UNIVERSITY OF BAHRAIN

College of Engineering **Department of Chemical Engineering**

The Role of Crude Oil Selection in Optimizing the Economics of a Local Refinery with Lube Hydro-processing Capacity

Research Proposal submitted in partial fulfilment of the requirement for the degree of M.Sc. in Chemical Engineering

Prepared by:

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Defense committee's approval page

University of Bahrain

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Department of Chemical Engineering

M.Sc. in Chemical Engineering

Student: Lujayn Alsayoof with ID number: 20100429 defended her thesis by which he fulfilled the requirement for the degree of M.Sc. in Chemical Engineering entitled 'Finding a Tradeoff in a Refinery: Fuel versus Lube Base Oil Portfolio' on this day of June 2021.

The committee recommends awarding of M.Sc. Degree with the grade of:

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Academic department's stamp

Abstract

To increase the product value out of a crude barrel, some refineries produce Group III lube base oil (LBO) through catalytic hydroprocessing, in addition to the conventional fuels, such as gasoline, diesel, kerosene etc. The optimization of a refinery with fuels and lubes portfolios is considered a challenge since there are several tradeoffs which need to be addressed. The main challenge is the crude selection, since the conventional fuels qualities are determined by the physical properties of the crude oil, while the lube base oil quality is mainly determined by its viscosity index (VI), which strongly depends on the chemical composition of the processed crude oil. Additionally, the operating conditions such as the hydrocracking conversion is important in determining the yield and quality of the lube base oil. Moreover, the split of the downstream feedstock, such as Heavy Vacuum Gas Oil (HVGO) and Unconverted Oil (UCO) need to be determined and distributed to several conversion units in the refinery.

The purpose of this thesis is to propose an overall optimization methodology for a local refinery in Bahrain with a lube base oil processing capability, which has been processing two types of crudes only. Different than the limited works available in the literature, the current thesis has explicitly considered a complex refinery setup with several downstream feedstock split to be optimized. In addition, the inclusion of the Fluid Catalytic Cracking Unit (FCCU), which been ignored in previous studies, render the current formulation NLP. This is done by employing a crude classification model based on the Hydrocracking Unit (HCU) feed VI, and taking into account the change in VI and yields besides the other conventional bulk properties. This will optimize the selected crude types that maximize the products value and the overall refinery margin.

The results showed that allowing crude selection in the studied refinery can increase the contribution margin by US$30 million per month when compared to the current operation of processing two crudes only. Using the VI model to predict how VI changes through the hydrocracking and lube base oil units is required to ensure that final LBO quality is met. It has proved that crude selection changes with the required specification of LBO VI and the hydrocracking conversion. When Conversion decrease from 80% to 75%, volume of paraffinic crudes increases by 3% and 16% for VI spec at 120 and 125, respectively.

Dedication Page

This work is dedicated to my parents who always supported me during my education journey.

Acknowledgement

To begin with I thank almighty Allah for His countless blessings. I also am thankful to my supervisor, Professor Mohamed Bin Shams for his valuable guidelines and encouragement throughout my MSc journey, my family and friends who took care of me and supported me on the way, and my coworkers who provided me with the required information.

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Abbreviations

Refinery Units

CDU	Crude Distillation Unit
FCCU	Fluid Catalytic Cracking Unit
HCU	Hydrocracking Unit
HDU	Diesel Hydrotreating Unit
LBOU	Lube Base Oil Unit
RFU	Reformer Unit
VBU	Visebreaking Unit
VDU	Vacuum Distillation Unit

Refinery streams

ASP	Asphalt
BSGO	Black Slop Gas Oil from VDU
DSL	Diesel
FO	Fuel oil
HCGO	Heavy Cycle Gas Oil from FCCU
HCN	Heavy Catalytic Naphtha from FCCU
HDO	Heavy Diesel Oil from CDU
HSR	Heavy Straight Run Naphtha from CDU
HVGO	Heavy Vacuum Gas Oil from VDU
KR	Kerosene
LBO	Lube Base Oil
LCGO	Light Cycle Gas Oil from FCCU
LCN	Light Catalytic Naphtha from FCCU
LDO	Light Diesel Oil from CDU
LPG	Liquified Petroleum Gas
LSR	Light Straight Run Naphtha from CDU
MCN	Med Catalytic Naphtha from FCCU
MSR	Medium Straight Run Naphtha from CDU
R96	Reformate with 96 octane number
RFG	Refinery Fuel Gas
UCO	Unconverted Oil from HCU
VBR	Visbreaked Residue from VBU
VGO	Vacuum Gas Oil
VR	Vacuum Residue from VDU

Properties

CCR	Conradson Carbon Residue content
NTR	Nitrogen content
RVP	Reid Vapor Pressure
SLF	Sulfur content
VI	Viscosity Index

Indices and sets

b_{fp}, B_{fp}	Index, set of blended products to final products
c, C	Index, set of selected crude
fp, FP	Index, set of final products,
imp, IMP	Index, set of imports
iu, Iu	Index, set of inlet products supplied to refinery unit *u*
P, P	Index, set of intermediate products
u, U	Index, set of refinery units

Variables

$m^{C}{}_{D,c}$	Flowrate of crude *c* to distillation unit *D*
$m^{B}_{fp,b_{fp}}$	Flowrate of the blended intermediate material *bp* for final product *fp*
m^{EXP}_{fp}	Amount of produced and exported final product *fp*
m^{EXP}_{p}	Amount of exported intermediate product *p*
$m^{I}{}_{u,iu}$	Flowrate of inlet material *iu* to unit *u*
$m^{I}{}_{u,p}$	Flowrate of intermediate product *p* to unit *u*
$m^{I}{}_{u,c,iu}$	Flowrate of inlet material *iu* to unit *u* from crude *c*
$m^{IMP}_{fp,imp}$	Flowrate of the imported product *imp* into *fp*
CEU_u	Energy cost for each unit *u*
CCT_u	Catalyst cost for each unit *u*
C_u	The operating cost for unit *u*
EU_u	Total energy consumed in unit *u*
R	Gas to oil ratio for each unit and is equivalent to fuel gas, steam and electricity
V^{EXP}_{fp}	Volume of exported final product
V_u	Volume of unit feedrate

Parameters

AV_c	Availability of crude *c*
AV_{imp}	Availability of import *imp*
P_{FU}	Unit price of the fuel gas
P_c	Price of crude
P_{fp}	Price of final product
P_{imp}	Price of imported products for final products
$P_{u,CT}$	Unit price of catalyst per barrel of unit feed
Q_{Base}	Base quality of a typical feed to the FCCU
Q_{Delta}	Delta quality
Q_{Input}	Actual quality of the feed to the FCCU
Q_{fp}	Quality of final product *fp*
Q_{max}	Maximum limit of quality
Q_{min}	Minimum limit of quality
Q_p	Quality of intermediate product *p*
$f_{u,p}$	Fraction of the product *p* routed to unit *u*
m_c^l	Lower limit of blending ratio for the selected crude oil
m_c^u	Upper limit of blending ratio for the selected crude oil
$y_{D,c,p}$	Yield of product *p* from distillation unit *D* using crude *c*
$y_{u,iu,p}$	Yield of product *p* from unit *u* using inlet *iu*
$\rho_{u,p}$	Density of product *p* from unit *u*
$CP_{u,max}$	Maximum limit of unit capacity
$CP_{u,min}$	Minimum limit of unit capacity
$Yield_{Base}$	Base yield of typical FCCU feed
$Yield_{Delta}$	Delta in the FCCU yield for a given shift in a feed quality
$Yield_{New}$	New required yield at the actual FCCU feed quality
z	Shift factor

Other

MBPD	Thusand barrel per day

Chapter 1

Introduction to the study

This chapter is an introduction to the thesis and gives an overview on the problem, questions to be answered, objective, significance and limitations of the thesis.

1.1 Introduction

The complexity of refineries is continuously increasing as new technologies are adopted to maximize the value out of a crude barrel. Consequently, optimization of refineries is also becoming a challenge especially with the stringent environmental regulations, the tight product specifications and the fluctuation in the crude oil prices.

Optimization is applied at various levels in the supply chain of the refining industry, i.e. strategic (policy), tactical (procedures), and operational levels (execution), to maximize the overall profit and margins. This covers planning and scheduling activities such as feedstock selection, process operation modes, flow direction between processes and units, finished product blending, and utilities (Zhang & Hua, 2007; Shah et.al., 2011; Khor & Varvarezos, 2016).

Petroleum refineries upgrade wide variety of crude oils into valuable final products which include the conventional fuels slate such as naphtha, gasoline, jet fuel, diesel and fuel oil, as well as the lube base oil slate. In contrast to the production of conventional fuels, production line of the lube base oil slate is distinguished by only certain refineries in the world. Different intermediate products are blended to get the final refinery products with the desired specifications. The resultant refinery products are directly related to the characteristics of the processed crude. The crude oil cost represents the largest portion of the overall refinery cost, which is usually over 80% for a typical refinery. Thus, crude selection plays a crucial rule in refinery optimization (Gary et al., 2007; Khor & Varvarezos, 2016; Noh et al., 2018).

To maximize the profit and the value of the products, refineries are expanding their product portfolio to include high value products such as

high-quality lube base oil (Group III). A base oil is the raw material for lubricants which are widely used in automotive and industrial sectors, e.g. motor oils, marine oils, transmission fluids, brake fluids, process oils, coolants and greases (Moon et al., 2000; Speight & Exall, 2014). Typically, high quality lube base oil is produced from heavy cuts, with a boiling point of greater than 360 °C such as Heavy Vacuum Gas Oil (HVGO) from the vacuum unit, through lube hydro-processing which is generally composed of hydro-treating/cracking followed by hydro-isomerization. High quality lube base oils have high and relatively stable market prices; thus, refineries with lube hydroprocessing capacity tend to maximize the production of lube base oil to increase their profit margin (Noh et al., 2018).

The factors which determine the quality of conventional fuel products are mostly physical such as API, sulfur content and boiling point range. On the other hand, the performance and quality of lube base oils are generally linked to the viscosity index (VI), pour point and stability. Among these properties, VI is the most important property that determines the quality grade of lube base oil and strongly depends on the chemical composition of the processed crudes. VI is a measure of viscosity change with temperature. Base oils with high VI values are less sensitivities to temperature changes and are more favored. Different crudes have different qualities and chemical composition, i.e. paraffins, naphthenes and aromatics, which impact base oils' final qualities (Sequeira, 1994; Lynch, 2007; Leffler, 2008; Noh et al., 2018). Thus, there is a tradeoff between the conventional fuels and lube base oils slates with respect to the crude selection. To address this tradeoff, a classification of the crudes based on the hydrocracking unit feed VI and chemical composition is required as well as other models to predict the change of VI through the conversion units all the way to the final lube base oil (LBO).

In addition to the role of crude selection in determining the lube base oil quality, the operational conditions such as conversion, affect the quantity (yield) of both the conventional fuels and the lube base oils slates. When the conversion rate in the hydrocracking unit increases, the yield of the unconverted oil (UCO) which is the feed to the lube base oil unit decreases, however, the quality of the UCO is enhanced as VI increases. Therefore, the overall yield versus the quality of the final lube base oil (LBO) have to be optimized.

The refinery has several intermediate streams, each of which can be potentially routed to different units. For example, The HVGO can be routed to the hydrocracking unit (HCU) and other conversion units such as fluid catalytic cracking unit (FCCU). Also, UCO which is the bottom product from the HCU can be routed to the lube base oil unit (LBOU) and the FCCU as well. At different market prices and required specifications, the optimal split of HVGO and UCO to each respective unit has to be determined.

In general, the above relations and tradeoffs render decision of crude selection and conversion as good candidates for rigorous optimization. (Lynch, 2007; Noh et al., 2018).

Optimization in refineries has been widely studied using formal mathematical programming techniques, including crude oil unloading and blending, refinery planning and scheduling, and final product blending (Li, et al., 2005; Neiro & Pinto, 2005; Oddsdottir, et al., 2013).

Since most of the previous refinery optimization studies, focused on the conventional fuels of which their qualities address only the physical bulk properties only, VI which strongly depends on the chemical composition of the feedstock, was not explicitly addressed.

The purpose of this thesis is to develop an overall optimization methodology for a refinery with a lube base oil processing capability, such as the local refinery in Bahrain, which has been processing two types of crudes only since its inception. Aiming to maximize the overall refinery margin, a crude classification model based on the which accounts for the changes in the yields, VI and the other conventional bulk properties through the units will be incorporated within the mathematical formulation while selecting the optimal crude types and feed split to the units.

1.2 Research problem

Since the establishment of the local refinery in Bahrain, only two types of crudes, i.e. Arabian light and Bahrain crudes have been processed in the refinery. The current crude capacity is around 267 thousand barrel per day (MBPD). Post the ongoing Bahrain Modernization Project (BMP), the capacity of the refinery is expected to increase to 380 MBPD, which allows processing extra amount of crudes. This render the crude selection an attractive option to increase the revenue and margins, given that no studies on crude selection were conducted earlier on the studied local refinery.

As both gasoline and diesel engine technology advances, new demands are placed on lubricants production and performance (Moon, et al., 1998; Lynch, 2007). For that, the studied refinery has established a lube base oil plant in 2011 with an investment of US$430 million. It is the largest of its kind in the Middle East and is capable to produce very high viscosity index (VHVI), Group III lubricant base oils from the unconverted oil (UCO) which is the hydrocracker unit bottom product. Since lube base oils have high and stable market prices (~ >US$90/bbl) and their demand is continuously increasing (especially those of superior performance), refineries with a lube processing capability tend to maximize base oil production (Lynch, 2007; Noh et al., 2018).

For the conventional fuels slate, the crude selection is affected by bulk physical properties such as API, Sulphur content and boiling range. While for the lube base oils slate, the crude selection is mainly linked to the chemical composition of the crude oil which determines the VI. Therefore, the crudes which are preferred for conventional fuels production are not necessarily suitable for base oils production and a tradeoff is needed when

selecting the best crudes to maximize the refinery's profit margin (Sequeira, 1994; Lynch, 2007; Leffler, 2008; Noh et al., 2018). Furthermore, the selection of lube-suitable crude oils in a refinery with a lube base oil unit, often conflicts with the economics of general refining crude oils. Since the characteristic of crude oil is restricted when making lube base oils, the production of relatively small volumes of base oils makes a large imposition on the crude purchasing requirements of a refinery. If suitable crudes are only available at high prices, then there is an economic penalty for the refinery (Leffler, 2008; Prince, 2010).

Group III lubricant base oils are produced through catalytic hydrocracking route, where the unconverted oil (UCO) which is bottom product from the hydrocracker unit (HCU) is sent to the lube hydroisomersation plant to produce the final lube base oil. The yield of the lube base oils is controlled by the conversion of the HCU. The hydrocracking unit can work as both fuels and lubes upgrader by manipulating the conversion of the unit.

As the conversion rate increases in the hydrocracker unit, the VI of UCO increases, but the yield, i.e. produced amount of the lube base oil decreases, which leads to a decrease in the overall margin at a fixed crude selection (Prince, 2010; Noh et al., 2018). Therefore, there is a clear tradeoff between yield and quality of the lube base oil which need to be addressed.

Moreover, there are several units in the refinery which compete for intermediate feedstocks. The heavy vacuum gas oil (HVGO) produced from the vacuum distillation unit, is a feed to both the hydrocracker unit and the fluid catalytic cracking unit (FCCU), where the UCO produced from HCU can be fed to the LBOU and FCCU. Therefore, the split of feedstock sent to the fuels and lubes upgrading plants has to be optimized

as these interactions are very important to the logistics and production economics of producing base oils (Prince, 2010).

In summary, the tradeoff problem between fuels and lubes in terms of crude selection, qualities and conversion is a problem that has not been addressed in the studied refinery and has been lacking or overlooked in the planning optimization literature. Ignoring these tradeoffs may result in economical penalties, therefore, there is a need to address such tradeoffs within a systematic framework.

1.3 Research questions

This thesis should answer the following:

- Is it economically attractive to consider processing multiple crudes versus two crudes only in the studied refinery?
- Is it economically attractive to address the tradeoff between conventional fuels and lube base oils slates in terms of crude selection and cracking conversion?
- How can the products required specifications such as LBO VI, in addition to the cracking conversion affect the overall crude selection?
- What is the effect of the cracking conversion on the LBO yields and quality?
- What is the effect of refinery constrains, such as unit capacities, conversions, demands and prices on the overall refinery profit?
- What is the optimal split of the feedstock to the both the fuels and lube base oil plants?

1.4 Research objective

The objectives of the research are summarized in the following:

- Develop an optimization framework which can maximize the overall refinery margin through selecting optimal crude types for a refinery with lube processing capability.
- Determine the effect of crude's chemical constituents and properties on the lube base oil quality by using suitable crude classification criteria and models from literature to predict VI of the final lube base oil from each crude.
- Use models from literature and real data on the units' yields, hydrocracking conversion and change in VI, and incorporate the refinery constrains to study their effects on the crude selection, optimal split of feedstock to respective units (HVGO to HCU and FCCU and UCO to LBOU and FCCU) and overall profit.
- State findings and recommendations to the refinery's decision makers through studying different case scenarios.

1.5 Research significance

Since there have been no studies conducted in the local refinery to evaluate the effect of processing different crudes in the refinery, this thesis should give an insight to the refinery's strategists and decision makers on the economics behind considering different crudes selection to produce conventional fuels and lube base oils, and thus, steer the future planning based on the proposed results accordingly.

Moreover, most of the proposed models study simple refineries and rarely include a lube hydroprocessing unit with Fluid Catalytic Cracking Unit. There is obviously a lack in addressing VI changes through lube hydro-processing refineries despite the need, which can have a remarkable impact on the overall refinery optimization. This study will contribute to the overall refinery optimization by studying the effect of crude selection and predicting VI of the base oil on the overall refinery margin, for a complex refinery with a lube hydroprocessing capacity. It will explore different opportunities and options to maximize the refinery profit through comparing different case studies with different prices and conversion scenarios.

1.6 The study's setting and limitations

This thesis was done while working full time, which limited the time available for research and writing.

The modelling of the studied refinery was carried out using General Algebraic Modeling System (GAMS) which was a new programming language to be learnt and used.

There is limited data available from the studied local refinery. Most of the yield data used are based on real test runs that covers specific operating range where simulation-based data may be preferable to cover wider range. Therefore, hydrocracking unit yields and conversion in the analysis were limited to 75% and 80%. Also, the studied refinery usually produce two main grades of Group III lube base oils, at VI of 120 and 125. Therefore, the analysis was limited to those two grades.

1.7 Research terminologies

- **Conventional fuels:** fuel products which their quality mainly depend on physical properties. These include naphtha, gasoline, kerosene, diesel, asphalt and fuel oil.
- **Lube base stock/oil:** base stock is petroleum fraction used in producing lubricants or an API-licensed oil (API, 2002; Lynch, 2007).
- **Group III base oil:** base oils that are differentiated by having more than 90% saturates, less than 0.03% sulfur content and a viscosity index above than 120. This group is produced through hydrocracking and isomerization process (API, 2002; Lynch, 2007)
- **Viscosity index (VI):** VI is a measure of the extent of viscosity change with temperature. The higher the VI, the smaller its change in viscosity. The VIs of natural oils range from negative values for oils from naphthenic crudes to about 100 for paraffinic crudes (Gary et al., 2007; Lynch, 2007)
- **Hydrocracking conversion:** ratio of the feed converted to fuel products over the total fresh feed.
- **Refinery margins:** The gross margin of a refinery is computed as the total revenues from product sales minus the cost of crude oil. The contribution margin is computed by deducting the variable cost from the gross margin. The net margin is computed by deducting the fixed cost from the contribution margin (Gary et al., 2007).

Chapter 2

Theoretical Framework and Literature Review

This chapter provides a theoretical and literature review on the subjects. It starts with an introduction on the refinery planning and optimization and the work related to it in literature. Then it provides a description on the studied refinery, crude oil properties and classification, in addition to the base oil and its production process. It also states the tradeoffs exist in a refinery with lube hydroprocessing capability.

2.1 Refinery planning and optimization

A typical petroleum supply chain is illustrated in Fig. 1. The chain involves activities outside of the refinery gates such as crude exploration, procurement and transportation, in addition to the distribution of the final products. It also covers all entities within the refinery gates such as crude oil storage, refinery operations, blending and storage of final products (Khor & Varvarezos, 2016; Neiro & Pinto, 2005; Shah et al., 2011).

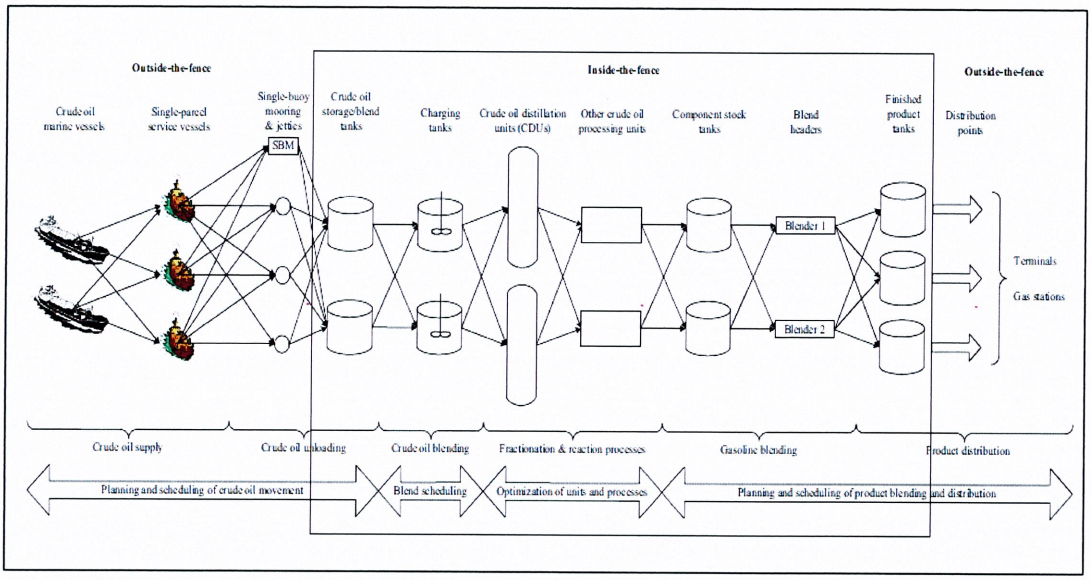


Figure 1. Typical petroleum supply chain.
(Khor & Varvarezos, 2016)

The main objective of any refinery is to convert crude oil into valuable final products such as naphtha, gasoline, kerosene, diesel, fuel oil and lube oil. Petroleum refineries are complex entities, because the quality and quantity of the finished products are impacted by the processed crudes and their yields, in addition to the refinery configuration and unit capacities. Therefore, planning and optimization are required to ensure profitability and to provide a continuous revaluation of the corporate supply-chain operation and performance (Alhajri et al., 2011; Joly, 2012; Shah et al., 2011).

The goal of optimization in general is to find the values of the variables in a process which yield the best value of a performance criterion (Edgar et al., 2001). The goal of refinery optimization is to push the operations towards the maximal profit by finding a tradeoff between feedstock selection, process operation modes, flow direction between processes, finished products' blending, and utilities (Joly, 2012; B. J. Zhang & Hua, 2007).

There are different time scales and decisions levels involved in modeling refinery operations' optimization (Edgar et al., 2001; Joly, 2012; Khor & Varvarezos, 2016; Neiro & Pinto, 2005; Shah et al., 2011), and they can be summarized as follows:

- Years in strategic planning, where expansion projects are evaluated
- Months in tactical or production planning, where plans support opportunities of crude oil spot purchases and align refinery operations with market product demands
- Weeks to hours in scheduling, where operating strategies are set to meet specific product delivery order commitments
- Minutes to seconds in advanced and regulatory control systems

The type of planning scale in this project will be tactical or monthly planning. Optimization of the production planning is a crucial task for a petroleum refinery to ensure having a positive overall economic performance. Nevertheless, it is a difficult task, because of the large scale of the system and the complexity of the processes involved (Guerra & Le Roux, 2011; Khor & Varvarezos, 2016; Leiras et al., 2013). Production planning relies on information like process topology, plant capacity, operating constraints, market demand, and operational costs involved in the processes. It specifies which crude or intermediate products to purchase

to align refinery operational objectives with product demands, and determines products allocation, distribution, and storage resources in the chain (Shah et al, 2011).

To support production planning decision making, refineries generally use commercial packages based on linear programming (LP) and non-linear programming (NLP) models, such as PIMS (AspenTech), GRTMPS (Haverly Systems), TRIOS (UOP Limited) and RPMS (Honeywell Hi-Spec Solutions). The use of commercial packages has systematized the development of production plans of the whole refinery, which can be interpreted as general trends. On the other hand, many petroleum companies have developed their own LP tools that is carefully structured in terms of economics and marginal values, which provides meaningful information on solution explanation and sensitivity analysis (Joly, 2012; Khor & Varvarezos, 2016).

The optimization-based refinery management has been widely studied. This includes the aspects of crude oil unloading and blending, refinery planning and scheduling, and final product blending optimization. There have been various studies which formulated the problem in formal mathematical programming techniques, e.g., LP, MILP, NLP, and MINLP (Noh et al., 2017). Most planning models in literature are represented using LP or MILP formulations but few have been representing planning problems using nonlinear models (Trespalacios & Grossmann, 2014).

One of the first contributions to consider nonlinearity in production planning was by Moro et al. (1998). The main objective of their study was to develop an NLP model to increase diesel production in the refinery.

Zhang and Zhu (2000) proposed a novel modeling and decomposition strategy tackle large-scale refinery optimization problems. Their approach decomposes the overall refinery into master-level (site level) and sub-models (process level). In this approach, the site level determines operating rules and common issues for each process, then the process level optimization results are fed back to the site level for further optimization. They applied a deterministic global optimization method, combining linear relaxation and branch-and-bound decomposition to solve a bilinear problem where the iterative procedure continues until a specified tolerance is met. Later on, Zhang et al. (2001) presented one of the first MINLP models for refinery planning, which optimizes the subsystems of the main material processing system (LP) with hydrogen network (NLP) and utility system (MILP), all of which gives rise to an overall MINLP model.

Li et al., (2005) proposed simplified empirical nonlinear process models for crude distillation units, FCC unit and product blending. Their proposed model considers crude characteristics, product yields and qualities as well as regression models based on crude properties for API gravity, pour point, and octane number of CDU distillates to address the influence of CDU cut points' changes and nonlinearity on the properties.

Neir and Pinto (2005) proposed a large-scale multiperiod MINLP model that address fundamental issues related to production planning and variable demands in oil refineries. The model includes continuous variables on flowrates, properties, and production levels, binary variables on selection and distribution of crude oil types, linear models for crude oil and product terminals and nonlinear models for process units and properties.

Elkamel et al., (2008) presented an MINLP multi objective model for the refinery planning, seeking to maximize profit while reducing CO_2

emissions by incorporating mitigation options of flow rate balancing, fuels switching, and CO_2 capture.

Alattas et al., (2011) developed a single period NLP using fractionation index (FI) for CDU operations and later on (Alattas et al., 2012) modified their model to an MINLP model, to determine the sequencing, changeovers, and processing times of crude oils over multiple time periods.

Most of the previous refinery optimization studies have focused on the conventional fuel products such as gasoline, diesel and fuel oil and did not address the tradeoff problem for a refinery which have the capability to produce both, conventional fuels, and lube base oils. The fact is that a tradeoff exists, because the specifications of the conventional fuels depend on the physical bulk properties of the feed such as boiling point and sulfur, while the property of a significant importance to the lube base oils specifications, that is, Viscosity Index (VI), depends on the chemical composition of the feed. Therefore, the crude selection problem in a refinery with lube base oil producing capability need to be explicitly addressed.

Noh et al., (2018) has developed an LP optimization-based strategy for crude selection in a refinery with lube base oil producing capability. The crude oil was classified into five types based on the VI of the vacuum gas oil (VGO). In addition, predictive models were developed to predict the change in VI and yields at different hydrocracking conversion. The models were then added to the overall refinery optimization model, to maximize the overall refinery margin, while simultaneously satisfying all the specifications of the lube and fuel products.

Although Noh et al., (2018) work is a good starting point to address the tradeoff in refineries which are capable to produce lube base oil, their proposed refinery model was not intended to a complex refinery, i.e. does not have a Fluid Catalytic Cracking Unit (FCCU). Also, the hydrocracking unit (HCU) and lube base oil unit (LBOU) were modeled to receive streams that is following a single path. This is not usually the case in real refinery operations, since the feed can be potentially split among several units where a tradeoff of these splits is sought. Therefore, this thesis will extend Noh et al. (2018) work by incorporating NLP refinery model and address the tradeoffs in terms of crude selection, optimal feed split to the conversion units (HCU, FCCU and LBOU), and the quality versus yields of lube base oils at different crude conversion.

2.2 Refinery Description

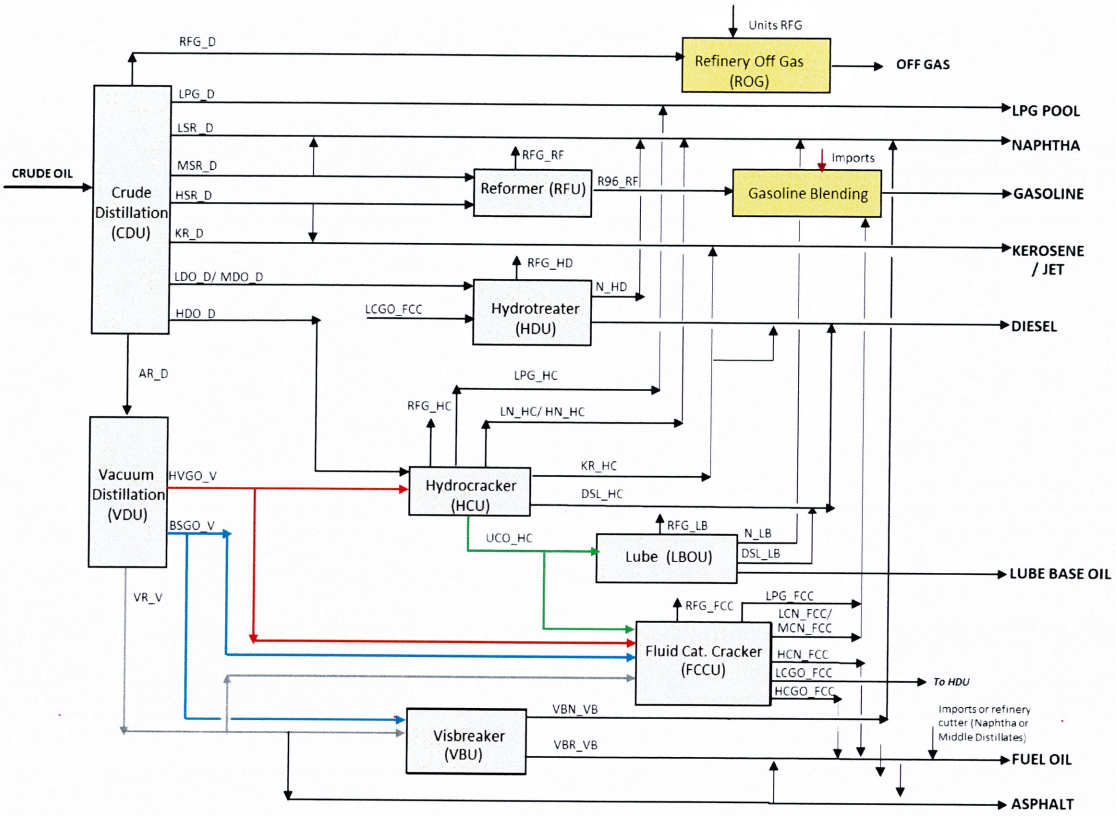


Figure 2. Schematic of the local refinery with Lube Base Oil Unit.

Figure 2 shows a schematic of the local refinery under study with a lube base oil unit which will be used in this thesis. The studied refinery consists of an atmospheric Crude Distillation Unit (CDU) and Vacuum Distillation Unit (VDU), conversion units such as Reformer Unit (RFU), Fluid Catalytic Cracking Unit (FCCU), Hydrocracking Unit (HCU) and Lube Base Oil Unit (LBOU), as well as other units such as Diesel Hydrotreating Unit (HDU) and Visebreaking Unit (VBU).

The crude oil is first processed in the atmospheric crude distillation unit where it is separated into off gas, straight run naphtha (light, medium and heavy), kerosene, straight run diesel (light, medium and heavy) and atmospheric reside.

Part of the medium and heavy straight run naphtha (MSR and HSR) is routed to the reformer to produce reformate (R96) which is the main gasoline component, while the balance is routed to the naphtha pool.

The straight light and medium diesel streams (LDO and MDO) along with Light Cycle Gas Oil (LCGO) from FCCU are routed to the HDU to produce ultralow sulfur diesel, while Heavy Diesel Oil (HDO) is routed to the HCU.

The atmospheric residue is then sent to the vacuum units where it is further separated into Heavy Vacuum Gas Oil (HVGO), Black Slop Gas Oil (BSGO) and vacuum residue (VR).

The HVGO is routed to both FCCU and HCU to be cracked into various fuel products, while the BSGO is processed in both FCCU and VBU.

The VR is mainly routed to VBU to produce naphtha (VBN) and visbreaked residue (VBR) which is a fuel oil stream with low kinematic viscosity. The VR can also be processed in FCC or routed to asphalt plant. The fuel oil is produced by blending VBR, Heavy Catalytic Naphtha (HCN) and Heavy Cycle Gas Oil (HCGO) from FCCU, and imports or refinery cutters (usually naphtha, kerosene and diesel materials).

The feed to HCU is both HDO and HVGO where they are cracked to various fuel products including naphtha, kerosene, diesel and Unconverted Oil (UCO) which is the bottom product from the HCU unit. The UCO is mainly processed in the lube unit to mainly produce high quality lube base oil (LBO) through catalytic hydroprocessing, and can also be routed to the FCCU.

The gasoline components used for gasoline blending include R96 from the reformer as well as Liquified Petroleum Gas (LPG), Light

Catalytic Naphtha (LCN) and Med Catalytic Naphtha (MCN) from FCCU. In the studied refinery, the gasoline components are sold to a gasoline blending company to handle the blending operation separately. Gasoline blending is the process of combining several feedstocks, together with small amounts of additives to make a mixture meeting certain quality specifications.

The refinery fuel gas (RFG) streams are collected from several units in the refinery and then pooled into one stream as refinery off gas (ROG). After using small percent of it internally, e.g. for heating, this stream is sold to another company (e.g. the local Natural Gas Liquid Plant) to recover valuable components.

2.3 Crude oil

Petroleum or crude oil is a naturally occurring complex mixture of hydrocarbon compounds with a high energy content. It has minor amounts of nitrogen-, oxygen-, and sulfur-containing compounds as well as trace amounts of metal-containing compounds (Speight, 2006; Tissot & Welte, 1984). The elementary composition of most crude oils falls within the ranges shown in Table 1 (Gary et al., 2007; Speight, 2006).

Table 1. Crude oil elemantal composisiton (wt%)

Component	**Composition (wt%)**
Carbon	83.0- 87.0
Hydrogen	10.0- 14.0
Sulfur	0.05- 6.0
Nitrogen	0.1- 2.0
Oxygen	0.05- 1.5
Metals	0.0-0.1

The hydrocarbons found in petroleum are classified into the following types (Gary et al., 2007; Leffler, 2008; Speight, 2006):

- Paraffins: which are series of hydrocarbons which are saturated with hydrogen and connected by a single bond.
- Olefins: which do not naturally occur in crude oils but are formed during refinery processing, e.g. cracking. They are very similar in structure to paraffins, but at least two of the carbon atoms are joined by double bonds. Olefins are generally undesirable in finished products because they are easily oxidized and polymerized to form gums. However, some olefins are desirable in gasoline because they have higher octane numbers than paraffins

- Naphthenes or cycloparaffin: which are saturated hydrocarbons containing one or more rings, each of which may have one or more paraffin side chains.
- Aromatics: which are series of hydrocarbons containing a benzene ring, which is unsaturated but very stable.

2.3.1 Crude distillation

The crude distillation units (atmospheric and vacuum) are the first major processing units in the refinery. They are used to separate the crude oils by distillation into fractions according to boiling point so that each of the processing units following will have feedstocks that meet their particular specifications (Gary et al., 2007).

To further specify the character of crude oil, the refiners lump certain compounds into groups called fractions. Fractions or cuts are the generic names for all the compounds that boil between two given temperatures, called cut points, where each cut has specific yields and properties (Leffler, 2008) Refineries can change cut points to vary the yields and balance products based on market demand.

Cut points are usually determined using true boiling point (TBP) data. The points are determined by using a column with high reflux and good separation. This is often done in a column with fifteen theoretical plates and a reflux ratio of 5 to 1 according to ASTM D2892.

2.3.1 Crude properties

The main reason for rejecting a crude is the inability to manufacture the desired qualities and quantities of products given the process facilities available to the refiner (Sequeira, 1994). Since crude oils are very complex, relatively simple analytical tests are usually run on the crude, and the results of these are used with empirical correlations to evaluate the crude oils as feedstocks for the particular refinery (Gary et al., 2007).

The most common properties of crudes are discussed in this section.

2.3.1.1 API gravity

The density of crude oils is usually expressed in terms of API gravity rather than specific gravity. It is measured in °API and can be calculated from specific gravity, i.e. weight of material compared to an equal volume of water, as following:

$$API = \frac{141.5}{\text{Specific gravity}} - 131.5 \qquad (1)$$

Most petroleum fractions and crude oils are lighter than water, i.e., have API gravities greater than 10 and specific gravities less than 1. Crude oils are generally classified as light and heavy based on the API gravity range. The API gravity of light crudes is greater than 31, intermediate crudes API is between 22 and 31 and heavy crudes API is less than 22 (Gary et al., 2007; Speight, 2006).

2.3.1.2 Sulfur content

Sulfur may be present in crude oil as dissolved sulfur and hydrogen sulfide or as organic compounds such as mercaptans and thiophenes. Many of these compounds occur naturally in crude petroleum whereas others are formed during processing.

Crudes are also classified based on the sulfur content as sweet i.e. sulfur content of less than 1.0 wt% and sour i.e. sulfur content of higher than 1.0 wt%. Sour crudes generally require more extensive processing compared to sweet crudes.

The general classification on API and sulfur helps in determining the price of a specific barrel of crude as well as how much its demand (Speight, 2006).

2.3.1.3 Total acid number

The Total Acid Number (TAN) is the quantity of potassium hydroxide to neutralize the acid of 1 g of oil. A crude is considered highly Acidic with a TAN of around 3 mg. Levels between 0.5 and 3.0 mg crudes are considered acidic. Below 0.5 mg crudes are considered normal and with levels below 0.05 mg they are considered to have very low acidity. The acidity is primarily from carboxylic acids which also are called naphthenic acids. Highly acidic crudes require the use of expensive alloy steel equipment, because they have a high potential to cause corrosion problems, especially in the atmospheric and vacuum distillation units where the hot crude oil first encounters hot metal surfaces.

2.3.1.4 Watson characterization factor

Several correlations between yield and the aromaticity and paraffinicity of crude oils have been proposed using physical properties, but the most widely is the UOP or Watson characterization factor (K_w) (Gary et al., 2007; Speight, 2006).

$$K_w = \frac{T_B^{\frac{1}{3}}}{G} \qquad (2)$$

Where T_B is the mean average boiling point in $°R$ and G is the specific gravity at $60°F$.

The Watson characterization factor is an indicator of the paraffinicity of the crude oil. It ranges from less than 10 for highly aromatic materials to almost 15 for highly paraffinic compounds. Crude oils usually range between 10.5 for a highly naphthenic crude and 12.9 for a paraffinic base crude (Gary et al., 2007; Speight, 2006). It can be seen that Watson characterization factor can be used as a simple indicator of the suitability of the crude for LBO production.

2.3.1.5 Pour point

The pour point t is the lowest temperature at which oil will move, pour, or flow. This temperature gives a good indication of the condition of the oil in the reservoir and play an important role in oil transportation through pipelines (Gary et al., 2007; Speight, 2006). The higher the pour point, the more paraffin content in the crude, and the more likely it is to lose its flow properties. If the pour point is high, issues will arise with regards to its pumpability and transportation across the refinery and the units.

The pour point ranges from -70°C for light distillates and occasionally as much as positive 90 °C degrees for heavy Residues.

2.3.1.6 Viscosity

The viscosity of an oil is a measure of its resistance to flow, that is, its readiness to flow when acted upon by an external force. Similar to the pour point, the higher the viscosity, the more transportation and pumping problems arise in moving the crude between storage and processing facilities across lines. The two most common types of viscosity are

dynamic and kinematic. The conversion from absolute viscosity to kinematic viscosity is given by the following equation:

$$v = \frac{\mu}{\rho} \tag{3}$$

where υ is the kinematic viscosity in stokes, μ is the dynamic viscosity in poises and ρ is density in grams per cubic centimeter

The dynamic viscosity gives information on the force needed to make the fluid flow at a certain rate, while kinematic viscosity tells how fast the fluid is moving when a certain force is applied (Gary et al., 2007; Leffler, 2008; Speight, 2006)

The kinematic viscosity of whole crudes is often in the range of 2 to 10 centistokes, while heavy crudes could have viscosities higher than 100 centistokes.

2.3.3 Crude oil benchmark

There are dozens of different oil benchmarks which are used because there are different grades of crude oil globally. Benchmarks make referencing types of oil easier for sellers and buyers. The price of the crude as mentioned earlier, is highly dependent on its grade (API and its sulfur content) and its location .They are usually pegged to one of three primary benchmarks (Speight,2006; Editorial Dept , 2009; Oilscams Organisation, 2017) as below:

1. **West Texas Intermediate (WTI):** is an extremely high-quality crude oil extracted from wells in the U.S. and sent via pipeline to Cushing, Oklahoma. WTI crude has an API of 39.6 and sulphur content of 0.24 *wt*% which makes it a light and sweet crude. The gasoline refined from a single barrel of this crude is usually higher compared to other crudes. WTI is often priced from $1 to $2 per barrel higher than Brent Blend.

2. **Brent Blend:** it is a mix of 15 different oil fields in the North Sea. It has an API of 38.3° and sulphur content of 0.37 *wt*% which makes it a light and sweet crude. Brent Blend is quite excellent for making gasoline and middle distillates. It is a major benchmark for other crude oils in Europe and Africa and is usually priced from $2 to $4 per barrel higher than Dubai/ Oman crude.

3. **Dubai/Oman**: consist of crudes from Dubai, Oman or Abu Dhabi. It has an 31.0° API and a sulfur content of 2.0 *wt*%. It is a useful reference for oils of a slightly lower grade than WTI or Brent in the Gulf and the Middle East.

Overall, there is a lack of a systematic methodology for crude evaluation and selection in refineries, noting that crude selection plays a major role in determining refinery's profit and margins.

2.3.4 Crude classification based on chemical composition

The U.S. Bureau of Mines has classified oils into paraffinic, naphthenic, and intermediate crudes according to their API gravity and distillate fractions at different temperatures and pressures, i.e. from 250°C to 275°C at atmospheric pressure and from 275°C to 300°C at 40 mmHg pressure as shown in Table 2 (Gary et al., 2007; Lane & Garton, 1935; Sequeira, 1994; Tissot & Welte, 1984).

Table 2. U.S. Bureau of Mines classification of crudes

Classification	**Key fractions, °API**	
	250 to 275°C	**275 to 300°C**
Paraffin	40	30
Paraffin, intermediate	40	20-30
Intermediate, paraffin	33-40	30
Intermediate	33-40	20-30
Intermediate, naphthene	33-40	20-30
Naphthene, intermediate	33	20-30
Naphthene	<33	<20

Although crude oils from worldwide sources showed that 85% of the crudes fell into one of the three classes (Speight, 2006), the criteria for the classification is relatively ambiguous and coarse without considering the compositional details (Tissot and Welte, 1978; Noh et al., 2017).

Refiners have also classified crude oils based on their experience as paraffin base, naphthene base, mixed base, and asphalt base based on wax (long chain of paraffins) and asphalt content. Paraffin base crude oils contain wax with low or no asphalt content, naphthene base crude oils contain small amount or no wax and contain no asphalt, mixed base crude oils contain wax and asphalt, and asphalt base crude oils contain high sulfur and nitrogen contents and asphaltic residue (Sequeira, 1994; Pillon, 2007).

An early attempt to give the classification system a quantitative basis suggested that crude oils are considered asphaltic if the distillation residue contained less than 2% wax (Speight, 2006). A classification according to the chemical composition for the crude cuts of distillation range between 250°C and 300°C was proposed as shown in Table 3. The cuts are classified into paraffinic (P), Paraffinic–naphthenic (P-N), Naphthenic (N), Paraffinic–naphthenic–aromatic (P-N-A) and aromatic (A) based on the composition of paraffins, naphthene, aromatics, wax, and asphalt (Speight, 2006). However, the difficulty that arises in using such a classification is that in the fractions boiling above 200°C, the molecules can no longer be placed in one group, because most of them are of a typically mixed nature (Speight, 2006, Pillon, 2007).

Table 3. Classification of crude by chemical composition in volume% (250°C to 300°C)

Class	Paraffins	Naphthene	Aromatics	Wax	Asphalt
P	>46, <61	>22, <32	>12, <25	<10	<6
P-N	>42, <45	>38, <39	>16, <20	<6	<6
N	>15, <26	>61, <76	>8, <13	0	<6
P-N-A	>27, <35	>36, <47	>26, <33	<1	<10
A	<8	>57, <78	>20, <25	<0.5	<20

(Speight, 2006).

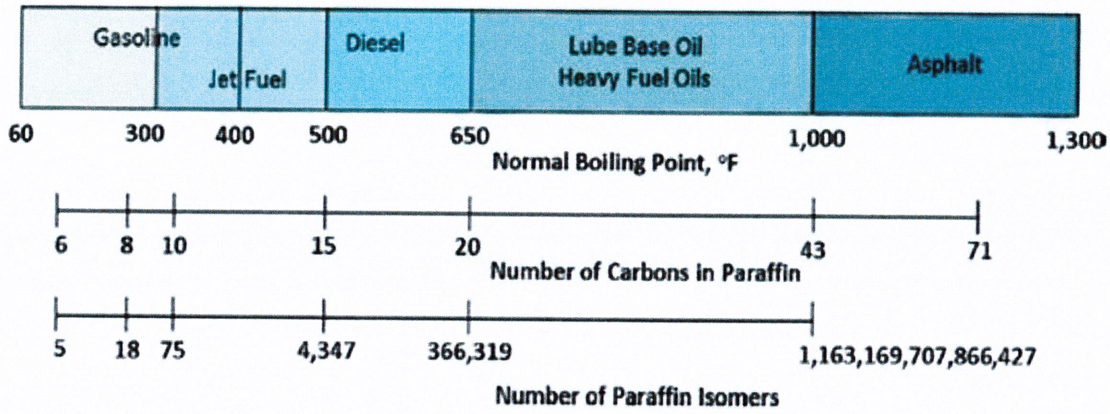


Figure 3. Complexity of heavy hydrocarbon with higher boiling point (Noh et al., 2018 as cited in Read, 1976)

The distillation range used in this crude classification corresponds to fuel products only which are below 360 °C, while distillation range for the lube base oil feedstock is above 360 °C.

Selection of lube-suitable crude oils is challenging because of the high boiling range cuts, which include the base oils, and their complex chemical composition. In general, lube base oils contain heavy and complex chemical components with carbon number greater than 20 and numerous isomers, which have distillation range of higher than those of typical fuel products as shown in Fig. 3.

2.3.4.1 Crude classification based on high boiling point cuts

To predict the VI of the final LBO product, the crude has to be classified based on the VI and chemical composition of its heavy high boiling point cuts (usually > 360 °C) such as HDO and HVGO which are the feed to the hydrocracker unit. There have been studies such as those of Sarpal et al. (1997) and Verdier et al. (2009) on the effect of the crude molecular structure on VI through using analytical data obtained from Nuclear Magnetic Resonance (NMR) or Infrared spectroscopy (IR) which were correlated through regression analysis. However, these studies were related to specific branches of crudes, and usually such analysis are relatively complex and difficult to apply in lube refinery.

Noh et al. (2018) estimated the carbon type composition (paraffins, naphthenes and aromatics) of the Vacuum Gas Oil cut (VGO), a nominal cut with boiling point higher than 360 °C, for 50 different crudes using the Viscosity Gravity Constant (VGC) and refractive intercept and then classified the crudes based on the VI value of VGO into 5 types Paraffinic (P), Paraffinic Intermediate (PI), Intermediate (I), Naphthenic Intermediate (NI) and Naphthenic (N) as shown in Table 4. Thus, if the information on the VGO's VI is available, it can be used directly to get the crude classification. It can be noticed that the VI value increases as the paraffins content increase, and that VGOs with similar VIs show consistent chemical compositions.

Also, properties like Watson characterization, refractive index and aniline point can also be referred to as a secondary indicator as shown in Table 5. Although these properties are bulk properties of VGO, they are related to the chemical composition, give an indication that different crude types are used and are easy to measure.

This classification helps in predicting the VI changes through the hydrocracking and lube hydro-processing units, which depend on the crude type and helps improving the optimization accuracy of lube production.

Table 4. Carbon type composition and VI criteria of VGO.

Crude Class	VGO VI	Paraffin	Naphthenes	Aromatics
P	>110	≥65.8	≤24.3	≤10.0
PI	90–110	62.2–65.7	24.3–26.1	10.0–11.7
I	50–90	55.2–62.2	26.1–29.7	11.7–15.1
NI	10–50	48.1–55.2	29.7–33.3	15.1–18.6
N	<10	≤48.1	≥33.3	≥18.6

(Noh et al., 2018)

Table 5. Classification of crude oil based on VGO VI

Crude Class	VGO VI	Watson	RI	Analine, °C	K-Vis, cSt
P	>110	>12.3	<1.4712	>100	<5.84
PI	90–110	12.1–12.3	1.4712–1.4785	95–100	5.84–6.94
I	50–90	11.8–12.1	1.4785–1.4833	84–95	6.94–9.13
NI	10–50	11.4–11.8	1.4833–1.5080	73–84	9.13–11.32
N	<10	<11.4	>1.5080	>73	>11.32

(Noh et al., 2018)

2.4 Base oil

Base oils are one of the specialty products that can be produced by a refinery and are mainly used to manufacture lubricants required for automobile engines and other machines operated at high speed.

Lube base oils are produced from high boiling fractions (≥ 360 °C) such as vacuum gas oil fraction and residue of crude oil (Lynch, 2007). As per the American Petroleum Institute (API), the lube base oil is classified into five categories based on the sulfur content, saturate content and viscosity index (VI) as shown in Table 6 (API, 2002).

The viscosity index is a significant indicator of the lube base oil quality. It is a measure of the change in viscosity between two standard temperatures, 100°F (40°C) and 212°F (100°C). The higher the index, the lower the change in viscosity at different temperatures and hence the better the quality of the product. Group II and III are high quality lubes due to their high VI and have a higher demand compared to Group I due to the tight customer requirements and environmental regulations (API, 2002; Lynch 2007; Noh et al., 2017). Group IV base oils are full synthetic (polyalphaolefin) oils and group V includes all other base oils not included in groups I through IV. These are mostly used in extreme cold conditions and high heat applications (API, 2002).

The quality of lube base oils is linked to the viscosity index (VI) which strongly depends on the chemical composition of the feed (Leffler, 2008; Lynch, 2007; Sequeira, 1994). Petroleum distillates and residues contain a complexity of hydrocarbons, and the identification of individual structures is only possible for products with the lowest molecular weight (Lynch, 2007). Therefore, the compounds of similar chemical classification, i.e.

paraffinic, naphthenic and aromatics are generally lumped together to study their effect on the lube products quality (Lynch, 2007).

Table 6. API classification of lube base oil

Group	Sulfur Mass %	Saturates Mass%	VI
I	>0.03	<90	≥80 <120
II	≤0.03	≥90	≥80 <120
III	≤ 0.03	≥90	≥120
IV	All polyalphaolefins		
V	All stocks not included in groups I–IV (e.g., esters, pale oils)		

(API, 2002)

Although normal paraffins have the highest VI, they are undesirable in high content since they have very high pour points. Some isoparaffins, naphthenes and aromatics also have high pour points and are undesirable as lube base oils. Aromatics generally have the lowest VI and oxidative stability. Naphthenes generally have intermediate VI's and very low pour points which make them useful in the manufacture of specialty lubricants. The preferred compounds for the manufacture of base oils are the isoparaffins of high VI and low pour point (Sequeira, 1994). Table 6 summarizes the lube base oil properties which vary with the hydrocarbon types (Lynch, 2007; Sequeira, 1994).

Different crude oils can have different concentrations of these three molecule types, i.e. paraffins, naphthenes and aromatics, therefore, selection of lube-suitable crude oils often conflicts with the economics of general refining crude oils and gives an extra cost burden for the lube business units to recover in the marketplace (Leffler, 2008).

Table 7. Properties of Base Oil Component

Component	n-paraffin	Iso-paraffin	Napthene	Aromatics
Viscosity index	High	High	Medium	Low
Pour point	High	Low	Low	Low
Oxidative stability	Good	Good	Fair	Poor
Thermal stability	Good	Good	Fair	Poor

(Sequeira, 1994).

Refineries with lube unit produce heavier than C_{20} range products (atmospheric residue). Unless a crude oil is extremely heavy, with very little straight-run naphtha and distillate, it is difficult to economically justify a stand-alone base oil refinery with no coproduction of fuels (Klerk, 2011).

To meet the VI and other properties of the lube base oil, it is highly important to select the appropriate feedstock and the right operating conditions e.g. the conversion rate in the hydrocracking lube hydro-processing units. As mentioned earlier, there is also a tradeoff between the yield and VI of the lube base oil, meaning that, at higher conversion rate in the hydrocracker unit, the yield of the base oil decreases which consequently lowers the overall refinery margin, but on the other hand, it improves the VI (Lynch, 2007; Noh et al., 2018). As a result, the decisions of crude selection, lube base oils quality and the hydrocracking conversion are all interrelated and depend on the price differentials of the refinery products, which make them good candidates for rigorous optimization (Noh et al., 2018).

2.4.1 Base oil production process

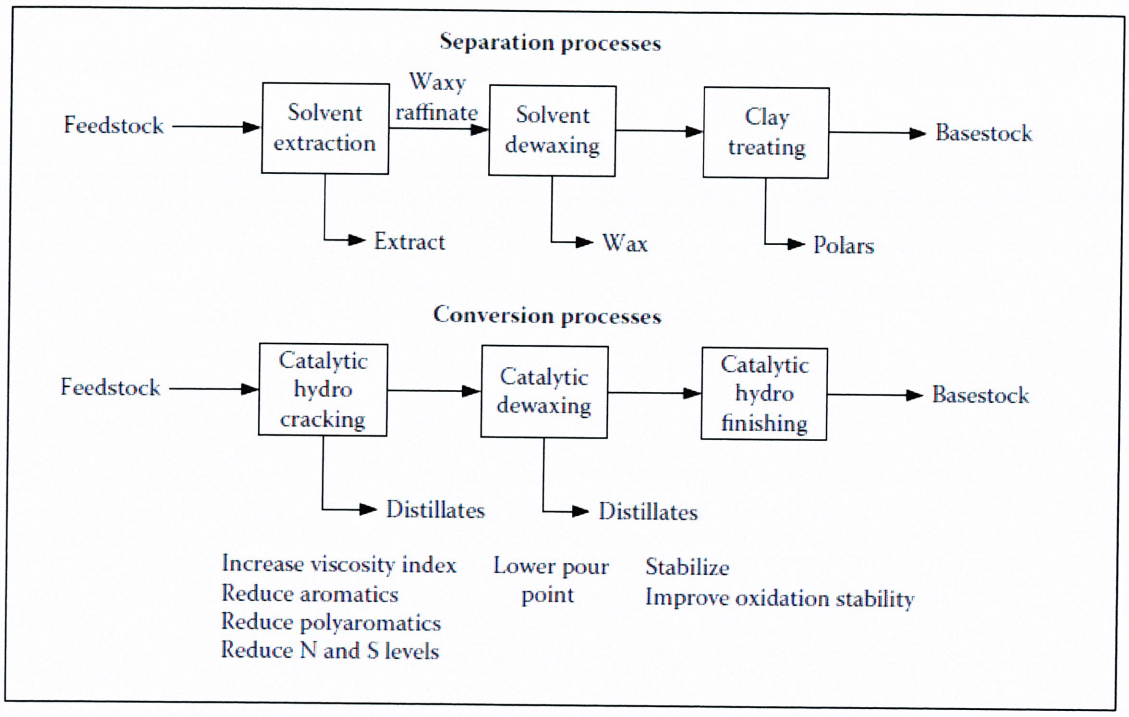


Figure 4. Comparison between separation and conversion process routes for base oil production.
(Lynch, 2007)

In the early days of the petroleum industry, only crude fractions which are rich in paraffins were considered suitable to produce base stocks of high viscosity index, through acid treating and cold wax settling. However, fractions from other crudes which contain more aromatics and are of lower viscosity index, detract from their use as base oils (Sequeira, 1994).

There are two main processing routes by which base oils are produced. Solvent extraction and catalytic hydroprocessing as shown in Fig.4 (Lynch, 2007; Sequeira, 1994)

Solvent extraction is the conventional process based on chemical separation. The undesirable chemical compounds including polyaromatics are removed using solvent-based separation methods (solvent refining). The by-products (extracts) represent a yield loss in producing the base stock. The base stock properties are determined by molecules originally in

the crude, since molecules in the final base stock are unchanged from those in the feed. The major purposes of the solvent extraction step are to reduce the temperature dependence of the viscosity (i.e., increase the VI) of the raffinate and improve the oxidation stability. In the dewaxing step, the wax in the raffinate is removed to lower the pour point through crystallization. The last step it is usually subjected to clay treatment, which improves color and performance by removing polyaromatics, nitrogen, sulfur, and any oxygen compounds

Catalytic hydroprocessing is a chemical conversion process that have been developed to upgrade the fractions from the less desirable crude oils and cannot be upgraded to the desired quality levels by the solvent extraction processes. This process involves three steps:

- Catalytic hydrocracking, where part of the aromatics in the feedstock is saturated by hydrogenating them to cycloparaffins, and the feed sulfur and nitrogen are both essentially eliminated. The VI in this step increases.
- Catalytic dewaxing, where the long chain paraffins (wax) are selectively cracked to smaller chain of n-paraffins or isomerized to low melting isoparaffins to meet the required pour point specifications. The VI of the base oil is reduced in this step because the wax has high VI compared to other components in the feed.
- Catalytic hydrofinishing, where most of to the remaining aromatics are saturated to make base stocks stable for storage and to improve their performance.

The lube base oils of Group II and III are always produced using the catalytic route. The advantages of the conversion route are many including less dependence on supplies of expensive high-quality "lube" crudes,

which are increasingly in short supply and give higher base stock yields and quality (Hilbert et al., 2013; Lynch, 2007).

The identification of good crudes for lube oil processing cannot be simply determined from crude assays which are normally used to evaluate the properties of fuel oriented crude oil (Noh et al., 2018). Accordingly, several refiners have developed their own screening and evaluation methods specified to their operations such as batch processing and atmospheric fractionation of narrow cuts of the crude oils followed by testing both the base stocks and the products (Sequeira, 1994; Pirro et al, 2016). However, these methods require long time to study the effect of limited crude types on the lube oils quality and yield.

Generally, the change of quality and yield of lube base oil from crude oils were empirically observed. Such heuristic approaches make refineries vulnerable to sub-optimal and infeasible operation especially when crude type and operating conditions are changed and might incorporate significant economic losses due to the production of off-spec lube base oils (Noh et al., 2018). To optimize refineries with lube processing capacity, VI prediction model is needed to predict the change of VI during the lube processing units. Overall, high quality lube base oils have high and relatively stable market prices; thus, refineries with lube hydroprocessing capacity tend to maximize the production of lube base oil to increase their profit margin (Noh et al., 2018).

Despite the need, there is a lack in models that predict lube base quality, i.e. VI changes through lube hydro-processing units in the overall refinery optimization. Including models to estimate and predict the VI in the refining model, is crucial to reflect how crude selection changes based on the required lube base oil quality and prices.

Chapter 3

Approach and Model Formulation

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The chapter starts with the methodological approach which consist of three parts, crude evaluation and classification, process units and yield models and VI prediction model. Then, the mathematical formulation and the calculations of yields and VI change are listed in detail.

3.1 Refinery modelling and methodology

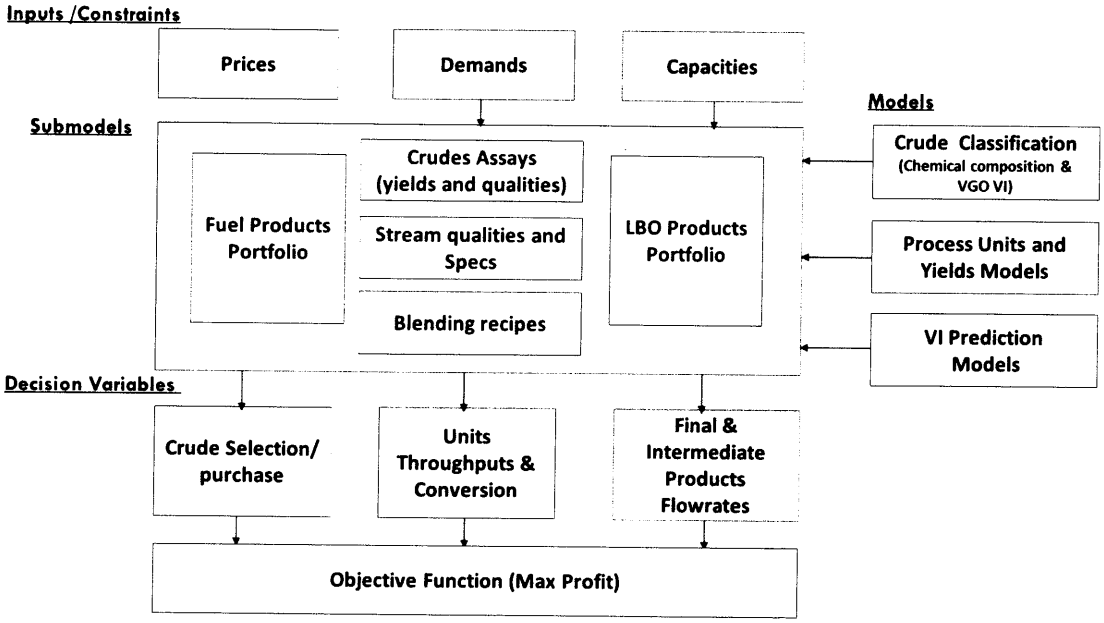


Figure 5. The overall scheme of the lube-based refinery optimization

The proposed refinery optimization model is shown in Fig.5. The model consists of three parts, crude evaluation and classification, process units and yield models and VI prediction model.

In the first part, a crude basket will be created using a crude assay tool by evaluating several crudes based on bulk properties such as API, sulfur, TAN as well VGO VI. In the second part, process models will be formulated. This includes applying material balance on each unit in and out streams and blending of final products, and estimating the yields for conversion unit, i.e. FCCU and HCU by using simulation and actual plant data. In the third part, the viscosity model by Noh et al. (2018) will be used to estimate the VI for the crude oils VGO all the way to the final lube base oil product. The model objective function is formulated to maximize the refinery profit by identifying the best crudes which are suitable for the production of both, fuels and lube base oil, the units' throughputs, optimum hydrocraking conversion, as well as the flow rates of the intermediate and final products.

3.2 Crude basket & screening

To facilitate the crude selection process, crude assay tools are usually used such as Haverly's H/CAMS and Aspen Assay Management. Crude assays give information about crude properties and indicate the key properties (yield and quality) to be expected in each specified cut.

A screening process was applied to 50 types of crudes available in the assay tool data base. Those crudes have different properties and from different locations available in the market.

Since the crude selection is a new practice in the studied refinery, an initial screening process was applied. In general, the acceptance of a crude depends on whether it will be processed as a neat crude or as part of a blend. Regardless of the processing criteria, there are few properties which have be checked before importing a crude to ensure smooth transportation, pumping and storage. These properties and limits that the crudes were checked against are RVP, pour point and H_2S level which are mainly based on general refinery practices.

- Reid Vapor Pressure (RVP): this pressure is used to characterize the volatility of gasoline and crude oils, and is usually specified by crude oil purchasers, particularly if the crude is to be transported by tanker or truck prior to reaching the refinery. The limit should be lower than 12 psi (83 kPa) to avoid evaporation of the light components in the crude during transportation (Stewart & Arnold, 2009).
- Pour point: the pour point of a crude oil are important for the transportation and flow of crude oil especially during low temperature (Speight, 2006). The crude oil pour point should be at least 10 °C lower than the normal atmospheric temperature. The

limit set is a maximum of 15 °C, based on the sea water temperature recorded in recent years.

- Hydrogen sulfide (H_2S) level: high levels of dissolved H_2S render crudes dangerously toxic and cause a threat in the storage area. Therefore, a limit of 10 ppm maximum was set, which is based on the Occupational Safety and Health Administration (OSHA) safety standards and the Arab light content of dissolved H_2S which is less than 10 ppm.

If the selected crude was to be processed as a neat crude, it should have similar properties of the currently being processed crudes, i.e. Arab light and Bahrain. On the other hand, blending of crudes give more flexibility on the selected crudes. Below are general guidelines on the crudes main properties based on the refinery practices and reference to the currently being processed crudes:

- The API gravity of the Arab light and Bahrain crudes are approximately 33° and 29° respectively. Any crude above 40°, and below 29° should not exceed 30% of the total crude blend. This is because the crude column has a limitation on the total condensates and residue quantity and a very light or heavy crude cannot be processed alone.
- The sulfur content should be at most 2.0 wt% (which is the typical sulfur content of Bahrain crude) or lower. If the level is higher than 2.5%, it should not exceed 30% of the total crude blend.
- The TAN of the whole crude should not exceed 0.5 mgKOH/g, because the current refinery metallurgy is not capable to handle crudes with high acidity.

After applying the screening process, 17 crudes out of 50 were qualified and a basket of acceptable crudes was created. The crudes were then fractioned using TBP through a crude assay tool, i.e. H/CAMS to get yield data and properties on each fraction from the atmospheric and vacuum distillation columns. The cut points used in this thesis are listed in Table 8.

Table 8. TBP cut points used for crude oil fractions

Cut	Initial Boiling Point (IBP), °C	End Boiling Point (EBP), °C
RFG	<-30	-30
LPG	-30	14
LSR Naphtha	14	105
MSR Naphtha	105	140
HSR Naphtha	140	220
Kerosene	220	253
LDO Diesel	253	329
MDO Diesel	329	383
HDO Diesel	383 (>360) (1)	445
AR	**445**	**>445+**
HVGO	445 (>360) (1)	560
BSGO	560	600
VR	600	>600

Note (1): The classification in Table 5 is applicable

The classification suggested by Noh et al. (2018) in Table 5 was applied based on the VI of the HCU feed, i.e. HDO and HVGO cuts. These crudes are then used in the model and further quality constraints are added, e.g. sulfur and nitrogen content in the feed which are listed in section 3.5.

3.3 Yield models

There are two different modeling structures which typically used to represent the product's yield for refinery optimization. The first is vector models which is relatively simple and is used when there are no variations in feed qualities and operating conditions which might cause yield variation. The second is delta base models which are used to model process unit yield changes as a function of feedstock quality or process severity (Gary et al., 2007). The delta base models are usually used to represent complex process such as FCCU, in which the yields highly vary with changing feedstock or operation conditions. The yield models used for the process units in this thesis are all modeled as simple vectors, except for FCCU which is modeled as delta base, where yields change as the density of the feed varies.

3.3.1 HCU yields

The hydrocracking conversion rate defined by Eq. 4 is the most important operating variable which represents the reaction severity in both HCU and LBOU. It is defined as the ratio of the feed converted to fuel products over the total fresh feed to the unit. The unconverted oil (UCO) is the bottom product from HCU and the main feedstock to LBOU. It can also be routed to the FCCU if needed. Thus, the yield structure of the LBOU changes with the conversion rate. As the conversion rate increases, the yield of fuel products such as naphtha, kerosene, diesel are increased, while the yield of the UCO is decreased. According to this, the yield model in HCU is a function of the conversion rate.

$$Conversion\ (\%) = \frac{Fresh\ Feed - Unconverted\ oil\ (UCO)}{Fresh\ Feed} \times 100 \quad \textbf{(4)}$$

The yields versus conversion real data were available from actual local refinery at a conversion of 75, 80 and 99% and it is depicted in Fig. 6. As noticed, all HCU products increase with increasing the conversion except for the heavy diesel and the unconverted gas oil (UCO). It is also noticed that the change in the yields is linear for a conversion between 75% and 95%, except for light and heavy diesel which change nonlinearly with conversion.

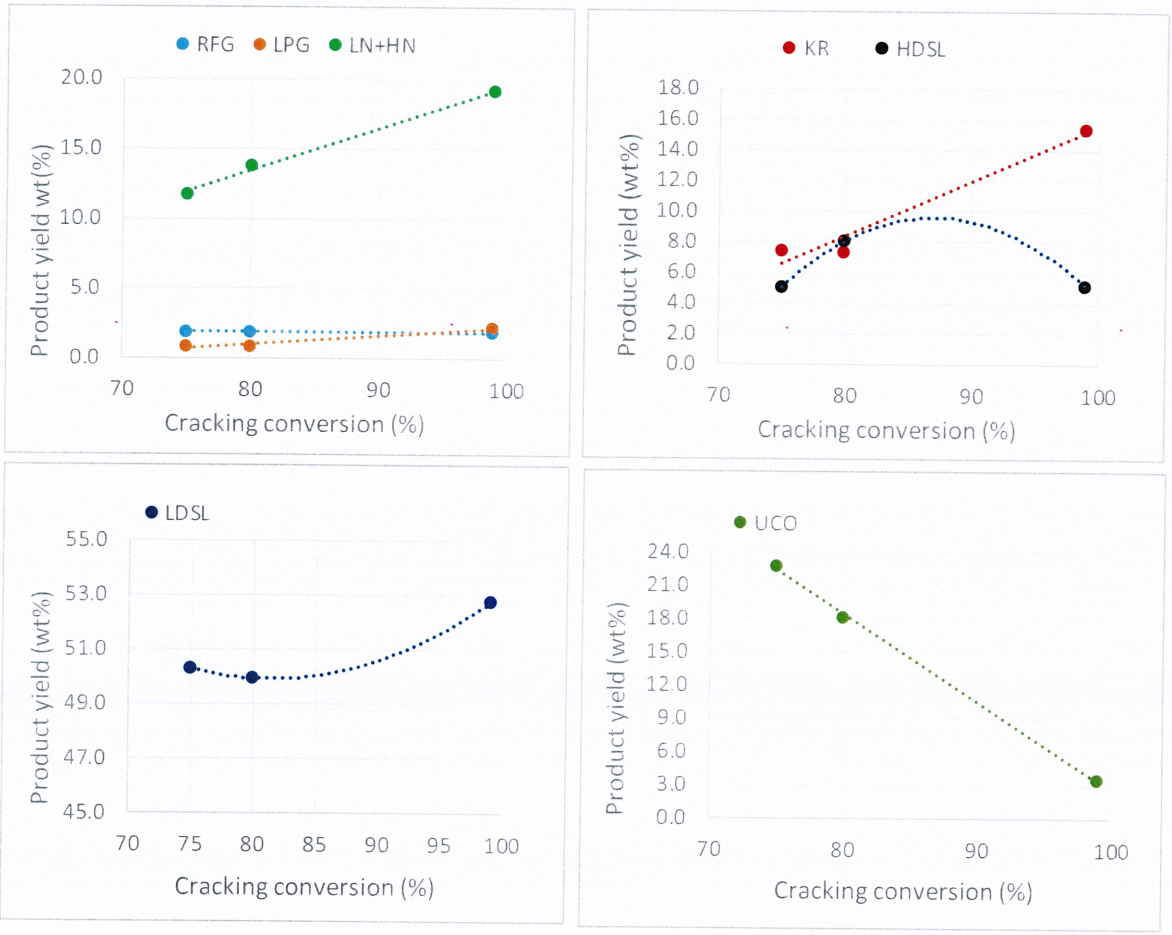


Figure 6. Yield structure of HCU as function of hydrocracking conversion, from the local refinery

3.3.2 FCCU yields

FCCU is one of the most widely used catalytic cracking process. It is rare for FCCU to process a single type of feed but multiple feed with varying compositions. FCCU can process several feedstocks including HVGO, BSGO, UCO and VR, each at different qualities. It also may operate at different conditions. To account for variations in feed composition, the concept of the delta base vector is useful (Chang et al., 2012).

The new yield based on the actual feed's quality is calculated using Eq. 5.

$$Yield_{New} = Yield_{Base} + z \times Yield_{Delta} \quad (5)$$

Where $Yield_{New}$ is the new required yield at the actual feed quality, $Yield_{Base}$ is the base yield for a typical FCCU feed, z is the shift factor that corrects the change in the yields and $Yield_{Delta}$ is the delta in the yield for a given shift in a feed quality. The shift factor z, is calculated using Eq. 6.

$$z = \frac{Q_{Input} - Q_{Base}}{Q_{Delta}} \quad (6)$$

Where Q_{Input} is the actual quality of the feed, Q_{Base} is the base quality of a typical FCCU feed, and Q_{Delta} is the delta quality used to adjust the yield for changes in feedstock quality or severity from the base.

The delta base vector data for FCCU used in this thesis is shown in Table 8. The conversion is assumed constant at 53% and the delta is based on a change in the density (ρ) at 15° C of the feed to FCCU. As noticed in Table 9, a shift of -0.0192 wt% in the feed SG, i.e. lighter feed to FCCU,

will increase the gases and naphtha production and decrease light and heavy cycle gas oils.

Table 9. Delta-Base vector yields for FCCU based on feed density shift

Activity	Base Vector	Delta Vector
Feed density (kg/l)	0.9546	-0.0192
Yields (wt%)		
RFG	0.0862	0.0063
LPG	0.0544	0.0057
LCN	0.1796	0.0116
MCN	0.1354	0.0063
HCN	0.0277	0.0009
LCGO	0.2504	-0.0072
HCGO	0.2663	-0.0236

Since the FCCU feedrate and the feed split, i.e. combination of HVGO, BSGO, UCO and VR are all unknown and to be optimized, the density of the feed is unknown as well. The calculation of SG is shown in section 3.5.

3.4 Viscosity Index (VI) models

The VI in the proposed model is first calculated for the HCU feed (HDO and HVGO) from the crude and vacuum distillation columns, respectively. The delta of VI increases for UCO through HCU, which is the bottom product from HCU and the feed to LBOU and FCCU, and decreases for the LBO final product through LBOU. The proposed VI models are based on Noh et al. (2018) correlations as following:

- First the VI of the HCU feed (HDO and HVGO) is obtained from crude assay tool and then each crude is classified based on HCU feed VI using the classification in Table 5. Although Noh et al., (2018) suggested that VGO VI can be estimated from bulk properties through equations based on linear regression, these equations were not used in this thesis, since the VI data is available for the heavy cuts in the crude assay. The latter is useful in reducing uncertainties in the developed optimization model.
- Secondly, the VI of the UCO which is the bottom product from HCU and the feed to LBOU and FCCU is estimated, by calculating the increase in VI through HCU. The VI relations, shown in Table 10, are function of the unit conversion and are calculated using equations based on simulation and pilot study results in the local refinery under study. These relations reflect the tradeoff between the yield and quality of the UCO, i.e. as the conversion increases, the UCO and LBO yields decrease but the VI of the UCO increases.
- Thirdly, the VI of the final LBO product is estimated by calculating the decrease in VI after processing UCO in the LBOU as shown in Table 10. The delta in VI was obtained using an empirical yield

model based on pilot plant data for the waxy distillate from a real commercial plant.

Table 10. The change of the VI through HCU and LBOU.

Hydrocracking unit		
Crude Type	**Conversion**	ΔVI
P	$0< k\leq 40$	$0.6462(k)$
	$40< k\leq 80$	$0.6462(40) +0.4342 (k-40)$
PI	$0< k\leq 30$	$0.9438(k)$
	$30< k\leq 60$	$0.9438(30)-0.5305(k-30)$
	$60< k\leq 80$	$0.9438(30)-0.5305(30) +0.3402(k-60)$
I/ NI	$0< k\leq 45$	$0.9197(k)$
	$30< k\leq 65$	$0.9197(45)+0.76(k-45)$
	$60< k\leq 80$	$0.9197(45)+0.76(20)+0.6882(k-65)$
N	$0 < k\leq 30$	$1.8067(k)$
	$30 < k\leq 80$	$1.8067(30)+1.1884 (k-30)$
Lube base oil unit		
Crude Type	ΔVI	
P	*-11*	
PI	*-17*	
I/NI/N	*-23*	

3.5 Mathematical formulation

A mathematical model is formulated for the studied refinery in Fig.2 which represents the connections between the streams and units, and the blending of final products. The proposed mathematical formulation extends the models and parameters given by Noh et al. (2018) and Favennec (2001). The new formulation differs by the addition of FCCU, VBU and streams with multiple destination to the conversion units. The overall model is nonlinear due to the FCCU submodel.

The following sets and indices are defined for the overall mathematical programming formulation:

$u \in U = \{Units\} = \{D, V, HD, RF, FCC, HC, LB, VB\}$

$c \in C = \{Selected\ Crudes\} = \{C_1, \dots C_{17}\}$

$fp \in FP = \{Final\ Products\}$
$= \{RFG, LPG, NAP, KR, R96, LCN, MCN, DSL, LBO, FO, ASP\}$

$p \in P = \{Intermediate\ Products\}$

$imp \in IMP = \{Imports\ for\ final\ products\ blending\}$

$i_u \in I_u = \{Inlet\ of\ intermediate\ products\ \ to\ unit\ u\}$

$b_{fp} \in B_{fp} = \{blended\ products\ to\ final\ products\}$

For each unit u, a set of inlet products I_u supplied to the unit is defined as follows:

$I_{HDU} = \{LDO_D, MDO_D, LCGO_{FCC}\}$

$I_{RF}.\{MSR_D,\ HSR_D, HN_D, MCN_{FCC}, VBN_{VB}\}$

$I_{FCCU} = \{HVGO_V, BSGO_V, VR_V, UCO_{HC}\}$

$I_{HCU} = \{HDO_D, HVGO_V\}$

$I_{LBOU} = \{UCO_{HC}\}$

$I_{VBU} = \{BSGO_V, VR_V\}$

For each final product *fp*, a set of allowed blended products B_{fp} is defined as follows:

$B_{ROG} = \{RFG_D, RFG_{HD}, RFG_{RF}, RFG_{FCC}, RFG_{HC}, RFG_{LB}, RFG_{VB}\}$

$B_{LPG} = \{LPG_D, LPG_{FCC}, LPG_{HC}\}$

$B_{NAP} = \{ LSR_D, MSR_D, HSR_D, N_{HD}, LN_{HC}, HN_{HC}, N_{LB}, VBN_{VB}\}$

$B_{GSL} = \{ LPG_{FCC}, LCN_{FCC}, MCN_{FCC}, R96_{RF}\}$

$B_{KR} = \{HSR_D, KR_D, KR_{HC}\}$

$B_{DSL} = \{DSL_{HD}, HN_{HC}, KR_{HC}, LDSL_{HC}, HDSL_{HC}, DSL_{LB}\}$

$B_{LBO} = \{LBO_{LB}\}$

$$B_{FO} = \begin{Bmatrix} VR_V, RS_{VB}, HCGO_{FCC}, KR_D, DSL_{HD}, HN_{HC}, \\ KR_{HC}, LDSL_{HC}, HDSL_{HC}, HCN_{FCC}, LCGO_{FCC} \end{Bmatrix}$$

$B_{ASP} = \{VR_V\}$

The decision variables are as following:

$$m = \left\{m^C_{D,c}, m^I{}_{u,iu}, m^B_{fp,b_{fp}}, m^{IMP}_{fp,imp}, m^{EXP}_{p}, m^{EXP}_{fp}\right\}$$

Where $m^C{}_{D,c}$ is the amount of crude *c* to distillation unit *D*, $m^I{}_{u,iu}$ is the amount of inlet material *iu* to unit *u*, $m^B_{fp,b_{fp}}$ is the amount of the intermediate product *p* used in blending (b_{fp}) of the final product *fp*, $m^{IMP}_{fp,imp}$ is the amount of the imported products *imp* used in blending final products *fp*, m^{EXP}_{p} is the amount of exported intermediate product *p*, and m^{EXP}_{fp} is the amount of exported final product *fp*. The unit of measure for *m* is in tonne per day.

3.5.1 Objective function

The objective (contribution margin) of the proposed model is to increase the overall refinery margin. It is defined as the revenue of the products minus the cost of the crude, imported materials and operating cost:

$$Max\ f = \sum_{fp} P_{fp} V_{fp}^{EXP} - \sum_{c} P_c V_{D,c}^{C} - \sum_{imp} P_{imp} V_{fp,imp}^{IMP} - \sum_{u} C_u \qquad (7)$$

Where V is volume in barrel (bbl), P_{fp}, P_c and P_{imp} are the prices of the final product *fp* in US$/bbl, crude c and the imported material *imp* respectively, and C_u is the operating cost for unit u.

3.5.2 Equality Constrains

The equality constrains include the material balance on the overall refinery, intermediate products, final products and energy balance.

Overall Material Balance:

The sum of the products minus the processed crudes and imports should equal zero as follow:

$$\sum_{fp} m_{fp}^{EXP} - \sum_{c} m^{C}{}_{c} - \sum_{imp} m_{fp,imp}^{IMP} = 0 \qquad (8)$$

Intermediates and Final Products Material Balance:

The flowrate of the exported intermediate product equals the production rate of the product from distillation unit and other units minus the amount of the product routed to other units and used in blending of final product. The material balances for the intermediate products can be generalized as follow:

$$m_p^{EXP} = \sum_c y_{D,c,p} m_{D,c}^C + \sum_{u \neq D} \sum_{iu} y_{u,iu,p} m^I{}_{u,iu} - \sum_{u \neq D} m^I{}_{u,p} - \sum_{fp} m_{fp,b_{fp}}^B \quad (9)$$

where $y_{D,c,p}$ is the yield of product p from distillation unit D using crude c, $y_{u,iu,p}$ is the yield of product p from unit u using inlet iu.

The amount of exported final products equals the amount of blended products and imported products. It can be generalized as follow:

$$m_{fp}^{EXP} = \sum_{b_{fp}} m_{fp,b_{fp}}^B + \sum_{imp} m_{fp,imp}^{IMP} \quad (10)$$

Energy balance and operating cost

The operating cost for each unit (C_u) (US$) is a summation of the of the energy cost in the unit (CEU_u) and catalyst cost in the unit (CCT_u) as below:

$$C_u = CEU_u + CCT_u \quad (11)$$

The energy required to each unit includes fuel gas, steam and power (EU) and is calculated as below:

$$EU_u = V_u R_u \quad (12)$$

where EU_u is the total energy consumed in each unit u, V_u is the unit volume feedrate (bbl) and R_u is the gas to oil ratio (MSCF/bbl) for each unit and is equivalent to fuel gas, steam and electricity. The values for R are available in Appendix D. The energy cost in each unit is calculated as below:

$$CEU_u = EU_u . P_{FU} = V_u R P_{FU} \quad (13)$$

where P_{FU} is the price of the fuel gas (US$/MSCF).

The catalyst cost is calculated for HDU, HCU, LBOU and FCCU:

$$CCT_u = \sum_u V_u \cdot P_{u,CT} \tag{14}$$

where $P_{u,CT}$ is the catalyst unit cost per barrel of unit feed. This cost varies for FCCU unit because each feed type has different catalyst requirement.

Volume calculations:

The volumetric flowrate to each unit (V_u) and the volume of exported final product (V_{fp}^{EXP}) are calculated using the density ρ of the intermediate streams p and the blended streams to final products *bfp* as below:

$$V_u = \sum_{iu} \frac{m^I{}_{u,iu}}{\rho_{iu}} \tag{15}$$

$$V_{fp}^{EXP} = \sum_{bfp} \frac{m^B_{fp,b_{fp}}}{\rho_{bfp}} + \sum_{imp} \frac{m^{IMP}_{fp,imp}}{\rho_{imp}} \tag{16}$$

3.5.2 Inequality Constrains

Properties:

Blending different components will result in having new properties of the final product. These properties are based on mixing rules. The simplest and practical mixing rule applicable to most physical properties is linear as below:

$$Q_{min} \leq Q_{fp} = \sum_{p} x_p \, Q_p \leq Q_{\max} \tag{17}$$

where Q_{fp} is the quality of the final product *fp*, Q_p is the quality of the blended component p, x_p is the fraction (volumetric or weight-based) of the blended component p, $Q_{min}$and Q_{max} are the lower and upper bounds, respectively.

The sulfur content (SLF) to HDU and HCU as well as the nitrogen content (NTR) to HCU and Conradson Carbon Residue (CCR) of the FCCU feed are constrained as given below:

The sulfur content in HDU feed:

$$\begin{aligned} \sum_{c} \left(m^{I}{}_{HD,c,LDO\_D} . SLF_{LDO,c} + m^{I}{}_{HD,c,MDO\_D} . SLF_{MDO,c} \right) \\ + m^{I}_{HDU,LCGO} . SLF_{LCGO} \\ \leq \left(\sum_{c} \left(m^{I}{}_{HD,c,LDO\_D} + m^{I}{}_{HD,c,MDO\_D} \right) \right. \\ \left. + m^{I}_{HDU,LCGO} \right) . 1.6 \; wt\% \end{aligned} \tag{18}$$

The sulfur content in HCU feed:

$$\begin{aligned} \sum_{c} \left(m^{I}{}_{HC,c,HDO\_D} . SLF_{c,HDO\_D} + m^{I}{}_{HC,c,HVGO\_V} . SLF_{c,HVGO\_V} \right) \\ \leq \left(\sum_{c} \left(m^{I}{}_{HC,c,HDO\_D} . SLF_{c,HDO\_D} \right. \right. \\ \left. \left. + m^{I}{}_{HC,c,HVGO\_V} . SLF_{c,HVGO\_V} \right) \right) . 3.0 \; wt\% \end{aligned} \tag{19}$$

The nitrogen content in HCU feed:

$$\sum_{c}\left(m^{I}{}_{HC,c,HDO\_D}\,.\,NTR_{c,HDO\_D} + m^{I}{}_{HC,c,HVGO\_V}.\,NTR_{c,HVGO\_V}\right) \leq \left(\sum_{c}\left(m^{I}{}_{HC,c,HDO\_D}\,.\,SLF_{c,HDO\_D} + m^{I}{}_{HC,c,HVGO\_V}.\,SLF_{c,HVGO\_V}\right)\right).1250\,ppm \quad \textbf{(20)}$$

The Conradson Carbon Residue content (wt%) in FCCU feed:

$$\sum_{c}\left(\boldsymbol{m^{I}{}_{FCC,c,HVGO\_V}}.\boldsymbol{CCR_{c,HVGO\_V,}} + \boldsymbol{m^{I}{}_{FCC,c,BSGO\_V}}.\boldsymbol{CCR_{c,BSGO\_V}} + \boldsymbol{m^{I}{}_{FCC,c,VR\_V}}.\boldsymbol{CCR_{c,VR\_V}}\right) + \boldsymbol{m^{I}{}_{FCC,UCO\_HC}}.\boldsymbol{CCR_{UCO\_HC}} \leq \left(\sum_{c}\left(\boldsymbol{m^{I}{}_{FCC,HVGO\_V,c}} + \boldsymbol{m^{I}{}_{FCC,BSGO\_V,c}} + \boldsymbol{m^{I}{}_{FCC,VR\_V,c}}\right) + \boldsymbol{m^{I}{}_{FCC,UCO\_HC}}\right).\boldsymbol{5.7\ wt\%} \quad \textbf{(21)}$$

The quality constraints used for the final products are as follows:

- Gasoline: sulfur (*S*), Reid vapor pressure (*RVP*) and research octane umber (*RON*). Since the blending of gasoline is done outside the refinery and the gasoline components are sold as final products (as discussed section 2.2), the above constraints will not be considered in the model.
- Kerosene: sulfur
- Diesel: sulfur, density and cetane index (*CI*)
- Fuel oil: sulfur and kinematic viscosity (*KV*)
- Lube base oil: viscosity index (*VI*)

The equations and specification limits are provided in Appendix A.

The viscosity index of the LBO Group III should be maintained between 120 and 125 and is constrained as below:

$$V^{EXP}{}_{LBO,c} .125 \geq \sum_{c} \frac{m^{B}{}_{LBO,c}\, VI_{LBO,c}}{\rho_{LBO,c}} \geq V^{EXP}{}_{LBO,c} .120 \qquad \textbf{(22)}$$

The viscosity index of the LBO from each crude $VI_{LBO,c}$ is calculated as shown in Eq. 23:

$$VI_{LBO,c} = f_{HCU,HDO} VI_{HDO,c} + f_{HCU,HVGO} VI_{HVGO,c} + \Delta VI_{HCU,c} + \Delta VI_{LBOU,c} \qquad \textbf{(23)}$$

where $f_{HCU,HDO}$ and $f_{HCU,HVGO}$ are the fraction of the HDO and HVGO routed to HCU, each are approximately between 40 to 50% of the total feed, $+\Delta VI_{HCU,c}$ is the increase in VI through HCU and $\Delta VI_{LBOU,c}$ is the decrease in VI through LBOU which are estimated using Table 10 as illustrated in section 3.4.

Capacities:

Each unit has volume capacity restriction which must be restricted as following:

$$CP_{u,min} \leq V_u \leq CP_{u,max} \qquad \textbf{(24)}$$

where $CP_{u,min}$ and $CP_{u,max}$ are the minimum and maximum limits of the unit capacity, respectively.

Availability of crudes and imports:

Availability of crude and the imported products used for blending are included within the inequality constraint set, where AV_c and AV_{imp} are the maximum available amount of crude or imported products respectively.

$$m^C{}_c \leq AV_c \tag{25}$$

$$m^{IMP}{}_{impfp} \leq AV_{imp} \tag{26}$$

3.5.2 FCCU feed density

The source of non-linearity in the developed model is attributed to the unknown total FCCU feed density. The density of the FCCU feed ($\rho_{FCC\,feed}$) is calculated in by dividing the mass flowrate over the volume flowrate (V_{FCC}) as shown in Eq. 27 and Eq. 28. In the nominator and the denominator, the mass flow rate of HVGO, BSGO, VR and UCO are all unknowns and to be optimized. Moreover, since HVGO, BSGO, and VR can be selected from different crudes, their induvial densities are also unknowns, creating the non-linearity in the model.

$$\rho_{FCC\,feed} = \frac{FCCU\ mass\ feed\ rate}{FCCU\ volume\ feed\ rate} = \\ = \frac{\sum_c (y_{V,c,HVGO}\, m^c_{D,c} + y_{V,c,BSGO}\, m^c_{D,c} + y_{V,c,VR}\, m^c_{D,c}) + m^I{}_{FCC,UCO}}{V_{FCC}} \tag{27}$$

$$V_{FCC} = \sum_c (y_{V,c,HVGO}\, m^c_{D,c}/\rho_{c,HVGO} + y_{V,c,BSGO}\, m^c_{D,c}/\rho_{c,BSGO} \\ + y_{V,c,VR}\, m^c_{D,c}/\rho_{c,VR}) + m^I{}_{FCC,UCO}/\rho_{HC,UCO} \tag{28}$$

The model was implemented in the General Algebraic Modelling System (GAMS IDE) using a laptop computer with Intel Core i7 CPU at 2.50 GHz PC Platform. The computational time is approximately 0.15 seconds. The model was solved using the non-linear CONOPT solver with different initial starting points. The model optimizes all intermediate and

final product streams across the oil refinery while meeting capacities, demand, and quality constraints. These constraints can be easily modified to include new data. The GAMS code is shown in Appendix E.

Chapter 4

Results, Discussion and Recommendation

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This chapter represents case studies using a group of the screened crudes to illustrate the benefit of the proposed model on the optimal decision. The cases include the evaluation of the proposed model with and without taking into account the change in VI, yield and quality tradeoff of the LBO optimum feed split to the conversion units and comparison of the current and proposed operation. The chapter also includes sensitivity analysis of the nonlinear model by varying the initial starting points, conclusion and future recommendation.

To interrogate the proposed refinery model, different case studies are considered in this section. The screening criteria mentioned in section 3.2 was applied to 50 crudes and 17 representative crudes were considered in this study. Those crudes were classified using Table 5 into Paraffinic (P), Paraffinic Intermediate type (PI), Intermediate (I) and Naphthenic Intermediate type (NI).

Table 11 shows the basic crude information including crude type, price, properties including API, TAN, and VI., while Table 12 show the main yields of the crudes including diesel, HDO, HVGO, AR and VR. The prices of the final products are shown in Table 13. More information about the crudes, units' yields and qualities are listed in Appendix B and C.

Table 11. Crude classification, prices and information

Crude	Crude Class	Price ($/bbl)	API	TAN (mgKOH/g)	Sulfur (wt %)	VI of HCU Feed
C1	I	65.60	33.2	0.09	1.85	77
C2	I	65.59	29.4	0.20	2.04	68
C3	P	67.65	30.6	0.15	2.44	136
C4	I	67.40	27.8	0.20	2.75	70
C5	NI	68.01	32.9	0.19	0.16	26
C6	P	67.03	27.4	0.26	2.89	131
C7	I	67.03	29.7	0.01	2.61	59
C8	I	66.24	31.5	0.10	1.93	68
C9	I	67.87	30.3	0.62	1.46	81
C10	I	69.40	32.8	0.20	2.32	79
C11	I	67.57	45.6	0.17	0.09	76
C12	I	69.40	30.6	0.10	2.86	63
C13	I	69.94	21.8	0.10	3.50	54
C14	P	69.55	42.1	0.21	0.04	125
C15	P	68.55	33.8	0.10	0.08	132
C16	PI	71.90	37.6	0.10	0.40	94
C17	P	70.36	37.0	0.09	0.33	114

Table 12. Main crudes yields (wt%)

Crude	Diesel (LDO & MDO)	HDO	HVGO	AR	VR
C1	22.8	9.5	13.6	32.2	14.9
C2	25.1	9.6	14.4	34.1	16.0
C3	19.5	9.2	14.9	39.5	20.1
C4	19.1	8.7	14.2	44.6	25.8
C5	33.8	10.7	11.7	19.0	5.2
C6	19.2	8.9	16.2	45.5	24.4
C7	20.6	9.3	14.9	41.8	22.8
C8	23.7	10.8	15.7	31.5	11.8
C9	19.0	10.4	18.1	44.9	21.9
C10	22.1	8.4	14.0	33.6	15.8
C11	22.6	6.4	10.3	17.6	4.7
C12	20.0	9.9	15.1	38.1	18.9
C13	16.7	8.1	13.4	51.9	34.2
C14	30.4	10.9	8.1	12.8	3.4
C15	21.9	14.4	18.1	40.1	17.4
C16	23.8	10.2	14.1	25.6	8.2
C17	24.3	9.8	13.7	26.0	9.4

Table 13. Final products prices

Final Product	Price US$/bbl
ROG	20.36
LPG	40.36
NAP	55.55
R96	76.15
LCN	71.94
MCN	68.90
KR	76.25
DSL	76.74
LBO	97.24
FO	54.99
ASP	57.31

(Marketing Department of the local refinery, 2019)

The case scenarios in this section will be evaluated at two conversions, namely 75 or 80% and at VI specification of 120 or 125.

4.1 Optimization with and without lube quality model

The crude selection was studied at two sets of HC conversion, 75% and 80%, with and without the lube quality model given in section 3.4. Figures 7 and 8 show the overall results of the optimization for the selected crudes and the associated products with and without the lube quality model for different cracking conversions.

At conversion of 75%, the crudes selected without accounting to the VI changes in the optimization model, are 81% intermediate and 19% naphthenic intermediate. The final VI specification of the LBO is 112 which violates the spec of group III base oils as shown in Fig. 10 and Table 14. Using the VI model with a spec of 120, gives an optimal crude split of 3% paraffinic, 90% intermediate and 7% naphthenic intermediate. When the spec increases to 125, the model selects 25% paraffinic, 69% intermediate and 6% naphthenic intermediate crudes.

At conversion of 80%, the crudes types' distribution without using the VI model are 82% intermediate and 18% naphthenic intermediate. The VI of the LBO is 118 which is not within the spec of group III base oils as shown in Fig. 10 and Table 15. Using the VI model with a spec of 120, gives crudes split of 83% intermediate and 17% naphthenic intermediate. When the spec increases to 125, the model selects 9% paraffinic to reach the required VI, 83% intermediate and 8% naphthenic intermediate crudes.

It can be noticed that at a lower conversion, more paraffinic crude is required because the change in VI is lower in HCU at low conversion compared to the change at high conversion. Since the paraffinic crudes are more expensive, the contribution margin using the VI model is lower at low conversion as shown in Fig. 9.

When the conversion decreases from 80% to 75%, the contribution margin decreases by MUS$59/day and MUS$75/day at VI spec of 120 and 125, respectively. This is because of the higher crude cost required to meet the higher spec of VI. Although the yield of LBO is higher at lower conversion, the LBO revenue is not enough to overcome the crudes cost, which means that the VI quality of the lubes has a higher impact on the crude selection and overall margin. On the other hand, the contribution margin without using the VI model is higher at lower conversion because of the higher overall products revenue (higher production of out of spec LBO as shown in Fig. 8 and Fig 10) compared to the cost of the selected crudes which do not satisfy the LBO final specification.

Figure 10 shows the yield and VI of LBO by the cracking conversion. Regardless of the LBO specification, the LBO yield is higher at lower conversion. When the VI specification is not accounted for, the resulting LBO cannot meet the VI specifications of Group III, because its VI value is lower than 120. Even if the hydrocracking conversion is increased up to 80%, it is difficult to meet the VI specification of the Group III from the selected crude set.

Table 14. Results at the optimal point at cracking conversion of 75%

Conversion at 75%	Withuot VI model	VI model-120	VI model-125
Margin, MUS$	3,981	3,891	3788
Product Revenue, MUS$/day	21,787	21,653	21,724
Crude Cost, MUS$/day	17,696	17,654	17,827
Operating Cost, MUS$/day	109	109	109
VI of LBO	112	120	125
Crude selection	P=0% I= 81% NI=19%	P=3% I= 90% NI=7%	P=25% I= 69% NI=6%

Table 15. Results at the optimal point at cracking conversion of 80%

Conversion at 80%	Withuot VI model	VI model-120	VI model-125
Margin, MUS$	3,961	3,950	3,863
Product Revenue, MUS$/day	21,728	21,708	21,655
Crude Cost, MUS$/day	17,658	17,648	17,681
Operating Cost, MUS$/day	110	110	110
VI of LBO	118	120	125
Crude selection	P=0% I= 82% NI=18%	P=0% I= 83% NI=17%	P=9% I= 83% NI=8%

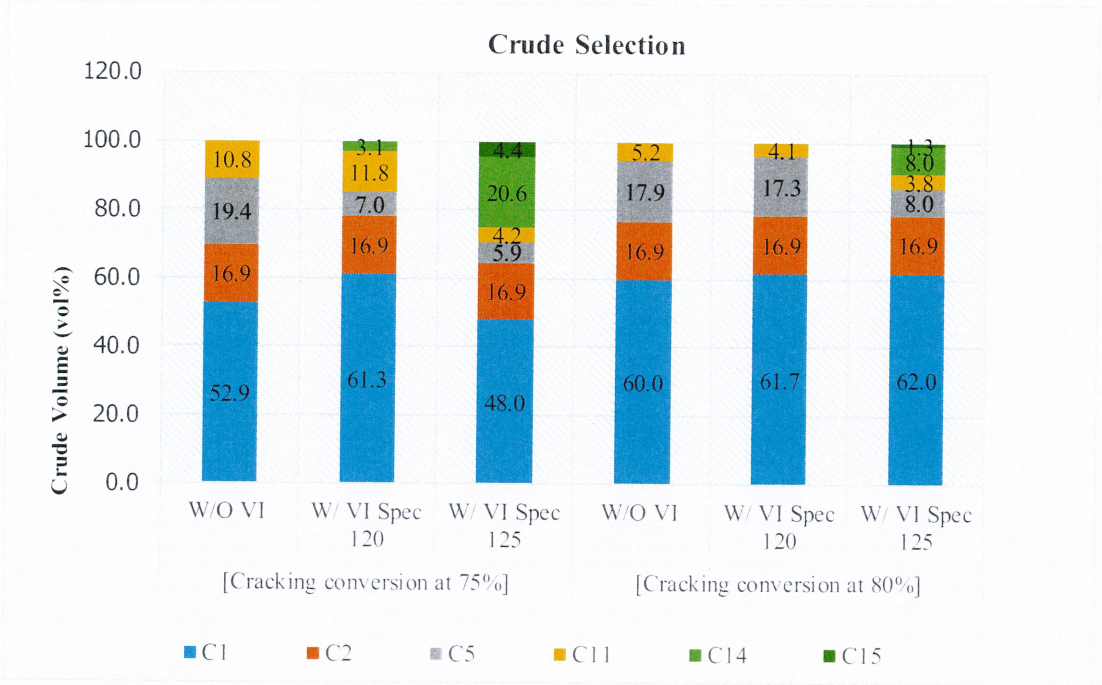


Figure 8. Optimal crude selection with (W) and without (W/O) VI model at different hydrocracking conversion.

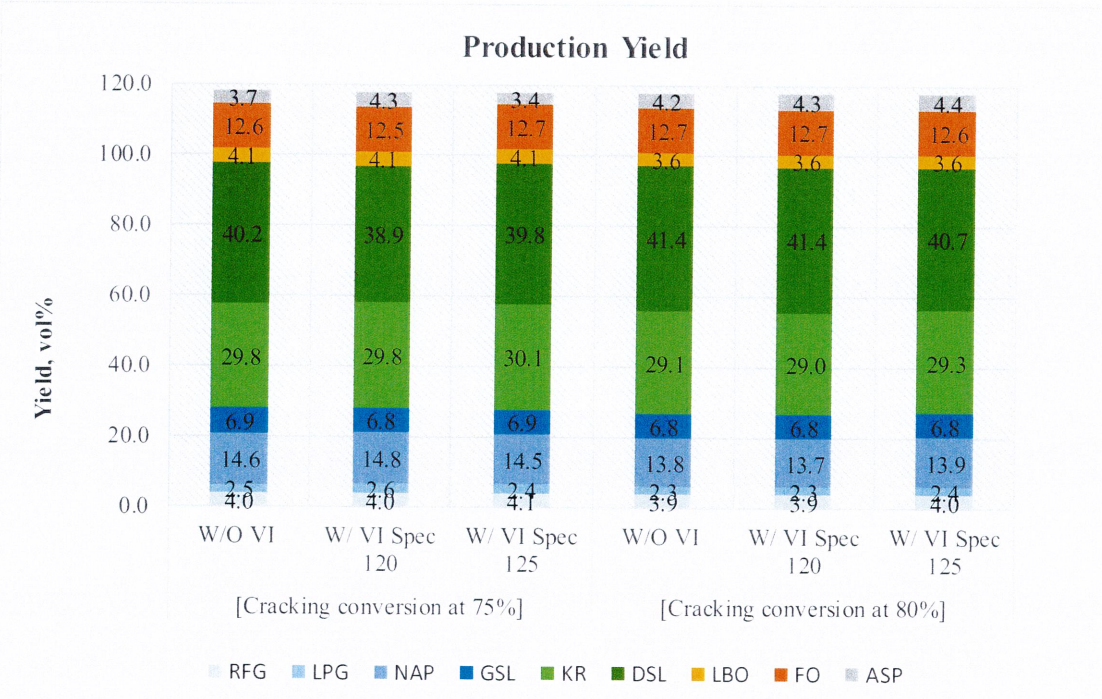


Figure 7. Products yield at different hydrocracking conversion with and without VI model.

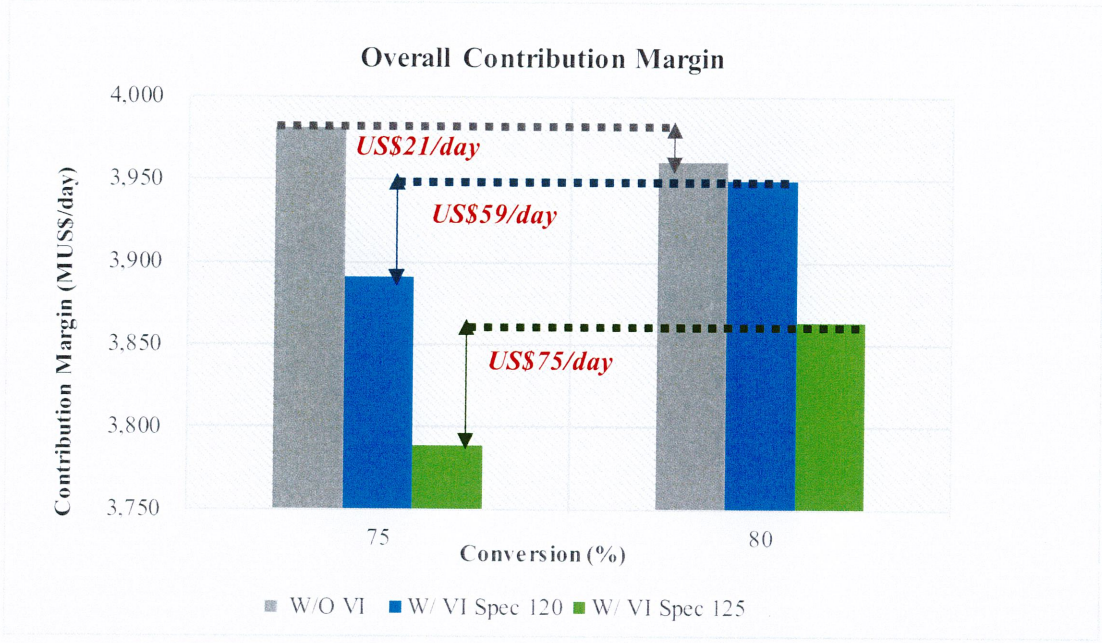


Figure 10. Contribution margin with and without VI model by hydrocracking conversion.

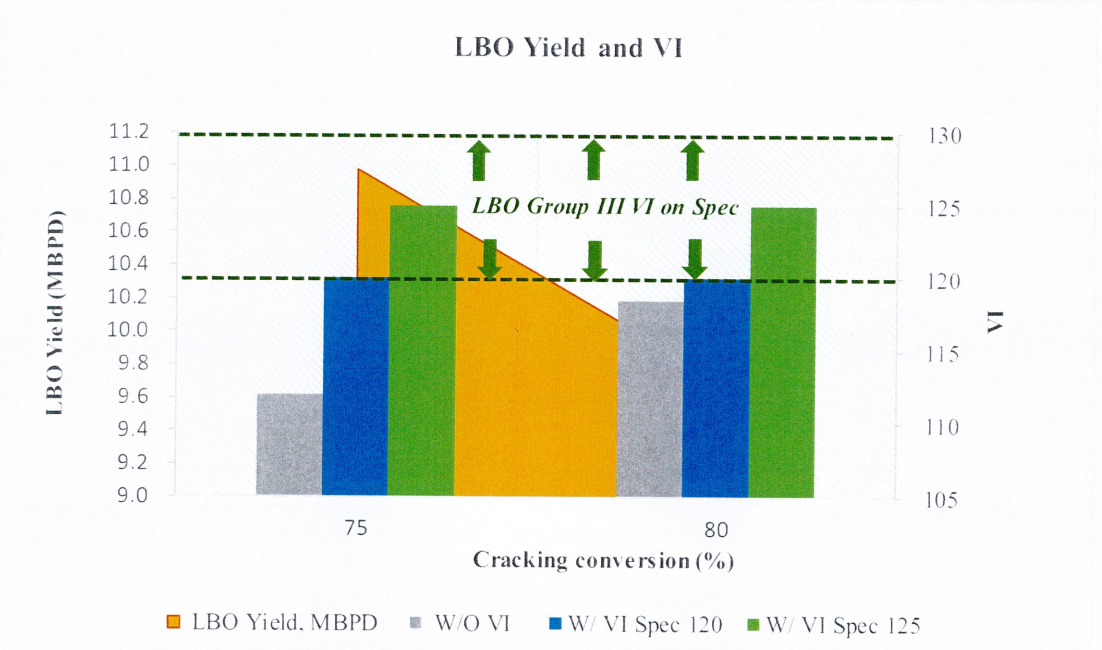


Figure 9. Yield and VI of LBO at 75 and 80% hydrocracking conversions.

4.2 Yield vs quality of LBO

To study the tradeoff between quality and yield of LBO, a set of crudes were selected and fixed at two cases, one at 75% and 80%. The selected crudes are shown in Table 16.

Table 16. LBO yield, VI and contribution margin at constant crude selection and different hydrocracking conversions

Crude	Class	Vol %
C1	I	62.0
C2	I	16.9
C5	NI	8.0
C11	I	3.8
C14	P	8.0
C15	P	1.3
Conversion	**75 %**	**80 %**
LBO Yield (MBPD)	11.0	9.7
VI	121	125
Contribution margin (MUS$/day)	3,862	3,863

Figure 11 shows the LBO yield versus the VI quality at low and high cracking conversion. The crude selection in both scenarios was maintained constant as shown in Table 16, to study the effect of the yield and quality at different conversions.

At low conversion of 75%, the LBOU feedrate is maximized and 11 MBPD of LBO is produced. However, the quality of the LBO is at 121 only, which is lower compared to its counterpart at higher conversion. At high conversion of 80%, lower LBO yield is produced at 9.7 MBPD, however, the VI is higher at 125. The contribution margin is higher at higher conversion by US$1000/day. This shows that there is a tradeoff

between the yield and the quality of the LBO at different cracking conversions.

Figure 12 shows the drop in the contribution margin by increasing the VI of LBO. The crude selection in this case was governed by optimization. Since the minimum specification for LBO Group III is 120, any increase in VI is considered a quality giveaway, giving that the price of LBO Group III is constant at US$/97bbl. The drop in the contribution margin is approximately US$21,000 per each VI unit per day when LBO VI is between 120 and 130. The drop in the margin can be estimated using the equations below:

$$Contribution\ Margin\ (\frac{MUS\$}{day}) = -20.9\ (VI) + 6467.9 \qquad \textbf{(29)}$$

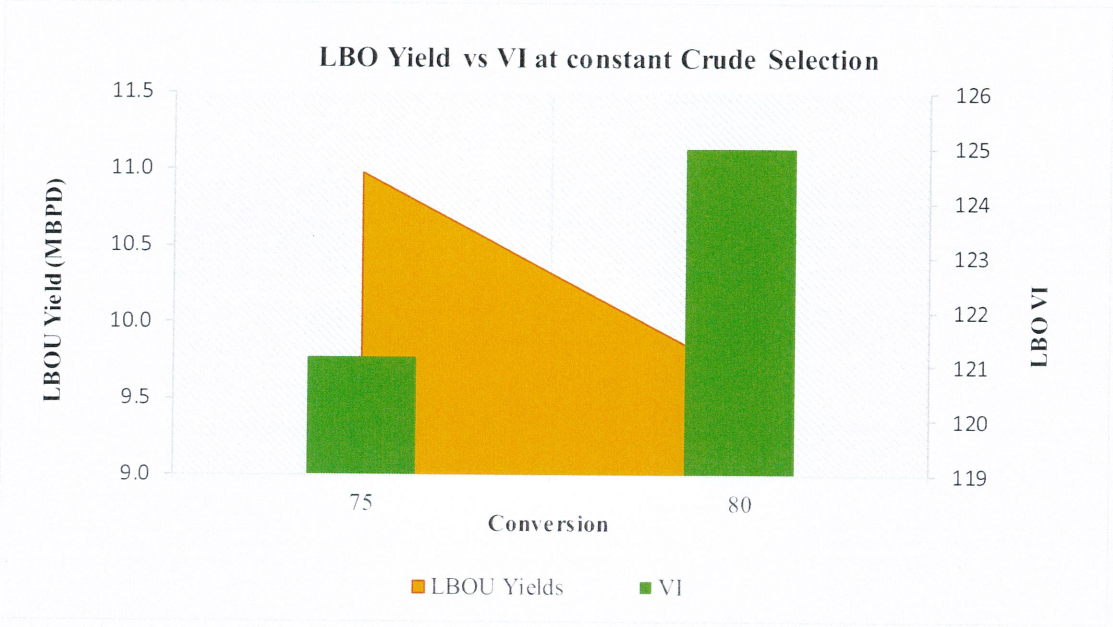


Figure 11. Yield and VI of LBO at a constant crude selection mix and different hydrocracking conversion.

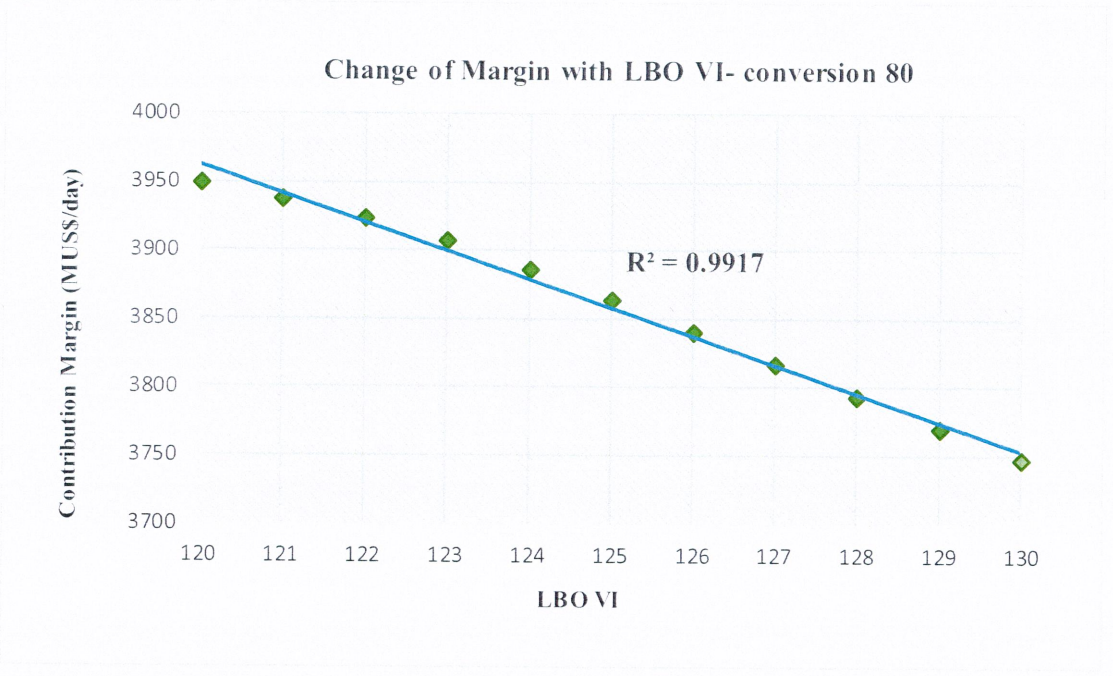


Figure 12. The change of contribution margin with changing the spec of LBO VI at 80% hydrocracking conversion.

4.3 Optimum feed split

Figure 13 represents the volume of UCO split to LBOU and FCCU at various price delta between LBO and gasoline components, while Fig. 14 represents the split at various price delta between LBO and diesel. The cracking conversion is maintained at 80%, LBO VI spec at 125 and the crude selection is constant at each run. The maximum UCO that can be produced from HCU at a conversion of 80% is 10.6 MBPD, hence the maximum UCO that can be fed to LBOU is 10.6 MBPD and the minimum feedrate to the unit is 6.0 MBPD.

The LBO price is usually the highest among other products prices and the LBO is usually higher than gasoline and diesel by approximately 20 to 25 US$/bbl. As a result, LBOU feedrate is almost always maximized.

As noticed in Fig. 13, the UCO to the LBOU is maintained at maximum when the price of LBO is higher than that of gasoline by US$2.3/bbl, while UCO feedrate to FCCU at this price is nil. As the price delta decreases between the LBO and gasoline, the UCO fed to LBOU decreases below 10.6 MBPD and that to FCCU increases, hence increasing the total feedrate to FCCU to above than 13 MBPD. When the price delta reaches US$1.7/bbl, the LBOU is maintained at minimum of 6.0 MBPD and UCO to FCCU is maintained at maximum rate of 4.5 MBPD, with a total feedrate of 17.5 MBPD. With every US$0.1/bbl drop in the price delta between LBO and the gasoline components, the contribution margin decreases by approximately US$800/day.

In Fig. 14, the UCO to the LBOU starts to decrease from maximum feedrate when the LBO price is lower than the diesel by approximately US$4.0/bbl and below. The LBOU feedrate is maintained at minimum of 6 MBPD when the price delta is higher than US$4.6/bbl. With every

US$0.1/bbl drop in the price delta between LBO and the diesel, the contribution margin decreases by approximately US$804/day.

In general, as the price between the LBO and gasolines shrinks, it is more attractive to produce more gasoline through increasing FCCU feedrate, given that UCO is a light feedstock to the FCCU compared to other feedstocks, which lowers the overall density of the FCCU feed and increases the production of gasoline yield. On the other hand, the LBO price must be below diesel price for the LBOU to decrease below maximum. At this level, FCCU feedrate will increase, LCGO production will increase and processed in HDU, and the overall diesel production will increase.

Figure 15 shows the feedrate composition to the FCCU, HCU and LBOU at low and high cracking conversion using the typical prices as shown in Table 13. The crude selection in this case was opened for optimization and the LBO VI spec was maintained at 125 shown in Fig 7.

The HVGO produced from the vacuum unit can be fed to both HCU and FCCU, while UCO produced from HCU can be fed to both LBOU and FCCU.

At low HCU conversion, 75%, 13.2 MBPD of UCO is produced from HCU, out of which 12 MBPD is fed to LBOU (maximum feedrate) and the balance is fed to FCCU at a rate of 1.2 MBPD.

On the other hand, when HCU conversion is high at 80%, only 10.6 MBPD of UCO is produced and is entirely fed to LBOU. Consequently, the HVGO, BSGO and VR fed to FCCU increased by 18, 8 and 6% respectively because of the lack of additional UCO.

The FCCU in both scenarios was maintained at minimum of 13 MBPD while HCU was maximized to 53 MBPD. The UCO is a better feedstock

to FCCU compared to BGSO and VR because it enhances the yield of the gasoline components. However, at the typical prices of LBO prices (which are higher than gasoline prices), the UCO to LBOU is always maximized to produce high value Group III LBO.

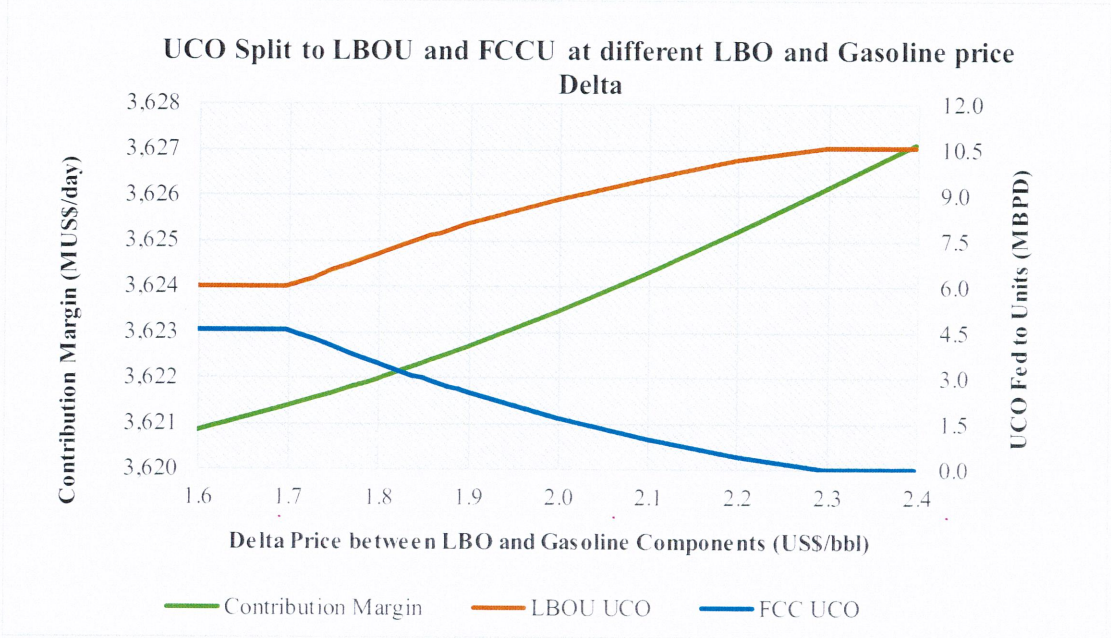


Figure 13. UCO Split to LBOU and FCCU at different LBO and gasoline price delta, constant crude selection, hydrocracking conversion of 80% and VI spec of 125.

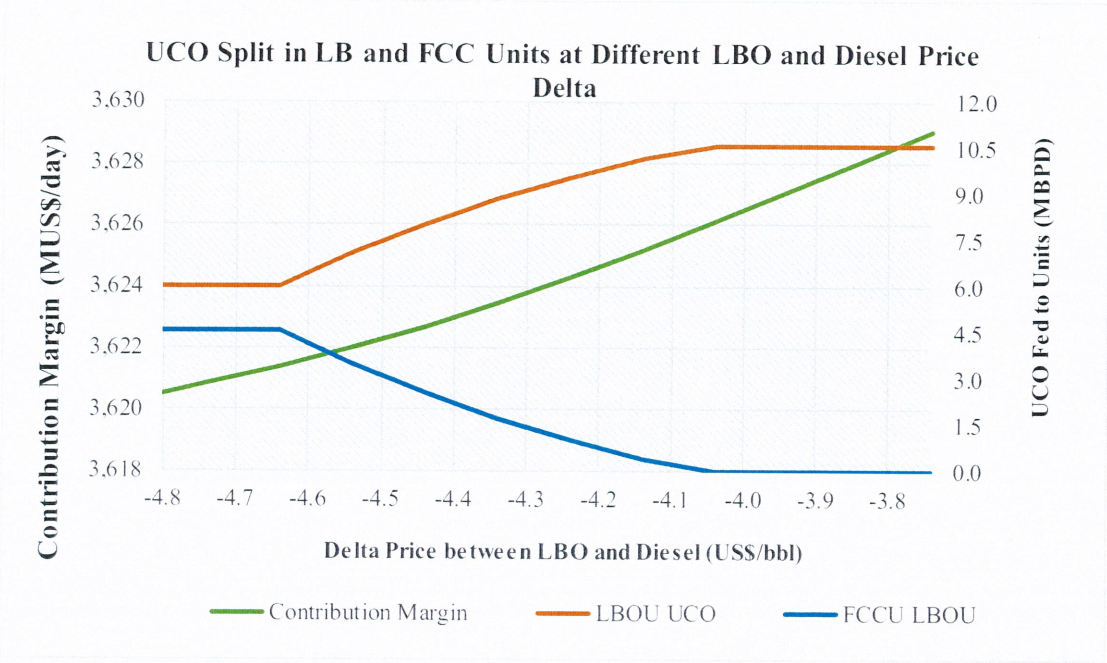


Figure 14. UCO Split to LBOU and FCCU at different LBO and diesel price delta, constant crude selection, hydrocracking conversion of 80% and VI spec of 125.

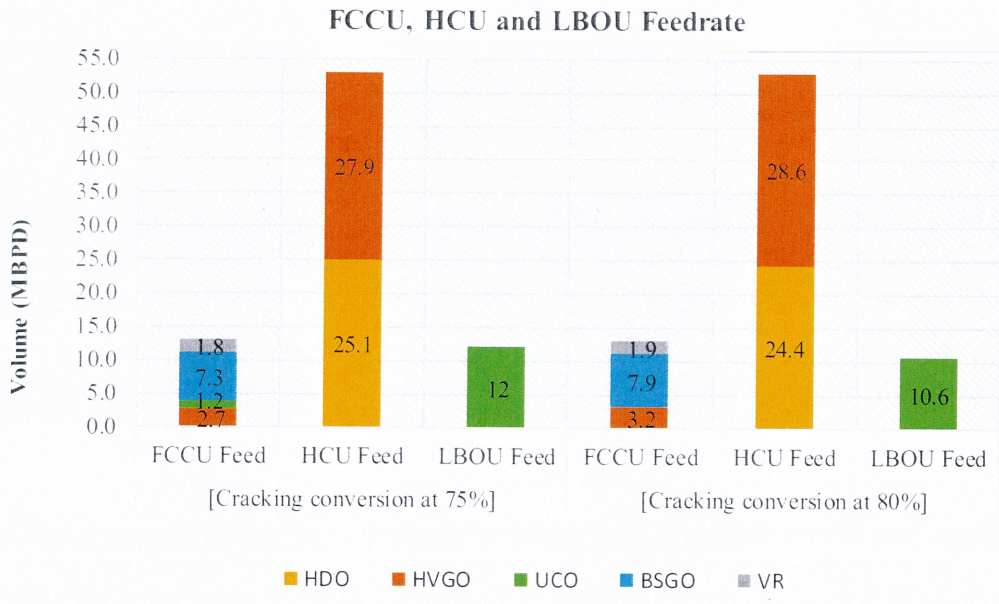


Figure 15. Feedrate composition of FCCU, HCU and LBOU at different hydrocracking conversion and crude selection.

4.4 Crude selection without price and availability constraint

In this scenario, all the crudes are assumed to have the same price at US$65/bbl with no maximum limitation on the imported volume. The VI model is used in this scenario and the required specification is assumed constant at 125. Figure 16 shows the crude selection, production yields and conversion units feedrate for this case. At 75%, the model selects 48.9%, 49.1% and 2.1% of paraffinic, intermediate, and naphthenic- intermediate crudes respectively. At 80% conversion, the selection changes to 26.5%, 64.3% and 9.2% respectively.

When compared to Fig. 7, the model selects C2 (Bahrain crude) which was originally limited to maximum of 45 MBPD and C17 (Texas crude) which is more expensive compared to other crudes due to geographical source effect.

In general, crude 2 is rich with middle distillates (kerosene and diesel) and HVGO which can help maximizing the feedrate to the HCU and FCCU and increasing the sales of kerosene and diesel in the same time.

At a low conversion, the higher selection of C17 enhances the VI of the LBO. Also, this crude has high HVGO yield which can satisfy the maximum requirement of HCU and increase FCCU to 15.8 MBPD (above the minimum of 13 MBPD) as shown in Fig. 16. On the other hand, when the price effect is considered, C17 is not selected due to its higher price compared its counterparts, and C14 (Tapis crude) and C15 (Bach Ho crude) are selected instead. Since C14 and C15 have less HVGO compared to C17, the FCCU was always at the minimum of 13 MBPD at low and high conversion as shown in Fig. 15.

On the product yields, it can be noticed that the kerosene production is higher while asphalt production is lower at 75% conversion. This is

because C17 has high kerosene yield and lower VR yield compared to the other selected crudes. Also, since FCCU had higher ratio of HVGO feed, the overall density of the feed was lower which contributed to higher gasoline production.

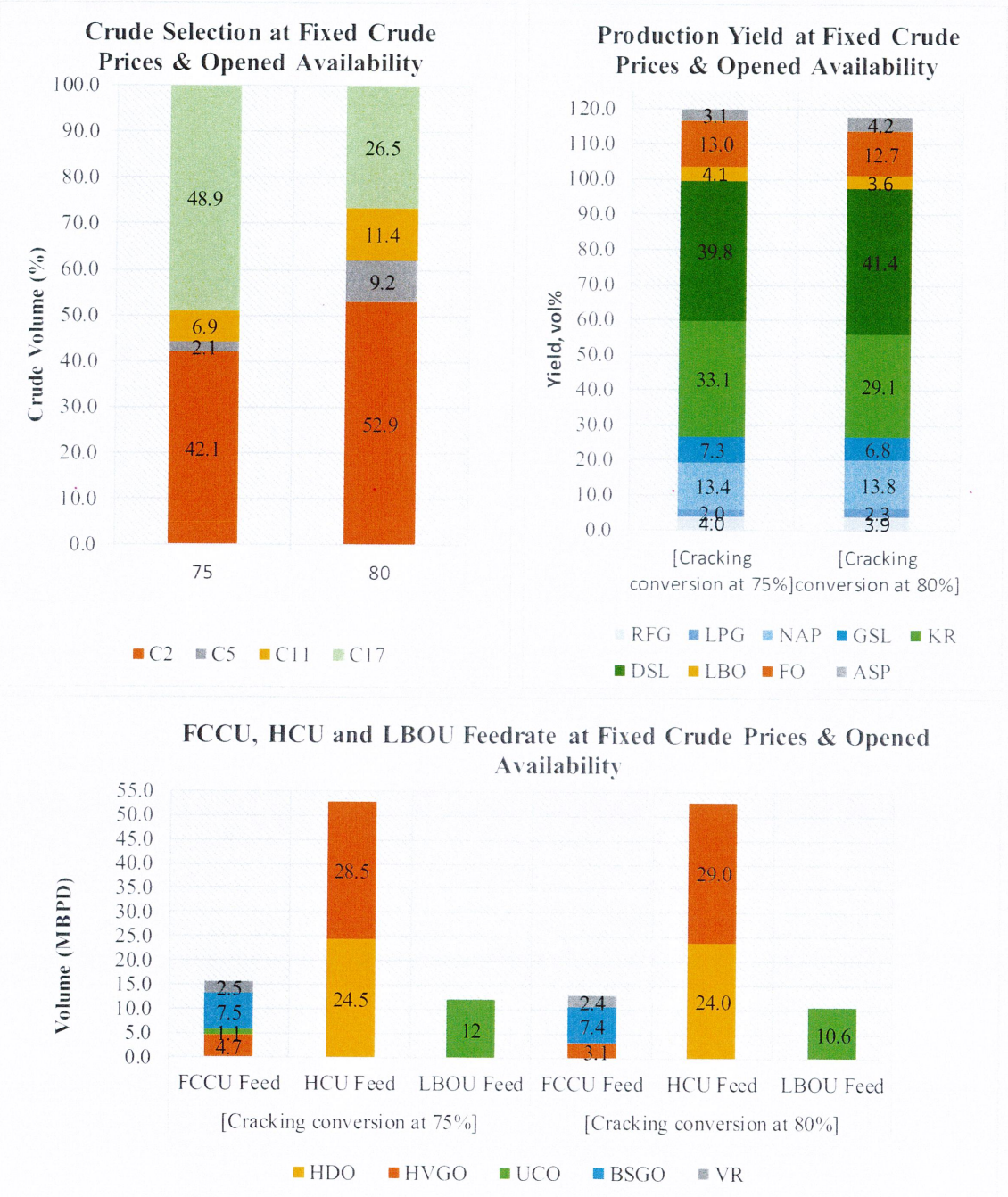


Figure 16. Crude selection, production yields and conversion units feedrate at fixed crude prices & opened availability, VI spec at 125.

4.5 Crude selection vs current operation

In this scenario, the current refinery operation, i.e. processing two crudes only which are Arab light and Bahrain crudes, was compared to an opened case of free crude selection. Both cases were evaluated at the same cracking conversion and VI spec, 80% and 125 respectively. Processing Arab light and Bahrain crudes can meet the final VI spec of VI at 125. As noticed in Table 17, opening the refinery to crude selection, increases the profit by US$103,000/day, which is equivalent to US$30 million per month. Although the cost of the crudes is higher in the free crude selection case by US$166,000/day since other crudes are costlier, the products revenue is higher by US$270,000/day mainly because of the higher middle distillate production (kerosene and diesel) as shown in Fig. 17.

Table 17. Comparison between the current (2 crudes) and the proposed (free crude selection) schemes

	Current Operation without crude selection	**Operation with crude selection**
Contribution Margin, MUS$/day	3760	3863
Product Revenue, MUS$/day	21,384	21,654
Crude Cost, MUS$/day	17,515	17,681
Operating Cost, MUS$/day	109	110
VI of LBO	125	125
Conversion, %	80	80
Crude selection	P=0% I= 100% NI=0%	P=9% I= 83% NI=8%

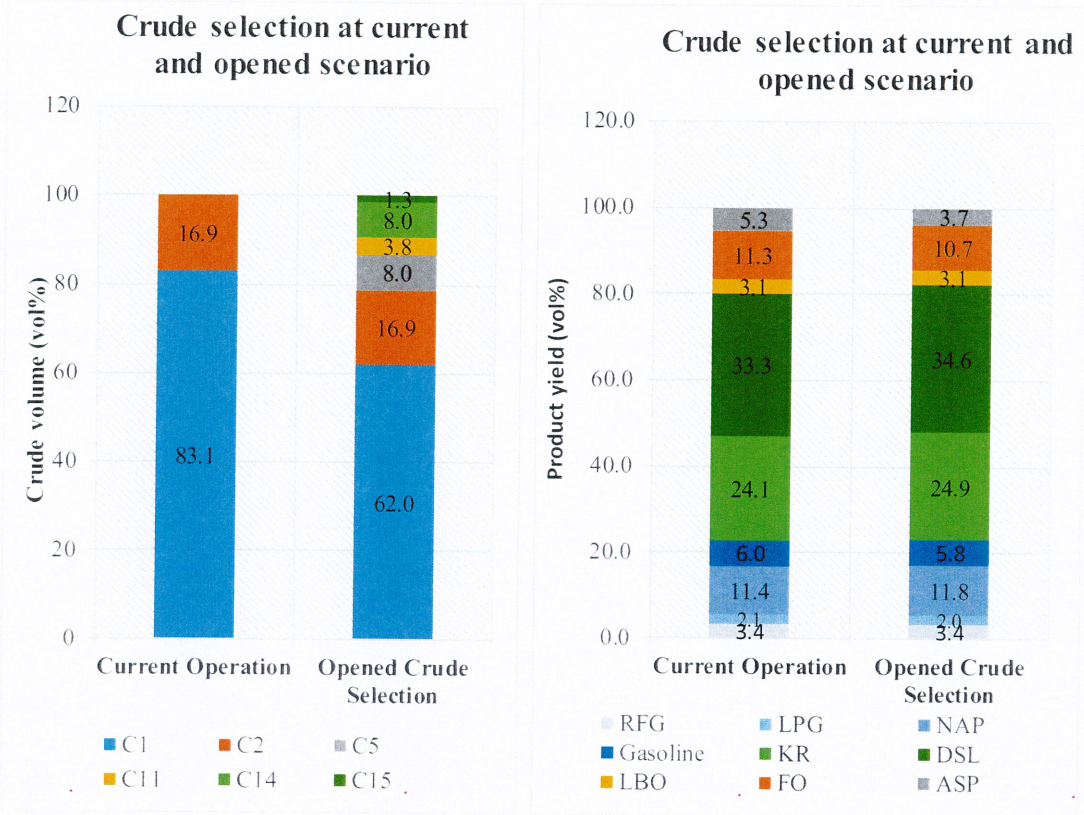


Figure 17. Crude selection and production yield at current (2 crudes) and the proposed (free crude selection) schemes.

4.6 Variation of starting points for solving nonlinear model

Since the nonlinear algorithms highly depend on the user supplied initial points, a heuristic sensitive analysis was done, by giving random initial points for some of the decision variables such as the amount of each purchased crude ($m^{C}_{D,c}$) and FCCU feed density ($\rho_{FCC\,feed}$), to study the effect on the objective function (contribution margin).

Different initial points were randomly selected for the 17 crudes at 10 different runs. Figure. 18 shows the change of crude selection at each run compared to the optimum run. These runs were conducted at a hydrocracking conversion of 80% and a VI spec of 125. The amounts of each purchased crude were selected to be varied since they are critical variables and affect the whole downstream processing units. In addition, the total crude cost accounts for almost 80% of the total refinery cost. Figure.19 shows the contribution margin for each run compared to the optimum run. It can be noticed that the contribution margins for all the conducted runs are lower than that of the optimum run, i.e. all less than MUS$3,863/day. Table 18 shows the marginal value of each crude at the optimum run. The marginal value or also called the shadow price can be defined as the change in the optimal objective value if the decision variable changed by one unit, given that all other decision variables and constraints remain the same. It can be noticed from the table that all the other nonoptimal crudes have negative marginal values if they were to increase by one more barrel.

In addition to varying the amount of purchased crude, the density of the FCCU density was varied since it is the variable responsible for the model's nonlinearity. The change in the contribution margin with the FCCU feed density is shown in Fig. 20, where the hydrocracking

conversion is at 80% and the VI spec at 125. The optimum density of the FCCU feed at the optimum crude run is 0.966. When the density of the FCCU feed was forced at lower and upper values, other decision variables including the purchased crudes will vary to meet the FCCU feed density. Also, the contribution margins for the runs before and after the optimum point were noticed to be lower than that at the optimum run of MUS$3,863/day. When the density of the FCCU feed was forced to be lower, more HVGO (feed of low density) had to be routed to FCCU, by lowering HCU feed. On the other hand, when the density of the FCCU feed was forced to be higher, heavier crudes had to purchased, which lower the yield of light and middle distillate products, and heavier material like BSGO and VR were routed to FCCU, which lower the gasoline yields in the unit.

Overall, several areas around the optimal solution were explored through a heuristic analysis and it can be concluded that the model was not stuck at a local optimum.

Table 18. Marginal values of each crude

Crude	Marginal Value (US$/bbl)
C1	-
C2	-
C3	-2.1
C4	-5.7
C5	-
6	-1.3
C7	-5.2
C8	-2.1
C9	-4.1
C10	-6.1
C11	-
C12	-6.3
C13	-15.1
C14	-
C15	-
C16	-4.6
C17	-1.1

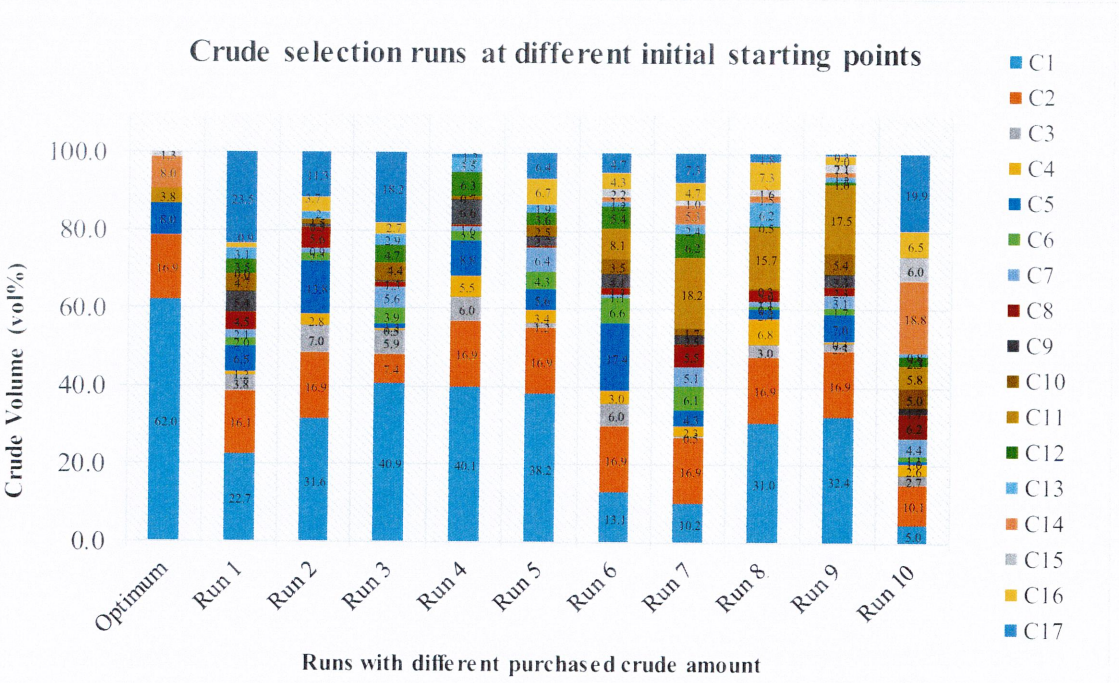


Figure 18. The change of purchased crude at random initial starting points, for hydrocracking conversion of 80% and VI of 125.

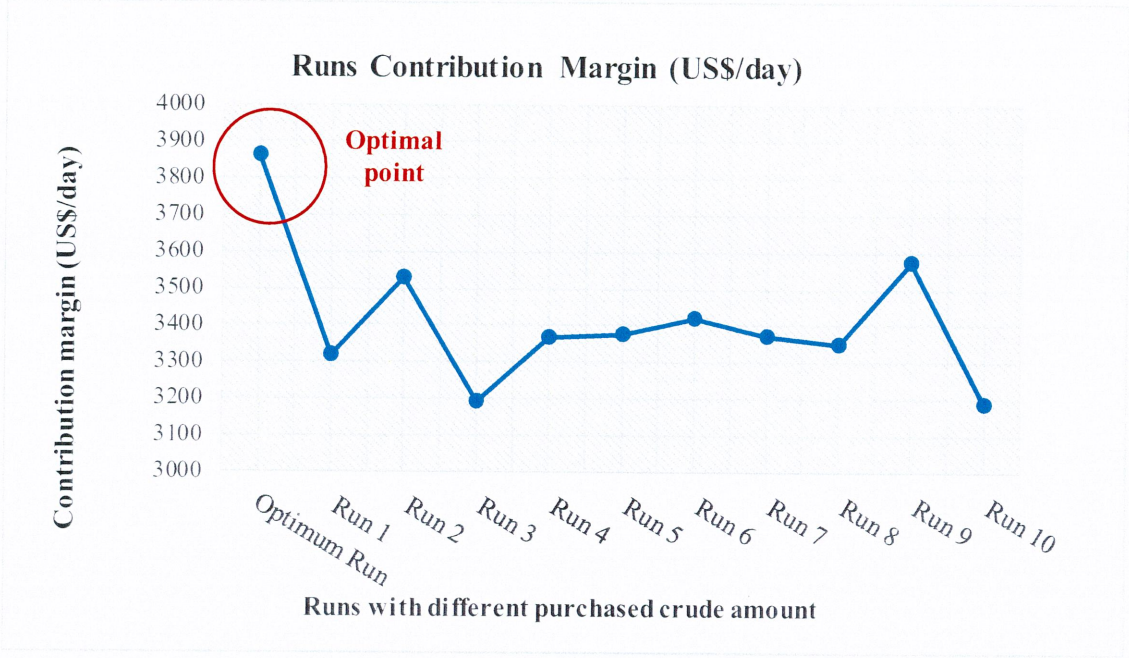


Figure 19. The change of contribution margin with purchased crude at random initial starting points.

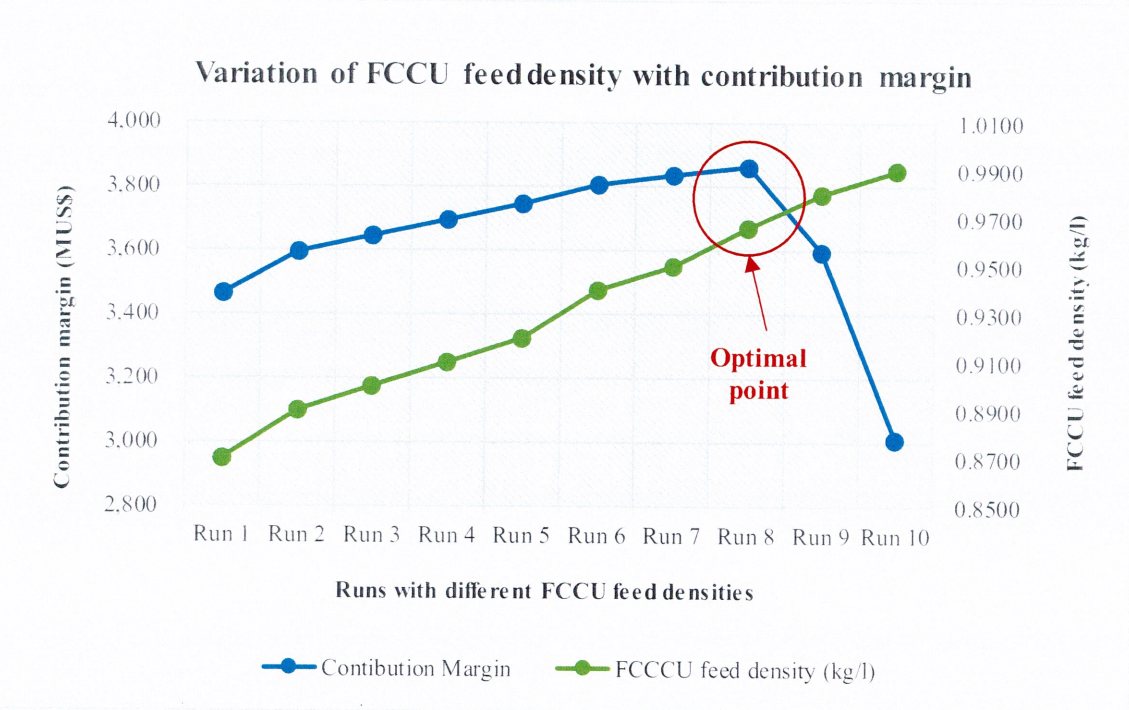


Figure 20. The change of contribution margin with FCCU feed density, for hydrocracking conversion of 80% and VI of 125.

4.7 Conclusion

An overall optimization methodology for a refinery with a lube base oil processing capability was developed, while considering the changes in the yields, conversion, LBO VI, besides other conventional bulk properties, to select the optimal crude types that maximize the overall refinery margin.

The studied local refinery has been processing two types of crudes only, since its inception. It is expected that if crude selection is considered in the refinery at a constant operation condition (cracking conversion at 80%, VI spec at 125); the contribution margin may increase by US$30 million per month. The crude selection in the refinery is impacted by the final VI spec of the LBO. When the LBO spec is ignored and is excluded from the overall refinery model, the crude selection is more fuel oriented and the final VI quality of the LBO does not meet the Group III specifications. The VI model to predict how VI change through the hydrocracking unit and the lube base oil unit has proved that more paraffinic crude is required as the final spec of the LBO VI increases. The percentage of the paraffinic crude decreases as the conversion of the hydrocracking unit increases because the UCO VI increases at higher conversion. Lowering the conversion is not beneficial

because more expensive paraffinic crudes are required to meet the higher spec of VI. At typical prices and free crude selection, the optimum crudes selected have a limited amount of HVGO, which is always maximized to HCU to maintain the unit at maximum feedrate. Similarly, UCO is also always maximized to LBOU to produce high value Group III LBO, while FCCU is kept at minimum of 13 MBPD. At low cracking conversion, extra UCO is routed to FCCU, and it enhances the yield of the gasoline components. The optimum UCO split between the LBOU and FCCU depends on the delta price between LBO, gasoline and diesel.

4.8 Future recommendations

In order to improve the optimization model, a number of future recommendations are proposed as following:

- This study was focused on developing a tactical production planning optimization model for a refinery with lube base oil unit with detailed information on yield and quality model rather than scheduling for a real execution. The refinery model proposed in this study can be extended to multi-period planning which takes into account operations with shutdown schedules, and the change in prices and inventories. In such cases, the refinery model can be used to determine the amount of various crude oil types to be purchased and stored at each defined period under a given price change scenario or computing the unit margin of each crude oil.
- Several refinery operations include pooling, which means the mixing of several streams prior to subsequent use, such as in crude units and other conversion units. However, this is one of the largest problems in modeling a refinery process since it includes the modeling of nonlinear ratio constraints This can be addressed in future work.
- The VI specification and conversion were not included as decision variables and rather, they were evaluated in different case scenarios and compared based on the optimal objective function values. If all these parameters were included as decision variables in the optimization, the overall problem becomes a mixed integer nonlinear program (MINLP), which can be difficult to solve. This option can be further studied in future.

- The conversion which was studied was high and low at 75% and 80% only because these are the two modes the unit operate at and because there is no accurate data on yield vs conversion since the simulation model for the HCU is still under development. Continuous conversion at wider range can be considered when data is available in future.
- Since the refinery can operate at periods where the market is volatile, e.g. pandemic period, stochastic optimization can be applied to take into account the uncertainties in prices.

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Appendix A

Detailed equations for the optimization formulation

A.1. Equality constraint: material balances for the intermediate products

A.1.1 Crude and Vacuum units:

$$m^{EXP}_{c,RFG\_D} = y_{D,c,RFG\_D}.m^{C}{}_{D,c} - m^{B}{}_{RFG,c,RFG\_D} = 0$$

$$m^{EXP}_{c,LPG\_D} = y_{D,c,LPG\_D.}.m^{C}{}_{D,c} - m^{B}{}_{LPG,c,LPG\_D} = 0$$

$$m^{EXP}_{c,LSR\_D} = y_{D,c,LSR\_D}.m^{C}{}_{D,c} - m^{B}{}_{NAP,c,LSR\_D} = 0$$

$$m^{EXP}_{c,MSR\_D} = y_{D,c,MSR\_D}.m^{C}{}_{D,c} - m^{I}{}_{RF,c,MSR\_D} - m^{B}{}_{NAP,c,MSR\_D} = 0$$

$$m^{EXP}_{c,HSR\_D} = y_{D,c,HSR\_D}.m^{C}{}_{D,c} - m^{I}{}_{RF,c,HSR\_D} - m^{B}{}_{NAP,c,HSR\_D} - m^{B}{}_{KR,c,HSR\_D} = 0$$

$$m^{EXP}_{c,KR\_D} = y_{D,c,KR\_D}.m^{C}{}_{D,c} - m^{B}{}_{KR,c,KR\_D} - m^{B}{}_{FO,c,KR\_D} = 0$$

$$m^{EXP}_{c,LDO\_D} = y_{D,c,LDO\_D}.m^{C}{}_{D,c} - m^{I}{}_{HD,c,LDO\_D} = 0$$

$$m^{EXP}_{c,MDO\_D} = y_{D,c,MDO\_D}.m^{C}{}_{D,c} - m^{I}{}_{HD,c,MDO\_D} = 0$$

$$m^{EXP}_{c,HDO\_D} = y_{D,c,HDO\_D}.m^{C}{}_{D,c} - m^{I}{}_{HC,c,HDO\_D} = 0$$

$$m^{EXP}_{c,HVGO\_V} = y_{V,c,HVGO\_V}.m^{C}{}_{D,c} - m^{I}{}_{HC,c,HVGO\_V} - m^{I}{}_{FCC,c,HVGO\_V} = 0$$

$$m^{EXP}_{c,BSGO\_V} = y_{V,c,BSGO\_V}.m^{C}{}_{D,c} - m^{I}{}_{FCC,c,BSGO\_V} - m^{I}{}_{VB,c,BSGO\_V} = 0$$

$$m^{EXP}_{c,R\_V} = y_{V,c,VR\_V}.m^{C}{}_{D,c} - m^{I}{}_{FCC,c,VR\_V} - m^{I}{}_{VB,c,VR\_V} - m^{B}{}_{FO,c,VR\_V} - m^{B}{}_{ASP,c,VR\_V} = 0$$

A.1.2 Crude and Vacuum intermediate pools:

$$\sum_{c} m^{B}{}_{RFG,c,RFG\_D} = m^{B}{}_{RFG,RFG\_D}$$

$$\sum_{c} m^{B}{}_{LPG,c,LPG\_D} = m^{B}{}_{LPG,LPG\_D}$$

$$\sum_{c} m^{B}{}_{NAP,c,LSR\_D} = m^{B}{}_{NAP,LSR\_D}$$

$$\sum_{c} m^{I}{}_{RF,c,MSR\_D} = m^{I}{}_{RF,MSR\_D}$$

$$\sum_{c} m^{B}{}_{NAP,c,MSR\_D} = m^{B}{}_{NAP,MSR\_D}$$

$$\sum_{c} m^{I}{}_{RF,c,HSR\_D} = m^{I}{}_{RF,HSR\_D}$$

$$\sum_{c} m^{B}{}_{NAP,c,HSR\_D} = m^{B}{}_{NAP,HSR\_D}$$

$$\sum_{c} m^{B}{}_{KR,c,HSR\_D} = m^{B}{}_{KR,HSR\_D}$$

$$\sum_{c} m^{B}{}_{KR,c,KR\_D} = m^{B}{}_{KR,KR\_D}$$

$$\sum_{c} m^{B}{}_{FO,c,KR\_D} = m^{B}{}_{FO,KR\_D}$$

$$\sum_{c} m^{I}{}_{HD,c,LDO\_D} = m^{I}{}_{HD,LDO\_D}$$

$$\sum_{c} m^{I}{}_{HD,c,MDO\_D} = m^{I}{}_{HD,MDO\_D}$$

$$\sum_{c} m^{I}{}_{HC,c,HDO\_D} = m^{I}{}_{HC,HDO\_D}$$

$$\sum_{c} m^{I}{}_{HC,c,HVGO\_V} = m^{I}{}_{HC,HVGO\_V}$$

$$\sum_{c} m^{I}{}_{FCC,c,HVGO\_V} = m^{I}{}_{FCC,HVGO\_V}$$

$$\sum_{c} m^{I}{}_{FCC,c,BSGO\_V} = m^{I}{}_{FCC,BSGO\_V}$$

$$\sum_{c} m^{I}{}_{VB,c,BSGO\_V} = m^{I}{}_{VB,BSGO\_V}$$

$$\sum_{c} m^{I}{}_{FCC,c,VR\_V} = m^{I}{}_{FCC,VR\_V}$$

$$\sum_{c} m^{I}{}_{VB,c,VR\_V} = m^{I}{}_{VB,VR\_V}$$

$$\sum_{c} m^{B}{}_{FO,c,VR\_V} = m^{B}{}_{FO,VR\_V}$$

$$\sum_{c} m^{B}{}_{ASP,c,VR\_V} = m^{B}{}_{ASP,VR\_V}$$

A.1.3 Hydrocracking unit:

$$m^{EXP}_{RFG\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,RFG\_HC} - m^{B}{}_{RFG,RFG\_HC} = 0$$

$$m^{EXP}_{LPG\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,LPG\_HC} - m^{B}{}_{LPG,LPG\_HC} = 0$$

$$m^{EXP}_{LN\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,LN\_HC} - m^{B}{}_{NAP,LN\_HC} = 0$$

$$m^{EXP}_{HN\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,HN\_HC} - m^{I}{}_{RF,HN\_HC} - m^{B}{}_{NAP,HN\_HC} - m^{B}{}_{DSL,HN\_HC} - m^{B}{}_{FO,HN\_HC} = 0$$

$$m^{EXP}_{KR\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,KR\_HC} - m^{B}{}_{KR,KR\_HC} - m^{B}{}_{DSL,KR\_HC} - m^{B}{}_{FO,KR\_HC} = 0$$

$$m^{EXP}_{LDSL\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,LDSL\_HC} - m^{B}{}_{DSL,LDSL\_HC} - m^{B}{}_{FO,LDSL\_HC} = 0$$

$$m^{EXP}_{HDSL\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,HDSL\_HC} - m^{B}{}_{DSL,HDSL\_HC} - m^{B}{}_{FO,HDSL\_HC} = 0$$

$$m^{EXP}_{UCO\_HC} = (m^{I}{}_{HC,HDO\_D} + m^{I}{}_{HC,HVGO\_V}).y_{HC,UCO\_HC} - m^{I}{}_{LB,UCO\_HC} - m^{I}{}_{FCC,UCO\_HC} = 0$$

A.1.4 Lube Base Oil unit:

$$m^{EXP}_{RFG\_LB} = m^{I}{}_{HC,UCO\_HC}.y_{LB,RFG\_LB} - m^{B}{}_{RFG,RFG\_LB} = 0$$

$$m^{EXP}_{N\_LB} = m^{I}{}_{HC,UCO\_HC}.y_{LB,N\_LB} - m^{B}{}_{NAP,N\_LB} = 0$$

$$m^{EXP}_{DSL\_LB} = m^{I}{}_{HC,UCO\_HC}.y_{LB,DSL\_LB} - m^{B}{}_{DSL,DSL\_LB} = 0$$

$$m^{EXP}_{LBO\_LB} = m^{I}{}_{HC,UCO\_HC}.y_{LB,LBO\_LB} - m^{B}{}_{LBO,LBO\_LB} = 0$$

A.1.5 Hydrotreating unit:

$$m^{EXP}_{RFG\_HD} = (m^{I}{}_{HD,LDO\_D} + m^{I}{}_{HD,MDO\_D} + m^{I}{}_{HD,LCGO\_FCC}).\ y_{HD,RFG\_HD} - m^{B}{}_{RFG,RFG\_HD} = 0$$

$$m^{EXP}_{N\_HD} = (m^{I}{}_{HD,LDO\_D} + m^{I}{}_{HD,MDO\_D} + m^{I}{}_{HD,LCGO\_FCC}).\ y_{HD,N\_HD} - m^{B}{}_{NAP,N\_HD} = 0$$

$$m^{EXP}_{DSL\_HD} = (m^{I}{}_{HD,LDO\_D} + m^{I}{}_{HD,MDO\_D} + m^{I}{}_{HD,LCGO\_FCC}).\ y_{HD,DSL\_HD} - m^{B}{}_{DSL,DSL\_HD} - m^{B}{}_{FO,DSL\_HD} = 0$$

A.1.6 Fluid Catalytic Cracking unit:

$$m^{EXP}_{RFG\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,RFG\_FCC} - m^{B}{}_{RFG,RFG\_FCC} = 0$$

$$m^{EXP}_{LPG\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,LPG\_FCC} - m^{B}{}_{LPG,LPG\_FCC} = 0$$

$$m^{EXP}_{LCN\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,LCN\_FCC} - m^{B}{}_{LCN,LCN\_FCC} = 0$$

$$m^{EXP}_{MCN\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,MCN\_FCC} - m^{B}{}_{MCN,MCN\_FCC} = 0$$

$$m^{EXP}_{HCN\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,HCN\_FCC} - m^{B}{}_{NAP,MCN\_FCC} - m^{B}{}_{FO,MCN\_FCC} = 0$$

$$m^{EXP}_{LCGO\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,LCGO\_FCC} - m^{I}{}_{HD,LCGO\_FCC} - m^{B}{}_{FO,LCGO\_FCC} = 0$$

$$m^{EXP}_{HCGO\_FCC} = (m^{I}{}_{FCC,HVGO\_V} + m^{I}{}_{FCC,BSGO\_V} + m^{I}{}_{FCC,VR\_V} + m^{I}{}_{FCC,UCO\_HC}).y_{FCC,HCGO\_FCC} - m^{B}{}_{FO,HCGO\_FCC} = 0$$

A.1.7 Reforming unit:

$$m^{EXP}_{RFG\_RF} = (m^{I}{}_{RF,MSR\_D} + m^{I}{}_{RF,HSR\_D} + m^{I}{}_{RF,HN\_HC} + m^{I}{}_{RF,VBN\_VB}).y_{RF,RFG\_RF} - m^{B}{}_{RFG,RFG\_RF} = 0$$

$$m^{EXP}_{R96\_RF} = (m^{I}{}_{RF,MSR\_D} + m^{I}{}_{RF,HSR\_D} + m^{I}{}_{RF,HN\_HC} + m^{I}{}_{RF,VBN\_VB}).y_{RF,R96\_RF} - m^{B}{}_{R96,R96\_RF} = 0$$

A.1.8 Visebreaking unit:

$$m^{EXP}_{RFG\_VB} = (m^{I}{}_{VB,BSGO\_V} + m^{I}{}_{VB,VR\_V}).y_{VB,RFG\_VB} - m^{B}{}_{RFG,RFG\_VB} = 0$$

$$m^{EXP}_{VBN\_VB} = (m^{I}{}_{VB,BSGO\_V} + m^{I}{}_{VB,VR\_V}).y_{VB,VBN\_VB} - m^{I}{}_{RF,VBN\_VB} - m^{B}{}_{NAP,VBN\_VB} = 0$$

$$m^{EXP}_{VBR\_VB} = (m^{I}{}_{VB,BSGO\_V} + m^{I}{}_{VB,VR\_V}).y_{VB,VBR\_VB} - m^{B}{}_{FO,VBR\_VB} = 0$$

A.2. Equality constraint: material balances for the final products

$$m_{RFG}^{EXP} = m^{B}{}_{RFG,RFG\_D} + m^{B}{}_{RFG,RFG\_HC} + m^{B}{}_{RFG,RFG\_LB} + m^{B}{}_{RFG,RFG\_HD} + m^{B}{}_{RFG,RFG\_FCC} + m^{B}{}_{RFG,RFG\_RF} + m^{B}{}_{RFG,RFG\_VB}$$

$$m_{LPG}^{EXP} = m^{B}{}_{RFG,LPG\_D} + m^{B}{}_{RFG,LPG\_HC} + m^{B}{}_{RFG,LPG\_FCC}$$

$$m_{NAP}^{EXP} = m^{B}{}_{NAP,LSR\_D} + m^{B}{}_{NAP,MSR\_D} + m^{B}{}_{NAP,HSR\_D} + m^{B}{}_{NAP,N\_HD} + m^{B}{}_{NAP,LN\_HC} + m^{B}{}_{NAP,HN\_HC} + m^{B}{}_{NAP,N\_LB} + m^{B}{}_{NAP,HCN\_FCC} + m^{B}{}_{NAP,VBN\_VB}$$

$$m_{R96}^{EXP} = m^{B}{}_{R96,R96\_RF}$$

$$m_{LCN}^{EXP} = m^{B}{}_{LCN,LCN\_FCC}$$

$$m_{MCN}^{EXP} = m^{B}{}_{MCN,MCN\_FCC}$$

$$m_{KR}^{EXP} = m^{B}{}_{KR,HSR\_D} + m^{B}{}_{KR,KR\_D} + m^{B}{}_{KR,KR\_HC}$$

$$m_{DSL}^{EXP} = m^{B}{}_{DSL,DSL\_HD} + m^{B}{}_{DSL,HN\_HC} + m^{B}{}_{DSL,KR\_HC} + m^{B}{}_{DSL,LDSL\_HC} + m^{B}{}_{DSL,HDSL\_HC} + m^{B}{}_{DSL,DSL\_LB}$$

$$m_{LB}^{EXP} = m^{B}{}_{LB,LBO\_LB}$$

$$m_{FO}^{EXP} = m^{B}{}_{FO,VR\_V} + m^{B}{}_{FO,VBR\_V} + m^{B}{}_{FO,HCGO\_FCC} + m^{B}{}_{FO,KR\_D} + m^{B}{}_{FO,DSL\_HD} + m^{B}{}_{FO,HCN\_FCC} + m^{B}{}_{FO,LCGO\_FCC} + m^{B}{}_{FO,KR\_HC} + m^{B}{}_{FO,HN\_HC} + m^{B}{}_{FO,LDSL\_HC} + m^{B}{}_{FO,HDSL\_HC}$$

$$m_{ASP}^{EXP} = m^{B}{}_{ASP,VR\_V}$$

A.3. Inequality constraint: quality specifications for the final products

Kerosene Sulfur

$$\sum_{b_{KR}} m^{B}{}_{KR,b_{KR}}.SLF_{b_{KR}} \leq m_{KR}^{EXP}.0.3\ wt\%$$

Diesel sulfur, density and cetane index

$$\sum_{b_{DSL}} m^{B}{}_{DSL,b_{DSL}}.SLF_{b_{DSL}} \leq m_{DSL}^{EXP}.0.001\ wt\%$$

$$V_{DSL}^{EXP}.0.79 \leq m_{DSL}^{EXP} \leq V_{DSL}^{EXP}.0.86$$

$$\sum_{b_{DSL}} \frac{m^{B}{}_{DSL,b_{DSL}} CI_{b_{DSL}}}{\rho_{b_{DSL}}} \geq V_{DSL}^{EXP}.52$$

FO sulfur and kinematic viscosity

$$\sum_{b_{FO}} m^{B}{}_{FO,b_{FO}}.SLF_{b_{FO}} \leq m_{FO}^{EXP}.3.5\ wt\%$$

$$V_{FO}^{EXP}.240 \leq \sum_{b_{FO}} \frac{m^{B}{}_{FO,b_{FO}}.KV_{b_{FO}}}{\rho_{b_{FO}}} \leq V_{FO}^{EXP}.380$$

Lubes VI

$$VI_{LBO,c} = f_{HCU,HDO}VI_{HDO,c} + f_{HCU,HVGO}VI_{HVGO,c} + \Delta VI_{HCU,c} + \Delta VI_{LBOU,c}$$

$$\sum_{c} \frac{m^{B}{}_{LBO,c}\, VI_{LBO,c}}{\rho_{LBO,c}} \geq V^{EXP}{}_{LBO,c}.120$$

A.4. Inequality constraint: unit capacity volumes limitation

CDU (D)

$$195 \leq V_D \leq 267 \text{ (MBPD)}$$

VDU (V)

$$66 \leq V_V \leq 116 \text{ (MBPD)}$$

Reformer (RF)

$$6 \leq V_{RF} \leq 15 \text{(MBPD)}$$

HDU (HD)

$$28 \leq V_{HD} \leq 70 \text{ (MBPD)}$$

HCU (HC)

$$40 \leq V_{HC} \leq 53 \text{ (MBPD)}$$

LBOU (LB)

$$6 \leq V_{LB} \leq 12 \text{ (MBPD)}$$

FCCU (FC)

$$13 \leq V_{FCC} \leq 32 \text{ (MBPD)}$$

VBU (VB)

$$16 \leq V_{VB} \leq 24 \text{ (MBPD)}$$

A.5. Inequality constraint: unit inlet quality limits

The sulfur content to HDU:

$$\sum_{c}\left(m^{I}{}_{HD,c,LDO_D}\,.SLF_{LDO,c} + m^{I}{}_{HD,c,MDO_D}.SLF_{MDO,c}\right) + m^{I}_{HDU,LCGO}.SLF_{LCGO}$$

$$\leq \left(\sum_{c}\left(m^{I}{}_{HD,c,LDO_D} + m^{I}{}_{HD,c,MDO_D}\right) + m^{I}_{HDU,LCGO}\right).1.6\ wt\%$$

The sulfur content to HCU:

$$\sum_{c}\left(m^{I}{}_{HC,c,HDO\_D}\,.SLF_{c,HDO\_D} + m^{I}{}_{HC,c,HVGO\_V}.\ SLF_{c,HVGO\_V}\right)$$

$$\leq \left(\sum_{c}\left(m^{I}{}_{HC,c,HDO\_D}\,.SLF_{c,HDO\_D}\right.\right.$$

$$\left.\left. + m^{I}{}_{HC,c,HVGO\_V}.\ SLF_{c,HVGO\_V}\right)\right).3.0\ wt\%$$

The nitrogen content to HCU:

$$\sum_{c}\left(m^{I}{}_{HC,c,HDO\_D}\,.NTR_{c,HDO\_D} + m^{I}{}_{HC,c,HVGO\_V}.\ NTR_{c,HVGO\_V}\right)$$

$$\leq \left(\sum_{c}\left(m^{I}{}_{HC,c,HDO\_D}\,.SLF_{c,HDO\_D}\right.\right.$$

$$\left.\left. + m^{I}{}_{HC,c,HVGO\_V}.\ SLF_{c,HVGO\_V}\right)\right).1250\ ppm$$

The Conradson Carbon Residue (wt%) content to FCCU:

$$\sum_{c}\left(m^{I}{}_{FCC,c,HVGO\_V}.CCR_{c,HVGO\_V,}+m^{I}{}_{FCC,c,BSGO\_V}.CCR_{c,BSGO\_V}+m^{I}{}_{FCC,c,VR\_V}.CCR_{c,VR\_V}\right)$$

$$+m^{I}{}_{FCC,UCO\_HC}.CCR_{UCO\_HC}$$

$$\leq\left(\sum_{c}\left(m^{I}{}_{FCC,HVGO\_V,c}+m^{I}{}_{FCC,BSGO\_V,c}+m^{I}{}_{FCC,VR\_V,c}\right)\right.$$

$$\left.+m^{I}{}_{FCC,UCO\_HC}\right).5.7\ wt\%$$

Appendix B

Crude Information

Table B.1. Crude yield structure (wt%)

	RFG	LPG	LSR	MSR	HSR	KR	LDO	MDO	HDO	HVGO	BSGO	VR
C1	0.33	1.32	7.45	6.55	13.97	5.84	13.26	9.58	9.53	13.61	3.67	14.89
C2	0.10	0.37	3.91	4.52	15.58	6.73	15.41	9.69	9.64	14.36	3.66	16.02
C3	0.25	1.56	8.25	4.49	12.20	5.04	11.30	8.21	9.23	14.93	4.46	20.07
C4	0.18	1.27	7.41	4.49	9.60	4.64	11.19	7.92	8.75	14.24	4.47	25.84
C5	0.03	0.55	6.80	7.27	13.55	8.23	21.65	12.18	10.73	11.67	2.14	5.21
C6	0.44	1.39	6.22	3.85	9.99	4.42	11.53	7.71	8.92	16.21	4.91	24.42
C7	0.30	1.17	6.70	4.24	11.11	4.76	11.98	8.59	9.33	14.90	4.14	22.77
C8	0.44	0.83	7.36	5.21	13.97	6.23	13.84	9.83	10.84	15.73	3.88	11.85
C9	0.29	1.18	6.23	3.97	9.64	4.30	10.70	8.32	10.43	18.05	4.98	21.91
C10	0.21	1.00	9.79	7.06	12.78	4.99	13.68	8.43	8.42	13.98	3.89	15.76
C11	0.65	3.05	15.92	8.33	18.97	6.59	14.21	8.35	6.37	10.29	2.58	4.69
C12	0.26	1.09	8.07	5.42	12.28	4.83	11.81	8.22	9.92	15.12	4.12	18.88
C13	0.19	0.59	5.08	4.12	9.25	4.13	9.76	6.93	8.08	13.42	4.22	34.23
C14	0.52	1.51	10.65	8.07	16.85	8.26	19.64	10.79	10.90	8.11	1.30	3.43
C15	0.10	0.56	4.69	4.01	9.46	4.77	12.74	9.14	14.39	18.10	4.65	17.39
C16	0.36	1.69	10.66	7.64	14.20	5.91	13.90	9.87	10.17	14.06	3.38	8.18
C17	0.19	0.99	9.29	7.04	15.73	6.70	14.52	9.79	9.75	13.71	2.91	9.39

Table B.2. Specific gravity (SG) of distillated products from each crude at 15 °C

	RFG	LPG	LSR	MSR	HSR	KR	LDO	MDO	HDO	HVGO	BSGO	VR
C1	0.5004	0.5858	0.6769	0.7360	0.7836	0.8158	0.8487	0.8875	0.9133	0.9448	0.9751	1.0501
C2	0.4897	0.5873	0.6942	0.7437	0.7842	0.8193	0.8510	0.8945	0.9121	0.9479	0.9726	1.0567
C3	0.4409	0.5798	0.6846	0.7475	0.7784	0.8174	0.8488	0.8911	0.9133	0.9424	0.9813	1.0600
C4	0.5155	0.5885	0.6729	0.7331	0.7813	0.8138	0.8488	0.8892	0.9169	0.9447	0.9774	1.0686
C5	0.5164	0.5922	0.7052	0.7616	0.8073	0.8505	0.8684	0.8974	0.9285	0.9434	0.9720	1.0310
C6	0.4840	0.5824	0.6692	0.7320	0.7782	0.8135	0.8513	0.8863	0.9188	0.9501	0.9819	1.0744
C7	0.4337	0.5953	0.6726	0.7310	0.7735	0.8181	0.8458	0.8841	0.9180	0.9495	0.9775	1.0528
C8	0.4248	0.5917	0.6827	0.7434	0.7870	0.8283	0.8570	0.8918	0.9229	0.9541	1.0038	1.0893
C9	0.4336	0.5886	0.6769	0.7341	0.7750	0.8167	0.8428	0.8756	0.9042	0.9288	0.9509	1.0222
C10	0.4337	0.5937	0.6764	0.7340	0.7861	0.8214	0.8544	0.8933	0.9209	0.9474	0.9872	1.0766
C11	0.4331	0.5926	0.6798	0.7396	0.7815	0.8160	0.8402	0.8688	0.8890	0.9043	0.9319	0.9843
C12	0.4308	0.5920	0.6683	0.7382	0.7823	0.8163	0.8505	0.8892	0.9231	0.9521	0.9819	1.0681
C13	0.4273	0.5940	0.6818	0.7407	0.7848	0.8282	0.8599	0.8951	0.9257	0.9620	1.0039	1.0931
C14	0.4555	0.5871	0.6875	0.7455	0.7808	0.8250	0.8445	0.8512	0.8713	0.9024	0.9383	0.9923
C15	0.4469	0.5914	0.6930	0.7396	0.7789	0.8114	0.8264	0.8409	0.8602	0.8809	0.9162	0.9990
C16	0.4335	0.5891	0.6891	0.7549	0.7926	0.8253	0.8465	0.8760	0.8973	0.9190	0.9515	1.0145
C17	0.4868	0.5786	0.6825	0.7511	0.7911	0.8271	0.8471	0.8733	0.8941	0.9156	0.9255	1.0075

Table B.3. Sulfur of distillated products from each crude (wt%)

	RFG	LPG	LSR	MSR	HSR	KR	LDO	MDO	HDO	HVGO	BSGO	VR
C1	0.0	0.0	0.0	0.0	0.1	0.4	1.3	2.3	2.4	3.0	3.5	4.4
C2	0.0	0.0	0.0	0.0	0.1	0.3	1.1	2.4	2.6	3.2	3.7	4.8
C3	0.0	0.0	0.0	0.0	0.1	0.5	1.3	2.2	2.6	3.3	3.9	5.8
C4	0.0	0.0	0.0	0.0	0.1	0.4	1.4	2.5	2.8	3.3	4.1	6.0
C5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.3	0.4	0.6
C6	0.0	0.0	0.0	0.0	0.1	0.5	1.5	2.2	2.9	3.5	4.3	6.1
C7	0.0	0.0	0.0	0.1	0.1	0.5	1.6	2.5	3.1	3.9	4.6	6.1
C8	0.0	0.0	0.0	0.0	0.2	0.7	1.6	2.1	2.6	2.9	3.4	4.7
C9	0.0	0.0	0.0	0.0	0.1	0.3	0.6	1.0	1.3	1.7	2.2	3.3
C10	0.0	0.0	0.0	0.1	0.1	0.4	1.5	2.4	2.6	3.3	4.3	6.4
C11	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.3	0.3
C12	0.0	0.0	0.0	0.0	0.1	0.6	1.7	2.6	3.2	3.8	4.7	7.0
C13	0.0	0.0	0.1	0.2	0.4	1.2	2.0	2.4	2.9	3.4	4.1	6.4
C14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2
C15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2
C16	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.5	0.5	0.7	1.1	1.6
C17	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.5	0.7	1.3

Table B.4. Nitrogen of distillated products from each crude (ppm)

	RFG	LPG	LSR	MSR	HSR	KR	LDO	MDO	HDO	HVGO	BSGO	VR
C1	0	0	0	0	4	8	20	390	575	1178	1825	3852
C2	0	0	0	0	5	8	20	208	427	910	1577	3236
C3	0	0	0	0	0	4	24	306	575	1082	1993	4904
C4	0	0	0	0	0	0	17	189	484	1202	2381	5464
C5	0	0	0	1	2	11	56	386	1233	2965	5427	9366
C6	0	2	45	62	62	62	75	297	569	1046	1877	4230
C7	0	0	0	0	0	2	27	265	653	1405	2486	5268
C8	0	0	0	0	0	4	98	510	1143	2282	3644	6415
C9	0	0	0	0	0	2	28	218	620	1307	2180	5031
C10	0	0	0	0	0	3	59	515	1038	1596	2347	5419
C11	0	0	0	0	0	1	9	99	300	707	1247	2066
C12	0	0	0	0	0	2	43	346	780	1397	2232	4972
C13	0	0	0	0	0	5	192	721	1684	2714	3688	8696
C14	0	0	0	0	0	2	19	86	205	632	1609	2916
C15	0	0	0	0	0	3	49	227	526	1183	2439	6421
C16	0	0	0	0	0	2	28	302	755	1731	3488	7416
C17	0	0	0	1	3	10	68	316	735	1539	2403	5102

Table B.5. Kinematic viscosity of distillated products from each crude at 50 °C (cSt)

	RFG	LPG	LSR	MSR	HSR	KR	LDO	MDO	HDO	HVGO	BSGO	VR
C1	0	0	0	1	1	2	3	7	17	107	1,117	>9999
C2	0	0	0	1	1	2	3	8	19	121	1,208	>9999
C3	0	0	0	1	1	2	3	6	16	88	622	>9999
C4	0	0	0	1	1	1	3	7	20	106	1,081	>9999
C5	0	0	0	1	1	2	3	9	36	223	3,355	>9999
C6	0	0	0	1	1	2	3	8	20	157	3,670	>9999
C7	0	0	0	1	1	2	3	7	22	160	1,738	>9999
C8	0	0	0	0	1	2	3	8	23	187	26,650	>9999
C9	0	0	0	1	1	2	3	8	26	125	1,164	>9999
C10	0	0	0	1	1	2	3	8	23	113	826	>9999
C11	0	0	0	1	1	2	3	7	19	61	427	>9999
C12	0	0	0	1	1	2	3	7	22	159	1,283	>9999
C13	0	0	0	1	1	2	3	9	32	119	1,032	>9999
C14	0	0	0	1	1	2	3	6	15	54	818	>9999
C15	0	0	0	1	1	2	3	7	14	47	493	>9999
C16	0	0	0	1	1	2	3	8	21	93	925	>9999
C17	0	0	0	1	1	2	3	8	17	72	466	>9999

Table B.6. Whole crude properties

	SG	Sulfur (wt%)
C1	0.8590	1.85
C2	0.8755	2.04
C3	0.8672	2.44
C4	0.8842	2.83
C5	0.8598	0.16
C6	0.8862	2.89
C7	0.8756	2.91
C8	0.8648	1.93
C9	0.8708	1.46
C10	0.8582	2.32
C11	0.7919	0.09
C12	0.8689	2.86
C13	0.9215	3.50
C14	0.8074	0.04
C15	0.8516	0.08
C16	0.8314	0.40
C17	0.8351	0.33

Table B.7. HCU feed VI

	HDO	HVGO
C1	82	72
C2	69	66
C3	152	121
C4	84	57
C5	32	20
C6	152	109
C7	76	41
C8	87	50
C9	93	70
C10	97	62
C11	77	75
C12	69	56
C13	55	53
C14	137	112
C15	144	121
C16	106	82
C17	153	75

Table B.8. Conradson Carbon (wt%)

	HVGO	BSGO	VR
C1	1.3	4.3	27.7
C2	1.3	4.0	29.8
C3	1.6	5.5	28.6
C4	0.8	3.7	29.6
C5	0.6	5.8	20.7
C6	1.2	4.1	32.3
C7	1.2	4.5	26.8
C8	1.3	7.7	36.4
C9	0.7	4.0	22.8
C10	1.4	7.0	30.5
C11	0.2	2.5	16.2
C12	1.4	7.0	29.2
C13	1.5	7.3	34.3
C14	0.5	4.6	19.4
C15	0.4	3.6	20.1
C16	0.8	5.4	22.3
C17	0.0	0.0	25.4

Appendix C

Units and intermediate products information

C.1. HDU yields and qualities

Table C.1. HDU yields and qualities

	RFG	N	DSL
Yield (wt%)	0.92	1.99	97.09
SG	0.4406	0.76	0.834
Sulfur (wt%)	0.000	0.000	0.001
CI	-	-	61.5
KV (cSt)	-	-	3

C.2. HCU yields and qualities

Table C.2. HCU yields and qualities

	RFG	LPG	LN	HN	KR	LDSL	HDSL	UCO
Yields at different hydrocracking conversion (wt%)								
75%	1.93	0.87	7.51	4.23	7.42	50.28	5.03	22.72
80%	1.92	0.86	6.81	6.97	7.38	49.93	8.05	18.08
99%	1.85	2.20	5.83	13.31	15.44	52.74	5.16	3.48
Qualities								
SG	0.4589	0.5740	0.6879	0.7530	0.8070	0.8319	0.8314	0.8404
Sulfur (wt%)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CI	-	-	-	69.4	54.0	58.8	80.1	-
KV (cSt)	-	-	-	1	1	4	4	19

C.3. LBOU yields and qualities

Table C.3. LBOU yields and qualities

	RFG	N	DSL	LBO
Yield (wt%)	**1.30**	**4.00**	**2.55**	**92.14**
SG	0.69	0.7242	0.83	0.846
Sulfur (wt%)	0.000	0.000	0.000	0.000
CI	-	-	63.2	-
Conradson Carbon (wt%)	-	-	-	0.0

C.4. FCCU yields and qualities

Table C.4. FCCU yields and qualities

	RFG	LPG	LCN	MCN	HCN	LCGO	HCGO
Yields (wt%)							
Base yield SG at 0.9546	8.62	5.44	17.96	13.54	2.77	25.04	26.63
Delta yield Delta of -0.0192	0.63	0.57	1.16	0.63	0.09	-0.72	-2.36
Qualities							
SG	0.5355	0.5679	0.7173	0.7636	0.8481	0.9437	1.0482
Sulfur (wt%)	-	-	0.1	0.1	0.6	3.3	4.8
KV (cSt)	-	-	-	-	1	3	454

C.5. Reformer yields and qualities

Table C.5. Reformer yields and qualities

	RFG	REF
Yield (wt%)	9.1	90.9
SG	0.2724	0.7767

C.6. VBU yields and qualities

Table C.6. VBU yields and qualities

	RFG	VBN	VBR
Yield (wt%)	1.3	3.3	95.4
SG	0.4370	0.6809	1.0320
Sulfur (wt%)	-	0.7	4.5
KV (cSt)	-	-	704

Appendix D

Operating cost information

D.1. Operating cost information

Table D.1. Fuel and catalyst consumption in each unit

	R (gas to oil ratio), MSCF/bbl	Catalyst consumoption, US$/bbl feed
CDU & VDU	0.13	-
HDU	0.08	0.09
Reformer	0.85	0.05
FCCU	0.09	0.25 [1]
HCU	0.15	0.17
LBOU	0.11	0.14
VBU	0.24	-

Note: FCCU catalyst consumption (US$/bbl) depends on the feed: 0.0 for UCO, 0.25 for HVGO, 2.30 for BSGO, and 4.5 for VR.

Appendix F

GAMS code

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$onText

Production Planning with multiple crude options- Bapco

process- units CDU, HDU, HCU,... etc


$offText

*****************************************************************************************************

**Sets

*****************************************************************************************************

Set


CP   'crude oils and intermediate products'


/  C1, C2, C3 , C4, C5, C6, C7,


C8, C9, C10, C11, C12, C13, C14, C15, C16, C17 'crudes'

RFG_c, LPG_c, LSR_c, MSR_c, HSR_c, KR_c, LDO_c, MDO_c, HDO_c, AR_c 'intermediates from crude unit'


HVGO_v, BSGO_v, VR_v      'intermediates from vacuum unit'


RFG_hc75, LPG_hc75, LN_hc75, HN_hc75, KR_hc75, LDSL_hc75, HDSL_hc75, UCO_hc75  'intermediates from HCU @75 conv'

RFG_hc80, LPG_hc80, LN_hc80, HN_hc80, KR_hc80, LDSL_hc80, HDSL_hc80, UCO_hc80  'intermediates from HCU @80 conv'

RFG_hc99, LPG_hc99, LN_hc99, HN_hc99, KR_hc99, LDSL_hc99, HDSL_hc99, UCO_hc99  'intermediates from HCU @99 conv'

RFG_hc, LPG_hc, LN_hc, HN_hc, KR_hc, LDSL_hc, HDSL_hc, UCO_hc  'intermediates from HCU'

RFG_lb, N_lb, DSL_lb, MBO_lb      'intermediates from LBOU'

RFG_hd, N_hd, DSL_hd    'intermediates from HDU'

RFG_fcc, LPG_fcc, LCN_fcc, MCN_fcc, HCN_fcc, LCGO_fcc, HCGO_fcc  'intermediates from FCCU'
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RFG_fcc_B , LPG_fcc_B , LCN_fcc_B , MCN_fcc_B, HCN_fcc_B, LCGO_fcc_B , HCGO_fcc_B 'intermediates from FCCU Base'

RFG_fcc_D , LPG_fcc_D , LCN_fcc_D , MCN_fcc_D, HCN_fcc_D, LCGO_fcc_D , HCGO_fcc_D 'intermediates from FCCU Delta'

RFG_plt, REF_plt 'intermediates from Platformer (reformer)'

RFG_vb, VBN_vb, RS_vb 'intermediates from VBU'

*CTR 'imported cutters'

*B91 'imported gasoline 91'

*B95 'imported gasoline 95'

/

C(CP) 'crudes' / C1, C2, C3 , C4, C5, C6, C7,

C8, C9, C10, C11, C12, C13, C14, C15, C16, C17 /

P(CP) 'intermediate products'

/

RFG_c, LPG_c, LSR_c, MSR_c, HSR_c, KR_c, LDO_c, MDO_c, HDO_c, AR_c 'intermediates from crude unit'

HVGO_v, BSGO_v, VR_v 'intermediates from vacuum unit'

RFG_hc75, LPG_hc75, LN_hc75, HN_hc75, KR_hc75, LDSL_hc75, HDSL_hc75, UCO_hc75 'intermediates from HCU @75 conv'

RFG_hc80, LPG_hc80, LN_hc80, HN_hc80, KR_hc80, LDSL_hc80, HDSL_hc80, UCO_hc80 'intermediates from HCU @80 conv'

RFG_hc99, LPG_hc99, LN_hc99, HN_hc99, KR_hc99, LDSL_hc99, HDSL_hc99, UCO_hc99 'intermediates from HCU @99 conv'

RFG_hc, LPG_hc, LN_hc, HN_hc, KR_hc, LDSL_hc, HDSL_hc, UCO_hc 'intermediates from HCU'

RFG_lb, N_lb, DSL_lb, MBO_lb 'intermediates from LBOU'

RFG_hd, N_hd, DSL_hd 'intermediates from HDU'

RFG_fcc, LPG_fcc, LCN_fcc, MCN_fcc, HCN_fcc, LCGO_fcc, HCGO_fcc 'intermediates from FCCU'

RFG_fcc_B , LPG_fcc_B , LCN_fcc_B , MCN_fcc_B, HCN_fcc_B, LCGO_fcc_B , HCGO_fcc_B 'intermediates from FCCU Base'

RFG_fcc_D , LPG_fcc_D , LCN_fcc_D , MCN_fcc_D, HCN_fcc_D, LCGO_fcc_D , HCGO_fcc_D 'intermediates from FCCU Delta'

RFG_plt, REF_plt 'intermediates from Platformer'

RFG_vb, VBN_vb, RS_vb 'intermediates from VBU'

*CTR

*CTR is added in P just foe BFP (FO neds CTR)

/

U 'Units' / DV, HD, PLT, FCC, FCC_B, FCC_D, HC_75, HC_80, HC_99, HC, LB, VB/

FP 'Final Products' /RFG, LPG, NAP, KR, DSL, LBO, FO, ASP, LCN_fcc_f, MCN_fcc_f, REF_plt_f/

*IMP(CP) 'components imported' / CTR, B91, B95 /

Iu(U,P) ' inlet feed P to unit u'

/

HD.(LDO_c, MDO_c, HDO_c, LCGO_fcc)

PLT.(MSR_c, HSR_c, HN_hc, MCN_fcc,VBN_vb)

FCC.(HVGO_v,BSGO_v,VR_v, UCO_hc)

HC.(HDO_c, HVGO_v)

LB.(UCO_hc)

VB.(AR_c, BSGO_v, VR_v)

/

BFP (FP, P) 'set of Blended intermediate products into final products'

/

RFG.(RFG_c, RFG_hd, RFG_plt, RFG_fcc, RFG_hc, RFG_lb, RFG_vb)

LPG.(LPG_c, LPG_fcc, LPG_hc)

NAP.(LSR_c, MSR_c, HSR_c, N_hd, LN_hc, HN_hc, N_lb, VBN_vb)

KR.(HSR_c, KR_c, KR_hc)

DSL.(DSL_hd, HN_hc, KR_hc, LDSL_hc, HDSL_hc, DSL_lb)

LBO.(MBO_lb)

FO.(VR_v, RS_vb, HCGO_fcc, KR_c, DSL_hd, HN_hc, KR_hc, LDSL_hc, HDSL_hc, HCN_fcc, LCGO_fcc)

ASP.(VR_v)

/

*Prop 'Properties' /SLF, RVP, CI, KV, VI /

;

*conversion choose between 99, 80, 75,if 99 LBOU should be zero

scalar k 'conversion' /80/;

****

**yields

****

Table YD (C, P)'yields from each crude, wt%, sum=1'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	BSGO_v	VR_v
C1	0.0033	0.0132	0.0745	0.0655	0.1397	0.0584	0.1326	0.0958	0.0953	0.1361	0.0367	0.1489
C2	0.0010	0.0037	0.0391	0.0452	0.1558	0.0673	0.1541	0.0969	0.0964	0.1436	0.0366	0.1602

C3	0.0025	0.0156	0.0825	0.0449	0.1220	0.0504	0.1130	0.0821	0.0923	0.1493	0.0446
0.2007											
C4	0.0018	0.0127	0.0741	0.0449	0.0960	0.0464	0.1119	0.0792	0.0875	0.1424	0.0447
0.2584											
C5	0.0003	0.0055	0.0680	0.0727	0.1355	0.0823	0.2165	0.1218	0.1073	0.1167	0.0214
0.0521											
C6	0.0044	0.0139	0.0622	0.0385	0.0999	0.0442	0.1153	0.0771	0.0892	0.1621	0.0491
0.2442											
C7	0.0030	0.0117	0.0670	0.0424	0.1111	0.0476	0.1198	0.0859	0.0933	0.1490	0.0414
0.2277											
C8	0.0044	0.0083	0.0736	0.0521	0.1397	0.0623	0.1384	0.0983	0.1084	0.1573	0.0388
0.1185											
C9	0.0029	0.0118	0.0623	0.0397	0.0964	0.0430	0.1070	0.0832	0.1043	0.1805	0.0498
0.2191											
C10	0.0021	0.0100	0.0979	0.0706	0.1278	0.0499	0.1368	0.0843	0.0842	0.1398	0.0389
0.1576											
C11	0.0065	0.0305	0.1592	0.0833	0.1897	0.0659	0.1421	0.0835	0.0637	0.1029	0.0258
0.0469											
C12	0.0026	0.0109	0.0807	0.0542	0.1228	0.0483	0.1181	0.0822	0.0992	0.1512	0.0412
0.1888											
C13	0.0019	0.0059	0.0508	0.0412	0.0925	0.0413	0.0976	0.0693	0.0808	0.1342	0.0422
0.3423											
C14	0.0052	0.0151	0.1065	0.0807	0.1685	0.0826	0.1964	0.1079	0.1090	0.0811	0.0130
0.0343											
C15	0.0010	0.0056	0.0469	0.0401	0.0946	0.0477	0.1274	0.0914	0.1439	0.1810	0.0465
0.1739											
C16	0.0036	0.0169	0.1066	0.0764	0.1420	0.0591	0.1390	0.0987	0.1017	0.1406	0.0338
0.0818											
C17	0.0019	0.0099	0.0929	0.0704	0.1573	0.0670	0.1452	0.0979	0.0975	0.1371	0.0291
0.0939											

;

Table Y(U, P)'yields related to each unit'

	RFG_hc75	LPG_hc75	LN_hc75	HN_hc75	KR_hc75	LDSL_hc75	HDSL_hc75	UCO_hc75
HC_75	0.0193	0.0087	0.0751	0.0423	0.0742	0.5028	0.0503	0.2272

+

	RFG_hc80	LPG_hc80	LN_hc80	HN_hc80	KR_hc80	LDSL_hc80	HDSL_hc80	UCO_hc80
HC_80	0.0192	0.0086	0.0681	0.0697	0.0738	0.4993	0.0805	0.1808

+

	RFG_hc99	LPG_hc99	LN_hc99	HN_hc99	KR_hc99	LDSL_hc99	HDSL_hc99	UCO_hc99
HC_99	0.0185	0.0220	0.0583	0.1331	0.1544	0.5274	0.0516	0.0348

+

	RFG_lb	N_lb	DSL_lb	MBO_lb
LB	0.013	0.040	0.026	0.921

+

	RFG_hd	N_hd	DSL_hd
HD	0.009	0.020	0.971

+

	RFG_plt	REF_plt
PLT	0.091	0.909

+

	RFG_fcc_B	LPG_fcc_B	LCN_fcc_B	MCN_fcc_B	HCN_fcc_B	LCGO_fcc_B	HCGO_fcc_B
FCC_B	0.0862	0.0544	0.1796	0.1354	0.0277	0.2504	0.2663

+

	RFG_fcc_D	LPG_fcc_D	LCN_fcc_D	MCN_fcc_D	HCN_fcc_D	LCGO_fcc_D	HCGO_fcc_D
FCC_D	0.0063	0.0057	0.0116	0.0063	0.0009	-0.0072	-0.0236

+

RFG_vb VBN_vb RS_vb

VB 0.01 0.03 0.95

;

Parameter

Yhc(U,P) 'HCU yields';

*This is separated from the table to allow different conversion, to chnage conversion, change in above.

Yhc('HC','RFG_hc')= Y('HC_75','RFG_hc75')$(k=75) +Y('HC_80','RFG_hc80')$(k=80) +Y('HC_99','RFG_hc99')$(k=99) ;

Yhc('HC','LPG_hc')= Y('HC_75','LPG_hc75')$(k=75) +Y('HC_80','LPG_hc80')$(k=80) +Y('HC_99','LPG_hc99')$(k=99) ;

Yhc('HC','LN_hc')= Y('HC_75','LN_hc75')$(k=75) +Y('HC_80','LN_hc80')$(k=80) +Y('HC_99','LN_hc99')$(k=99) ;

Yhc('HC','HN_hc')= Y('HC_75','HN_hc75')$(k=75) +Y('HC_80','HN_hc80')$(k=80) +Y('HC_99','HN_hc99')$(k=99) ;

Yhc('HC','KR_hc')= Y('HC_75','KR_hc75')$(k=75) +Y('HC_80','KR_hc80')$(k=80) +Y('HC_99','KR_hc99')$(k=99) ;

Yhc('HC','LDSL_hc')= Y('HC_75','LDSL_hc75')$(k=75) +Y('HC_80','LDSL_hc80')$(k=80) +Y('HC_99','LDSL_hc99')$(k=99) ;

Yhc('HC','HDSL_hc')= Y('HC_75','HDSL_hc75')$(k=75) +Y('HC_80','HDSL_hc80')$(k=80) +Y('HC_99','HDSL_hc99')$(k=99) ;

Yhc('HC','UCO_hc')= Y('HC_75','UCO_hc75')$(k=75) +Y('HC_80','UCO_hc80')$(k=80) +Y('HC_99','UCO_hc99')$(k=99) ;

****

**QUALITY Information

****

Parameter

dcr(C) 'density of crudes'

/

C1 0.8590

C2 0.8796

C3 0.8672

C4 0.8842

C5 0.8598

C6 0.8862

C7 0.8756

C8 0.8648

C9 0.8708

C10 0.8582

C11 0.7919

C12 0.8689

C13 0.9215

C14 0.8074

C15 0.8516

C16 0.8314

C17 0.8351

/

;

Table dc(C,P)'density of products related to each crudes'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	BSGO_v	VR_v
C1	0.5004	0.5858	0.6769	0.7360	0.7836	0.8158	0.8487	0.8875	0.9133	0.9448	0.9751	1.0501
C2	0.4897	0.5873	0.6942	0.7437	0.7842	0.8193	0.8510	0.8945	0.9121	0.9479	0.9726	1.0567
C3	0.4409	0.5798	0.6846	0.7475	0.7784	0.8174	0.8488	0.8911	0.9133	0.9424	0.9813	1.0600
C4	0.5155	0.5885	0.6729	0.7331	0.7813	0.8138	0.8488	0.8892	0.9169	0.9447	0.9774	1.0686
C5	0.5164	0.5922	0.7052	0.7616	0.8073	0.8505	0.8684	0.8974	0.9285	0.9434	0.9720	1.0310
C6	0.4840	0.5824	0.6692	0.7320	0.7782	0.8135	0.8513	0.8863	0.9188	0.9501	0.9819	1.0744
C7	0.4337	0.5953	0.6726	0.7310	0.7735	0.8181	0.8458	0.8841	0.9180	0.9495	0.9775	1.0528
C8	0.4248	0.5917	0.6827	0.7434	0.7870	0.8283	0.8570	0.8918	0.9229	0.9541	1.0038	1.0893
C9	0.4336	0.5886	0.6769	0.7341	0.7750	0.8167	0.8428	0.8756	0.9042	0.9288	0.9509	1.0222
C10	0.4337	0.5937	0.6764	0.7340	0.7861	0.8214	0.8544	0.8933	0.9209	0.9474	0.9872	1.0766
C11	0.4331	0.5926	0.6798	0.7396	0.7815	0.8160	0.8402	0.8688	0.8890	0.9043	0.9319	0.9843
C12	0.4308	0.5920	0.6683	0.7382	0.7823	0.8163	0.8505	0.8892	0.9231	0.9521	0.9819	1.0681

C13	0.4273	0.5940	0.6818	0.7407	0.7848	0.8282	0.8599	0.8951	0.9257	0.9620	1.0039
1.0931											
C14	0.4555	0.5871	0.6875	0.7455	0.7808	0.8250	0.8445	0.8512	0.8713	0.9024	0.9383
0.9923											
C15	0.4469	0.5914	0.6930	0.7396	0.7789	0.8114	0.8264	0.8409	0.8602	0.8809	0.9162
0.9990											
C16	0.4335	0.5891	0.6891	0.7549	0.7926	0.8253	0.8465	0.8760	0.8973	0.9190	0.9515
1.0145											
C17	0.4868	0.5786	0.6825	0.7511	0.7911	0.8271	0.8471	0.8733	0.8941	0.9156	0.9255
1.0075											

;

Table SLFc(C,P) 'sulfur of products related to each crudes'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	
BSGO_v	VR_v										
C1	0.0018	0.0152	0.0237	0.0355	0.0962	0.4208	1.3409	1.8664	2.3584	2.9592	3.4957
4.4079											
C2	0.0005	0.0024	0.0016	0.0089	0.0502	0.2956	1.0994	2.0024	2.5675	3.1519	3.6668
4.8307											
C3	0.0002	0.0078	0.0241	0.0388	0.1313	0.4936	1.2764	2.1597	2.6409	3.2528	3.9414
5.8062											
C4	0.0000	0.0011	0.0074	0.0178	0.1113	0.4185	1.3932	2.4942	2.8075	3.3352	4.0791
5.9801											
C5	0.0000	0.0002	0.0014	0.0030	0.0167	0.0489	0.1072	0.1853	0.2493	0.3264	0.4213
0.5553											
C6	0.0000	0.0008	0.0051	0.0130	0.0953	0.4653	1.4781	2.2289	2.8657	3.4998	4.2765
6.0717											
C7	0.0000	0.0053	0.0386	0.0552	0.1114	0.5368	1.5882	2.4552	3.1333	3.9118	4.5690
6.1408											

C8	0.0000	0.0000	0.0225	0.0339	0.1576	0.7407	1.6233	2.1136	2.5885	2.9017	3.4410
4.6803											
C9	0.0000	0.0000	0.0254	0.0386	0.0885	0.2630	0.5904	1.0298	1.3130	1.6855	2.2145
3.3433											
C10	0.0000	0.0000	0.0214	0.0651	0.1449	0.4410	1.4805	2.4175	2.6143	3.3217	4.3473
6.4360											
C11	0.0000	0.0000	0.0052	0.0040	0.0050	0.0129	0.0613	0.1990	0.2043	0.2134	0.2675
0.3245											
C12	0.0000	0.0000	0.0269	0.0378	0.1067	0.5800	1.6616	2.6390	3.2134	3.8279	4.7069
6.9550											
C13	0.0000	0.0000	0.1096	0.1538	0.3969	1.2360	1.9838	2.4267	2.9125	3.4344	4.0552
6.3519											
C14	0.0000	0.0000	0.0009	0.0015	0.0039	0.0152	0.0396	0.0607	0.0632	0.0762	0.1092
0.1573											
C15	0.0000	0.0000	0.0016	0.0009	0.0013	0.0075	0.0365	0.0641	0.0662	0.0942	0.1442
0.2082											
C16	0.0000	0.0000	0.0028	0.0044	0.0134	0.0554	0.2145	0.4688	0.5340	0.7203	1.0710
1.5905											
C17	0.0000	0.0002	0.0021	0.0048	0.0178	0.0714	0.2203	0.3451	0.4042	0.4871	0.7285
1.3366											

;

Table NTRc(C,P) 'nitrogen of products related to each crudes'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	BSGO_v	VR_v
C1	0.0	0.0	0.0	0.0	3.5	7.6	20.4	390.2	574.6	1178.2	1825.3	3851.6
C2	0.0	0.0	0.0	0.2	4.8	8.1	19.9	208.2	427.4	910.3	1576.6	3235.7
C3	0.0	0.0	0.0	0.1	0.5	3.6	23.9	305.8	574.7	1082.2	1992.5	4903.7
C4	0.0	0.0	0.0	0.0	0.0	0.2	16.6	188.7	484.2	1202.2	2381.5	5464.4

C5	0.0	0.0	0.2	0.5	2.0	10.8	56.3	386.1	1233.5	2965.1	5426.7	9366.5
C6	0.0	1.7	44.7	62.2	62.2	62.3	75.2	296.7	568.5	1045.5	1876.9	4230.3
C7	0.0	0.0	0.0	0.1	0.4	2.0	27.0	265.5	652.7	1404.9	2485.7	5268.4
C8	0.0	0.0	0.1	0.2	0.5	4.4	97.7	510.0	1143.0	2282.3	3644.4	6415.5
C9	0.0	0.0	0.1	0.2	0.4	1.8	27.9	218.0	620.3	1306.9	2180.3	5031.3
C10	0.0	0.0	0.0	0.0	0.4	2.8	58.6	514.7	1038.0	1596.0	2346.7	5418.9
C11	0.0	0.0	0.0	0.0	0.1	0.7	9.4	99.3	300.0	707.3	1246.8	2066.2
C12	0.0	0.0	0.0	0.0	0.2	1.9	43.0	346.0	780.1	1396.6	2232.4	4971.8
C13	0.0	0.0	0.0	0.1	0.1	5.0	192.4	721.3	1683.8	2714.0	3687.8	8695.9
C14	0.0	0.0	0.1	0.2	0.4	1.9	19.5	86.3	204.6	631.8	1608.5	2915.6
C15	0.0	0.0	0.1	0.2	0.5	2.9	48.8	227.4	525.8	1183.5	2438.7	6420.6
C16	0.0	0.0	0.0	0.0	0.2	1.6	27.6	302.4	755.1	1731.0	3487.7	7416.4
C17	0.0	0.0	0.2	0.6	2.7	10.0	67.5	315.6	735.2	1538.9	2402.9	5101.8

;

Table CCRc(C,P) 'CCR of products related to each crudes'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	BSGO_v	VR_v
C1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	4.3	27.7
C2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.3	4.0	29.8
C3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	5.5	28.6
C4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	3.7	29.6
C5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	5.8	20.7
C6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	4.1	32.3
C7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	4.5	26.8
C8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	7.7	36.4

C9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	4.0	22.8
C10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	7.0	30.5
C11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.5	16.2
C12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	7.0	29.2
C13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	7.3	34.3
C14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	4.6	19.4
C15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	3.6	20.1
C16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	5.4	22.3
C17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.4

;

Table KVc(C,P)'kinematic viscosity of products related to each crudes @50C'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	BSGO_v	VR_v
C1	0.3162	0.3162	0.4169	0.5890	0.9265	1.5770	2.9166	7.4448	17.2358	106.8863	1116.8347	389769
C2	0.3162	0.3162	0.4218	0.5866	0.9102	1.5601	3.0013	8.1294	19.3725	120.9292	1208.1357	183543
C3	0.3162	0.3162	0.3548	0.5054	0.8517	1.5820	2.9002	6.1883	15.7030	88.3058	621.9733	803587584
C4	0.3162	0.3162	0.3715	0.5122	0.8564	1.4791	2.8477	7.1001	19.6231	105.5825	1081.3771	190556672
C5	0.3162	0.3162	0.4181	0.5923	0.9755	1.7018	3.1945	9.1948	36.2458	222.6081	3355.1628	9902382
C6	0.3162	0.3162	0.3779	0.5714	0.9283	1.6543	3.0912	7.5297	20.4936	156.7730	3669.9714	135845584896

C7 0.3162 0.3162 0.3893 0.5600 0.8759 1.5368 2.8370 7.1364 21.9384
160.2487 1737.7396 219194720

C8 0.3162 0.3162 0.3547 0.4997 0.8725 1.5775 2.8002 7.7037 23.4613
186.6694 26649.6367 37557760000

C9 0.3162 0.3163 0.4070 0.5751 0.8983 1.5846 2.9623 8.2321 25.7546
124.5301 1164.3385 69267200

C10 0.3162 0.3224 0.4696 0.6494 0.9953 1.6277 3.1531 7.9214 22.6407
113.4683 825.5861 46460180

C11 0.3162 0.3163 0.3958 0.5385 0.8653 1.5829 2.9092 7.1891 18.6920
60.5091 427.1392 124128

C12 0.3162 0.3162 0.3830 0.5627 0.8765 1.5259 2.8378 7.0935 21.8235
158.6321 1282.9172 47255592

C13 0.3162 0.3162 0.3954 0.5505 0.8652 1.5403 2.8229 8.8583 31.7802
119.4558 1031.8582 1983128403968

C14 0.3162 0.3165 0.4162 0.5728 0.9052 1.6423 2.9264 6.3921 14.5500
53.7789 818.4878 407132

C15 0.3162 0.3211 0.4672 0.6349 0.9732 1.6419 3.0126 6.6328 14.4248
46.9875 492.5596 1612013

C16 0.3162 0.3163 0.4287 0.5985 0.9145 1.5622 2.9511 7.7254 20.5688
92.9754 925.3593 302711

C17 0.3162 0.3162 0.4238 0.6026 0.8922 1.6062 3.1064 7.6806 16.9696
71.7101 466.1288 209524

;

Table KVIc(C,P)'VI@ 50C of products related to each crudes'

	RFG_c	LPG_c	LSR_c	MSR_c	HSR_c	KR_c	LDO_c	MDO_c	HDO_c	HVGO_v	BSGO_v	VR_v
C1	0	0	-1705	-823	-485	-255	-74	117	240	423	576	805
C2	0	0	-1609	-827	-495	-259	-66	132	254	433	580	783
C3	0	0	0	-1029	-533	-254	-75	85	228	407	543	981
C4	0	0	0	-1007	-530	-278	-80	109	256	422	574	954
C5	0	0	-1679	-817	-458	-229	-51	152	325	478	631	890
C6	0	0	0	-857	-484	-238	-59	119	261	452	635	1066
C7	0	0	0	-881	-517	-264	-81	110	269	454	599	956
C8	0	0	0	-1050	-519	-255	-84	123	277	465	717	1046
C9	0	0	0	-849	-502	-253	-70	134	288	435	578	933
C10	0	0	0	-728	-448	-244	-54	128	273	428	560	925
C11	0	0	0	-932	-524	-254	-74	112	250	374	521	770
C12	0	0	0	-875	-516	-267	-80	109	269	453	584	925
C13	0	0	0	-902	-524	-263	-82	146	311	432	572	1103
C14	0	0	0	-854	-498	-241	-73	91	218	363	559	807
C15	0	0	0	-748	-459	-241	-66	98	217	350	529	845
C16	0	0	0	-806	-492	-258	-71	124	262	411	566	798
C17	0	0	0	-799	-506	-249	-58	123	238	389	526	787

;

Table SLF(U,P)'sulfur of products from each unit'

	RFG_hd	N_hd	DSL_hd

HD 0.0001 0.0001 0.001

+

RFG_hc LPG_hc LN_hc HN_hc KR_hc LDSL_hc HDSL_hc UCO_hc

HC 0.0001 0.0001 0.00042 0.00027 0.00026 0.00032 0.00035 0.00035

+

RFG_fcc LPG_fcc LCN_fcc MCN_fcc HCN_fcc LCGO_fcc HCGO_fcc

FCC 0.0001 0.0001 0.06502 0.1329 0.5605 3.3099 4.7597

+

RFG_vb VBN_vb RS_vb

VB 0.0001 0.6983 4.4601 ;

Table d(U,P)'density of products from each unit'

RFG_hd N_hd DSL_hd

HD 0.44 0.76 0.83

+

	RFG_hc	LPG_hc	LN_hc	HN_hc	KR_hc	LDSL_hc	HDSL_hc	UCO_hc
HC	0.51	0.57	0.69	0.75	0.81	0.8319	0.8314	0.8404

+

	RFG_lb	N_lb	DSL_lb	MBO_lb
LB	0.6900	0.7301	0.8300	0.8460

+

	RFG_plt	REF_plt
PLT	0.27	0.78

+

	RFG_fcc	LPG_fcc	LCN_fcc	MCN_fcc	HCN_fcc	LCGO_fcc	HCGO_fcc
FCC	0.54	0.56	0.72	0.76	0.85	0.94	1.05

+

	RFG_vb	VBN_vb	RS_vb
VB	0.44	0.68	1.03

;

Table CI(U,P)'Cetane Index of products from each unit'

	RFG_hd	N_hd	DSL_hd
HD	0	0	61.5

+

	RFG_hc	LPG_hc	LN_hc	HN_hc	KR_hc	LDSL_hc	HDSL_hc	UCO_hc
HC	0	0	0	69.4	54.0	58.8	80.1	0

+

	RFG_lb	N_lb	DSL_lb	MBO_lb
LB	0	0	63.2	0 ;

Table KV(U,P) 'kinematic viscosity of products from each unit'

	RFG_hd	N_hd	DSL_hd
HD	0	0	3.0687

+

	RFG_hc	LPG_hc	LN_hc	HN_hc	KR_hc	LDSL_hc	HDSL_hc	UCO_hc
HC	0	0	0	1.0	1.3	4.0	4.0787	18.5246

+

	RFG_fcc	LPG_fcc	LCN_fcc	MCN_fcc	HCN_fcc	LCGO_fcc	HCGO_fcc
FCC	0	0	0	0	1.274	2.9826	454.2817

+

	RFG_vb	VBN_vb	RS_vb
VB	0	0	703.9498 ;

Table KVI(U,P) 'kinematic viscosity of products from each unit'

	RFG_hd	N_hd	DSL_hd
HD	0	0	2

+

	RFG_hc	LPG_hc	LN_hc	HN_hc	KR_hc	LDSL_hc	HDSL_hc	UCO_hc
HC	0	0	0	-350	-240	1	132	245

+

	RFG_fcc	LPG_fcc	LCN_fcc	MCN_fcc	HCN_fcc	LCGO_fcc	HCGO_fcc
FCC	0	0	0	0	-233	-30	500

+

	RFG_vb	VBN_vb	RS_vb
VB	0	0	800

;

Table KUOP(C,P) 'UOP of HDO and HVGO from each crude'

	HDO_c	HVGO_v
C1	11.7339	11.7960
C2	11.7587	11.7437
C3	11.7431	11.8418
C4	11.7003	11.8107
C5	11.5514	11.7609
C6	11.6794	11.7494
C7	11.6853	11.7464
C8	11.6235	11.6770
C9	11.8705	12.0100
C10	11.6502	11.7734
C11	12.0592	12.3348
C12	11.6247	11.7086
C13	11.5906	11.5980
C14	12.3109	12.2646
C15	12.4865	12.6230
C16	11.9523	12.1223
C17	11.9939	12.1760

;

Table PP(C,P) 'pour point of HDO and HVGO from each crude'

	HDO_c	HVGO_v
C1	26.5009	43.2747
C2	22.1310	38.7064
C3	23.6437	42.2554
C4	21.4022	35.7634
C5	25.6383	42.9963
C6	24.4188	44.5971
C7	16.8993	29.8790
C8	14.2789	38.7292
C9	20.4277	37.1553
C10	29.2673	49.5124
C11	24.0229	41.3209
C12	20.8891	36.9348
C13	18.2054	29.4618
C14	41.7139	57.0614
C15	45.1353	61.0688
C16	28.3389	48.3296
C17	34.4123	50.6902

;

Table VI_VGO(C,P)'VI of HDO and HVGO from each crude'

	HDO_c	HVGO_v

```
C1      82      72

C2      69      66

C3      152     121

C4      84      57

C5      32      20

C6      152     109

C7      76      41

C8      87      50

C9      93      70

C10     97      62

C11     77      75

C12     69      56

C13     55      53

C14     137     112

C15     144     121

C16     106     82

C17     153     75

;

*****************************************************************************************************

**Prices

*****************************************************************************************************


Parameter  Prc(C) 'prices of crudes'

*this is with no landed cost


/

C1          65.60
```

C2 65.59

C3 67.65

C4 67.40

C5 68.01

C6 67.03

C7 67.03

C8 66.24

C9 67.87

C10 69.40

C11 67.57

C12 69.40

C13 69.94

C14 69.55

C15 68.55

C16 71.90

C17 70.36

/;

Parameter Prfp(FP) 'prices of products'

/

RFG 20.36

LPG 40.36

NAP 55.55

KR 76.25

DSL 76.74

LBO 97.24

FO 54.99

ASP 57.31

LCN_fcc_f 71.94

MCN_fcc_f 68.90

REF_plt_f 76.15

/;

Parameter DVI_HC(C) 'delta VI after hydroccraking';

Parameter DVI_LB(C) 'delta VI after lubes hydroisomerisation';

****

**Variables:

*x is flow rate (m in the mathematical formulation)

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Variable

xC(C) ,

xFP (FP) ,

xI(U, P) ,

xB(FP, P) ,

xIc (C, U, P),

xBc (C,FP, P),

VFP(FP),

Crude_Feed(C), Total_Crude_Feed, HD_Feed , PLT_Feed , FCC_Feed , HC_Feed , LB_Feed , VB_Feed,

SLF_KR_vl, d_DSL_vl, SLF_VDSL_vl, CI_DSL_vl, SLF_FO_vl, KVI_FO_vl , VI_LBO_vl ,HD_Feed_SLF_vl, HC_Feed_SLF_vl,
HC_Feed_NTR_vl,

VFP_CC, Feed_CCR_vl

Profit ,

VR_crudes_v

*FCC parameters

dens,

z ,

Yfcc(U,P)

*Cost

FLC_CDU , FLC_HD , FLC_PLT , FLC_FCC , FLC_HC , FLC_LB , FLC_VB, FLC_T,

CLC_HD , CLC_PLT, CLC_FCC , CLC_HC, CLC_T,

Crude_Cost, FP_Rev,

GRM;

Positive Variable

xC(C) ,

xFP (FP) ,

xI(U, P) ,

xB(FP, P) ,

xIc (C, U, P),

xBc (C,FP, P),

VFP(FP),

Crude_Feed(C), Total_Crude_Feed, HD_Feed , PLT_Feed , FCC_Feed , HC_Feed , LB_Feed , VB_Feed

*Cost

FLC_CDU , FLC_HD , FLC_PLT , FLC_FCC , FLC_HC , FLC_LB , FLC_VB, FLC_T,

CLC_HD , CLC_PLT, CLC_FCC , CLC_HC, CLC_T;

;

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**Equations

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Equation

**Equality Constrains Equations:

*overall material balance

EQC_mo,

*intermediate products material balance (defining equations)

EQC_mI_RFG_c (C), EQC_mI_LPG_c(C) , EQC_mI_LSR_c(C), EQC_mI_MSR_c(C) , EQC_mI_HSR_c(C) , EQC_mI_KR_c(C) , EQC_mI_LDO_c(C),

EQC_mI_MDO_c(C), EQC_mI_HDO_c(C) ,

EQC_mI_HVGO_v(C), EQC_mI_BSGO_v(C) , EQC_mI_VR_v(C) ,

EQ_xB_RFG_c, EQ_xB_LPG_c, EQ_xB_LSR_c, EQ_xI_MSR_c, EQ_xB_MSR_c, EQ_xI_HSR_c, EQ_xB_NAP_HSR_c, EQ_xB_KR_HSR_c

EQ_xB_KR_KR_c, EQ_xB_FO_KR_c, EQ_xI_LDO_c, EQ_xI_MDO_c

EQ_xI_HD_HDO_c, EQ_xI_HC_HDO_c, EQ_xI_HC_HVGO_v, EQ_xI_FCC_HVGO_v

EQ_xI_FCC_BSGO_v, EQ_xI_VB_BSGO_v

EQ_xI_FCC_VR_v, EQ_xI_VB_VR_v, EQ_xB_FO_VR_v, EQ_xB_ASP_VR_v ,

EQC_mI_RFG_hc , EQC_mI_LPG_hc, EQC_mI_LN_hc , EQC_mI_HN_hc, EQC_mI_KR_hc, EQC_mI_LDSL_hc , EQC_mI_HDSL_hc , EQC_mI_UCO_hc ,

EQC_mI_RFG_lb , EQC_mI_N_lb , EQC_mI_DSL_lb , EQC_mI_MBO_lb ,

EQC_mI_RFG_hd , EQC_mI_N_hd , EQC_mI_DSL_hd ,

EQC_mI_RFG_fcc , EQC_mI_LPG_fcc , EQC_mI_LCN_fcc , EQC_mI_MCN_fcc , EQC_mI_HCN_fcc , EQC_mI_LCGO_fcc, EQC_mI_HCGO_fcc,

EQC_mI_RFG_plt , EQC_mI_REF_plt ,

EQC_mI_RFG_vb , EQC_mI_VBN_vb , EQC_mI_RS_vb ,

EQ_xI_all_HVGO_v,

*final products material balance (defining equations)

EQC_mI_RFG, EQC_mI_LPG, EQC_mI_NAP, EQC_mI_KR, EQC_mI_DSL, EQC_mI_LBO, EQC_mI_FO, EQC_mI_ASP ,

EQC_mI_LCN_fcc_f, EQC_mI_MCN_fcc_f, EQC_mI_REF_plt_f,

*Volumes of final products

EQC_mI_VRFG, EQC_mI_VLPG, EQC_mI_VNAP, EQC_mI_VKR, EQC_mI_VDSL, EQC_mI_VLBO,

EQC_mI_VFO, EQC_mI_VASP, EQC_mI_VLCN_fcc_f, EQC_mI_VMCN_fcc_f, EQC_mI_VREF_plt_f

*Equations for feed rates in volume

EQ_DV_Feed, EQ_HD_Feed, Eq_PLT_Feed , Eq_FCC_Feed, EQ_HC_Feed , EQ_LB_Feed , EQ_VB_Feed ,

EQ_C1, EQ_C2, EQ_C3, EQ_C4, EQ_C5, EQ_C6, EQ_C7, EQ_C8, EQ_C9,

EQ_C10, EQ_C11, EQ_C12, EQ_C13, EQ_C14, EQ_C15, EQ_C16, EQ_C17,

EQ_xlc_HDO,

EQ_dmnd_VFP_ASP,

EQ_dmnd_VFP_LPG,

EQ_UCO_FCC,

EQ_BSGO_FCC,

EQ_VR_FCC,

EQ_VR_ASP,

EQ_VR_FO,

EQ_HN_hc_FO,

EQ_HCN_fcc_FO,

EQ_KR_c_FO,

VR_crudes,

*Caps

Capl_DV, Capl_HD , Capl_PLT , Capl_FCC , Capl_HC , Capl_LB , Capl_VB ,

Capu_DV , Capu_HD , Capu_PLT , Capu_FCC , Capu_HC ,Capu_LB , Capu_VB ,

*EQC,

*EQR,

*EQe,

EQ_XC_Feed(C),

*Qualities:

EQ_SLF_KR ,EQ_SLF_KR_vl,

EQ_d_DSL_g,EQ_d_DSL_l ,EQ_d_DSL_vl,

EQ_SLF_VDSL, EQ_SLF_VDSL_vl,

EQ_CI_DSL, EQ_CI_DSL_vl,

EQ_SLF_FO, EQ_SLF_FO_vl,

*EQ_KV_FO_g ,EQ_KV_FO_l, EQ_KV_FO_vl,

EQ_KVI_FO_g ,EQ_KVI_FO_l, EQ_KVI_FO_vl,

EQ_VI_LBO, EQ_VI_LBO_vl,

*EQ_VI_LBO_l

EQ_VFP_CC ,

EQ_HD_Feed_SLF,

EQ_HD_Feed_SLF_vl,

EQ_HC_Feed_SLF,

EQ_HC_Feed_SLF_vl,

EQ_HC_Feed_NTR,

EQ_HC_Feed_NTR_vl,

Eq_FCC_Feed_CCR,

Eq_FCC_Feed_CCR_vl,

*FCC Delta base

EQ_z ,

EQ_dens,

EQ_yRFG_fcc,

EQ_yLPG_fcc,

EQ_yLCN_fcc,

EQ_yMCN_fcc,

EQ_yHCN_fcc,

EQ_yLCGO_fcc ,

EQ_yHCGO_fcc ,

*Cost

EQ_FLC_CDU, EQ_FLC_HD, EQ_FLC_PLT, EQ_FLC_FCC, EQ_FLC_HC, EQ_FLC_LB, EQ_FLC_VB, EQ_FLC_T,

EQ_CLC_HD, EQ_CLC_PLT , EQ_CLC_FCC , EQ_CLC_HC, EQ_CLC_T ,

EQ_Crude_Cost, EQ_FP_Rev,

EQ_GRM,

OBJ

;

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** Equality Constraint

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*1) overall material balance

*EQC_mo .. sum(C,xC(C)) - sum(FP,xFP(FP)) =l=200 ;

*2)Material balance of intermediates

*Distillation Columns DV

EQC_mI_RFG_c(C).. YD(C, 'RFG_c')*xC(C) - xBc(C,'RFG', 'RFG_c') =e=0 ;

EQC_mI_LPG_c(C).. YD(C, 'LPG_c')*xC(C) - xBc(C,'LPG', 'LPG_c') =e=0 ;

EQC_mI_LSR_c(C).. YD(C, 'LSR_c')*xC(C) - xBc(C,'NAP','LSR_c') =e=0 ;

EQC_mI_MSR_c(C).. YD(C, 'MSR_c')*xC(C) - xIc(C,'PLT','MSR_c')- xBc(C,'NAP','MSR_c') =e=0 ;

EQC_mI_HSR_c(C).. YD(C, 'HSR_c')*xC(C) - xIc(C,'PLT','HSR_c')- xBc(C,'NAP','HSR_c')-xBc(C,'KR','HSR_c')=e=0 ;

EQC_mI_KR_c(C).. YD(C, 'KR_c')*xC(C) - xBc(C,'KR','KR_c') - xBc(C,'FO','KR_c') =e=0 ;

EQC_mI_LDO_c(C).. YD(C, 'LDO_c')*xC(C) - xIc(C,'HD', 'LDO_c') =e=0 ;

EQC_mI_MDO_c(C).. YD(C, 'MDO_c')*xC(C) - xIc(C,'HD','MDO_c') =e=0 ;

EQC_mI_HDO_c(C).. YD(C, 'HDO_c')*xC(C) - xIc(C,'HD','HDO_c') - xIc(C,'HC','HDO_c') =e=0 ;

EQC_mI_HVGO_v(C) .. YD(C, 'HVGO_v')*xC(C) - xIc(C,'HC','HVGO_v')-xIc(C,'FCC','HVGO_v') =e=0 ;

EQC_mI_BSGO_v(C) .. YD(C, 'BSGO_v')*xC(C) - xIc(C,'FCC','BSGO_v')- xIc(C,'VB','BSGO_v') =e=0 ;

EQC_mI_VR_v(C) .. YD(C, 'VR_v')*xC(C) - xIc(C, 'FCC','VR_v') - xIc(C, 'VB','VR_v')-xBc(C,'FO','VR_v')-xBc(C,'ASP','VR_v') =e=0;

*pools from all crude to one stream

EQ_xB_RFG_c.. Sum(C, xBc(C,'RFG', 'RFG_c')) =e= xB('RFG', 'RFG_c');

EQ_xB_LPG_c.. Sum(C, xBc(C,'LPG', 'LPG_c')) =e= xB('LPG', 'LPG_c');

EQ_xB_LSR_c.. Sum(C,xBc(C,'NAP','LSR_c')) =e= xB('NAP','LSR_c');

EQ_xI_MSR_c.. Sum(C, xIc(C,'PLT','MSR_c')) =e= xI('PLT','MSR_c');

EQ_xB_MSR_c.. Sum(C, xBc(C,'NAP','MSR_c')) =e= xB('NAP','MSR_c') ;

EQ_xI_HSR_c.. Sum(C, xIc(C,'PLT','HSR_c')) =e= xI('PLT','HSR_c') ;

EQ_xB_NAP_HSR_c.. Sum(C, xBc(C,'NAP','HSR_c')) =e= xB('NAP','HSR_c');

```
EQ_xB_KR_HSR_c.. Sum(C, xBc(C,'KR','HSR_c'))  =e= xB('KR','HSR_c') ;

EQ_xB_KR_KR_c.. Sum(C, xBc(C,'KR','KR_c'))  =e= xB('KR','KR_c') ;

EQ_xB_FO_KR_c.. Sum(C, xBc(C,'FO','KR_c'))  =e= xB('FO','KR_c') ;

EQ_xI_LDO_c.. Sum(C, xIc(C,'HD', 'LDO_c')) =e= xI('HD', 'LDO_c') ;

EQ_xI_MDO_c.. Sum(C, xIc(C,'HD','MDO_c'))  =e= xI('HD','MDO_c') ;

EQ_xI_HD_HDO_c.. Sum(C, xIc(C,'HD','HDO_c'))  =e= xI('HD','HDO_c');

EQ_xI_HC_HDO_c.. Sum(C, xIc(C,'HC','HDO_c'))  =e= xI('HC','HDO_c') ;

EQ_xI_HC_HVGO_v.. Sum(C, xIc(C,'HC','HVGO_v')) =e= xI('HC','HVGO_v') ;

EQ_xI_FCC_HVGO_v.. Sum(C, xIc(C,'FCC','HVGO_v')) =e= xI('FCC','HVGO_v') ;

EQ_xI_FCC_BSGO_v.. Sum(C, xIc(C,'FCC','BSGO_v')) =e= xI('FCC','BSGO_v') ;

EQ_xI_VB_BSGO_v.. Sum(C, xIc(C,'VB','BSGO_v')) =e= xI('VB','BSGO_v') ;

EQ_xI_FCC_VR_v.. Sum(C, xIc(C, 'FCC','VR_v')) =e= xI('FCC','VR_v') ;

EQ_xI_VB_VR_v.. Sum(C,xIc(C, 'VB','VR_v')) =e= xI('VB','VR_v') ;

EQ_xB_FO_VR_v.. Sum(C, xBc(C,'FO','VR_v'))  =e= xB('FO','VR_v') ;

EQ_xB_ASP_VR_v.. Sum(C, xBc(C,'ASP','VR_v')) =e= xB('ASP','VR_v') ;


EQ_xI_all_HVGO_v.. Sum(C, YD(C, 'HVGO_v')*xC(C))-Sum(C, xIc(C,'HC','HVGO_v'))-Sum(C, xIc(C,'FCC','HVGO_v'))=e=0;


*HCU  - need to check if (C) is required


EQC_mI_RFG_hc .. ((xI('HC','HDO_c')+xI('HC','HVGO_v'))* Yhc('HC', 'RFG_hc')) - xB('RFG', 'RFG_hc') =e=0 ;


EQC_mI_LPG_hc .. ((xI('HC','HDO_c')+xI('HC','HVGO_v'))* Yhc('HC', 'LPG_hc')) - xB('LPG', 'LPG_hc') =e=0 ;


EQC_mI_LN_hc .. ((xI('HC','HDO_c')+xI('HC','HVGO_v'))* Yhc('HC', 'LN_hc'))- xB('NAP', 'LN_hc') =e=0 ;
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```
EQC_ml_HN_hc .. ((xl('HC','HDO_c')+xl('HC','HVGO_v'))* Yhc('HC', 'HN_hc')) -xl('PLT','HN_hc') - xB('NAP', 'HN_hc')- xB('DSL',
'HN_hc')- xB('FO', 'HN_hc') =e=0 ;

EQC_ml_KR_hc .. ((xl('HC','HDO_c')+xl('HC','HVGO_v'))* Yhc('HC', 'KR_hc')) - xB('KR', 'KR_hc')- xB('DSL', 'KR_hc')- xB('FO',
'KR_hc') =e=0 ;

EQC_ml_LDSL_hc.. ((xl('HC','HDO_c')+xl('HC','HVGO_v'))* Yhc('HC', 'LDSL_hc'))- xB('DSL', 'LDSL_hc')- xB('FO', 'LDSL_hc') =e=0
;

EQC_ml_HDSL_hc.. ((xl('HC','HDO_c')+xl('HC','HVGO_v'))* Yhc('HC', 'HDSL_hc'))- xB('DSL', 'HDSL_hc') - xB('FO', 'HDSL_hc') =e=0
;

EQC_ml_UCO_hc .. ((xl('HC','HDO_c')+xl('HC','HVGO_v'))* Yhc('HC', 'UCO_hc'))- xl('LB','UCO_hc') - xl('FCC','UCO_hc') =e=0 ;

*LB

EQC_ml_RFG_lb .. ((xl('LB','UCO_hc'))*Y('LB','RFG_lb')) - xB('RFG', 'RFG_lb') =e=0 ;

EQC_ml_N_lb .. ((xl('LB','UCO_hc'))*Y('LB','N_lb')) - xB('NAP', 'N_lb') =e=0 ;

EQC_ml_DSL_lb .. ((xl('LB','UCO_hc'))*Y('LB','DSL_lb')) - xB('DSL', 'DSL_lb') =e=0 ;

EQC_ml_MBO_lb .. ((xl('LB','UCO_hc'))*Y('LB','MBO_lb')) - xB('LBO', 'MBO_lb') =e=0 ;

*HDU

EQC_ml_RFG_hd .. ((xl('HD', 'LDO_c') +xl('HD','MDO_c') +xl('HD','HDO_c') +xl('HD','LCGO_fcc')) * Y('HD', 'RFG_hd')) - xB('RFG',
'RFG_hd') =e=0 ;

EQC_ml_N_hd .. ((xl('HD', 'LDO_c') +xl('HD','MDO_c') +xl('HD','HDO_c') +xl('HD','LCGO_fcc')) * Y('HD', 'N_hd')) - xB('NAP',
'N_hd') =e=0 ;

EQC_ml_DSL_hd .. ((xl('HD', 'LDO_c') +xl('HD','MDO_c') +xl('HD','HDO_c') +xl('HD','LCGO_fcc')) * Y('HD', 'DSL_hd')) - xB('DSL',
'DSL_hd')- xB('FO', 'DSL_hd') =e=0 ;
```

```
*FCC

*dens and z are for delta base yields

EQ_z ..  (dens- 0.9546)/(0.9354-0.9546) =e=z;

EQ_dens.. (sum(C,xIc(C,'FCC', 'HVGO_v') +  xIc(C,'FCC', 'BSGO_v') + xIc(C,'FCC', 'VR_v'))+ xI('FCC','UCO_hc')) =e=dens*(FCC_Feed)
;


*dens.l=0.92;

*z.l=1.8;

dens.lo= 0.9;

*z.lo=0.1;

FCC_Feed.lo=13;

*Yfcc.lo(U, P)=0.01;

Yfcc.L('FCC','RFG_fcc')=Y('FCC_B','RFG_fcc_B');

Yfcc.L('FCC','LPG_fcc')=Y('FCC_B','LPG_fcc_B');

Yfcc.L('FCC','LCN_fcc')=Y('FCC_B','LCN_fcc_B');

Yfcc.L('FCC','MCN_fcc')=Y('FCC_B','MCN_fcc_B');

Yfcc.L('FCC','HCN_fcc')=Y('FCC_B','HCN_fcc_B');

Yfcc.L('FCC','LCGO_fcc')=Y('FCC_B','LCGO_fcc_B');

Yfcc.L('FCC','HCGO_fcc')=Y('FCC_B','HCGO_fcc_B');

EQ_yRFG_fcc.. Y('FCC_B','RFG_fcc_B')+z*Y('FCC_D','RFG_fcc_D')=e=Yfcc('FCC','RFG_fcc');

EQ_yLPG_fcc..Y('FCC_B','LPG_fcc_B')+z*Y('FCC_D','LPG_fcc_D')=e= Yfcc('FCC','LPG_fcc')  ;

EQ_yLCN_fcc..Y('FCC_B','LCN_fcc_B')+z*Y('FCC_D','LCN_fcc_D')=e= Yfcc('FCC','LCN_fcc')  ;

EQ_yMCN_fcc.. Y('FCC_B','MCN_fcc_B')+z*Y('FCC_D','MCN_fcc_D')=e=Yfcc('FCC','MCN_fcc')   ;

EQ_yHCN_fcc.. Y('FCC_B','HCN_fcc_B')+z*Y('FCC_D','HCN_fcc_D')=e= Yfcc('FCC','HCN_fcc')   ;

EQ_yLCGO_fcc.. Y('FCC_B','LCGO_fcc_B')+z*Y('FCC_D','LCGO_fcc_D')=e= Yfcc('FCC','LCGO_fcc');

EQ_yHCGO_fcc.. Y('FCC_B','HCGO_fcc_B')+z*Y('FCC_D','HCGO_fcc_D')=e= Yfcc('FCC','HCGO_fcc') ;
```

EQC_ml_RFG_fcc .. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'RFG_fcc')) - xB('RFG', 'RFG_fcc') =e=0 ;

EQC_ml_LPG_fcc .. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'LPG_fcc')) - xB('LPG', 'LPG_fcc') =e=0 ;

EQC_ml_LCN_fcc .. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'LCN_fcc')) - xB('LCN_fcc_f', 'LCN_fcc') =e=0 ;

EQC_ml_MCN_fcc .. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'MCN_fcc')) - xB('MCN_fcc_f', 'MCN_fcc') =e=0 ;

EQC_ml_HCN_fcc .. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'HCN_fcc')) - xB('NAP', 'HCN_fcc') - xB('FO', 'HCN_fcc') =e=0 ;

EQC_ml_LCGO_fcc.. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'LCGO_fcc')) - xl('HD','LCGO_fcc') - xB('FO', 'LCGO_fcc') =e=0 ;

EQC_ml_HCGO_fcc.. ((xl('FCC','HVGO_v') + xl('FCC','BSGO_v') +xl('FCC','VR_v')+ xl('FCC','UCO_hc'))* Yfcc('FCC', 'LCGO_fcc')) - xB('FO', 'HCGO_fcc') =e=0 ;

*PLT (REF)

EQC_ml_RFG_plt .. ((xl('PLT','MSR_c') +xl('PLT','HSR_c') +xl('PLT','HN_hc')+xl('PLT','VBN_vb'))* Y('PLT', 'RFG_plt')) - xB('RFG', 'RFG_plt') =e=0 ;

EQC_ml_REF_plt .. ((xl('PLT','MSR_c') +xl('PLT','HSR_c') +xl('PLT','HN_hc')+xl('PLT','VBN_vb'))* Y('PLT', 'REF_plt')) - xB('REF_plt_f', 'REF_plt') =e=0 ;

*VB

EQC_ml_RFG_vb .. ((xl('VB','BSGO_v') +xl('VB','VR_v'))* Y('VB', 'RFG_vb'))- xB('RFG', 'RFG_vb') =e=0 ;

EQC_ml_VBN_vb .. ((xl('VB','BSGO_v') +xl('VB','VR_v'))* Y('VB', 'VBN_vb'))- xl('PLT','VBN_vb') - xB('NAP', 'VBN_vb') =e=0 ;

EQC_ml_RS_vb .. ((xl('VB','BSGO_v') +xl('VB','VR_v'))* Y('VB', 'RS_vb'))- xB('FO', 'RS_vb') =e=0 ;

*3)Material balance of the final products

```
EQC_ml_RFG .. xB('RFG','RFG_c')+ xB('RFG', 'RFG_hc') + xB('RFG', 'RFG_lb') +xB('RFG', 'RFG_hd') +xB('RFG', 'RFG_fcc') +
xB('RFG', 'RFG_plt')+xB('RFG', 'RFG_vb') =e= xFP('RFG') ;

EQC_ml_LPG .. xB('LPG','LPG_c')+ xB('LPG', 'LPG_hc')+ xB('LPG', 'LPG_fcc') =e= xFP('LPG') ;

EQC_ml_NAP .. xB('NAP','LSR_c') + xB('NAP','MSR_c')+ xB('NAP','HSR_c')+ xB('NAP', 'N_hd') + xB('NAP', 'LN_hc') + xB('NAP',
'HN_hc') +xB('NAP', 'N_lb')
        + xB('NAP', 'HCN_fcc')+xB('NAP', 'VBN_vb')=e=xFP('NAP') ;

EQC_ml_KR .. xB('KR','HSR_c') +xB('KR', 'KR_c') +xB('KR','KR_hc') =e=xFP('KR') ;

EQC_ml_DSL .. xB('DSL', 'DSL_hd')+ xB('DSL', 'HN_hc')+xB('DSL', 'KR_hc')+xB('DSL', 'LDSL_hc')+ xB('DSL', 'HDSL_hc') +xB('DSL',
'DSL_lb') =e=xFP('DSL');

EQC_ml_LBO .. xB('LBO', 'MBO_lb') =e=xFP('LBO') ;

EQC_ml_FO .. xB('FO','VR_v') +xB('FO', 'RS_vb') +xB('FO', 'HCGO_fcc') +
        xB('FO','KR_c') +xB('FO', 'DSL_hd') +xB('FO', 'HN_hc') +xB('FO', 'KR_hc')+xB('FO', 'LDSL_hc') +xB('FO', 'HDSL_hc')
        +xB('FO', 'HCN_fcc')+xB('FO', 'LCGO_fcc') =e=xFP('FO');

EQC_ml_ASP .. xB('ASP','VR_v') =e=xFP('ASP') ;

EQC_ml_LCN_fcc_f .. xB('LCN_fcc_f', 'LCN_fcc') =e=xFP('LCN_fcc_f') ;

EQC_ml_MCN_fcc_f .. xB('MCN_fcc_f', 'MCN_fcc') =e=xFP('MCN_fcc_f') ;

EQC_ml_REF_plt_f .. xB('REF_plt_f', 'REF_plt') =e=xFP('REF_plt_f') ;
```

*Volumes of final products

```
EQC_ml_VRFG .. sum(C, xBc(C,'RFG','RFG_c')/dc(C,'RFG_c'))+ xB('RFG', 'RFG_hc')/d('HC','RFG_hc') + xB('RFG',
'RFG_lb')/d('LB','RFG_lb')
            +xB('RFG', 'RFG_hd')/d('HD','RFG_hd') +xB('RFG', 'RFG_fcc')/d('FCC','RFG_fcc')
            + xB('RFG', 'RFG_plt') /d('PLT','RFG_plt') +xB('RFG', 'RFG_vb')/d('VB','RFG_vb')  =e=  VFP('RFG') ;

EQC_ml_VLPG .. sum(C, xBc(C,'LPG','LPG_c')/dc(C,'LPG_c'))+  xB('LPG', 'LPG_hc')/d('HC','LPG_hc')+ xB('LPG',
'LPG_fcc')/d('FCC','LPG_fcc') =e=  VFP('LPG')  ;

EQC_ml_VNAP .. sum(C,xBc(C,'NAP','LSR_c')/dc(C,'LSR_c')) +  sum(C,xBc(C,'NAP','MSR_c')/dc(C,'MSR_c'))+
sum(C,xBc(C,'NAP','HSR_c')/dc(C,'HSR_c'))
          + xB('NAP', 'N_hd')/d('HD','N_hd') + xB('NAP', 'LN_hc')/d('HC','LN_hc') + xB('NAP', 'HN_hc')/d('HC','HN_hc')
           +xB('NAP', 'N_lb')/d('LB','N_lb') + xB('NAP', 'HCN_fcc')/d('FCC','HCN_fcc')
           +xB('NAP', 'VBN_vb')/d('VB','VBN_vb')=e=VFP('NAP')    ;

EQC_ml_VKR  .. sum(C,xBc(C,'KR','HSR_c')/dc(C,'HSR_c') +xB('KR', 'KR_c')/dc(C,'KR_c'))
           +xB('KR','KR_hc')/d('HC','KR_hc') =e=VFP('KR')  ;

EQC_ml_VDSL .. xB('DSL', 'DSL_hd')/d('HD','DSL_hd')+ xB('DSL', 'HN_hc')/d('HC','HN_hc')+xB('DSL', 'KR_hc')/d('HC','KR_hc')
           +xB('DSL', 'LDSL_hc')/d('HC','LDSL_hc')+ xB('DSL', 'HDSL_hc')/d('HC','HDSL_hc')
           +xB('DSL', 'DSL_lb')/d('LB','DSL_lb') =e=VFP('DSL');

EQC_ml_VLBO .. xB('LBO', 'MBO_lb')/d('LB','MBO_lb') =e=VFP('LBO')    ;

EQC_ml_VFO  .. sum(C,xBc(C,'FO','VR_v')/dc(C,'VR_v'))  +xB('FO', 'RS_vb')/d('VB','RS_vb')  +xB('FO',
'HCGO_fcc')/d('FCC','HCGO_fcc') +
          sum(C, xBc(C,'FO','KR_c')/dc(C,'KR_c')) +xB('FO', 'DSL_hd')/d('HD','DSL_hd')
```

```
+xB('FO', 'HN_hc')/d('HC','HN_hc') +xB('FO', 'KR_hc')/d('HC','KR_hc')+xB('FO', 'LDSL_hc')/d('HC','LDSL_hc')
+xB('FO', 'HDSL_hc')/d('HC','HDSL_hc') +xB('FO', 'HCN_fcc')/d('FCC','HCN_fcc')
+xB('FO', 'LCGO_fcc')/d('FCC','LCGO_fcc')  =e=VFP('FO');

EQC_mI_VASP ..  sum(C,xBc(C,'ASP','VR_v')/dc(C,'VR_v')) =e=VFP('ASP') ;

EQC_mI_VLCN_fcc_f .. xB('LCN_fcc_f', 'LCN_fcc')/d('FCC','LCN_fcc')  =e=VFP('LCN_fcc_f') ;

EQC_mI_VMCN_fcc_f .. xB('MCN_fcc_f', 'MCN_fcc') /d('FCC','MCN_fcc')  =e=VFP('MCN_fcc_f') ;

EQC_mI_VREF_plt_f  .. xB('REF_plt_f', 'REF_plt') /d('PLT','REF_plt') =e=VFP('REF_plt_f') ;

*****************************************************************************************************
** Inequality Constraint
*****************************************************************************************************
*Volume Feed rates

EQ_XC_Feed(C)..  xC(C)/dcr(C) =e= Crude_Feed(C) ;

EQ_DV_Feed  ..  sum(C,(xC(C)/dcr(C)))  =e= Total_Crude_Feed  ;

EQ_HD_Feed .. sum(C, xIc(C,'HD', 'LDO_c')/dc(C,'LDO_c')+ xIc(C,'HD', 'MDO_c')/dc(C,'MDO_c')+ xIc(C,'HD',
'HDO_c')/dc(C,'HDO_c'))
+ xI('HD', 'LCGO_fcc')/d('FCC','LCGO_fcc') =e=HD_Feed  ;

Eq_PLT_Feed .. sum(C,xIc(C,'PLT','MSR_c')/dc(C,'MSR_c') + xIc(C,'PLT','HSR_c')/dc(C,'HSR_c')) + xI('PLT','HN_hc')/d('HC','HN_hc')
+xI('PLT','VBN_vb')/d('VB','VBN_vb') =e=PLT_Feed   ;
```

```
Eq_FCC_Feed.. sum(C,xlc(C,'FCC', 'HVGO_v')/dc(C,'HVGO_v') +  xlc(C,'FCC', 'BSGO_v')/dc(C,'BSGO_v') + xlc(C,'FCC',
'VR_v')/dc(C,'VR_v'))+ xl('FCC','UCO_hc')/d('HC','UCO_hc') =e=FCC_Feed ;

EQ_HC_Feed .. sum(C,xlc(C,'HC', 'HDO_c')/dc(C,'HDO_c')+ xlc(C,'HC', 'HVGO_v')/dc(C,'HVGO_v')) =e= HC_Feed  ;

EQ_LB_Feed.. xl('LB', 'UCO_hc')/d('HC','UCO_hc')=e= LB_Feed  ;

EQ_VB_Feed .. sum(C,xlc(C,'VB', 'BSGO_v')/dc(C,'BSGO_v') +xlc(C,'VB', 'VR_v')/dc(C,'VR_v'))  =e= VB_Feed  ;

*Upper Limit

Capl_DV  .. Total_Crude_Feed  =l= 267 ;

Capl_HD .. HD_Feed  =l=70  ;

Capl_PLT .. PLT_Feed =l=15  ;

Capl_FCC.. FCC_Feed =l=32 ;

Capl_HC .. HC_Feed =l=53  ;

Capl_LB.. LB_Feed =l=12  ;

Capl_VB .. VB_Feed  =l=24  ;

*Lower limit
```

```
Capu_DV .. Total_Crude_Feed  =g= 0 ;

Capu_HD .. HD_Feed  =g= 28;

Capu_PLT.. PLT_Feed  =g=6  ;

Capu_FCC .. FCC_Feed =g=13 ;

Capu_HC .. HC_Feed  =g=40 ;

Capu_LB.. LB_Feed  =g=6 ;

Capu_VB .. VB_Feed =g=15  ;

*constraints on demands

*Crudes constraints

EQ_C1..  Crude_Feed('C1')=g=0;

EQ_C2..  Crude_Feed('C2')=l=45;

EQ_C3..  Crude_Feed('C3')=g=0;

EQ_C4..  Crude_Feed('C4')=g=0;

EQ_C5..  Crude_Feed('C5')=g=0;

EQ_C6..  Crude_Feed('C6')=g=0;

EQ_C7..  Crude_Feed('C7')=g=0;

EQ_C8..  Crude_Feed('C8')=g=0;

EQ_C9..  Crude_Feed('C9')=g=0;

EQ_C10..  Crude_Feed('C10')=g=0;
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EQ_C11..  Crude_Feed('C11')=e=0;

EQ_C12..  Crude_Feed('C12')=g=0;

EQ_C13..  Crude_Feed('C13')=g=0;

EQ_C14..  Crude_Feed('C14')=e=0;

EQ_C15..  Crude_Feed('C15')=e=0;

EQ_C16..  Crude_Feed('C16')=g=0;

EQ_C17..  Crude_Feed('C17')=g=0;


*HDO to HDU should be closed (heavy diesel)

EQ_xIc_HDO..sum(C,xIc(C,'HD','HDO_c'))=e=0;


EQ_dmnd_VFP_ASP ..VFP('ASP')=g=0;

EQ_dmnd_VFP_LPG ..VFP('LPG')=g=0;


EQ_UCO_FCC.. xI('FCC','UCO_hc') =g=0  ;

EQ_BSGO_FCC.. xI('FCC','BSGO_v') =g=0  ;

EQ_VR_FCC.. xI('FCC','VR_v') =g=0  ;


EQ_VR_ASP..xFP('DSL')=g=0;


EQ_VR_FO.. xB('FO','VR_v')=g=0;

EQ_HN_hc_FO.. xB('FO', 'HN_hc')=g=0;

EQ_HCN_fcc_FO.. xB('FO', 'HCN_fcc')=g=0;

EQ_KR_c_FO.. xB('FO', 'KR_c')=g=0;


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*Qualities, g: greater
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*****************************************************************************************************

EQ_SLF_KR  .. sum(C,xBc(C,'KR','HSR_c')*SLFc(C,'HSR_c') +xB('KR', 'KR_c')*SLFc(C,'KR_c'))
              +xB('KR','KR_hc')*SLF('HC','KR_hc') =l=xFP('KR')* (0.3)  ;

EQ_SLF_KR_vl  .. sum(C,xBc(C,'KR','HSR_c')*SLFc(C,'HSR_c') +xB('KR', 'KR_c')*SLFc(C,'KR_c'))
              +xB('KR','KR_hc')*SLF('HC','KR_hc') =e=SLF_KR_vl;

EQ_d_DSL_g .. xFP('DSL')=g=0.79*VFP('DSL') ;

EQ_d_DSL_l .. xFP('DSL')=l=0.86*VFP('DSL') ;

EQ_d_DSL_vl .. xFP('DSL')=e=d_DSL_vl ;

EQ_SLF_VDSL .. xB('DSL', 'DSL_hd')*SLF('HD','DSL_hd')+ xB('DSL', 'HN_hc')*SLF('HC','HN_hc')+xB('DSL',
'KR_hc')*SLF('HC','KR_hc')
              +xB('DSL', 'LDSL_hc')*SLF('HC','LDSL_hc')+ xB('DSL', 'HDSL_hc')*SLF('HC','HDSL_hc')
              +xB('DSL', 'DSL_lb')*SLF('LB','DSL_lb') =l=xFP('DSL')*0.001;

EQ_SLF_VDSL_vl .. xB('DSL', 'DSL_hd')*SLF('HD','DSL_hd')+ xB('DSL', 'HN_hc')*SLF('HC','HN_hc')+xB('DSL',
'KR_hc')*SLF('HC','KR_hc')
              +xB('DSL', 'LDSL_hc')*SLF('HC','LDSL_hc')+ xB('DSL', 'HDSL_hc')*SLF('HC','HDSL_hc')
              +xB('DSL', 'DSL_lb')*SLF('LB','DSL_lb') =e=SLF_VDSL_vl;

EQ_CI_DSL .. xB('DSL', 'DSL_hd')*CI('HD','DSL_hd')/d('HD','DSL_hd')+ xB('DSL', 'HN_hc')*CI('HC','HN_hc')/d('HC','HN_hc')+
          xB('DSL', 'KR_hc')*CI('HC','KR_hc')/d('HC','KR_hc')
            +xB('DSL', 'LDSL_hc')*CI('HC','LDSL_hc')/d('HC','LDSL_hc')+ xB('DSL', 'HDSL_hc')*CI('HC','HDSL_hc')/d('HC','HDSL_hc')
```

```
+xB('DSL', 'DSL_lb')*CI('LB','DSL_lb')/d('LB','DSL_lb') =g=VFP('DSL')*52;

EQ_CI_DSL_vl .. xB('DSL', 'DSL_hd')*CI('HD','DSL_hd')/d('HD','DSL_hd')+ xB('DSL', 'HN_hc')*CI('HC','HN_hc')/d('HC','HN_hc')+
xB('DSL', 'KR_hc')*CI('HC','KR_hc')/d('HC','KR_hc')
+xB('DSL', 'LDSL_hc')*CI('HC','LDSL_hc')/d('HC','LDSL_hc')+ xB('DSL', 'HDSL_hc')*CI('HC','HDSL_hc')/d('HC','HDSL_hc')
+xB('DSL', 'DSL_lb')*CI('LB','DSL_lb')/d('LB','DSL_lb') =e=CI_DSL_vl;

EQ_SLF_FO .. sum(C,xBc(C,'FO','VR_v')*SLFc(C,'VR_v')) +xB('FO', 'RS_vb')*SLF('VB','RS_vb') +xB('FO',
'HCGO_fcc')*SLF('FCC','HCGO_fcc') +
sum(C, xBc(C,'FO','KR_c')*SLFc(C,'KR_c')) +xB('FO', 'DSL_hd')*SLF('HD','DSL_hd')
+xB('FO', 'HN_hc')*SLF('HC','HN_hc') +xB('FO', 'KR_hc')*SLF('HC','KR_hc')+xB('FO', 'LDSL_hc')*SLF('HC','LDSL_hc')
+xB('FO', 'HDSL_hc')*SLF('HC','HDSL_hc') +xB('FO', 'HCN_fcc')*SLF('FCC','HCN_fcc')
+xB('FO', 'LCGO_fcc')*SLF('FCC','LCGO_fcc') =l=XFP('FO')*3.5;

EQ_SLF_FO_vl .. sum(C,xBc(C,'FO','VR_v')*SLFc(C,'VR_v')) +xB('FO', 'RS_vb')*SLF('VB','RS_vb') +xB('FO',
'HCGO_fcc')*SLF('FCC','HCGO_fcc') +
sum(C, xBc(C,'FO','KR_c')*SLFc(C,'KR_c')) +xB('FO', 'DSL_hd')*SLF('HD','DSL_hd')
+xB('FO', 'HN_hc')*SLF('HC','HN_hc') +xB('FO', 'KR_hc')*SLF('HC','KR_hc')+xB('FO', 'LDSL_hc')*SLF('HC','LDSL_hc')
+xB('FO', 'HDSL_hc')*SLF('HC','HDSL_hc') +xB('FO', 'HCN_fcc')*SLF('FCC','HCN_fcc')
+xB('FO', 'LCGO_fcc')*SLF('FCC','LCGO_fcc') =e=SLF_FO_vl;

*Fuel oil kinematic viscosity (KV)at 50C

EQ_KVI_FO_g .. sum(C,xBc(C,'FO','VR_v')/dc(C,'VR_v')* KVc(C,'VR_v')) +xB('FO', 'RS_vb')/d('VB','RS_vb')* KV('VB','RS_vb')
+xB('FO', 'HCGO_fcc')/d('FCC','HCGO_fcc')* KV('FCC','HCGO_fcc')
+sum(C, xBc(C,'FO','KR_c')/dc(C,'KR_c')* KVc(C,'KR_c')) +xB('FO', 'DSL_hd')/d('HD','DSL_hd') * KV('HD','DSL_hd')
+xB('FO', 'HN_hc')/d('HC','HN_hc')* KV('HC','HN_hc') +xB('FO', 'KR_hc')/d('HC','KR_hc')* KV('HC','KR_hc')
```

```
+xB('FO', 'LDSL_hc')/d('HC','LDSL_hc')* KV('HC','LDSL_hc')

+xB('FO', 'HDSL_hc')/d('HC','HDSL_hc')* KV('HC','HDSL_hc')

+xB('FO', 'HCN_fcc')/d('FCC','HCN_fcc') * KV('FCC','HCN_fcc')

+xB('FO', 'LCGO_fcc')/d('FCC','LCGO_fcc')* KV('FCC','LCGO_fcc')  =g=VFP('FO')*240;


EQ_KVI_FO_l    .. sum(C,xBc(C,'FO','VR_v')/dc(C,'VR_v')* KVc(C,'VR_v')) +xB('FO', 'RS_vb')/d('VB','RS_vb')* KV('VB','RS_vb')

+xB('FO', 'HCGO_fcc')/d('FCC','HCGO_fcc')* KV('FCC','HCGO_fcc')

+sum(C, xBc(C,'FO','KR_c')/dc(C,'KR_c')* KVc(C,'KR_c')) +xB('FO', 'DSL_hd')/d('HD','DSL_hd') * KV('HD','DSL_hd')

+xB('FO', 'HN_hc')/d('HC','HN_hc')* KV('HC','HN_hc') +xB('FO', 'KR_hc')/d('HC','KR_hc')* KV('HC','KR_hc')

+xB('FO', 'LDSL_hc')/d('HC','LDSL_hc')* KV('HC','LDSL_hc')

+xB('FO', 'HDSL_hc')/d('HC','HDSL_hc')* KV('HC','HDSL_hc')

+xB('FO', 'HCN_fcc')/d('FCC','HCN_fcc') * KV('FCC','HCN_fcc')

+xB('FO', 'LCGO_fcc')/d('FCC','LCGO_fcc')* KV('FCC','LCGO_fcc')  =l=VFP('FO')*380;



EQ_KVI_FO_vl    .. sum(C,xBc(C,'FO','VR_v')/dc(C,'VR_v')* KVc(C,'VR_v')) +xB('FO', 'RS_vb')/d('VB','RS_vb')* KV('VB','RS_vb')

+xB('FO', 'HCGO_fcc')/d('FCC','HCGO_fcc')* KV('FCC','HCGO_fcc')

+sum(C, xBc(C,'FO','KR_c')/dc(C,'KR_c')* KVc(C,'KR_c')) +xB('FO', 'DSL_hd')/d('HD','DSL_hd') * KV('HD','DSL_hd')

+xB('FO', 'HN_hc')/d('HC','HN_hc')* KV('HC','HN_hc') +xB('FO', 'KR_hc')/d('HC','KR_hc')* KV('HC','KR_hc')

+xB('FO', 'LDSL_hc')/d('HC','LDSL_hc')* KV('HC','LDSL_hc')

+xB('FO', 'HDSL_hc')/d('HC','HDSL_hc')* KV('HC','HDSL_hc')

+xB('FO', 'HCN_fcc')/d('FCC','HCN_fcc') * KV('FCC','HCN_fcc')

+xB('FO', 'LCGO_fcc')/d('FCC','LCGO_fcc')* KV('FCC','LCGO_fcc')  =e=KVI_FO_vl   ;
```

*HDU Feed: sulfur should not exceed 1.6 ppm

```
EQ_HD_Feed_SLF .. sum(C, xIc(C,'HD', 'LDO_c')*SLFc(C,'LDO_c')+ xIc(C,'HD', 'MDO_c')*SLFc(C,'MDO_c')+ xIc(C,'HD',
'HDO_c')*SLFc(C,'HDO_c'))

+ xI('HD', 'LCGO_fcc')*SLF('FCC','LCGO_fcc')

=l=(sum(C, xIc(C,'HD', 'LDO_c')+ xIc(C,'HD', 'MDO_c')+ xIc(C,'HD', 'HDO_c'))+ xI('HD', 'LCGO_fcc'))*1.6 ;


EQ_HD_Feed_SLF_vl .. sum(C, xIc(C,'HD', 'LDO_c')*SLFc(C,'LDO_c')+ xIc(C,'HD', 'MDO_c')*SLFc(C,'MDO_c')+ xIc(C,'HD',
'HDO_c')*SLFc(C,'HDO_c'))

+ xI('HD', 'LCGO_fcc')*SLF('FCC','LCGO_fcc') =l=HD_Feed_SLF_vl   ;

*HCU Feed: sulfur and nitrogen

*sulfur 3 in paper, 2.9 in bapco design

*nitrogen 1500 in the paper, 1020 bapco typical, 1200 HVGO to fccu spec, 1250 in bapco design

EQ_HC_Feed_SLF .. sum(C,xIc(C,'HC', 'HDO_c')*SLFc(C,'HDO_c')+ xIc(C,'HC', 'HVGO_v')*SLFc(C,'HVGO_v'))

=l=(sum(C,xIc(C,'HC', 'HDO_c')+ xIc(C,'HC', 'HVGO_v')))*3.0;


EQ_HC_Feed_SLF_vl .. sum(C,xIc(C,'HC', 'HDO_c')*SLFc(C,'HDO_c')+ xIc(C,'HC', 'HVGO_v')*SLFc(C,'HVGO_v'))

=l= HC_Feed_SLF_vl;


EQ_HC_Feed_NTR .. sum(C,xIc(C,'HC', 'HDO_c')*NTRc(C,'HDO_c')+ xIc(C,'HC', 'HVGO_v')*NTRc(C,'HVGO_v'))

=l=(sum(C,xIc(C,'HC', 'HDO_c')+ xIc(C,'HC', 'HVGO_v')))*1250;


EQ_HC_Feed_NTR_vl .. sum(C,xIc(C,'HC', 'HDO_c')*NTRc(C,'HDO_c')+ xIc(C,'HC', 'HVGO_v')*NTRc(C,'HVGO_v'))

=l= HC_Feed_NTR_vl;


*FCCU CCR , based on actual data


Eq_FCC_Feed_CCR.. sum(C,xIc(C,'FCC', 'HVGO_v')* CCRc(C,'HVGO_v') +  xIc(C,'FCC', 'BSGO_v')* CCRc(C,'BSGO_v')

+ xIc(C,'FCC', 'VR_v')* CCRc(C,'VR_v'))+ xI('FCC','UCO_hc')*0
```

```
=l=sum(C,xlc(C,'FCC', 'HVGO_v') +  xlc(C,'FCC', 'BSGO_v')+ xlc(C,'FCC', 'VR_v')) *5.7;


Eq_FCC_Feed_CCR_vl.. sum(C,xlc(C,'FCC', 'HVGO_v')* CCRc(C,'HVGO_v') +  xlc(C,'FCC', 'BSGO_v')* CCRc(C,'BSGO_v')
+ xlc(C,'FCC', 'VR_v')* CCRc(C,'VR_v'))+ xl('FCC','UCO_hc')*0
=l=Feed_CCR_vl;


*****************************************************************************************************
*VI of LBO
*****************************************************************************************************


Parameter VI_VGO_final(C)'final VI after delta (this is without volumes)';
;


DVI_HC(C)= 43$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 >110 and k=80)
+51$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <110 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>90 and k=80)
+67$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <90 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>50 and k=80)
+67$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <50 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>10 and k=80)
+114$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <10 and k=80)
+
41$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 >110 and k=75)
+49$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <110 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>90 and k=75)
+63$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <90 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>50 and k=75)
+63$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <50 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>10 and k=75)
+108$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <10 and k=75) ;


DVI_LB(C)= -23$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 >110)
-17$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <110 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>90)
```

-17$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <90 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>50)

-11$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <50 and (VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2>10)

-11$ ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2 <10) ;

VI_VGO_final (C)= ((VI_VGO(C,'HDO_c') + VI_VGO(C,'HVGO_v'))/2) +DVI_HC(C) +DVI_LB(C);

*the Volume on both sides is assuming all UCO going to LBOU, will cancle each other anyways-this s to avoid adding the XI FCC term

EQ_VI_LBO .. (sum(C,((xIc(C,'HC','HDO_c')+xIc(C,'HC','HVGO_v'))* Yhc('HC', 'UCO_hc')*
VI_VGO_final(C))))*Y('LB','MBO_lb')/d('LB','MBO_lb')

=g= (sum(C,((xIc(C,'HC','HDO_c')+xIc(C,'HC','HVGO_v'))* Yhc('HC', 'UCO_hc'))*Y('LB','MBO_lb')/d('LB','MBO_lb')))*125;

EQ_VI_LBO_l .. (sum(C,((xIc(C,'HC','HDO_c')+xIc(C,'HC','HVGO_v')) Yhc('HC', 'UCO_hc')*
VI_VGO_final(C))))*Y('LB','MBO_lb')/d('LB','MBO_lb')

=l= (sum(C,((xIc(C,'HC','HDO_c')+xIc(C,'HC','HVGO_v')) Yhc('HC', 'UCO_hc'))*Y('LB','MBO_lb')/d('LB','MBO_lb')))*125;

EQ_VI_LBO_vl .. (sum(C,((xIc(C,'HC','HDO_c')+xIc(C,'HC','HVGO_v'))* Yhc('HC', 'UCO_hc')*
VI_VGO_final(C))))*Y('LB','MBO_lb')/d('LB','MBO_lb') =e=VI_LBO_vl ;

*this is MBO total based in total UCO to LBOU nothing to FCC

EQ_VFP_CC .. (sum(C,((xIc(C,'HC','HDO_c')+xIc(C,'HC','HVGO_v'))* Yhc('HC',
'UCO_hc'))*Y('LB','MBO_lb')/d('LB','MBO_lb')))=e=VFP_CC;

VR_Crudes..sum(C,YD(C, 'VR_v')*xC(C))=e=VR_crudes_v;

****

*Initial Guesses

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Crude_Feed.lo('C1')=0;

```
Crude_Feed.lo('C2')=0;

Crude_Feed.lo('C3')=0;

Crude_Feed.lo('C4')=0;

Crude_Feed.lo('C5')=0;

Crude_Feed.lo('C6')=0;

Crude_Feed.lo('C7')=0;

Crude_Feed.lo('C8')=0;

Crude_Feed.lo('C9')=0;

Crude_Feed.lo('C10')=0;

Crude_Feed.lo('C11')=0;

Crude_Feed.lo('C12')=0;

Crude_Feed.lo('C13')=0;

Crude_Feed.lo('C14')=0;

Crude_Feed.lo('C15')=0;

Crude_Feed.lo('C16')=0;

Crude_Feed.lo('C17')=20;


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*Costs

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*FLC fuel cost (MSCF/bbl* bbl= MSCF in Objective multiply by price US$/MSCF)

EQ_FLC_CDU..  0.13 * Total_Crude_Feed =e=FLC_CDU  ;


EQ_FLC_HD.. 0.075 * HD_Feed =e=FLC_HD ;


EQ_FLC_PLT.. 0.849 * PLT_Feed =e=FLC_PLT;
```

```
EQ_FLC_FCC.. 0.0909 * FCC_Feed =e=FLC_FCC ;

EQ_FLC_HC.. 0.151*  HC_Feed  =e=FLC_HC;

EQ_FLC_LB.. 0.109 * LB_Feed  =e= FLC_LB;

EQ_FLC_VB.. 0.2425 * VB_Feed  =e= FLC_VB;

EQ_FLC_T..  (FLC_CDU  +  FLC_HD + FLC_PLT + FLC_FCC + FLC_HC + FLC_LB +  FLC_VB)*1 =e= FLC_T ;

*CLC Catalyst cost- (US$/bbl* bbl= US$)

EQ_CLC_HD.. 0.08806 * HD_Feed =e=CLC_HD ;

EQ_CLC_PLT.. 0.048 * PLT_Feed =e=CLC_PLT;

EQ_CLC_FCC.. sum(C,xlc(C,'FCC', 'HVGO_v')/dc(C,'HVGO_v')*0.25 +  xlc(C,'FCC', 'BSGO_v')/dc(C,'BSGO_v')*2.3 + xlc(C,'FCC',
'VR_v')/dc(C,'VR_v')*4.5) =e=CLC_FCC ;

EQ_CLC_HC.. 0.17231*  HC_Feed  =e=CLC_HC;

EQ_CLC_T..  CLC_HD + CLC_PLT + CLC_FCC + CLC_HC=e= CLC_T;

*Feedstock cost

EQ_Crude_Cost..sum(C, Crude_Feed(C)* prc(C))=e= Crude_Cost;
```

```
*Product revenue

EQ_FP_Rev..sum(FP, VFP (FP)*prfp(FP))=e= FP_Rev;


*GRM

EQ_GRM..FP_Rev-Crude_Cost =e= GRM;

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**objective function

**********************************************************************************************************

OBJ..Profit =E=sum(FP, VFP (FP)*prfp(FP))-sum(C, Crude_Feed(C)* prc(C))-FLC_T-CLC_T;


Model Myref / all /;

Options nLP= conopt


solve Myref maximizing Profit using nlp;



display Profit.L, xC.L, xI.L, xB.L,  xFP.L,


Total_Crude_Feed.L,Crude_Feed.L, HD_Feed.L , PLT_Feed.L  , FCC_Feed.L  , HC_Feed.L , LB_Feed.L , VB_Feed.L ,Yfcc.L,


VFP.l , DVI_HC, DVI_LB, VI_VGO_final, VR_crudes_v.l, Y, Yhc ;

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**Submodels

**********************************************************************************************************



*$ontext
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```
Parameter


SLF_KR_value, d_DSL_value, SLF_VDSL_value, CI_DSL_value, SLF_FO_value, KVI_FO_value,
VI_LBO_value,SLF_HDU_Feed,SLF_HC_Feed, NTR_HC_Feed, CCR_FCC_Feed,

wt_Yield, Volume_Yield, Liquid_Recovery, Sub_Crude, Sub_CDU_C, Sub_CDU_P,Sub_CDU_T,Sub_HCU_Feed, Sub_HCU,

Sub_LBOU_Feed,Sub_LBOU, Sub_LBOU_t,Sub_LBOU_VI, Sub_FCC_Feed, Sub_FCC  ;


SLF_KR_value= SLF_KR_vl.l/xFP.l('KR');

d_DSL_value=d_DSL_vl.l/VFP.l('DSL');

SLF_VDSL_value=SLF_VDSL_vl.l/VFP.l('DSL');

CI_DSL_value=CI_DSL_vl.l/VFP.l('DSL');

SLF_FO_value=SLF_FO_vl.l/xFP.l('FO');

KVI_FO_value=KVI_FO_vl.l/VFP.l('FO');

VI_LBO_value=VI_LBO_vl.l  / (sum(C,((xIc.l(C,'HC','HDO_c')+xIc.l(C,'HC','HVGO_v') )* Yhc('HC',
'UCO_hc'))*Y('LB','MBO_lb')/d('LB','MBO_lb')));

SLF_HDU_Feed=HD_Feed_SLF_vl.l/((sum(C, xIc.l(C,'HD', 'LDO_c')+ xIc.l(C,'HD', 'MDO_c')+ xIc.l(C,'HD', 'HDO_c'))+ xI.l('HD',
'LCGO_fcc')));

SLF_HC_Feed=HC_Feed_SLF_vl.l/ (sum(C,xIc.l(C,'HC', 'HDO_c')+ xIc.l(C,'HC', 'HVGO_v')));

NTR_HC_Feed=HC_Feed_NTR_vl.l/ (sum(C,xIc.l(C,'HC', 'HDO_c')+ xIc.l(C,'HC', 'HVGO_v')));

CCR_FCC_Feed=Feed_CCR_vl.l/sum(C,xIc.l(C,'FCC', 'HVGO_v') +  xIc.l(C,'FCC', 'BSGO_v')+ xIc.l(C,'FCC', 'VR_v'));


wt_Yield=sum(FP, xFP.l(FP))/sum(C, xC.l(C))*100;

Liquid_Recovery=sum(FP, VFP.l(FP))/Total_Crude_Feed.l*100;

Volume_Yield(FP)=VFP.l(FP)/Total_Crude_Feed.l*100;

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*Sub_CDU

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```
Sub_Crude(C,"C_volumes")=Crude_Feed.l(C);

Sub_Crude(C,"C_Mass")=xC.l(C);

Sub_Crude("Total", "C_volumes")= Total_Crude_Feed.l ;

Sub_Crude("Total","C_Mass")= sum(C, xC.l(C)) ;

Sub_CDU_C(C,"RFG")= xBc.l(C,'RFG', 'RFG_c')/dc(C,'RFG_c');

Sub_CDU_C("Total","RFG")= sum(C, xBc.l(C,'RFG','RFG_c')/dc(C,'RFG_c'));


Sub_CDU_C(C,"LPG")= xBc.l(C,'LPG', 'LPG_c')/dc(C,'LPG_c');

Sub_CDU_C("Total","LPG")=sum(C, xBc.l(C,'LPG','LPG_c')/dc(C,'LPG_c'));


Sub_CDU_C(C,"NAP")= xBc.l(C,'NAP','LSR_c')/dc(C,'LSR_c');

Sub_CDU_C("Total","NAP")= sum(C,xBc.l(C,'NAP','LSR_c')/dc(C,'LSR_c'));


Sub_CDU_C(C,"MSR")= (xIc.l(C,'PLT','MSR_c')+ xBc.l(C,'NAP','MSR_c'))/dc(C,'MSR_c');

Sub_CDU_C("Total","MSR") = sum(C,(xIc.l(C,'PLT','MSR_c')+ xBc.l(C,'NAP','MSR_c'))/dc(C,'MSR_c'));


Sub_CDU_C(C,"HSR")=(xIc.l(C,'PLT','HSR_c')+xBc.l(C,'NAP','HSR_c')+xBc.l(C,'KR','HSR_c'))/dc(C,'HSR_c');

Sub_CDU_C("Total","HSR")=sum(C, (xIc.l(C,'PLT','HSR_c')+xBc.l(C,'NAP','HSR_c')+xBc.l(C,'KR','HSR_c'))/dc(C,'HSR_c')) ;


Sub_CDU_C(C,"KR")= (xBc.l(C,'KR','KR_c')+xBc.l(C,'FO','KR_c'))/dc(C,'KR_c');

Sub_CDU_C("Total","KR")=sum(C,(xBc.l(C,'KR','KR_c')+xBc.l(C,'FO','KR_c'))/dc(C,'KR_c'));


Sub_CDU_C(C,"LDO")= xIc.l(C,'HD', 'LDO_c')/dc(C,'LDO_c');

Sub_CDU_C("Total","LDO") =sum(C, xIc.l(C,'HD', 'LDO_c')/dc(C,'LDO_c'));


Sub_CDU_C(C,"MDO")= xIc.l(C,'HD','MDO_c')/dc(C,'MDO_c');

Sub_CDU_C("Total","MDO") =sum(C, xIc.l(C,'HD','MDO_c')/dc(C,'MDO_c'));
```

```
Sub_CDU_C(C,"HDO")= (xIc.I(C,'HD','HDO_c')+ xIc.I(C,'HC','HDO_c'))/dc(C,'HDO_c');

Sub_CDU_C("Total","HDO") =sum(C, (xIc.I(C,'HD','HDO_c')+ xIc.I(C,'HC','HDO_c'))/dc(C,'HDO_c'));

Sub_CDU_C(C,"HVGO")= (xIc.L(C,'HC','HVGO_v')+xIc.L(C,'FCC','HVGO_v'))/dc(C,'HVGO_v');

Sub_CDU_C("Total","HVGO") =sum(C, (xIc.I(C,'HC','HVGO_v')+xIc.I(C,'FCC','HVGO_v'))/dc(C,'HVGO_v'));

Sub_CDU_C(C,"BSGO")= (xIc.I(C,'FCC','BSGO_v')+xIc.I(C,'VB','BSGO_v'))/dc(C,'BSGO_v');

Sub_CDU_C("Total","BSGO") = sum(C, (xIc.I(C,'FCC','BSGO_v')+xIc.I(C,'VB','BSGO_v'))/dc(C,'BSGO_v'));

Sub_CDU_C(C,"VR")= (xIc.I(C, 'FCC','VR_v')+xIc.I(C, 'VB','VR_v')+xBc.I(C,'FO','VR_v')+xBc.I(C,'ASP','VR_v'))/dc(C,'VR_v');

Sub_CDU_C("Total","VR") = sum(C ,(xIc.I(C, 'FCC','VR_v')+xIc.I(C,
'VB','VR_v')+xBc.I(C,'FO','VR_v')+xBc.I(C,'ASP','VR_v'))/dc(C,'VR_v'));

Sub_CDU_P("RFG v", "MBPD")=Sub_CDU_C("Total","RFG");

Sub_CDU_P("LPG v", "MBPD")=Sub_CDU_C("Total","LPG");

Sub_CDU_P("NAP v", "MBPD")=Sub_CDU_C("Total","NAP");

Sub_CDU_P("MSR v", "MBPD")=Sub_CDU_C("Total","MSR") ;

Sub_CDU_P("HSR v", "MBPD")=Sub_CDU_C("Total","HSR");

Sub_CDU_P("KR v", "MBPD")=Sub_CDU_C("Total","KR");

Sub_CDU_P("LDO v", "MBPD")=Sub_CDU_C("Total","LDO");

Sub_CDU_P("MDO v", "MBPD")=Sub_CDU_C("Total","MDO") ;

Sub_CDU_P("HDO v", "MBPD")=Sub_CDU_C("Total","HDO");

Sub_CDU_P("HVGO v", "MBPD")=Sub_CDU_C("Total","HVGO");

Sub_CDU_P("BSGO v", "MBPD")=Sub_CDU_C("Total","BSGO") ;

Sub_CDU_P("VR v", "MBPD")=Sub_CDU_C("Total","VR") ;

Sub_CDU_T("Total", "MBPD")= Sub_CDU_P("RFG v", "MBPD")+ Sub_CDU_P("LPG v", "MBPD")+

Sub_CDU_P("NAP v", "MBPD")+ Sub_CDU_P("MSR v", "MBPD")+

Sub_CDU_P("HSR v", "MBPD")+ Sub_CDU_P("KR v", "MBPD")+

Sub_CDU_P("LDO v", "MBPD")+ Sub_CDU_P("MDO v", "MBPD")+

Sub_CDU_P("HDO v", "MBPD")+ Sub_CDU_P("HVGO v", "MBPD")+
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```
Sub_CDU_P("BSGO v", "MBPD")+ Sub_CDU_P("VR v", "MBPD");


Sub_CDU_P("RFG v", "vol%")=Sub_CDU_C("Total","RFG")/Total_Crude_Feed.L*100 ;

Sub_CDU_P("LPG v", "vol%")=Sub_CDU_C("Total","LPG")/Total_Crude_Feed.L *100;

Sub_CDU_P("NAP v", "vol%")=Sub_CDU_C("Total","NAP")/Total_Crude_Feed.L *100;

Sub_CDU_P("MSR v", "vol%")=Sub_CDU_C("Total","MSR") /Total_Crude_Feed.L *100;

Sub_CDU_P("HSR v", "vol%")=Sub_CDU_C("Total","HSR")/Total_Crude_Feed.L *100;

Sub_CDU_P("KR v", "vol%")=Sub_CDU_C("Total","KR")/Total_Crude_Feed.L*100;

Sub_CDU_P("LDO v", "vol%")=Sub_CDU_C("Total","LDO")/Total_Crude_Feed.L  *100;

Sub_CDU_P("MDO v", "vol%")=Sub_CDU_C("Total","MDO") /Total_Crude_Feed.L*100;

Sub_CDU_P("HDO v", "vol%")=Sub_CDU_C("Total","HDO") /Total_Crude_Feed.L *100;

Sub_CDU_P("HVGO v", "vol%")=Sub_CDU_C("Total","HVGO")/Total_Crude_Feed.L *100;

Sub_CDU_P("BSGO v", "vol%")=Sub_CDU_C("Total","BSGO")/Total_Crude_Feed.L  *100;

Sub_CDU_P("VR v", "vol%")=Sub_CDU_C("Total","VR") /Total_Crude_Feed.L *100;


Sub_CDU_T("Total", "vol%")= Sub_CDU_P("RFG v", "vol%")+ Sub_CDU_P("LPG v", "vol%")

+Sub_CDU_P("NAP v", "vol%")+Sub_CDU_P("MSR v", "vol%")

+Sub_CDU_P("HSR v", "vol%")+ Sub_CDU_P("KR v", "vol%")

+Sub_CDU_P("LDO v", "vol%")+Sub_CDU_P("MDO v", "vol%")

+Sub_CDU_P("HDO v", "vol%")+Sub_CDU_P("HVGO v", "vol%")

+Sub_CDU_P("BSGO v", "vol%")+Sub_CDU_P("VR v", "vol%");

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*Sub_HCU

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Sub_HCU_Feed(C," v HDO+HVGO feed")= xIc.l(C,'HC','HDO_c')/dc(C,'HDO_c')+xIc.l(C,'HC','HVGO_v')/dc(C,'HVGO_v');

Sub_HCU_Feed(C, "HDO v")= xIc.l(C,'HC','HDO_c')/dc(C,'HDO_c');
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Sub_HCU_Feed(C, "HVGO v")= xIc.I(C,'HC','HVGO_v')/dc(C,'HVGO_v');

Sub_HCU_Feed("total volume MBPD","HDO+HVGO feed")= sum(C,
xIc.I(C,'HC','HDO_c')/dc(C,'HDO_c')+xIc.I(C,'HC','HVGO_v')/dc(C,'HVGO_v'));

Sub_HCU('v RFG',"MBPD")=((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'RFG_hc'))/d('HC', 'RFG_hc')  ;

Sub_HCU('v LPG',"MBPD" )= ((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'LPG_hc'))  /d('HC', 'LPG_hc') ;

Sub_HCU('v LN',"MBPD" )=((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'LN_hc')) /d('HC', 'LN_hc');

Sub_HCU('v HN',"MBPD" )=((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'HN_hc')) /d('HC', 'HN_hc')  ;

Sub_HCU('v KR',"MBPD" )=((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'KR_hc'))/d('HC', 'KR_hc')  ;

Sub_HCU('v LDSL',"MBPD" )=((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'LDSL_hc')) /d('HC', 'LDSL_hc')     ;

Sub_HCU('v HDSL',"MBPD" )=((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'HDSL_hc')) /d('HC', 'HDSL_hc')   ;

Sub_HCU('v UCO',"MBPD" )= ((xI.I('HC','HDO_c')+xI.I('HC','HVGO_v'))* Yhc('HC', 'UCO_hc')) /d('HC', 'UCO_hc')  ;


Sub_HCU('v Total',"MBPD" )= Sub_HCU('v RFG',"MBPD")+ Sub_HCU('v LPG',"MBPD" )+  Sub_HCU('v LN',"MBPD" )+Sub_HCU('v
HN',"MBPD" )

+ Sub_HCU('v KR',"MBPD" )+Sub_HCU('v LDSL',"MBPD" )+Sub_HCU('v HDSL',"MBPD" )+ Sub_HCU('v UCO',"MBPD" );

Sub_HCU('v RFG',"vol%" )=Sub_HCU('v RFG',"MBPD")/ HC_Feed.I*100;

Sub_HCU('v LPG',"vol%" )=  Sub_HCU('v LPG',"MBPD" )/HC_Feed.I*100;

Sub_HCU('v LN',"vol%" )= Sub_HCU('v LN',"MBPD" )/HC_Feed.I*100;

Sub_HCU('v HN',"vol%" )=Sub_HCU('v HN',"MBPD" )/HC_Feed.I*100 ;

Sub_HCU('v KR',"vol%" )=Sub_HCU('v KR',"MBPD" )/HC_Feed.I*100;

Sub_HCU('v LDSL',"vol%")= Sub_HCU('v LDSL',"MBPD" )/HC_Feed.I*100;

Sub_HCU('v HDSL',"vol%")=Sub_HCU('v HDSL',"MBPD" )/HC_Feed.I*100;

Sub_HCU('v UCO',"vol%")= Sub_HCU('v UCO',"MBPD" )/HC_Feed.I*100;


Sub_HCU('v Total',"vol%")= Sub_HCU('v RFG',"vol%" )+Sub_HCU('v LPG',"vol%" )+Sub_HCU('v LN',"vol%" )+Sub_HCU('v
HN',"vol%" )

+Sub_HCU('v KR',"vol%" )+ Sub_HCU('v LDSL',"vol%")+  Sub_HCU('v HDSL',"vol%")+Sub_HCU('v UCO',"vol%");
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*Sub_LBOU

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Sub_LBOU_Feed( "LBOU Feed mass")=xI.l('LB','UCO_hc');

Sub_LBOU_Feed( "LBOU Feed volume")=xI.l('LB','UCO_hc')/d('HC', 'UCO_hc');

Sub_LBOU ("v RFG","MBPD")= xI.l('LB','UCO_hc')*Y('LB','RFG_lb')/d('LB','RFG_lb');

Sub_LBOU ("v Naphtha","MBPD")= xI.l('LB','UCO_hc')*Y('LB','N_lb')/d('LB','N_lb');

Sub_LBOU ("v DSL","MBPD")= xI.l('LB','UCO_hc')*Y('LB','DSL_lb')/d('LB','DSL_lb');

Sub_LBOU ("v MBO","MBPD")= xI.l('LB','UCO_hc')*Y('LB','MBO_lb')/d('LB','MBO_lb');

Sub_LBOU_t ("v Total","MBPD")=Sub_LBOU ("v RFG","MBPD")+Sub_LBOU ("v Naphtha","MBPD")+Sub_LBOU ("v
DSL","MBPD")+Sub_LBOU ("v MBO","MBPD");

Sub_LBOU ("v RFG ","vol%")= Sub_LBOU ("v RFG","MBPD")/LB_Feed.l*100;

Sub_LBOU ("v Naphtha","vol%")= Sub_LBOU ("v Naphtha","MBPD")/LB_Feed.l*100;

Sub_LBOU ("v DSL","vol%")= Sub_LBOU ("v DSL","MBPD")/LB_Feed.l*100;

Sub_LBOU ("v MBO","vol%")= Sub_LBOU ("v MBO","MBPD")/LB_Feed.l*100;

Sub_LBOU_t ("v Total","vol%")=Sub_LBOU ("v RFG ","vol%")+Sub_LBOU ("v Naphtha","vol%")+Sub_LBOU ("v
DSL","vol%")+Sub_LBOU ("v MBO","vol%");

Sub_LBOU_VI(C,"VI HDO")= VI_VGO(C,'HDO_c')$(xC.l(C)>0);

Sub_LBOU_VI(C,"VI HVGO")= VI_VGO(C,'HVGO_v')$(xC.l(C)>0);

Sub_LBOU_VI(C,"VI VGO")= ((VI_VGO(C,'HDO_c')+VI_VGO(C,'HVGO_v'))/2)$(xC.l(C)>0);

Sub_LBOU_VI(C,"DVI HC")=DVI_HC(C)$(xC.l(C)>0);

Sub_LBOU_VI(C,"DVI LB")=DVI_LB(C)$(xC.l(C)>0);

Sub_LBOU_VI(C,"VI VGO Final")=VI_VGO_final(C)$(xC.l(C)>0);

Sub_LBOU_VI("VI LBO Final", "VI HDO")= VI_LBO_value;


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*Sub_FCCU

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Sub_FCC_Feed("HVGO MBPD","Feed")= sum(C, xIc.l(C,'FCC', 'HVGO_v')/dc(C,'HVGO_v'));

Sub_FCC_Feed("BSGO MBPD","Feed")=  sum(C, xIc.l(C,'FCC', 'BSGO_v')/dc(C,'BSGO_v'));

Sub_FCC_Feed("VR MBPD", "Feed")= sum(C, xIc.l(C,'FCC', 'VR_v')/dc(C,'VR_v'));

Sub_FCC_Feed("UCO MBPD","Feed")=xI.l('FCC', 'UCO_hc')/d('HC','UCO_hc');

Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")=sum (C, xIc.l(C,'FCC', 'HVGO_v')/dc(C,'HVGO_v')+ xIc.l(C,'FCC',
'BSGO_v')/dc(C,'BSGO_v')+xIc.l(C,'FCC', 'VR_v')/dc(C,'VR_v'))+xI.l('FCC', 'UCO_hc')/d('HC','UCO_hc');


Sub_FCC_Feed("Feed Density","Feed")=dens.l;

Sub_FCC_Feed("Feed Concrbon","Feed")=CCR_FCC_Feed;




Sub_FCC ("v RFG","MBPD")= (( sum(C, xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'RFG_fcc')/d('FCC','RFG_fcc'));

Sub_FCC ("v LPG","MBPD")= (( sum(C,xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'LPG_fcc')/d('FCC', 'LPG_fcc'));

Sub_FCC ("v LCN","MBPD")= (( sum(C,xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'LCN_fcc')/d('FCC', 'LCN_fcc'));

Sub_FCC ("v MCN","MBPD")= (( sum(C,xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'MCN_fcc')/d('FCC', 'MCN_fcc'));

Sub_FCC ("v HCN","MBPD")= (( sum(C,xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'HCN_fcc')/d('FCC', 'HCN_fcc'));

Sub_FCC ("v LCGO","MBPD")= (( sum(C,xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'LCGO_fcc')/d('FCC', 'LCGO_fcc'));

Sub_FCC ("v HCGO","MBPD")= (( sum(C,xIc.l(C,'FCC','HVGO_v')/dc(C,'HVGO_v') + xIc.l(C,'FCC','BSGO_v')/dc(C,'BSGO_v')
+xIc.l(C,'FCC','VR_v')/dc(C,'VR_v'))+ xI.l('FCC','UCO_hc')/d('HC','UCO_hc'))* Yfcc.l('FCC', 'HCGO_fcc')/d('FCC', 'HCGO_fcc'));
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```
Sub_FCC ("v RFG","vol%")=Sub_FCC ("v RFG","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;

Sub_FCC ("v LPG","vol%")=Sub_FCC ("v LPG","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;

Sub_FCC ("v LCN","vol%")=Sub_FCC ("v LCN","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;

Sub_FCC ("v MCN","vol%")=Sub_FCC ("v MCN","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;

Sub_FCC ("v HCN","vol%")=Sub_FCC ("v HCN","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;

Sub_FCC ("v LCGO","vol%")=Sub_FCC ("v LCGO","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;

Sub_FCC ("v HCGO","vol%")=Sub_FCC ("v HCGO","MBPD")/Sub_FCC_Feed("FCCU Total Feed MBPD", "Feed")*100;


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display SLF_KR_value, d_DSL_value, SLF_VDSL_value, CI_DSL_value, SLF_FO_value, KVI_FO_value,
wt_Yield,VI_LBO_value,SLF_HDU_Feed,SLF_HC_Feed,NTR_HC_Feed, CCR_FCC_Feed,

Liquid_Recovery, Volume_Yield,Sub_Crude, Sub_CDU_C,Sub_CDU_P,Sub_CDU_T, Sub_HCU_Feed, Sub_HCU, Sub_LBOU_Feed,
Sub_LBOU, Sub_LBOU_t, Sub_LBOU_VI, Sub_FCC_Feed, Sub_FCC ;
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ملخص الدراسة

الهدف الرئيسي من التخطيط والتحسين في المصافي هو زيادة الهوامش من خلال التركيز على اختيار النفط الخام وتعظيم قيمة المنتج. لزيادة قيمة المنتج، تتبنى بعض المصافي هيكلين، حيث تقوم بإنتاج زيوت التشحيم الأساسية من المجموعة الثالثة من خلال المعالجة التحفيزية ، بالإضافة إلى الوقود التقليدي مثل البنزين والديزل والكيروسين، ومن هنا وجب التنويه لوجود العديد من التحديات التي يجب الإشارة إليها.

التحدي الأول الذي ستواجهه مصفاة ذات هيكلين هو اختيار النفط الخام. يتم عادة تحديد جودة الوقود التقليدي من خلال الخصائص الفيزيائية للنفط الخام مثل نقطة الغليان ومحتوى الكبريت. من ناحية أخرى ، يتم تحديد جودة زيت التشحيم الأساسي بشكل أساسي من خلال مؤشر اللزوجة وهو مقياس لدرجة تغير اللزوجة مع درجة الحرارة ، ويعتمد بشدة على التركيب الكيميائي للنفط المختار. يتطلب إيجاد الأوجية لمصفاة مع وحدة التشحيم نموذج تنبؤ يمكنه تقدير مؤشر اللزوجة لمنتجات التشحيم النهائية من خلال مراعاة الاختلافات بين الأنواع المختلفة من المواد الأولية. ومع ذلك ، فإن التنبؤ بمؤشر اللزوجة يمثل تحديًا نظرًا لوجود أنواع عديدة من الزيوت الخام حول العالم ، ولكل منها تركيبة كيميائية مختلفة . إلى جانب اختيار الخام ونوع المواد الأولية ، فإن ظروف التشغيل مثل التحويل في وحدة التكسير الهيدروجيني، مهمة في تحديد إنتاجية وجودة زيت قاعدة التشحيم. هذا يعني أنه مع زيادة معدل التحويل في وحدة التكسير الهيدروجيني للتشحيم ، يزداد مؤشر اللزوجة للمنتج ولكن الكمية المنتجة من زيت التشحيم الأساسي تنخفض مما يؤدي إلى انخفاض في الهامش الإجمالي .بالإضافة إلى ذلك ، يجب تحديد تقسيم المواد الأولية إلى عدة وحدات تحويل في المصفاة.

الغرض من هذه الأطروحة هو تطوير منهجية لتحقيق الأوجية للمصافي ذات إمكانية لإنتاج زيوت التشحيم الأساسية، كالمصفاة المحلية في البحرين والتي تقوم بمعالجة نوعين من النفط الخام فقط. المنهجية سوف تتضمن استخدام نموذج تصنيف للنفط الخام يعتمد على مؤشر اللزوجة ، ونماذج لتقدير التغيير في مؤشر اللزوجة والإنتاجية من خلال وحدات المصفاة ، لاختيار أنواع الخام المثلى التي تزيد من قيمة المنتجات والأرباح.

أظهرت النتائج أن السماح باختيار النفط الخام في المصفاة المدروسة يمكن أن يزيد هامش المساهمة بمقدار ٣٠ مليون دولار شهريًا بالمقارنة مع العملية الحالية التي تقوم بمعالجة خامين فقط. إن استخدام نموذج مؤشر اللزوجة مطلوب لضمان تلبية جودة زيوت التشحيم. فلقد أثبت أن اختيار النفط الخام يتغير مع المواصفات المطلوبة لزيوت التشحيم ومعدل التحويل في وحدة التكسير الهيدروجيني. عندما ينخفض معدل التحويل من ٨٠ ٪ إلى ٧٥ ٪ ، يزداد حجم النفط الخام البارافيني بنسبة ٣ ٪ و ١٦ ٪ عندما تكون مواصفات مؤشر اللزوجة عند ١٢٠ و ١٢٥ على التوالي.

جامعة البحرين

قسم الهندسة الكيميائية

كلية الهندسة

دور اختيار النفط الخام في تحسين اقتصاديات المصفاة المحلية بقدرة المعالجة المائية للتشحيم

أطروحة مقدمة في إطار الوفاء الجزئي بمتطلبات درجة ماجستير العلوم في الهندسة الكيميائية

إعداد:

لُجين محمد السيوف

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(أستاذ مشارك)

جامعة البحرين

مملكة البحرين

يونيو ٢٠٢١