to environmental concerns, and replaced with more environmentally friendly compounds like Methyl tert–butyl ether (MTBE), ethanol and Toluene. Similarly, different grades of crude oils are blended to get desired qualities for different reasons. Suffice it to note that crude oils from different origins often have differences in their physical and chemical properties, which are sometimes quite wide and significant (Oyekunle and Famakin, 2004). The foregoing has led to the classification of crude oils based on different parameters. Crude oils are classified based on their API gravities as light, medium and heavy. Also, they are classified based on their hydrocarbon composition, determined empirically by the characterisation factor as paraffinic, olefinic, naphthenic and aromatic. A final classification, though secondary but equally important, is based on sulfur content as sweet, medium or sour crude oils (Al Dahhan and Mahmood, 2019).

Blending of crude oils to achieve desired properties, as stated earlier, is for different reasons. First and most important is for refinability. Crude Distillation Unit (CDU) is designed based on the TBP and other properties of the crude. It therefore implies that every CDU is crude oil specific. Where crude oils with wide differences in properties are processed in a given CDU, the desired output is often not obtained (Ganji et al, 2010). To circumvent this problem of refining, two methods are generally employed: First, the blending of different crude oils to produce feedstock that meets the design requirements and specifications of the particular CDU (Abdulkareem and Kovo, 2006). Second, is the variation of operational parameters of the distillation process to achieve the desired product yield (Gembiki et al., 2007). Blending is, however, preferred in practice over the latter since it is easier to achieve. Manipulation of operational parameters and processes to achieve optimal output in the distillation of "deviant crude oil" is extremely cumbersome and often more costly. Lately, so much research effort has been directed to the subject of crude oil blending to optimize product yield. One of such works is the development of a mathematical programming model to maximize naphtha productivity via crude blending (Hassan et al, 2011). In the same vein, Ghanji et al. (2010) utilized LP and NLP models to determine suitable feedstocks for Refineries based on blending principles.

Another reason for crude blending is to enhance midstream operations of crude oil transportation, whether through pipelines, marine vessels or even trucks on land. Poor flowing crude oils cause fouling which forms clogs and eventually block pipelines, as well as cause instability of transporting vessels. Flow properties of crude oils such as viscosity, API gravity and pour point are enhanced by blending, and a great deal of empirical correlations have been developed in this regard (Ibrahim et al., 2019 and Hart (2013).

A third and common reason for crude oil blending is the commercial value of crude, largely determined by its sulfur content. Crudes with high sulfur content referred to as sour crudes are cheaper than the less sulfur sweet crudes. This is because of the damage that oxides, sulfates and sulfides of sulfur does to refinery components and equipment, and environmental regulations which requires the sharp reduction of crude oil sulphur to less than 0.5% by volume. Consequently, sulphur reduction is a major activity in crude oil trade and processing. Various methods developed for crude oil sulphur reduction includes but not limited to oxidation with presence of nitrogen oxide and absorption of the resulting sulphur trioxide in sulphuric acid solution (Guth et al., 1975), oxidation by peroxy acid and extraction of the resulting sulphur products with silica gel (Aida el al., 2000) and oxidation with hydrogen peroxide and catalyst in presence of radiation (Cullen, 2004). This process it was reported reduced sulphur content of the crude oil from 2.5% to 0.7%. Besides these chemically reactive processes, an alternative process for sulphur reduction in crude oil is blending crudes with different sulphur content. Sweet crudes are often blended with sour crudes to reduce the sourness and enhance its market value.

Optimization as a design and analytical tool in science has widespread use, especially in chemical processes such as distillation. Determination of the best mixing ratios of different Iraqi crude oils using the limiting values of API gravity, sulphur content and the Watson Factor through simulation using Aspen HYSYS and Matlab programs, and predicting the distillation products was carried out by Naji et al. (2021). While optimum mixing ratios were not achieved, upgrade of intermediary crude with high Sulphur content was. Similarly, a linear programming model was used to optimize the crude oil blending strategy that fed the atmospheric distillation unit in an Egyptian refining plant that delivers a certain amount of long residue with some limitations on its quantity and quality. The model was a matrix of constraints describing the limitations on the variables of the optimization problem (Hegazy et al. 2023).

Plant data of El Obeid refinery in North of Kordofan in Sudan was simulated using Aspen Hysys version 10.0 by Dafaalla et al. (2021). Aim of the work was to get appropriate volume percent of three different crude oils mixtures that converges the physical property parameters to the Nile blend which is the design feedstock. Quite excellent results were achieved in this work. Physicochemical parameters (pH, temperature, viscosity, specific and API gravity, pour point, water content, Acid No, Sulphur content, salt content and heavy metals namely: Zn, Pb, Mn, Co, Cd, Fe, Ni, Cr and V) of crude oil blends obtained in Nigeria were carried out (Dickson and Udossien, 2012). The results when compared to standards of the American Petroleum Institute (API) showed that crude oil blends obtained from Nigeria had low sulphur content, and are predominantly of the light crude oil category.

2.0 Methodology

This work presents a model that gives optimum blend of crude oils with differences in fractional composition with the aim to converge the output to predetermined feedstock quality. Specific objectives of the work include the determination of blend ratios that enhance yield of the low boiling fractions of Naphtha, Kerosene and Gas Oil, thereby reducing composition of the Atmospheric Residue. While literature is replete with similar models, relevance of the present work is in the simplicity of the emerging equation and the very empirical nature of the data used for its validation. To this end, compositions of three different crude oils were defined based on TBP fractional yields. Also, an objective function was defined for optimum yield of individual fractions of crude in the Blend. The work further defined appropriate constraints for the optimization problem.

2.1 Optimization Model for Crude Oil Blends

Optimization of the system was based on a single parameter of the Crude oils which was maximization of fractional yield (Y_i). Though Crude oil has more than a dozen fractions (products), the work is limited to the three lowest boiling liquid fractions and the resulting atmospheric residue. Now, considering the blending of three different types of Crudes for the three low boiling liquid fractions of Naphtha, Kerosene, Diesel and Residue, the system can be represented as follows:

Let;

$Naphtha\ fraction = x_1$, $Kerosene\ fraction = x_2$ and $Diesel\ fraction = x_3$ and $Residue = x_4$

Then, these four fractions can be represented for three different crude oil types as;

$$x_{11} + x_{12} + x_{13} + x_{14} = \sum_{i=1}^{n} x_{1i} \quad (1)$$

$$x_{21} + x_{22} + x_{23} + x_{24} = \sum_{i=1}^{n} x_{2i} \quad (2)$$

$$x_{31} + x_{32} + x_{33} + x_{34} = \sum_{i=1}^{n} x_{3i} \quad (3)$$

Therefore, composition of a blend of three different crude oils in terms of these four fractions can then be expressed as;

$$\sum_{i=1}^{n=4} x_{1i} + \sum_{i=1}^{n=4} x_{2i} + \sum_{i=1}^{n=4} x_{3i} = \sum_{m,\ i=1}^{m,n=3,4} x_{ji} \quad (4)$$

But the three crude types are mixed based on specific volumetric proportions to achieve optimal yield of product. Whence, defining the mixing ratio as R for any particular crude blend, and total yield of blend as Y_{ji}, objective function for maximization of fractional yield as proposed by Hou et al (2015) becomes:

$$Max\ Y_{ji} = Max \sum_{j,i=1}^{n=4} Y_{ji} x_{ji} = \sum_{j=1}^{n=4} R_j Y_j \quad (5)$$

$Y_{ji} = Yield\ of\ fraction\ in\ Crude\ Blend$

$x_{ji} = Composition\ of\ fraction\ in\ feed\ Crude$

$R_j = Ratio\ of\ feed\ compositions\ in\ Blend$

The optimization function in (5) above is however subject to particular conditions of the composition and properties of the respective feed crude oils and even the crude blends, generally referred to has the constraints of optimization. For instance, sum of the four fractions of individual feed crude oil must be equal to or less than unity as given in (6). Another important constraint imposed on this model is a minimum fractional recovery of 90% of feed composition for the first three lighter fractions (that is Naphtha, Kerosene and Gas Oil). Then, final constraint on the objective function is given by the mixing ratio, which is within the numerical range of zero and unity as shown in (8).

2.2 Constraints on Objective Function:

$$\sum_{j,i=1}^{n=4} x_{ji} \leq 1.0 \tag{6}$$

$$0 < R_j < 1 \tag{7}$$

2.3 Case Study – Sudanese Crude Oils

A case study of three Sudanese crude oils namely the Nile, Rawat and Thargath crude oils were used to test the models presented in the work by Dafaalla et al. (2021). Sudanese Nile Blend crude oil is a medium, sweet crude with low sulfur and metal content, produced in the Muglad Basin, specifically in blocks 1, 2A, 2B, 4, and 5A and transported via the 1600 km Greater Nile Oil Pipeline to the Bashayer Marine Terminal for export. The Nile Blend is processed domestically at refineries in El-Obeid and Khartoum and accounts for most of crude oil production from Southern Sudan.

Rawat is a Sudanese crude oil blend produced by Rawat Petroleum Operating Company Ltd (RPOC) in Southern Sudan. Characterized by high pour point of 54°C, high wax and aromatics contents of 26.3% and 42.50% respectively, the Rawat oil field located within a 20 sq km area of the 10,000 sq km Block 7 concession is estimated to have recoverable reserves of about 94.7 million barrels. Tharjath Oil Field is located in the Unity State of South Sudan within Block 5A concession area in the Muglad Basin. Started in the year 2000 and wholly owned by the Sudan Petroleum Operating Company (SPOC), the Tharjath oil field produced 1.09 million barrels of oil annually at inception. The Tharjath crude is a sour crude with appreciable levels of sulphur. The True Boiling Point data of these different crude oils, being the elementary distillation property and three mixtures of these are given in Table 1 and 2 respectively.

Table 1: True Boiling Point of Sudanese Crude Oils

Nile		**Rawat**		**Tharjath**	
Temp [°C]	**Vol %**	**Temp [°C]**	**Vol %**	**Temp [°C]**	**Vol %**
60	0.70	35	0.6	70	0.19
75	1.29	50	1.3	85	0.3
90	2.31	70	2.2	100	0.46
105	3.16	90	2.7	115	0.65
120	4.14	120	3.7	135	0.92
135	5.09	140	4.5	150	1.16
149	6.20	155	5.6	170	1.64
165	7.42	170	6.3	185	2.08
180	8.45	185	7.2	205	2.74
195	9.85	200	8.6	225	3.66
210	10.63	220	10.3	245	5.21
225	12.98	240	12.4	265	7.33
232	13.91	260	14.7	285	9.79
240	14.68	280	17.5	305	12.59

255	15.44	300	20.4	325	15.62
270	17.77	320	21.8	345	18.74
285	19.47	330	24.6	365	21.82
300	22.91	350	27.7	385	25.00
315	25.24	370	39.4	400	27.50
330	27.59	435	45	415	30.12
345	29.72	450	50.9	430	32.82
360	32.51	470	57.8	445	35.53
369	33.91	500	65	460	38.23
400	34.73	565	100	475	40.94

Table 2: Showing the Contents of Blends

Type of Crude	Blending Proportion
Mix 1	(60%Nile Blend+20%Rawat+20%Tharjath)
Mix 2	(40%Nile Blend+20%Rawat+40%Tharjath)
Mix 3	(80%Nile Blend+10%Rawat+10%Tharjath)

3.0 Results and Discussion

Table 3 shows that composition of the three Crude oils in this work do not have very wide differences in their fractional compositions. While volume fraction of Naphtha in Nile Crude is 0.00057, it is 0.00038 and 0.0009 for Rawat and Tharjath Crude oils respectively. Although, the difference in composition between Nile and Tharjath Crude oils is marginal, it is significant for Rawat which is higher than the former ones by an order of 10. For the kerosene fraction, Nile and Tharjath Crudes have approximately the same composition of 0.0488 and 0.0476 while Rawat has a lower value of 0.03. Similarly, Nile, Rawat and Tharjath Crudes have Gas oil compositions of 0.18, 0.20 and 0.17 respectively. This data is however consistent with theory as Crude oils from the same sedimentary basins have similarly and closely related properties including their compositions (Kawai and Totani, 1971). The data of composition also suggest the mixing of higher ratios of Rawat Crude oil for greater yield of Naphtha and Gas oil, while Nile and Tharjath Crudes give better yield of Kerosene.

Now, using compositions of the individual Crude oils as feed, the optimization model was tested for yield of the various fractions. The study sub – divides the Crude oils into four fractions, but focuses on the three low boiling or lighter fractions of Naphtha, Kerosene and Gas oil as primary targets for maximization as shown in the model equation.

Table 3: Fractional Yields

Crude Oil / Products	Nile 99.37 M^3/h	Rawat 19.37 M^3/h	Tharjath 99.37 M^3/h	Mix 1 99.37 M^3/h	Mix 2 99.37 M^3/h	Mix 3 99.37 M^3/h
Naphtha	0.057	0.075	0.099	0.03	0.038	71.83
Kerosene	4.832	0.585	4.869	4.76	5.87	0.343
Atm. Gas Oil	18.03	3.999	17.4	16.92	15.3	5.136
Residue	68.62	12.02	75.33	69.12	72.97	15.00

Three different Crude oil Blends, - 1, 2 and 3, having mixing ratios as given in Table 2 were used for validation of the design model. Suffice to note that the model equation sometimes resulted in yields higher than the theoretical molar rates (Richardson et al., xxxx/). Consequently, such results were normalized (Sankpal and Metre, 2020) by necessary application of the design constraints in equation (X) and (Y) and shown in Table 4.

Table 4: Normalized Compositions of Blends

Fractions	X_1	X_2	X_3	Y_{Pre}	Y_{Ind}
x_1	0.00057	0.00385	0.00099		
x_2	0.04832	0.0300	0.04869		
x_3	0.1803	0.2052	0.1740		
x_4	0.6862	0.6169	0.7533		
x_{Total}	**0.9154**	**0.8560**	**0.9770**		
$Blend - 1$					
Y_w	0.00037	0.00083	0.00022	0.00142	0.0003
Y_x	0.03160	0.00654	0.01061	0.04875	0.0476
Y_y	0.1179	0.04473	0.03793	0.2006	0.1692
Y_z	0.4488	0.13448	0.16422	0.7475	0.6912
Y_{Total}	**0.5986**	**0.1866**	**0.2130**	**0.9982**	
$Blend - 2$					
Y_w	0.00025	0.00083	0.00043	0.00150	0.0038
Y_x	0.02081	0.00646	0.02100	0.04825	0.0587
Y_y	0.0777	0.0442	0.07500	0.19685	0.153
Y_z	0.2956	0.1329	0.32452	0.75301	0.7297
Y_{Total}				**0.9996**	
$Blend - 3$					
Y_w	0.0005	0.0004	0.00009	0.00099	0.06492
Y_x	0.0422	0.0033	0.0053	0.0508	0.05136
Y_y	0.1575	0.0223	0.0190	0.1988	0.1500
Y_z	0.5994	0.0673	0.0823	0.7490	0.7183
Y_{Total}	**0.7996**	**0.0933**	**0.1066**	**0.9995**	

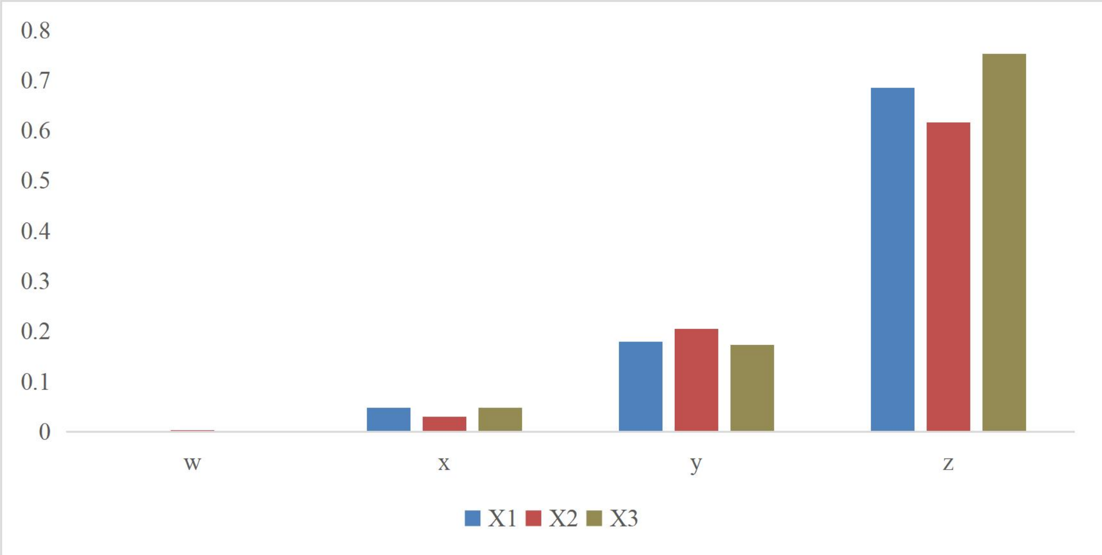

Figure 1: Fractional Composition of Different Crudes

Figure 2 shows yield prediction of the current model for various fractions compared to result of the previous model by Dafaalla et al (2021). The model generally predicted higher yields than the former. For instance, the volume prediction of the model for Naphtha was 0,00142 as against 0.0003 o the former for Blend – 1. This gives an error percent of over 300, way beyond acceptable limits. In the contrary, error percent between model prediction and simulation model was 2.4%, well within acceptable limits for this type of study (see Table 4 and Figure 2). Also, for Blend – 2, error values of 3.2%, 28.6%, 17.0% and 60% were recorded for the Residue, Gas oil, Kerosene and Naphtha respectively (see Table 4 and Figure 3).

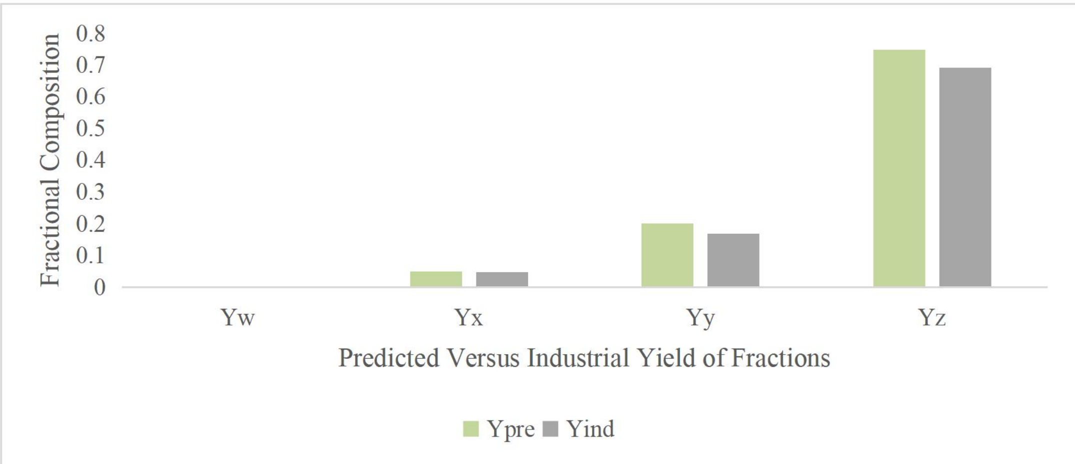

Figure 2: Fractional Composition of Crude Blend – 1

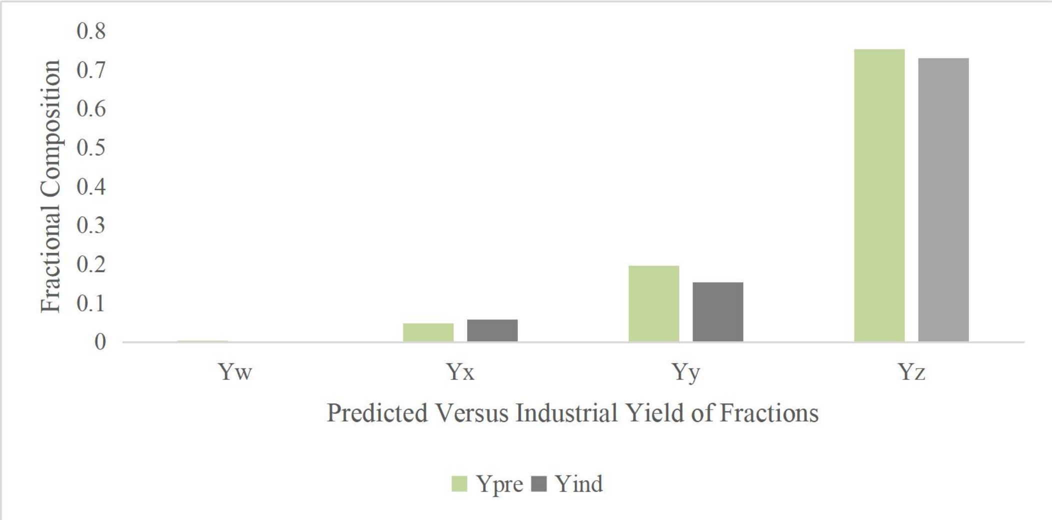

Figure 3: Fractional Composition of Crude Blend – 2

Finally, blend – 3 gave the best predictions of 4.2%, 32%, 1.1% and 98.6% respectively shown in Table 4 and Figure 4. The very low percentage errors predicted for the Residue and Kerosene fractions in Blend – 3 and those of Kerosene and Residue in Blend – 1 and – 2 respectively gives indication of the functionality of the model. In all, aggregate performance of the model based on percentage error of below 30 is about 67%.

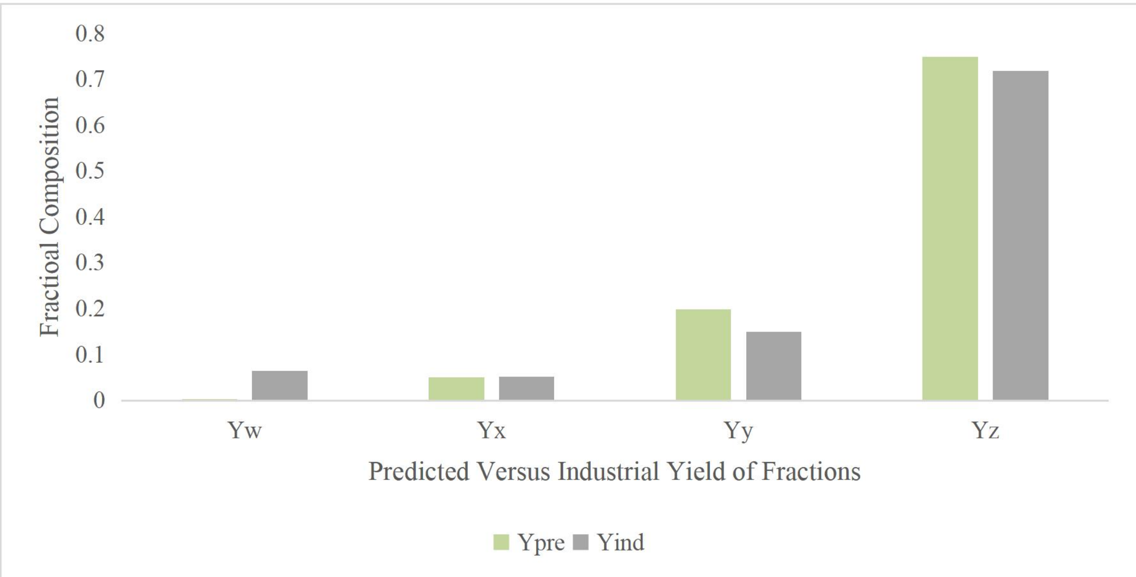

Figure 4: Fractional Composition of Crude Blend – 3

4.0 Conclusion

Mathematical modeling as a tool for scientific investigation has wide applications in all spheres of research, whether in the physical, social or management sciences. Versatile as it may be, the trust of its relevance is in its easy application. Often than not, mathematical models come in complex forms, both in formulation and deployment. This situation has rendered a great number of good research works inapplicable and useless. The present work is in sharp contrast to the foregoing, by its simplicity and applicability. Given any set of

Crude oils with defined properties as shown in this work, mixing ratios can be determined with exactitude for predetermined feed quality.

The model gave good predictive output in quite a number of cases for the three Crude oil Blends, especially with error value as low as 1.1%. Nevertheless, it also gave some error values that were intolerably high. Since the aggregate performance of the model with percentage error below 20% was above 60%, it is recommended for application, though it may require some further modification for more reliable results.

Declarations
Credit authorship contribution statement
IPW: Conceptualization. Wrote the original draft, Methodology, Validation, Resources, project administration, and review of manuscript.
Declaration of competing interest
The author declares no conflict of interest.
Funding
The author received no funding for this research.
Consent for publication
Not applicable
Ethics and Consent to Participate
Not applicable
Acknowledgement
The author wish to thank the management and technical staff of the Departments of Chemical Engineering, Federal University Otuoke for their administrative support.

References

Abdulkareem, A.S. and Kovo, A. S. (2006). Simulation of the Viscosity of Different Nigerian Crude Oil. *Leonardo Journal of Sciences, 8,* 7-12.

Aida, T., Yamamoto, D., Iwata, M. and Sakata, K. (2000). Development of Oxidative Desulphurization Process of Diesel Fuel. *Chemical Journal, 22,* 241–256.

Al Dahhan W.H. and Mahmood, S.M.A. (2019). Classification of Crude Oils and its Fractions on the Basis of Paraffinic, naphthenic and Aromatic. *Al Nahrain Journal of Science, 22*(3), pp 35 – 42.

Cullen, M. (2004). Treatment of Crude Oil Fractions of Fossil Fuels and Products Thereof. United State Patent, 0074812 A1.

Dafaalla, Y. A., Gasmelseed, G. A. and Hamed, T A. I. (2021). Simulation of the Blends of Different Types of Sudanese Heavy Crude Oil, 5(8), pp.136 – 143. Available on line at www.ajhssr.com

Dickson, U. J. and Udoessien, E. I. (2012). Physicochemical Studies of Nigeria's Crude Oil Blends, Petroleum & Coal, 54(3), pp. 243-251. Available online at www.vurup.sk/petroleum-coal

Eneckwe, C.B., Ibe, E.C. and Osaka, E.C. (2012). Optimization of Blends of Selected Foreign and Nigerian Crudes for Lubricant Production. *International Journal of Science and Engineering Investigations.*

Naji, F. A., Ateeq, A. A. and Al-Mayyahi M. A. (2021). Optimization of Blending Operation for The Iraqi Oils. *Journal of Physics: Conference Series.* 1773 012037, pp. 1 – 8

Ganji, H., S. Zahedi, M., Ahmadi Marvast, S., Sadi, K.M. and Shokri, S. (2010). Determination of Suitable Feedstock for Refineries Utilizing LP and NLP Models. *International Journal of Chemical Engineering and Applications, 1*(3) 225-310

Gembiki, V., Cowan, T. and Brierley G.R. (2007). Update Processing Operations to Handle Heavy Feedstock, Hydrocarbon Processing, 86(2), 41-42+44-46+48-53.

Guth, E.D., Helgeson, N.L., Arledge, K.W. and Brienza, A.R. (1975). *Petroleum Oil Desulphurization Process*, US Patent No. 3 919, November

Hassan, M.K., Kandiel, A. and Elkhayat, A. (2011), Improving Oil Refinery Productivity Through Enhanced Crude Oil Blending Using Linear Programming Modeling. *Asian Journal of Scientific Research.*

Hart, A. (2013). A review of Technologies for transporting Heavy Crude Oil and Bitumen via Pipelines. *Journal of Petroleum Exploration and Production Technology.*

Hegazy, H. A., Hassanean, M. M, and Shoaib, A. M. (2023). Optimum Blending of Crude Oils Using Linear Programming. *Egyptian Journal of Chemistry, 66* (13), pp. 1341 – 1353

Ibrahim, R. I., Manal, K. O. and Al Mufti, A. (2019). An Overview on the Recent Techniques for Improving the Flowability of Crude Oil in Pipeleines, International Conference on Petroleum Technology and Petrochemicals.

Igbagara, P. W., Akpa, J, Alah, J. and Okpanum, J. (2019), Journal of the Society of Chemical Engineers, l35, (2), pp. 35 – 41

Oyekunle, L. O. and Famakin, O.A. (2004). Studies of Nigerian Crudes I. Characterization of Crude Oil Mixtures. *Petroleum Science and Technology 22*(5&6):665-675.

Sankpal, K.A. and Metre, K.V. (2020). A Review on Data Normalization Techniques. *International Journal of Engineering Research and Technology, Vol. 9* (6), pp 1438