Improving refinery productivity through better utilization of crude oil blending using linear programming.

Master of Science in Engineering by advanced coursework and research:

Prepared by

Kunal Haridev Vanmali

602550

A Research Report Submitted to the:

School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Supervisor(s): Prof. S. Iyuke

December, 2014

DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted to the Degree of Master of Science, in Petroleum Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

………………………………………………………………………………

……….. Day of ……………..……………

DEDICATION

To my parents, Haridev and Renuka Vanmali, who have been sources of encouragement and inspiration to me throughout my life, a very special thank you for providing me with the love and support through the months of writing. Thank you for the myriad of ways in which, throughout my life, you have actively led me to realize my full potential.

ABSTRACT

Refinery Linear Programming (LP) Models and other mathematical techniques for optimization have evolved over many years to create solutions for complex crude oil blending problems. The objective of this case study was to develop a mathematical single period programming model to simulate blending problems to ensure the greatest possible revenue is generated. The yield of products at a refinery, given stringent environmental regulations on product qualities, the reducing availability of quality light, sweet, feedstock make refinery optimization a significant exercise to perform in order to stay in business. In this work a representation of a case study refinery model was presented, in which the overall gross profit margin, density, and sulphur content of the products were calculated, and evaluated to ensure they fall within the market specification and demand. The model is also able to predict operating variables like the cut-point temperatures in the Crude Distillation Unit which will result in the best outcome for the given scenario. The model formulation is illustrated, scenario based evaluations performed, and results discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Indices:

i, j, m, b	Processing Units
s	Streams

Sets:

B	Final blending units (b), $B \in I$
I	Processing units (i) in the refinery
J	Processing units (j) that can send products to unit (i), $J \in I$
M	Processing unit (m) can receive stream (s) from unit (i), $M \in I$
S	Product streams (s) of unit (i)
C	Crude oil (c), $c \in C$

Parameters:

Sp_i	Selling price of product from blending pool (i)
Cc_c	Cost of Crude Oil (c)
$Y_{i,s,m}$	Volumetric flow yield of stream (s) from processing unit (i) received by processing unit (m)
$Z_{i,s,m}$	Density yield of stream (s) from processing unit (i) received by processing unit (m)
$X_{i,s,m}$	Sulphur Content yield of stream (s) from processing unit (i) received by processing unit (m)
CT_s^U	Upper Cut-point temperature of stream (s)

$CT_s^{\ L}$	Lower Cut-point temperature of stream (s)
OC_i	Maximum Operating Capacity for unit (i)

Variables:

F_i	Volumetric flow rate of feed to unit (i)
F_c	Volumetric flow rate of crude oil feed (c) to the CDU
F_s	Volumetric flow rate of stream (s)
$F_{c,s}$	Volumetric flow rate of crude oil feed (c) of stream (s)
$F_{j,s}$	Volumetric Flow rate of possible streams (s) that can be received by processing unit (i) from unit (j)
CV_t	Upper Cut-point Temperature of stream (s)
CV_{t-1}	Lower Cut-point Temperature of stream (s)
$MidV_s$	Mid-Volume percent vaporized for stream (s)
$PD_{c.s}$	Average density of crude oil feed (c) for stream (s)
$PS_{c,s}$	Average sulphur weight percent of crude oil feed (c) for stream (s)
PD_s	Average density of stream (s)
PS_s	Average sulphur weight percent of stream (s)
PD_i	Average density of feed to unit (i)
PS_i	Average sulphur weight percent of feed to unit (i)
PD_s	Average density of product from unit (i)
PS_s	Average sulphur weight percent of product from unit (i)
$PD_{j,s}$	Average density of feed to unit (i) from unit (j) of stream (s)
$PS_{j,s}$	Average sulphur weight percent of feed to unit (i) from unit (j) of stream (s)

ABBREVIATIONS

CDU	Crude Distillation Unit
LP	Linear Programming
API	American Petroleum Institute
TBP	True Boiling Point
SA	South Africa
NHT	Naphtha Hydro Treatment Unit
KHT	Kerosene Hydro Treatment Unit
DHT	Diesel Hydro Treatment Unit
FCCPU	Fluid Catalytic Cracker Pretreater Unit
VBU	VisBreaker Unit Capacity
VDU	Vacuum Distillate Unit
FCCU	Fluid Catalytic Cracking Unit
GASP	Gas Plant
POLYU	Polymerization Unit
ISOMU	Isomerization Unit
CRU	Catalytic Reforming Unit
SAPIA	South African Petroleum Industry Association
AFQRJOS	Aviation Fuel Quality Requirements for Jointly Operated Systems
SANS	South African National Standard
API	American Petroleum Institute
ppm	Parts per million
SRU	Sulphur Recovery Unit
ASTM	American Society for Testing Materials
BLCO	Bonny Light Crude Oil
OCO	Oman Crude Oil

CHAPTER 1: INTRODUCTION

1.1 Motivation

The objective of any business is to create the greatest economic return on the owner's investment, whilst doing so in a sustainable manner. The objective of any oil refinery is process crude oil into higher value products which can be sold to the market at the lowest possible cost, to create the greatest profit whilst satisfying government policy and regulation on quality and its impact on the environment.

The global oil demand for the year 2011 was estimated to be 87.8 million barrels per day and is forecasted to reach 104.2 million barrels per day by 2030. This increase in demand will mean additional refining capacity will need to be built throughout the world, but more so in developing countries where the demand will be increasing more exponentially. (OPEC, 2012)

Refineries convert crude oil into marketable petroleum products of high value which are used throughout the world in everyday life such as liquefied petroleum gas, petrol, and diesel. Various physical and chemical methods are used in the refining process such as heat, pressure, and catalysts under widely varying process designs to convert this crude oil into petroleum products (Gary et al, 2007).

Modern refinery operations can become very complex due to the vast array of feedstock sources, qualities, sophisticated processing technology, and increasingly stringent product specifications. What adds to the complexity of this is that many of the various processing units and products are interrelated. This of course makes making economic decisions at the refinery very difficult as individual processes cannot be evaluated in isolation, as they have interrelated effects on the rest of the refinery.

The main objective of this study is to create a mathematical model to represent the major processes in the refinery relating to the production of petrol, diesel and jet fuel, and to analyze the economic result of this. The linear programming approach is to develop a set of equations, and an objective function to represent the economic evaluation of the problem. The set of equations define a feasible region that has an infinite number of solutions. The objective function is used to assign a relative value to each solution and the linear programming solution the best or optimal solution (Gary et al, 2007). This representation includes different crude oil assays, process units, product blending, and crude oil flow rates.

Refiners typically use linear programming models because they solve quickly, are relatively easy to maintain, and provide sufficient accuracy for economic decision making. The model developed has gone further and has included the CDU cut-point temperature optimization.

1.2 Research Objectives

The overall objectives of this study is to determine the best strategy for a refinery to meet final product quality specifications by the influence of crude oil blending while increasing desired production levels with minimal overall cost maximizing the gross profit.

To determine a graphical region where the case study refinery meets these specifications.

A linear programming model will then be used to evaluate different operational scenarios to evaluate how the refineries gross profit changes by varying crude oil participation in a blend, CDU cut-point temperatures, and overall product quantities.

A sensitivity analysis will be performed to evaluate which variables have the greatest impact.

1.3 Report Layout

CHAPTER 1: INTRODUCTION

This chapter addresses the latest issues in the petroleum refining industry and provides a motivation for research. It states the research objectives, and the organization of the research report.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a background about the petroleum refining industry and describes the major processing units and their main functions. It also represents a review of previous studies relating to the topic of research. This chapter also provides the basis of what the market demand is, and the individual product specifications, the crude oil costs, utility and maintenance costs, and product selling prices.

CHAPTER 3: MATHEMATICAL MODEL FOR REFINERY OPTIMIZATION

This chapter represents the processing units, their quality and productivity yields within the refinery. The overall refinery model is developed through simultaneously connecting the processing unit models with their properties blended.

CHAPTER 4: RESULTS AND ANALYSIS

This chapter involves discussion and analysis of the results obtained from the scenario simulations.

CHAPTER 5: CONCLUSIONS AND RECCOMENDATIONS.

This chapter provides the major behavior that can be concluded from using the model, and ways to better the model.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Refining is a unique and critical link in the petroleum supply chain from the wellhead to the pump. Petroleum refineries are large scale manufacturing facilities which are extremely capital intensive, which utilize complex processing schemes that take years to design and build. They transform crude oil into a variety of valuable marketable products which are vital to the lives we currently live today such as:

- Liquefied Petroleum Gas
- Petrol or Gasoline
- Jet Fuel
- Kerosene
- Diesel Fuel
- Lubricating oils and waxes
- Fuel Oil (used for power generation or as marine fuel)
- Asphalt (for paving and roofing uses)

The highest value products are without a doubt transportation fuels like petrol, diesel, and jet fuel, however there are many other lower value products like fuel oil and asphalt that still add to the gross profit. Many of these refined products are available are produced in multiple grades to meet different quality specifications.

2.2 Chemical Constituents of Crude Oil

In order to gain a proper understanding of this area of research one must understand the fundamentals of what is being refined: Crude Oil.

Millions of years ago, dead organic matter was deposited in areas of the earth, trapped by rock formations under high pressure and temperature, the organic matter was transformed into the crude oil we have today.

Each crude oil is unique and is a complex mixture of thousands of compounds. Most of the compounds in crude oil are hydrocarbons (organic compounds composed of carbon and hydrogen atoms). Other compounds in crude oil contain not only carbon and hydrogen, but also small (but important) amounts of other elements most notably sulphur, as well as nitrogen and certain metals like nickel and vanadium. (Nadkarni, 1991.)

The heavier (or more dense) the crude oil, the higher its C/H ratio. Due to the chemistry of oil refining, the higher the C/H ratio of a crude oil, the more intense and costly the refinery processing required to produce given volumes of gasoline and distillate fuels. Thus, the chemical composition of a crude oil and its various boiling range fractions influence refinery investment requirements and refinery energy use, the two largest components of total refining cost. The proportions of the various hydrocarbon classes, their carbon number distribution, and the concentration of different elements in a given crude oil determine the yields and qualities of the refined products that a refinery can produce from that crude, and hence the economic value of the crude. Different crude oils require different refinery facilities and operations to maximize the value of the product slates that they yield (ICCT, 2011).

Analyzing a crude oil can be done by reading the full description of a crude oil assay where many components and properties may be assessed, however two properties are especially useful for classifying and comparing crude oils namely the API gravity (which is essentially the density) and the sulphur content.

2.2.1 API Gravity

API Gravity is a measure of heavy or light the crude oil is compared to water. Lighter crudes contain higher quantities of smaller molecules which are easy to process into products like transportations fuels of which the demand is high, and continually growing. Heavy crudes contain higher quantities of larger molecules which will need a higher intensity (and more costly) level of processing to convert into high value products like transportation fuels. These types of crudes typically will yield higher amounts of lower value products like asphalt and fuel oil. Generally speaking, the lighter the crude is, the higher the market price will be for it.

API Gravity is expressed in degrees (°API) and varies inversely with the actual density. Figure 2.1 shows the constituents of typical light crude with 35° API gravity compared to typical heavy crude with 25° API gravity. It also shows the typical product demand in developed countries. It is important to note that for both light and heavy crude oils the demand for heavy oil products is less than the originating crude oils which mean oil refineries will at least need to be able to convert some heavy distillates into lighter products.

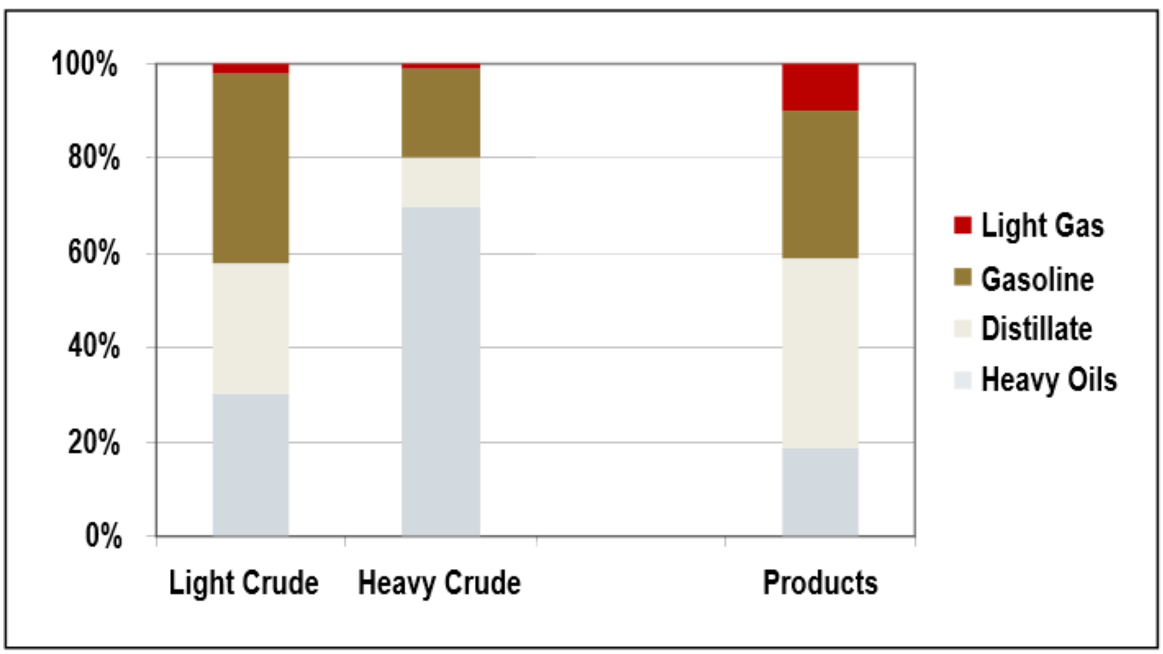

Figure 2.1: Typical natural yields of light and heavy crude oils. (ICCT, 2011)

2.2.2 Sulphur Content

Sulphur content in crude oil is one of the most significant parameters to refiners. Very high sulphur crudes can reduce the effectiveness or even deactivate catalysts that speed up desired chemical reactions in certain refining processes, causes damage to refinery piping, and equipment via corrosion, and lead to air emissions of sulphur compounds which are undesirable and be subject to stringent regulatory controls. The corrosive environment usually become more pronounced where refining occurs at higher temperatures and pressures. (Duissenov, 2012)

As a result refineries will need to be able to process the crude oil such that enough sulphur is removed to mitigate these unwanted effects whilst meeting end product sulphur limitations.

Sulphur content is usually expressed in weight percent (wt%) or by parts per million (ppm). Low sulphur crudes are generally referred to as sweet if the sulphur levels are less than 0.5 wt%, and high sulphur crudes are referred to as sour if they are above this threshold. As the boiling point of the crude increases, generally the sulphur wt% of the fraction also increases. Table 2.1 summarizes the crude oil classification.

Table 2.1: Crude oil classes (ICCT, 2011)

Crude Oil Class	Property Range	
	Gravity (°API)	Sulfur (wt.%)
Light Sweet	35-60	0-0.5
Light Sour	35-60	> 0.5
Medium Medium Sour	26-35	0-1.1
Medium Sour	26-35	> 1.1
Heavy Sweet	10-26	0-1.1
Heavy Sour	10-26	> 1.1

As the years go by, the average quality of the global crude oil slate has been gradually declining. Average API gravity has been decreasing slowly, and the average sulphur content has been increasing. A trend that is likely to continue for the foreseeable future as reserves of light and sweet crude are being diminished exponentially quickly. This is illustrated in Figure 2.2, showing the forecasted reduction of crude quality.

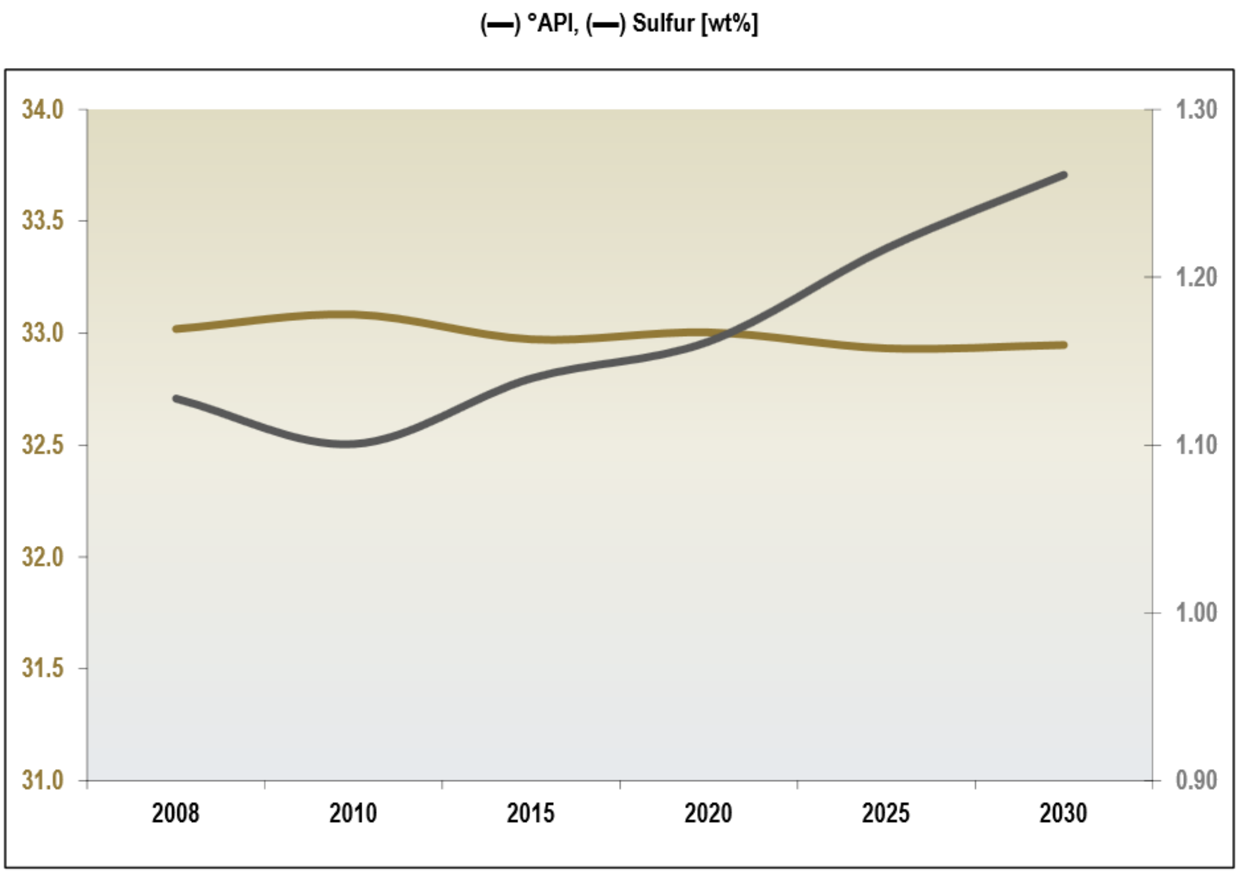

Figure 2.2: Graph of °API and sulphur content vs time (ICCT, 2011).

2.3 Refinery Processing

Figure 2.3 shows a very complex refinery which processes a variety of crude oil producing a range of quality fuels.

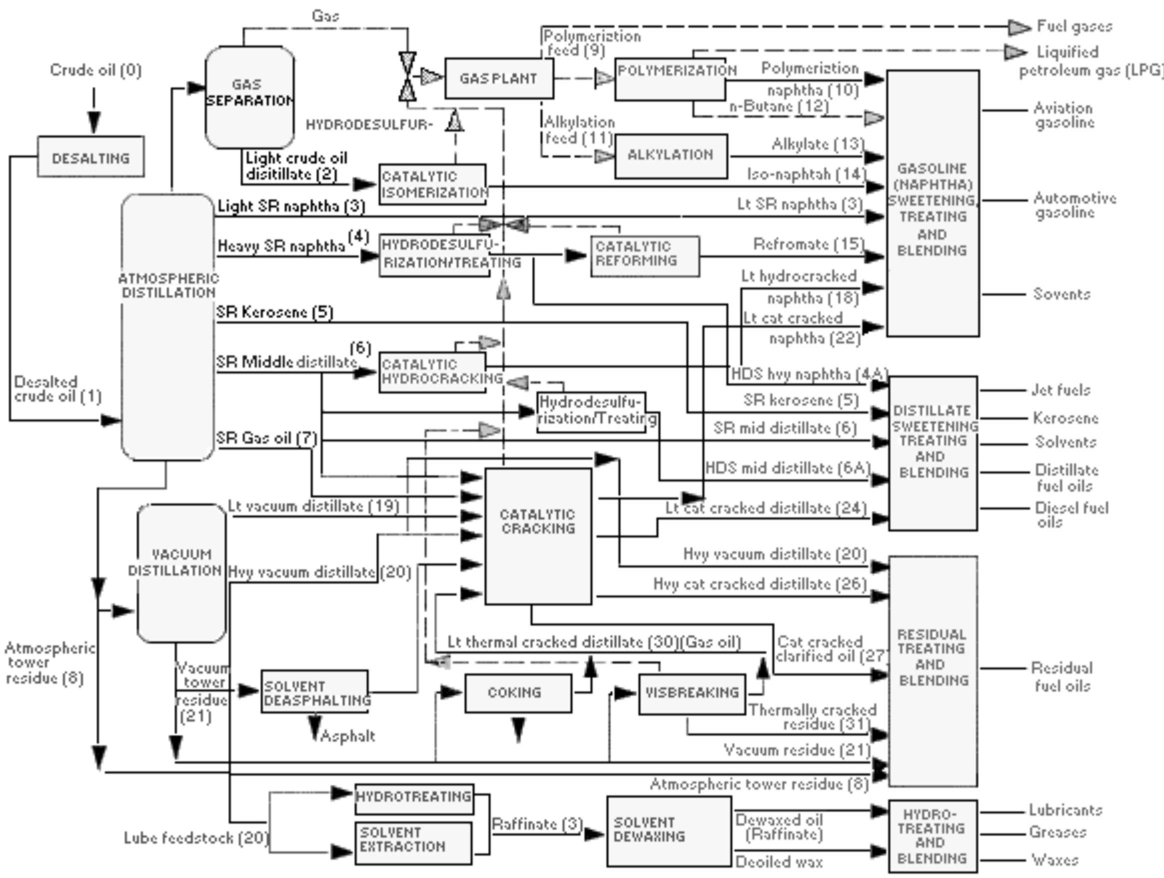

Figure 2.3: Schematic flow chart of a complex refinery (OTM, 2013)

Refineries have the ability to change the operating conditions of each of the processing units, enabling it to change the volume and quality of the products manufactured in order to meet the current market demand, and quality regulations. They will also need to change the configuration in order to adapt to changing crude oil blends that are available to be processed.

Refinery operations essentially fall into four categories (Alhajri, 2008):

1) Fractionation involve in separating crude oil, in atmospheric and vacuum distillation, into different hydrocarbon groups, or fractions.

2) Conversion processes:

A. Cracking (thermal and catalytic) involve in breaking large and heavy hydrocarbon molecules into smaller ones. Cracking can be achieved either through the application of heat (delayed coking) or by catalysts (FCC).

B. Rearrangement involve in restructuring the molecule and producing a new molecule with different characteristics, but the same number of carbon atoms (catalytic reforming and isomerization).

C. Combination involve in linking molecules together to form a larger molecule (alkylation and polymerization).

3) Treating processes involve in preparing streams for additional processing, and removing impurities like sulphur compounds (hydro treating).

4) Blending is used to get the final product, and it considers as the last phase of the refining process.

A more detailed description of the process units involved in the model represented by the case study refinery will follow.

2.3.1 Crude Distillation Unit

The Crude Distillation Unit (CDU) is the first major refining process in any refinery, regardless of the different types of crude processing units that follow downstream. The function of the CDU is to separate the crude oil into different fractions or streams which is categorized by the boiling or cut-point temperatures ranges based on their volatility or their ability to move into a gaseous state. Crude oil is heated up by a furnace and pumped into the CDU so the process may start. As the boiling point of different hydrocarbon molecules are reached, the vapors condense and the relevant streams of different crude fractions are pumped to the next relevant unit in the refinery for further processing. Light fractions are collected through atmospheric distillation whilst heavier fractions are collected in a vacuum tower at a lower pressure due to their higher boiling point ranges. Varying the cut point temperature will of course vary the distillation volumes in each stream and their properties. The CDU is illustrated in Figure 2.4.

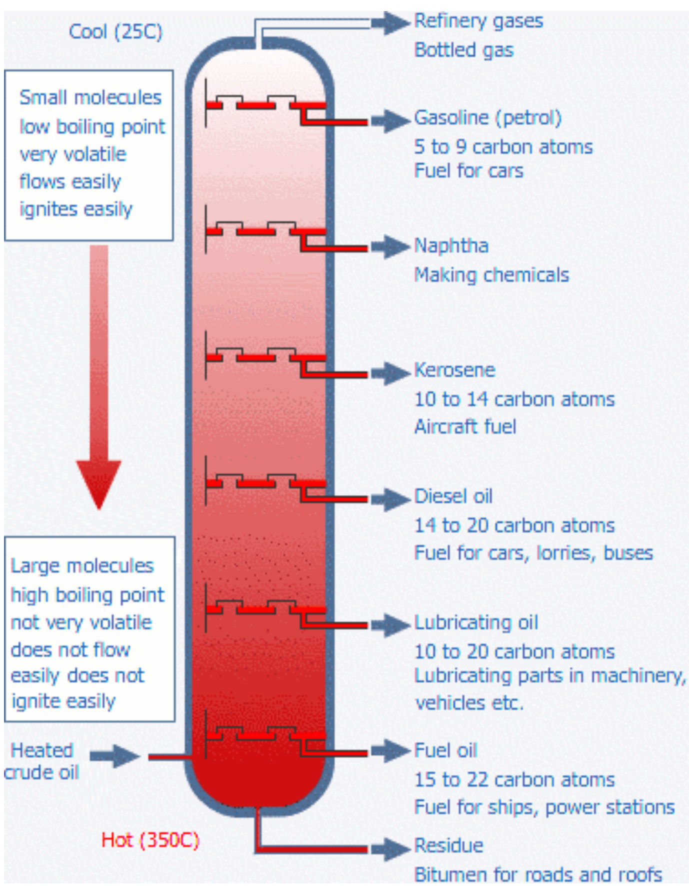

Figure 2.4: Illustration of crude distillation unit operation (EB, 2013)

2.3.2 Fluid Catalytic Cracking Unit

Fluid Catalytic Cracking Unit (FCCU) is a form of conversion, which “Crack” or breakdown high-boiling point hydrocarbon molecules which are generally low in demand and therefore low in economic value into smaller, lighter molecules which are suitable for processing and blending into streams to be used with other low-boiling point high value products. This enables the refinery to increase its yields of high value transportation fuels, provide flexibility for maintaining light product output in terms of fluctuations in the crude oil price. The FCCU unit makes use of a catalyst which is a material that speeds up the chemical reaction, without itself being involved in the reaction. Major yields from this process favor light petrol and LCO diesel, and also include heavy petrol and LPG. (Dechamps, 2013)

Table 2.2: FCCU volumetric flow yield parameters

Fluid Catalytic Cracking Unit	$Y_{i,s,m}$
LCO Diesel yield to Diesel Blending Unit	0.32
Light Petrol yield to Petrol Blending Unit	0.25
Heavy Petrol yield NHDT	0.1
LPG yield to GASP	0.17

2.3.3 Fluid Catalytic Cracking Pretreater Unit

Sulphur content in FCCU streams is dangerous as is likely to cause the FCCU catalyst to reduce its effectiveness. Many refineries use a FCCU Pretreater to desulphurize the stream before it enters the FCCU itself to remove the sulphur from the FCCU feed. It is well known that even after this pretreating the FCCU products still make up the bulk amount of sulphur in diesel and petrol blending pools. (Chung et al, 2007). It is assumed the sulphur reduction at this unit is 91%, $X_{i,s,m}$ = 0.09.

2.3.4 Catalytic Reforming Unit

The Catalytic Reforming Unit (CRU) performs an upgrading process which significantly increases the octane number in the output stream called reformate. The reformate is used primarily in the petrol blending pool, but also produces large amounts of LPG. Another important function that the CRU performs is to produce hydrogen gas (H_2) which is used throughout the refinery in many different processes (Dechamps, 2013)

Table 2.3: CRU volumetric flow yield parameters

Catalytic Reforming Unit	$Y_{i,s,m}$
Reformate yield to Petrol Blending Unit	0.7
LPG yield to GASP	0.15

2.3.5 Isomerization Unit

The Isomerization Unit (ISOMU) is another upgrading process which rearranges molecules of light naphtha creating a product called isomerate with a higher octane number and reduced density which is added to the petrol blending pool to help meet quality standards. Another added benefit of using isomerate is the product is very low in sulphur which also helps in the blending pool (Dechamps, 2013).

Table 2.4: CRU volumetric flow yield parameters

Isomerization Unit	$Y_{i,s,m}$
Isomerate yield to Petrol Blending Unit	0.98

2.3.6 Polymerization Unit

Like isomerization, Polymerization is another upgrading process which produces a high octane product called polymerate which is used in the blending process (Dechamps, 2013).

Table 2.5: POLYU volumetric flow yield parameters

Polymerization Unit	$Y_{i,s,m}$
Polymerate yield to Petrol Blending Unit	0.72

2.3.6 Hydro Treatment Units

Hydro treatment units are used to facilitate chemical reactions in refinery streams to remove unwanted compounds like sulphur and other heavy metals. The most important purpose for this is meet sulphur quality specifications, and further protecting the catalysts in downstream processing units. Other effects of hydro treating are product density reduction (Dechamps, 2013). For the purpose of this study it is assumed the DHT reduces the density of the product stream by 7%, $Z_{i,s,m}$ = 0.93.The sulphur content is reduced by 97% $X_{i,s,m}$ = 0.03 which is typical of diesel hydro treaters. The KHDT unit has no effect on the sulphur content of the stream due to the relatively high sulphur content specification discussed in the later chapter.

2.3.7 Vacuum Distillate Unit

The vacuum distillation is part of the distillation process, and distills the heavier fractions of crude oil. The way it works is by reducing the vapor pressure in the unit, to less than the CDU. The distillation works on the premise that boiling occurs when the vapor pressure of the liquid exceeds the ambient pressure allowing the residue portion of the distillation to vaporize easier.

Table 2.6: VDU volumetric flow yield parameters

Vacuum Distillation Unit	$Y_{i,s,m}$
Vacuum Distillate yield FCCPU	0.46
Vacuum Residue yield to VBU	0.48

2.3.8 VisBreaking Unit

VisBreaking is thermal cracking process, where the main purpose is to reduce the quantity of residue oil produced by the refinery. This increases the yield of middle distillate fractions; as a result the viscosity of the oil is reduced.

Table 2.7: VBU volumetric flow yield parameters

VisBreaking Unit	$Y_{i,s,m}$
Light Naphtha yield to NHDT	0.008
LPG yield to GASP	0.008
Diesel yield to DHT	0.024
Diesel yield to FCCPU	0.26

2.3.9 Gas Plant

The main purpose of the gas plant is compress the gas received from around the plant and pumps it to where it is needed.

Table 2.8: GASP volumetric flow yield parameters

Gas Plant	$Y_{i,s,m}$
LPG yield to POLYU	0.98

2.3.10 Blending Units

Product blending, the operation at the back end of every refinery, regardless of size or overall configuration. They blend refinery streams in various proportions to produce finished refined products whose properties meet all applicable industry and government standards, at minimum cost. The various standards pertain to physical properties like density and boiling range; chemical properties like sulphur content, and aromatics, and performance characteristics like octane number. Production of each finished product requires multi component blending because refineries produce no single blend component in sufficient volume to meet demand for any of the primary blended products such as petrol, jet fuel, and diesel fuel. Many blend components have properties that satisfy some but not all of the relevant standards for the refined product into which they must be blended, and finally cost minimization dictates that refined products be blended to meet, rather than exceed, specifications to the extent possible. This is called quality give-away. (ICCT, 2011)

2.4 Refinery Linear Programming

Historically a refinery scheduler would undertake the responsibility to manually plan and figure out production scheduling and blending by hand calculation, which is very time consuming especially if different blending scenarios are to be evaluated. This technique may improve productivity; however it is highly unlikely that this method will allow the refinery to reach an optimal productivity level (Kelly et al, 2003). This inefficiency led to the need for a mathematical optimization approach which was fast yet effective with the ability to make decisions.

The oil refining industry is a prolific field for the application of mathematical programming techniques (Bodington et al, 1990). In the field of operations research, analysts make use of many different programming techniques such as linear, non-linear, dynamic and simulation methods to name a few to optimize a mathematical model to produce a desired outcome.

According to Mark Schulze PhD, Linear programming (LP) is a relatively young mathematical discipline, dating from the invention of the simplex method by G. B. Dantzig in 1947. Historically, development in linear programming is driven by its applications in economics and management. Dantzig initially developed the simplex method to solve U.S. Air Force planning problems, and planning and scheduling problems still dominate the applications of linear programming. One reason that linear programming is a relatively new field is that only the smallest linear programming problems can be solved without a computer. The most popular method is the simplex method. This method of optimization is widely used around the globe and can make a great impact in optimizing refinery processes.

One of the first forms of linear programming in the oil refining space was done in 1971 by Allen H in his paper titled Linear Programming models for plant operations planning (Allen, 1971), which composed of a distillation unit, a cracker and fuel oil blending unit. Leira et al (2010) has worked further on Allen’s work by proposing a multi-period linear programming model to generalize his work.

More recently work done by Dunham et al (2009) proposed a mathematical model to optimize refinery crude oil purchasing by incorporating six different types of crude oils whilst accounting for refinery utility costs such as hydrogen production using a single time period.

Gothe-Lundgren et al (2000) showed a production planning and scheduling problem in an oil refinery where they modeled the transformation of crude oil into bitumen and naphthentic oil in order to satisfy market demand whilst taking into account costs of holding inventory and changing operational modes.

Many different approaches have been used to solve crude oil import scheduling, however not as many articles have been focused on varying crude oil flow rates and CDU cut-point temperatures to optimize feedstock blending.

The basis of the proposed research will follow the work of Hassan M et al (2011), who investigated the use of linear programming to enhance refinery productivity of naphtha exclusively. The research topic proposed will verify the linear programming approach used by Hassan et al (2011) for refinery optimization and will go further to include petrol, diesel, and jet fuel as final products and analyzing them with respect to certain aspects of South African regulatory specifications and relate them to market demands.

Today there are a few commercial software packages that refiners may purchase and which operators can simply adapt to their process. Aspen Tech's Process Industry Modeling System (PIMS) software is one of them, and according to their software brochure, claim to be used by more than 75% of the refineries worldwide. The software is based on Successive Linear Programming techniques. Other commonly used LP programs include Honeywell RPMS, and Haverly GRMPTS, which the user has to specify certain variables and inputs so the program can create accurate equations representing refinery processes.

2.5 Crude Oil Demand

South Africa is a country rich with natural resources; however does not have large reserves of crude oil, and as a result imports large volumes of the precious commodity. This has a profound effect on the economy as large sum of money leave the country in order to fulfill the demand for crude oil.

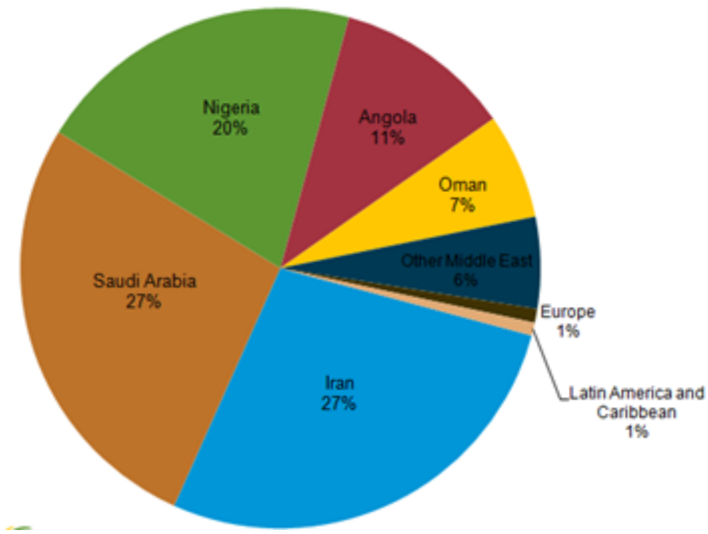

Figure 2.5: Graph showing South African Crude Oil Imports by Country (US EIA, 2012)

For the purpose of this study Bonny Light, a Nigerian Crude Oil and Oman Crude Oil, originating in Oman will be used as they are some of the popular crudes used in SA.

2.5.1 Petroleum Product Market Demands

According to the South African Petroleum Industry Association (SAPIA), in 2009 the demand for petrol, diesel, and jet fuel was 11 313, 9116, and 2731 Million liters respectively. This indicated a market ratio split of 0.49, 0.39, and 0.12 between the three major transportation fuels. This is illustrated in Figure 2.6.

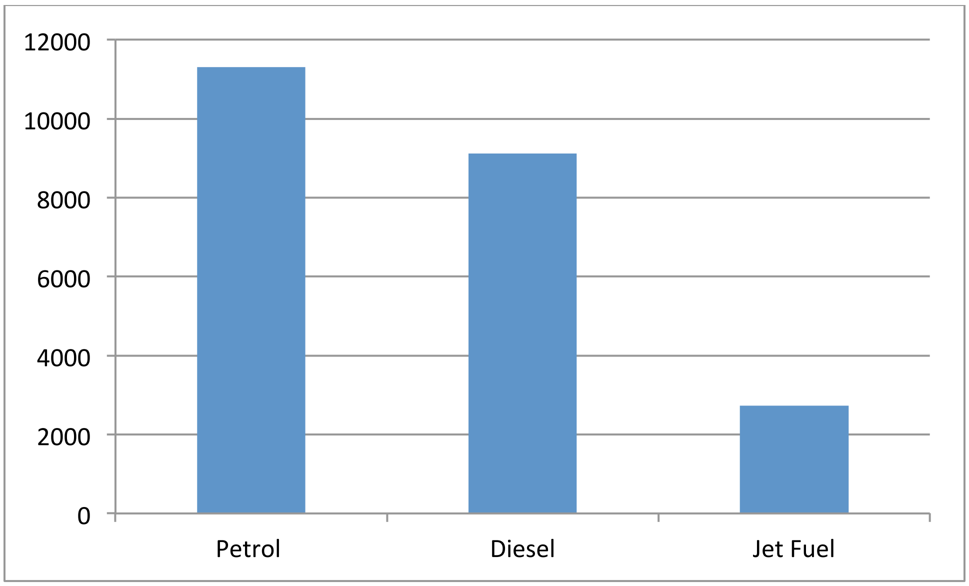

Figure 2.6: SA fuel demand split, 2009. (SAPIA,2010)

2.6 Petroleum Product Specifications

South African liquid fuel specification for Petrol and Diesel consumed in the country is determined by South African National Standard Association (SANS).

The latest standard for Unleaded Petrol is SANS 1598:2006 Edition 2, whilst for Automotive Diesel the latest standard is SANS 342:2006 Edition 4.

Aviation Turbine Fuel or jet fuel has an international standard, Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS). The international standard is due to the fact that many airplanes travel internationally and cross over many international borders whilst doing so. Adhering to a different standard for each country's airspace is impractical, and therefore an international standard was created.

Table 2.9 summarizes the different regulations with regard to the variables that are included in this study.

Table 2.9: Fuel standards and specifications (Shell, 2006) (ExxonMobile, 2005)

Fuel	Standard	Property	Requirement	Unit
Metal Free Unleaded Petrol	SANS 1598:2006	Sulphur Content	Max 500	mg/kg
		Density	0.710-0.785	kg/L @ 20° C
Standard Grade Automotive Diesel	SANS 342:2006	Sulphur Content	Max 500	mg/kg
		Density	Min 0.8	kg/L @ 20° C
A1 Jet Fuel	AFQRJOS	Sulphur Content	Max 0.3	wt %
			0.775 - 0.84	kg/L @ 20° C

2.7 Crude oil costs

The cost of the crude oil is a major factor with regards to the economic evaluation of the refinery. There are archives on the internet with databases of crude oil prices, history and evaluations. These databases charge a fee for their services; as a result a monthly report from the Platts.com website was obtained on the internet, however the crude oil prices used in the study were for the date 11th July 2013 (Platts, 2013). Transportation of crude oil was left out of the scope of this study, as finding accurate information in this regard proved to be difficult, this included the associated levies, fees, and insurance that are paid.

2.7.1 Refinery utility and maintenance costs

The utility and maintenance costs involved in a refinery is out of the scope of work for this study, however much of the energy used in a refinery is produced by burning low value products like fuel oil. The bi-products of some of the processing units like the FCCPU which produces hydrogen gas are used in the refinery.

2.7.2 Product sale prices

The product sale price for jet fuel was the average refinery gate price for Africa as estimated by the International Air Transport Association (IATA) for the 4th of July 2013. It must note the dates for which the different raw materials differ, and is used under the assumption that the price quoted stayed constant due to lack of freely available information.

The refinery gate prices for petrol and diesel were calculated by adding the average Basic Fuel Price (BFP) for the month of July 2013, and adding only the wholesale margin as described by SAPIA. All other levies, taxes, and charges are paid for by the consumer as have no economic effect on the refinery.

CHAPTER 3: RESEARCH METHODOLOGY AND MODEL DEVELOPMENT

In this chapter a case study oil refinery is considered with several different processing units. A mathematical model is built to suit the configuration for this particular refinery. For the purpose of this study crude oil flow rates, density, sulphur content, and CDU cut-point temperatures are being modeled as variables, whilst petrol, diesel, and jet fuel are the only product volumes being calculated. The case study refineries process layout may be seen in Figure 3.1.

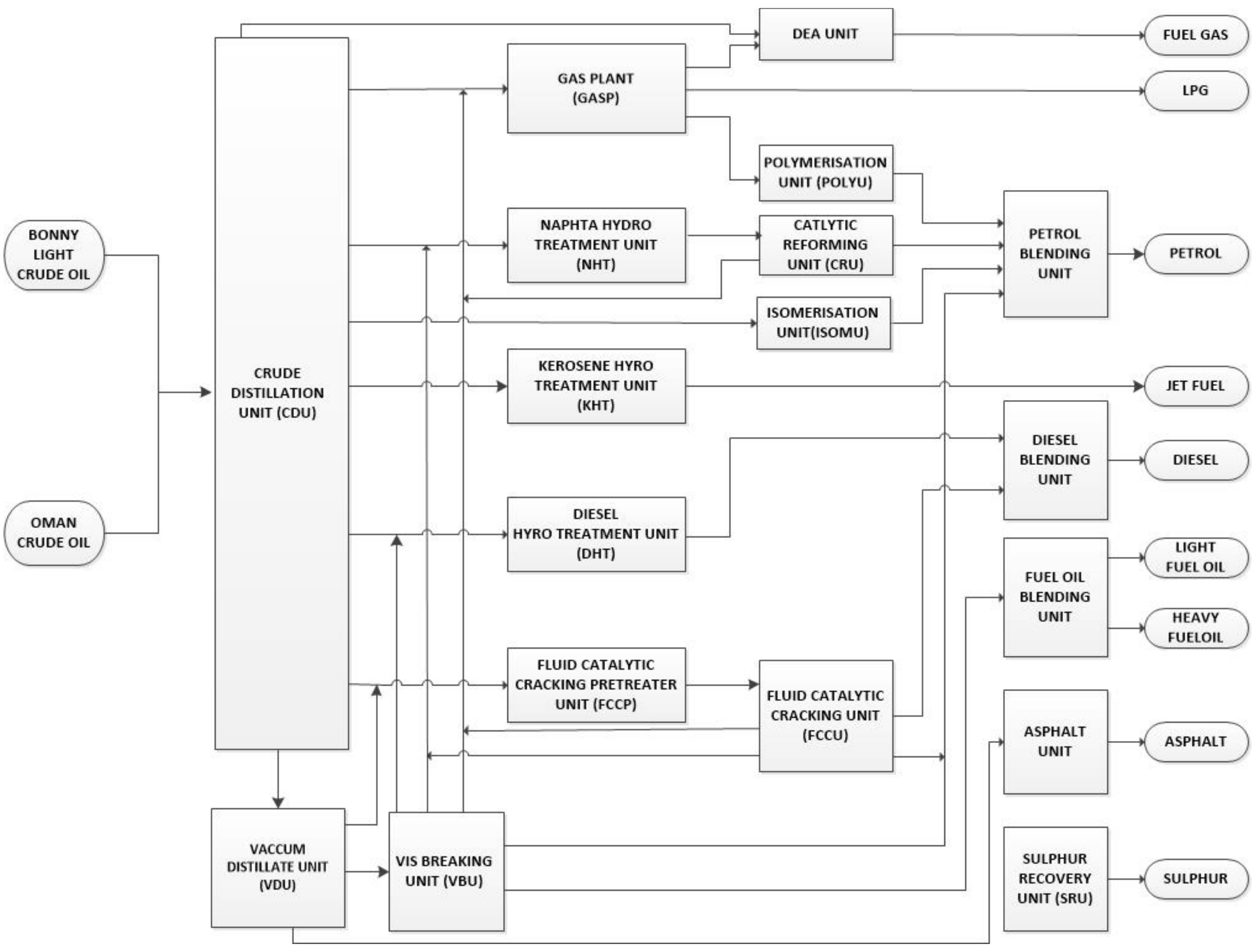

Figure 3.1: Schematic flow chart of case study refinery.(OTM,2013)

3.1 Model Assumptions

- The model is general for a South African refinery with similar refining capacities and utilizing the same process technology, and hence the model has a total refining capacity of 100 000 barrels/day.
- The case study is free to buy the selected crude mix supplies
- The refinery is free to deliver products without demand constraints unless the scenario specifies this
- Crude purchases cost limitation is not taken into account in the model
- No operating or maintenance costs, either fixed or variable are included in the study.
- Crude distillation and Vacuum distillation units compromise a collective structure as the receiving area for a crude oil fractionation
- Crude yields are taken from crude assay laboratory results
- Process unit yields are linear, and are based on typical unit yields
- Crude oil entering the CDU has already been desalted to remove water and mix completely homogenously
- Process unit yields for density ($Z_{i,s,m}$) and sulphur weight percent ($X_{i,s,m}$) are assumed to be 1 unless previously stated.

3.2 Model Formulation

The standard form of a LP optimization problem in matrix form follows:

Maximize $f(X) = c^T X$

……………………………………………………………………(3.1)

Subject to the constraints

$aX \le b$

$0 \le X$

Where X represents the vector of variables to be determined, b and c are vectors of known coefficients. The inequalities $aX \le b$, and $0 \le X$ at the constraints which will be applied. The objective function is the equation which will be maximized $c^T X$.

3.3 Objective function

$$\text{Maximize gross profit} = \sum_{i \in B} Sp_i F_i - \sum_{c \in C} Cc_c F_c \quad \text{……………………………………………..(3.2)}$$

The equation above expresses the overall gross refinery profit as summation of the product of sale price Sp_i of flow from unit (i) and the volumetric flow rate F_i from unit (i) from the set of final blending units (B),less the summation of the product of cost for the crude oil Cc_c for the refinery to function, and the volumetric flow rate F_c of crude oil (c) entering the CDU. The cost of the crude oil feedstock Cc_c purchased from the market is defined under set (C).

3.4 Crude Distillation Unit

Heated crude oil which is being fed into the CDU has different molecule sizes, and weights which are distilled or separated from each other due to their varying boiling point (vaporization) temperatures. These varying boiling point temperatures are tested in a laboratory environment to form a True Boiling Point curve (TBP) which is included in the crude oil assay. A The TBP curve is determined by the set testing method ASTM D 86 which is a world-wide test method relating to the atmospheric distillation of petroleum products using a laboratory batch distillation unit (Dechamps, 2013). A crude oil assay is an evaluation of the chemical makeup of the crude oil. Figure 3.2 shows the

TBP curve for Bonny Light Crude Oil, which is one of the crudes that are being used in this study.

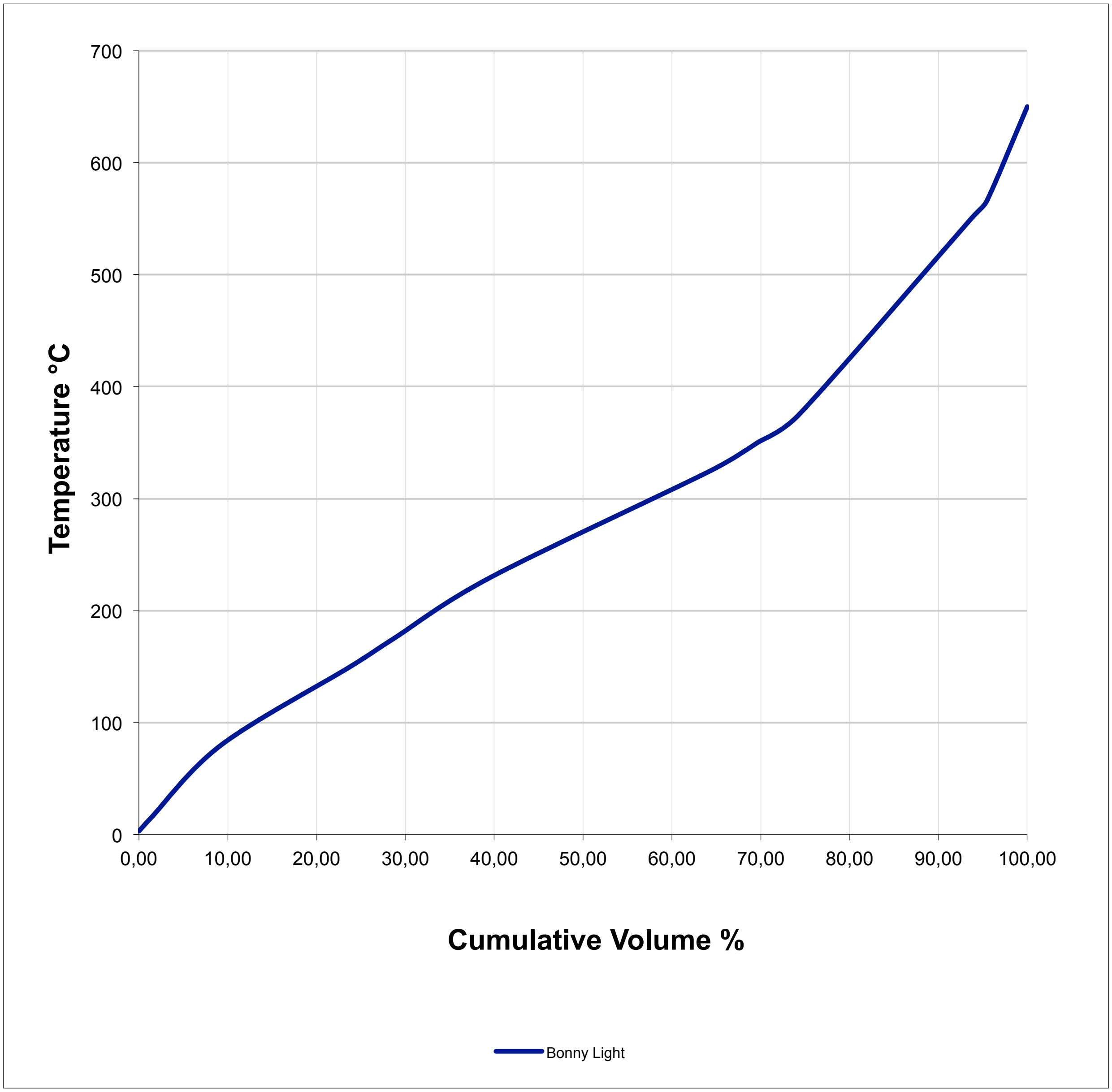

Figure 3.2: True Boiling Point Curve for Bonny Light Crude Oil

Each distillation stream leaving the CDU has a volumetric flow rate of:

$$F_s = \sum_{c \in C} F_c * (CV_t - CV_{t-1}) \qquad (3.3)$$

F_s represents the volumetric flow rate of the summation of the product of the flows F_c of crude oil (c), and the difference between the cumulative volume percent between the crude oil cut-point temperatures of stream (s) represented ($CV_t - CV_{t-1}$).

Each stream upper and lower Cut-point represented by CV_t and CV_{t-1} respectively has a range in which their value can vary in.

The density and sulphur content of each of the CDU streams (s) are functions of the Mid-Volume percent vaporized, $MidV_s$ which is calculated as:

$$MidV_s = (CV_t + CV_{t-1})/2 \qquad (3.4)$$

The average density $PD_{c,s}$ and sulphur content $PS_{c,s}$ of crude oil (c) for stream (s) can be determined by the sulphur weight percent, and density, vs cumulative volume percent curves by using the Mid-Volume percent vaporized, $MidV_s$ which has already been determined. The Mid-Volume is the average of the flow between the different cut-point temperatures. Figure 3.3 and 3.4 show the curve for these relationships for Bonny Light Crude Oil.

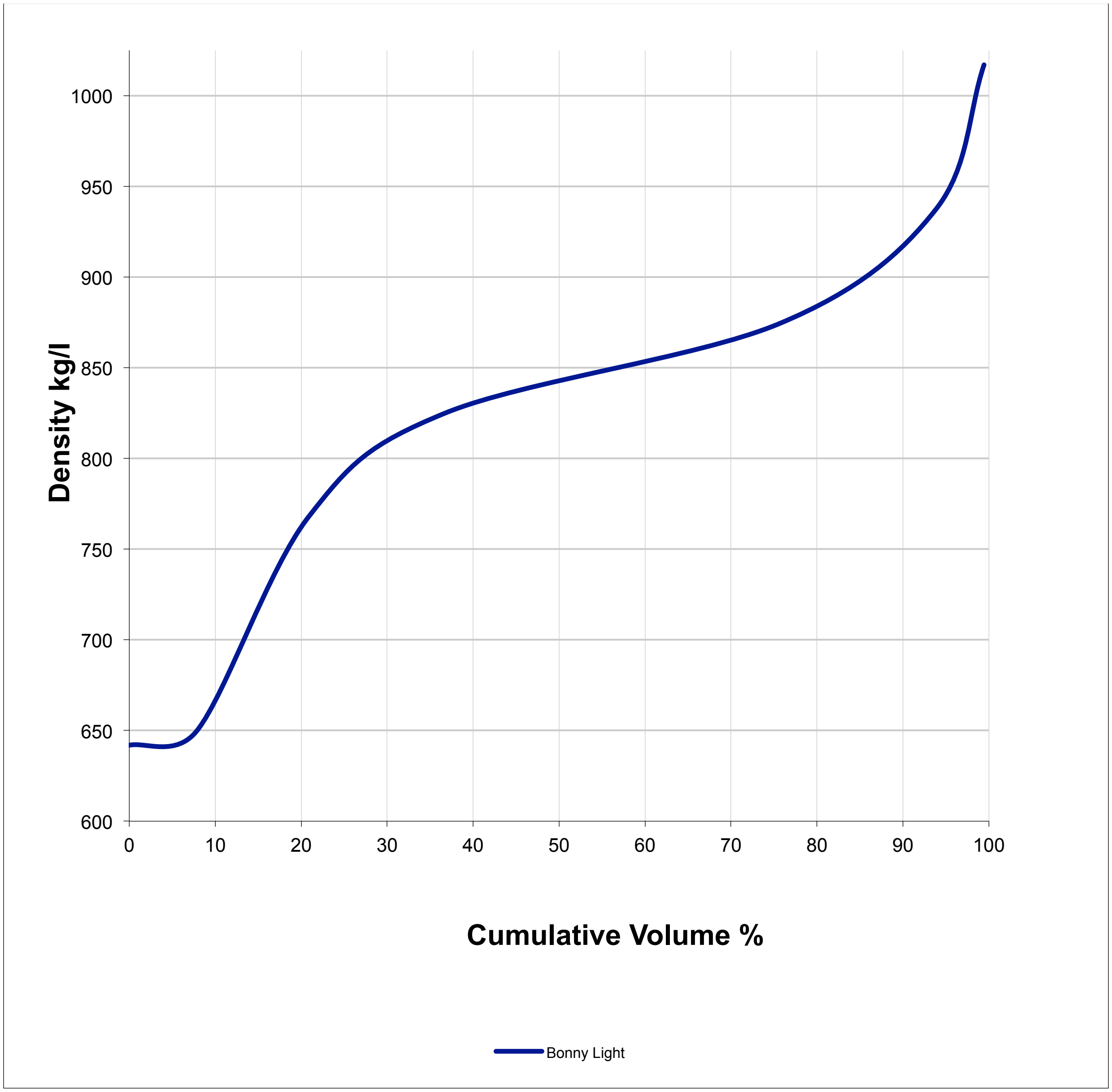

Figure 3.3: Graph of density vs cumulative volume percent for Bonny Light Crude Oil

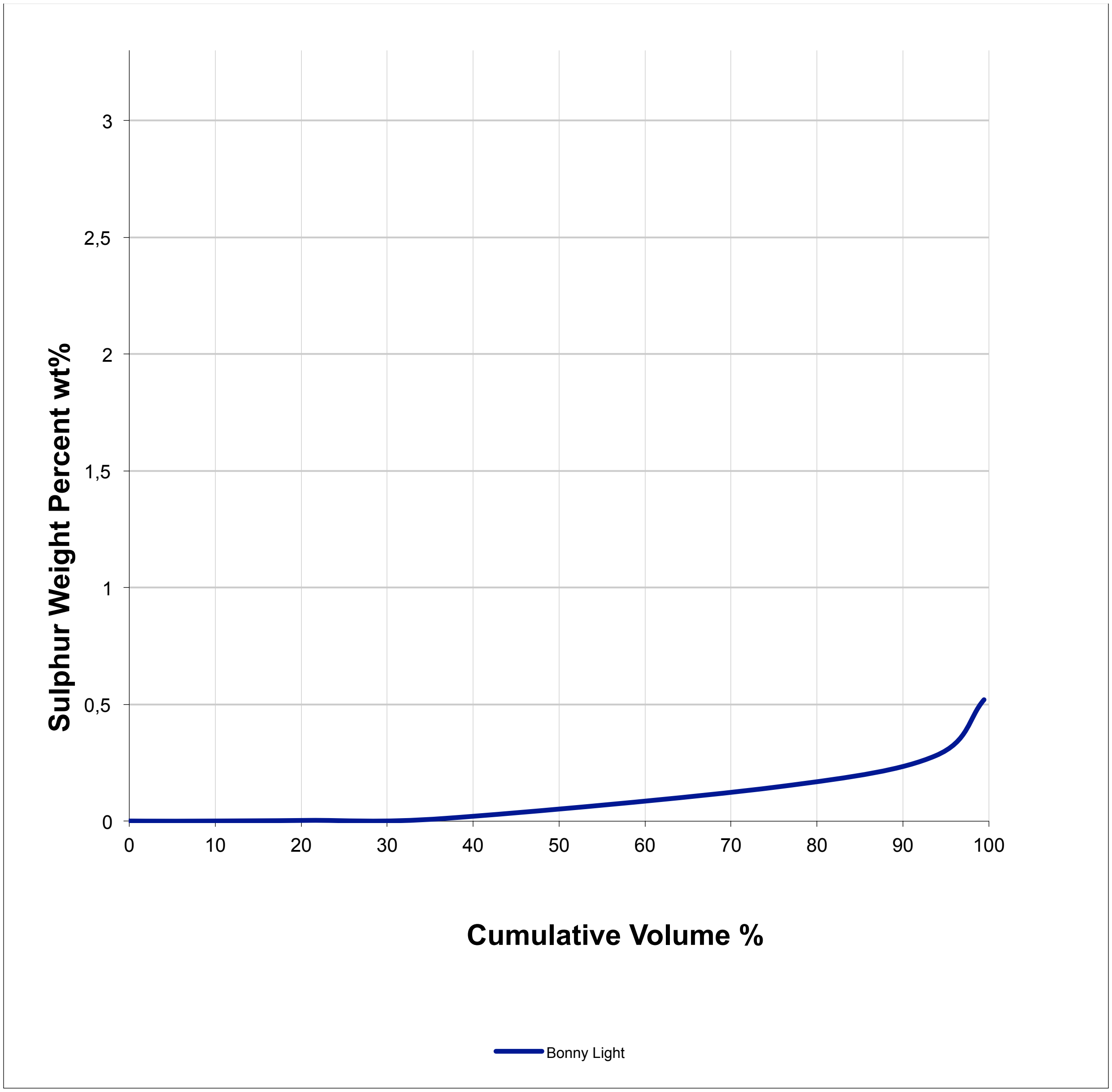

Figure 3.4: Graph of sulphur content vs cumulative volume percent for Bonny Light Crude Oil

The average density for each CDU stream is therefore:

$$PD_s = (\sum_{c \in C} F_{c,s} * PD_{c,s}) / (F_s) \quad \text{...(3.5)}$$

The average density of the product stream (s) from the CDU represented by PD_s is equal to the product of the summation of volumetric flow rate of crude oil (c) for streams (s), and the density of crude oil (c) for streams (s) from the CDU divided by the volumetric flow rate F_s of crude oil for streams (s).

The average sulphur weight percent for each CDU stream is therefore:

$$PS_s = (\sum_{c \in C} F_{c,s} * PD_{c.s} * PS_{c,s})/(F_s * PD_s) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

The average sulphur weight percent of the product stream (s) from the CDU is represented by PS_s is the product of the summation of all the volumetric flow rate of crude oil (c) for stream(s), and the density of crude oil (c) for stream (s) from the CDU, and the sulphur weight percent of crude oil (c) for streams (s) from the CDU, divided by the product of all the volumetric flows of crude oil F_s for streams (s), and the density of crude oil PD_s of stream(s).

3.5 General Model

A generic processing unit drawing is shown in Figure 3.5 to illustrate the mathematical representation.

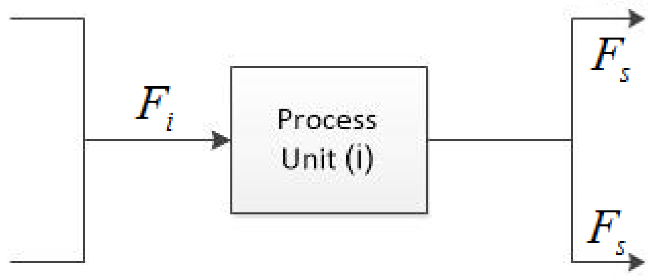

Figure 3.5: General model processing unit

Feed flow rate of processing units:

$$F_i = \sum_{j \in J} \sum_{s \in N} F_{j,s} \quad (3.7)$$

The volumetric feed flow rate F_i for any processing unit ($i \in I, I$ is the defined set of all the units in the refinery) is the summation of all the flow rates $F_{j,s}$ of the possible streams (s) that can be received by unit (i) from units ($j \in J$), where J is defined as the set of all units that can send streams (s) to unit (i) and *N* is defined as the set of all streams(s) from unit (j) to unit (i).

Product flows from processing units are split to feed different receiving units and is therefore:

$$F_s = F_i Y_{i,s,m} \quad (3.8)$$

The processing unit product output volumetric flow rate F_s is the product of the feed flow rate for processing unit (i) and yield parameter $Y_{i,s,m}$ for stream (s) from processing unit (i) received by processing unit (m)

Feed Density

$$PD_i = (\sum_j F_{j,s} * PD_{j,s})/(F_i) \text{...}(3.9)$$

The average density of the feed to unit (i) represented by PD_i is the product of the sum of all the volumetric flows of streams (s) from unit (j) to unit (i), and the density of streams (s) from unit (j) divided by the volumetric flow rate F_i to unit (i).

Product Density from the processing unit is therefore:

$$PD_s = PD_i * Z_{i,s,m}$$

The processing unit output average density PD_s is the product of the feed density PD_i to processing unit (i) and yield parameter $Z_{i,s,m}$ of stream (s) from processing unit (i) received by processing unit (m).

Feed Sulphur Content

$$PS_i = (\sum_j F_{j,s} * PS_{j.s} * PD_{j,s})/(F_i * PD_i) \text{...}(3.10)$$

The average sulphur weight percent of the feed to unit (i) represented by PS_i. The average sulphur weight percent is the product of the sum of all the volumetric flows of streams (s) from unit (j) to unit (i), and the sulphur weight percent of streams (s) from unit (j) to unit (i), and the density of streams (s) from unit (j) to unit (i) divided by the product of F_i and the density PD_i of unit (i).

Product sulphur weight percent from the processing unit is therefore:

$$PS_s = PS_i * X_{i,s,m} \text{...}(3.11)$$

The processing unit output average sulphur weight percent PS_s is the product of the feed sulphur content PS_i to processing unit (i) and yield parameter $X_{i,s,m}$ of stream (s) from processing unit (i) received by processing unit (m).

Constraints

Many different constraints are applied to the model, for each scenario these constraint limits will be specified unless already specified below.

Each CDU stream has an upper and lower cut-point represented by CT_s^U and CT_s^L respectively, and these have a range in which their value can vary in.

$CT_s^L \le CT_s \le CT_s^U$

The overall crude throughput for the refinery is limited to a maximum of 100000 bpd.

$\sum_{c \in C} F_c \le 100000$

The minimum participation of a specific crude oil:

$F_c \ge 10000$

Every crude oil flow must be non-negative:

$F_c \ge 0$

Each processing unit (i) has a maximum operating capacity of OC_i :

$0 \le F_i \le OC_i$

Table 3.1: Processing unit operating capacities

Process Unit	OC_i Operating Capacity (bpd)
CDU	100 000
NHT	20 000
KHT	15 000
DHT	38 000
FCCPU	40 000
VBU	13 000
VDU	27 000
FCCU	40 000
GASP	10 000
POLYU	10 000
CRU	20 000
ISOMU	15 000

3.6 Model computation

Each model was built in Microsoft Excel and solved using an evaluation version of Palisade Decision Tools: Evolver 6, and Top Rank 6 which is capable of optimizing linear, non-linear, mixed-integer, and other programming problems, whilst Top Rank is able to include a sensitivity analysis on variables.

Standard optimization programs such as Microsoft Excel's Solver are good at finding the best "local" solution, or combination of values to maximize or minimize the outcome of a straightforward spreadsheet model given certain constraints. They find a solution which seems to be producing favorable results and continue to work on that basis, without trying new solutions. This is known as "hill climbing" (PTE, 2013). However, these programs are not set up to handle more complicated, nonlinear problems where the best local solution may not be the best absolute answer. Evolver, using innovative "mutations" and combinations of solutions, or "organisms," is well-suited to finding the best overall answer by exploring the entire universe of possible answers (PTE, 2013).

Solving methods used (PTE, 2013):

Evolver uses six different solving methods that you can specify to find the optimal combination of adjustable cells. Different methods are used to solve different types of problems. The six methods are:

- Recipe - a set of variables which can change independently.
- Grouping - a collection of elements to be placed into groups.
- Order - an ordered list of elements.
- Budget - recipe algorithm, but total is kept constant.
- Project - order algorithm, but some elements precede others.
- Schedule - group algorithm, but assign elements to blocks of time while meeting constraints.

What the optimization does (PTE, 2013)

During an optimization, Evolver generates a number of trial solutions and uses genetic algorithms, OptQuest, or linear programming to continually improve results of each trial. With genetic algorithms, each possible solution becomes an independent "organism" that can "breed" with other organisms. The spreadsheet model acts as an environment for the organisms, determining which are "fit" enough to survive based on their results, and occasionally trying “mutations,” or completely new solutions.

The solver was set as default to use the genetic optimization algorithm with the parameters set as follows:

Population size: 50

Crossover rate: 0.5

Mutation rate: 0.1

The software gives the following description of how these parameters effect the optimization.

The population size tells Evolver how many organisms (or complete sets of variables) should be stored in memory at any given time. Although there is still much debate and research regarding the optimal population size to use on different problems, generally we recommend using 30-100 organisms in your population, depending on the size of your problem (bigger population for larger problems). The common view is that a larger population takes longer to settle on a solution, but is more likely to find a global answer because of its more diverse gene pool (PTE, 2013).

Crossover and Mutation. One of the most difficult problems with searching for optimal solutions, when your problem has seemingly endless possibilities, is in determining where to focus your energy. In other words, how much computational time should be devoted to looking in new areas of the “solution space”, and how much time should be devoted to fine-tuning the solutions in our population that have already proven to be pretty good.

The evolver solver was set to compute 20 000 trials before ending the optimization which took between 15 to 22 minutes to complete using a computer with an Intel Core i5, up to 2.80 Ghz processor.

CHAPTER 4: RESULTS AND DISCUSSION

In order to illustrate the model that was presented in chapter three, various different case studies will be performed and analyzed. Figure 2.3 represents the schematic flow chart of the case study refinery that was modeled.

The first processing unit in the refinery is the CDU, which consists of an atmospheric distillation column and a vacuum distillation tower. The refinery has in addition to this has three treating units, two conversion units, and multiple blending units.

4.1 Scenario 1

This scenario comprises of a graphical representation of crude oil blending between two crude oils.

Bonny Light Crude Oil, a Nigerian medium sweet crude and Oman, which is a medium sour crude. These crudes were chosen for the study as they are often used in SA. Processing unit capacities will be previously stated.

For this scenario, cut-point temperatures remain constant. This results in a linear model which will be used to represent an operational area for the crude Oil Blends with respect to the product specifications previously discussed.

Figure 4.1 shows graphically the following constraints, and the operational area. Minimum participation of each crude oil being 10%of the overall CDU throughput

$$F_c \geq 10000$$

Total blend of crude oils being less than 100 000 barrels/day.

$$\sum_{c \in C} F_c \leq 100000$$

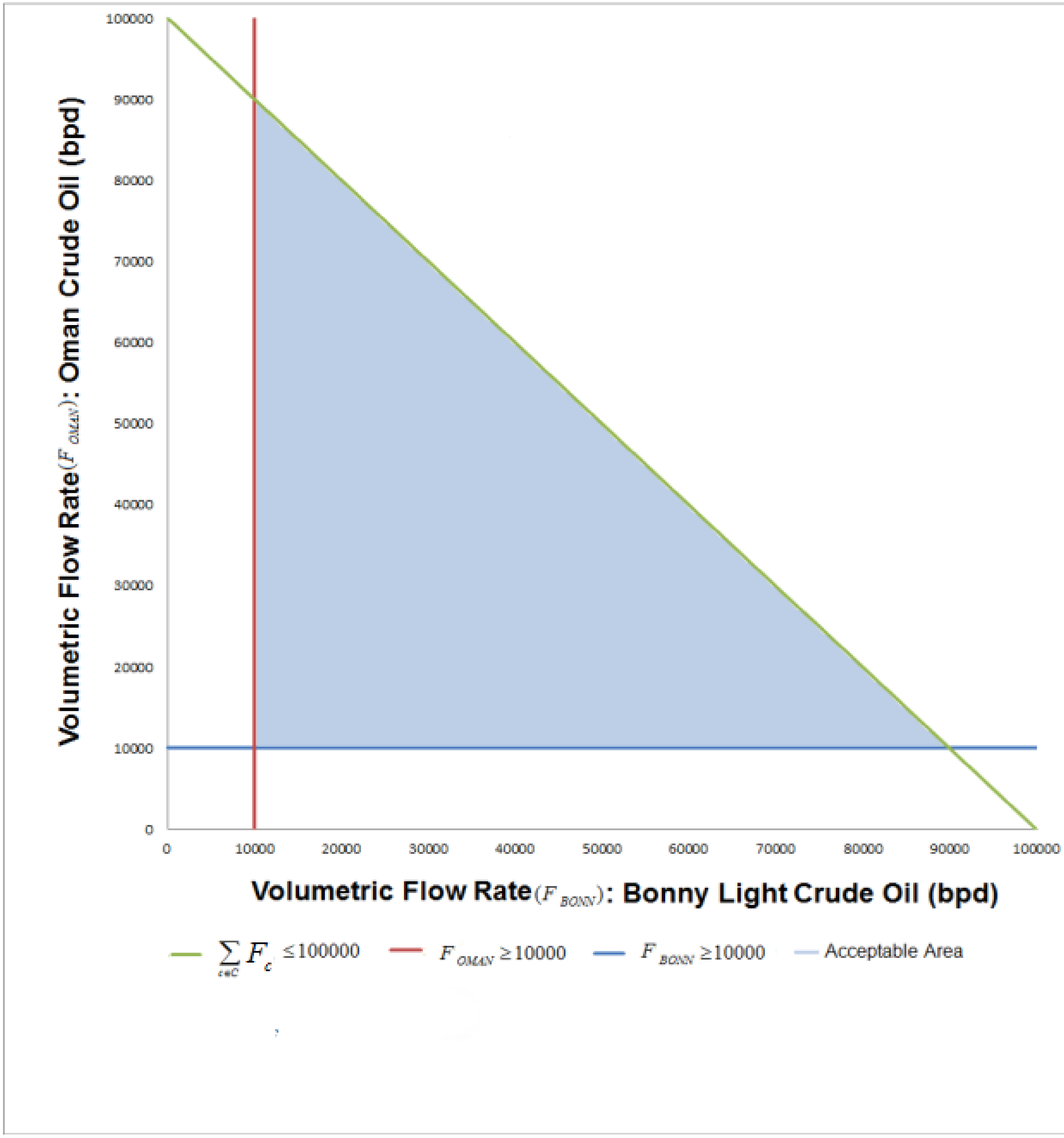

Figure 4.1: Acceptable operational area for crude blend

In Figure 4.1 the constraints previously mentioned enclose an acceptable area of the refinery crude oil flow rates. It will be illustrated how this acceptable area will reduce as the technical specification are added.

Figures 4.2 and 4.3 show the acceptable area with respect to the density and sulphur contentspecifications of jet fuel.

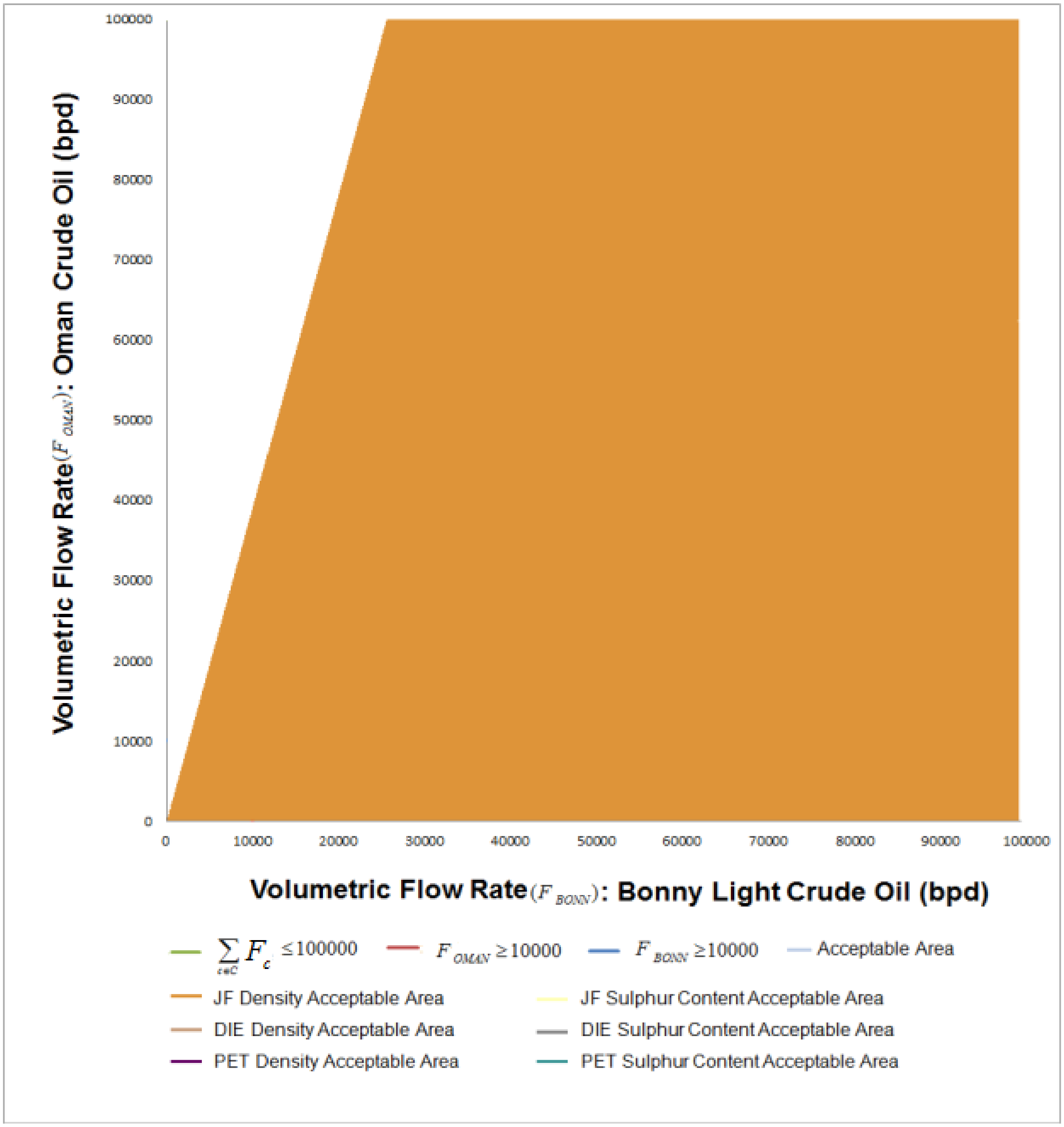

Figure 4.2: Acceptable operational area of density for jet fuel

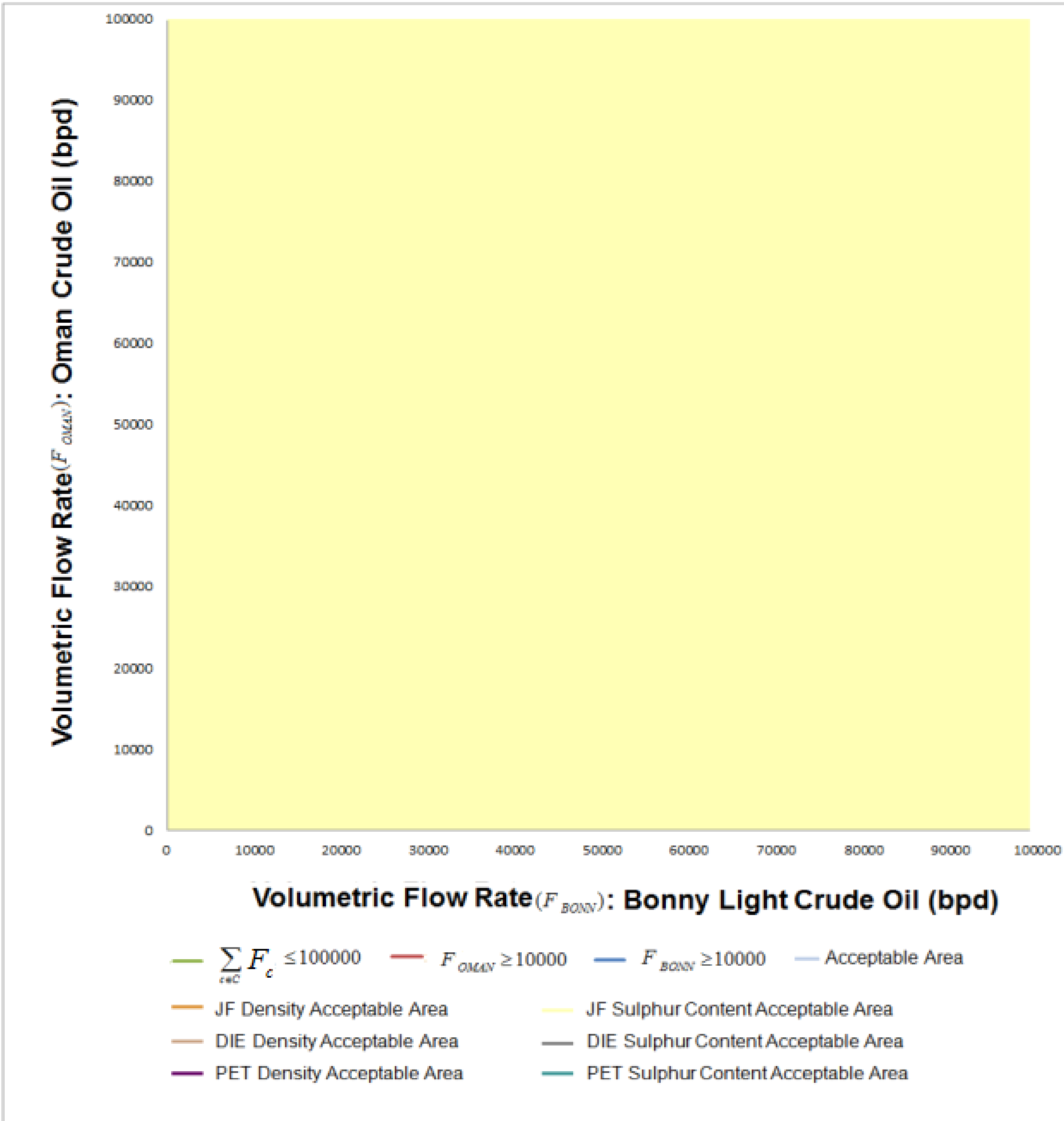

Figure 4.3: Acceptable operational area of sulphur content for jet fuel

From table 2.9, according to the international AFQRJOS specification the density of A1 Jet Fuel should be between 0.775 and 0.840 kg per liter at 15° C. From the model calculation, the density of the product made using the BLCO results in a density of 0.806 kg per liter whilst the OCO results in a density of 0.763 kg per liter. It is interesting to note that, the API° gravity for BLCO and OCO is 35.9 and 31.20 indicating that OCO has a higher density but has produced a lower density product. The reason for this is the API ° is an indication of the overall density of the crude oil and provides no indication of how the density of the crude oil changes between different boiling point temperature ranges.

This then explains why there is an area where a blend using mainly OCO with smaller quantities of BLCO where the JF produced does not meet the density specifications required. Since jet fuel is used in aero planes where space is limited, the density conformance for jet fuel is of added importance. The left edge of the acceptable area represents the point at which the density is 0.775 kg per liter, anything towards the right of this edge is acceptable, however the consumer would be receiving a product with additional density than what the specification limits it to which directly relates to the amount of energy in the fuel. This is known as quality give away, since the refinery could have changed the blend of crudes to ensure the least additional quality is given away. Reducing this margin is not always the best economic decision as balancing the quality give away of the other end products of the refinery, should they meet the specification. In this case, converting heavier fractions in the refinery to be blended have additional operating costs which may cause a reduction in the overall profitability for the refinery.

Similarly for A1 Jet Fuel the specification states the maximum sulphur content should be 0.3wt %, which is the equivalent of 3000ppm. When comparing this sulphur content to petrol and diesel specification in South Africa, it is clear that the AFQRJOS specification allows for a relatively high level to be used. For this reason, for the current refinery scenario any blend of the crude oil will meet the product specification. From the model calculation, the sulphur content of the product made using the BLCO results in a content of 0.009wt% whilst the OCO results in a content of 0.116wt%. The difference between these two values is expected as BLCO is much sweeter crude oil with an overall sulphur content of 0.15 wt%, compared to OCO which has an overall content of 1.540wt%.

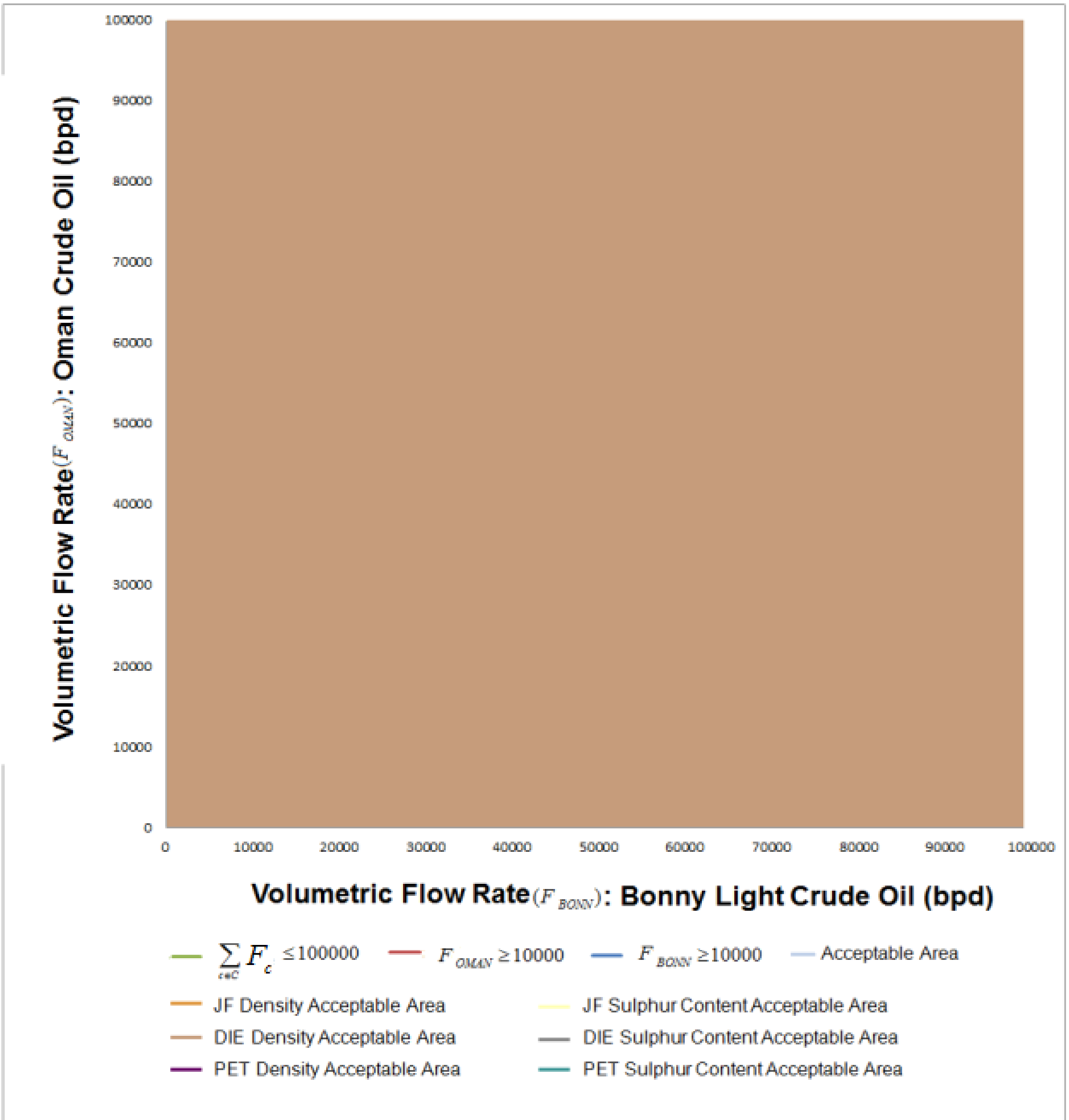

Figure 4.4: Acceptable operational area of density for diesel

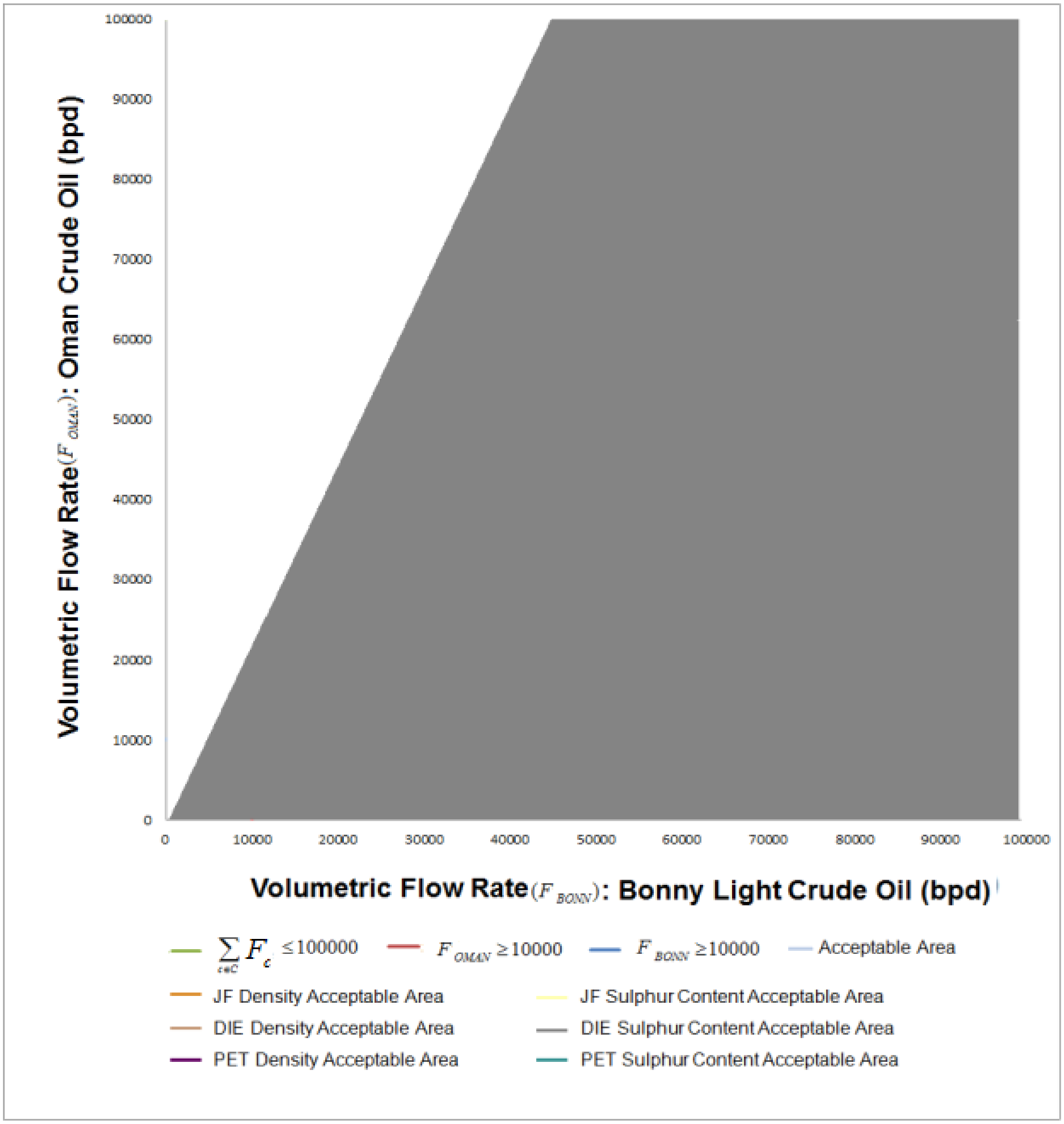

Figure 4.5: Acceptable operational area of sulphur content for diesel

From Table 2.9, SANS 342:2006 specification for Automotive Diesel states the density should be a minimum of 0.8 kg per liter @ 20° C. From the model calculation the density of BLCO and OCO is 810.07 kg per liter and 821.68 kg per liter respectively. This is an expected result, having both crude oils being reasonably light. They both meet the minimum specification for the product. In this case the bottom edge of the graph shows the minimum density point. Therefore any blending of OCO with the BLCO will result in a higher density. It is interesting to note that since the SANS specification does not offer a maximum density specification, in certain situations the refiner may opt to use a much heavier crude in the mix to take advantage of this if market demands favoured diesel production. Once again, the economic effect of this will have to take into account processing costs of refinery operations to meet the sulphur content, and other product specifications of the refinery. Note an additional assumption for density of diesel and petrol must be made, as the crude oil assay provides information on density @ 15°C whilst the SA SANS specifications make their density limitations @ 20°C. For the purpose of this study, it must therefore be assumed that the density difference of the products between the difference of the two temperatures is negligible.

Similarly the sulphur content specification states a maximum of 500 mg per kg which equates to a wt% of 0.05. As expected BLCO being a sweeter crude, results in an 0.0057 wt% compared to 0.067 wt% for OCO. This would indicate that the left edge of the acceptable area for the sulphur content for the product would be the minimum requirement, and a blend of increased proportion of BLCO with the OCO would result in a quality give away, having lower than neccesary sulphur content. The processing costs of hydrotreating sour streams can be reduced by decreasing the hydrotreating intensity.

Adding the Sulphur Content and Density specification limits of petrol reduces the operational area for the refinery as illustrated in Figure 4.6 and 4.7.

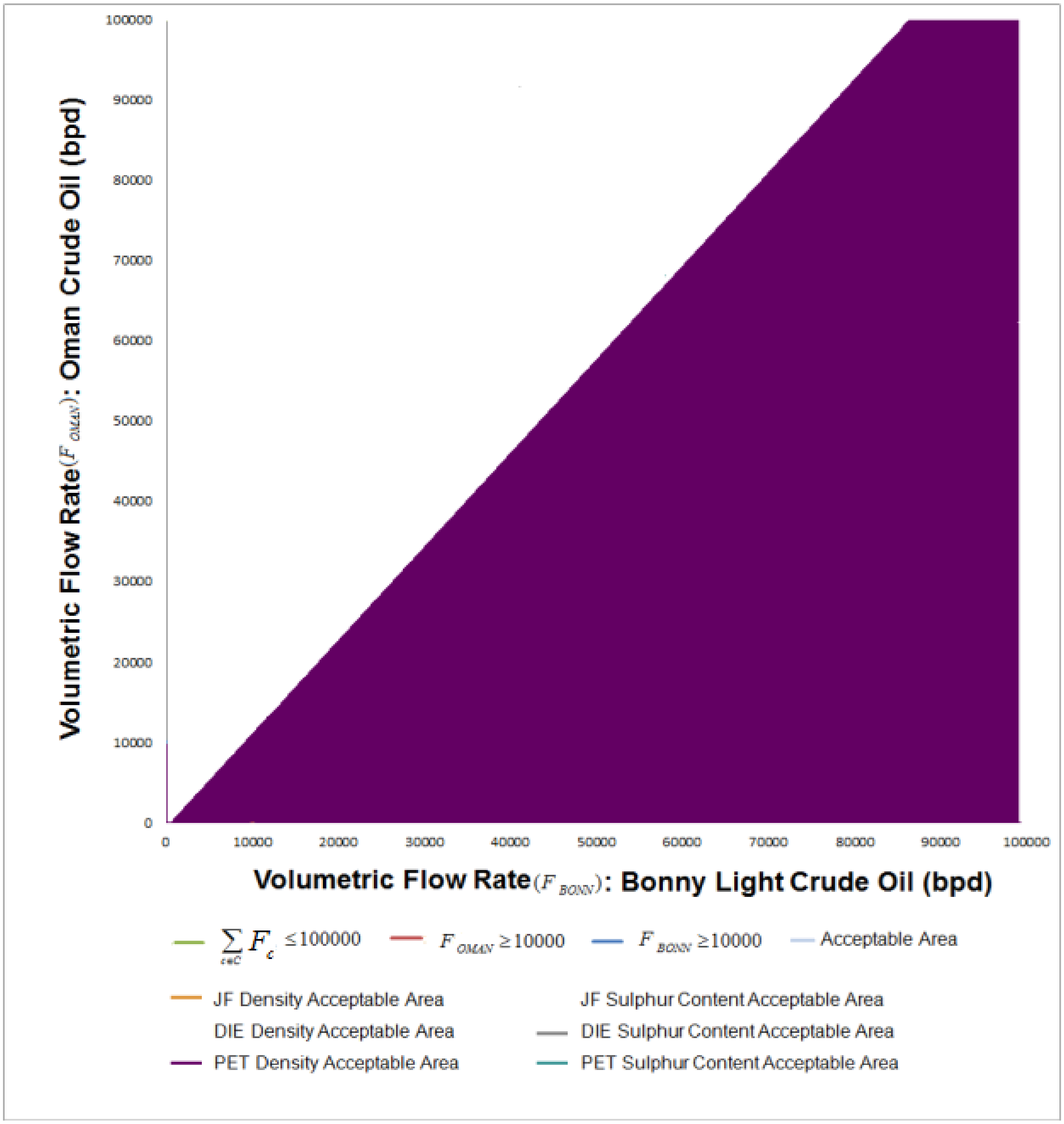

Figure 4.6: Acceptable operational area of density for petrol

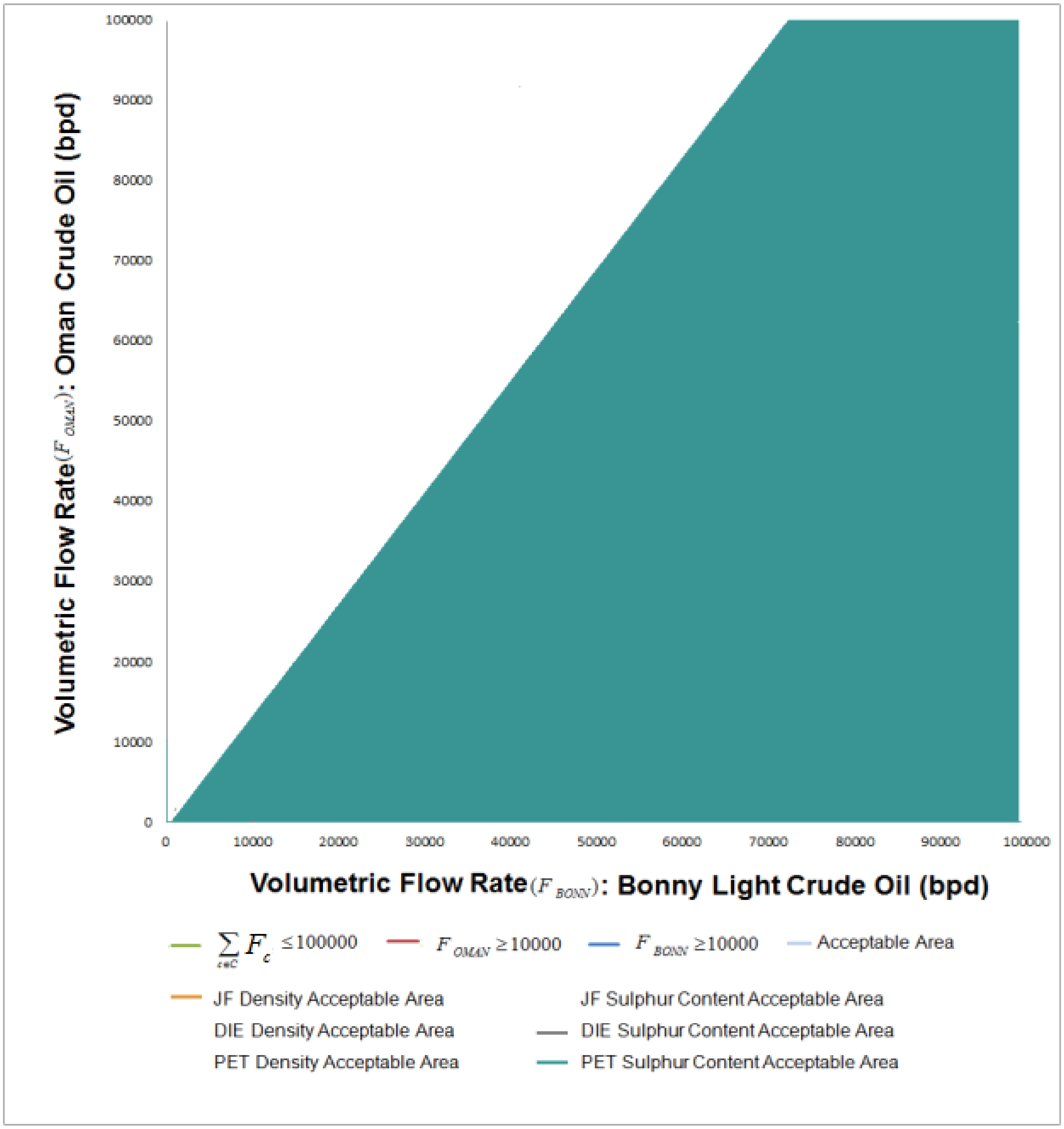

Figure 4.7: Acceptable operational area of sulphur content for petrol

From Table 2.9, SANS 1598:2006 specification for Unleaded Petrol states the density should be a between of 0.710 kg per liter and 0.785 kg per liter @ 20° C. From the model calculation the density of BLCO and OCO is 751.614 kg per liter and 803.735 kg per liter respectively. This is an expected result, as both crude oils are reasonably light. Only the BLCO meeting the specification range for the product. In this case the left edge of the graph shows the maximum density point to meet the specification. Therefore any additional blending of BLCO with the OCO will result in a lower density witch will reduce the quality give away. Again, the economic effect of this will have to take into account processing costs of refinery operations to meet the sulphur content, and other product specifications of the refinery.

Similarly the sulphur content specification states a maximum of 500 mg per kg which equates to a wt% of 0.05. As expected BLCO being a sweeter crude, results in an 0.00475wt% compared to 0.0709 wt% for OCO. This would indicate that the left edge of the acceptable area for the sulphur content for the product would be the minimum requirement, and a blend of increased proportion of BLCO with the OCO would result in a quality give away, having lower than neccesary sulphur content. The processing costs of hydrotreating sour streams can be reduced by decreasing the hydrotreating intensity.

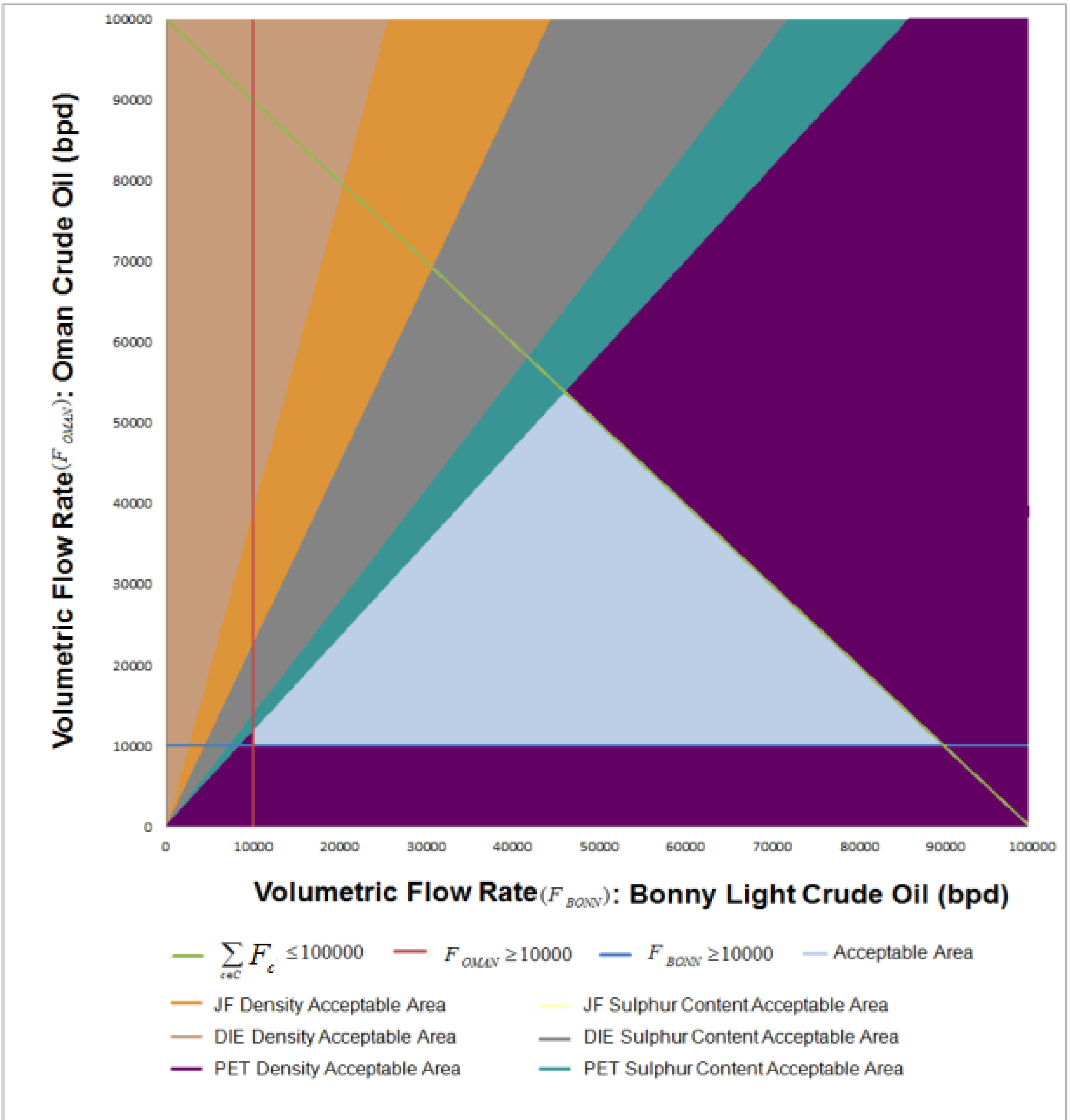

Figure 4.8: Overall acceptable operational area for crude oil blend

From Figure 19, the overall operating area is illustrated by representing the density and sulphur specifications for all the products at once. The blue area represents the overall acceptable area of blending for the proposed scenario.

Table 4.1: Overall results at point of highest gross refining profit

Gross Refining Profit (ZAR)	R 8758503.13
Jet Fuel Sulphur Content (wt %)	0.0157
Jet Fuel Density (kg/l)	804.08
Diesel Sulphur Content (wt%)	0.0110
Diesel Density (kg/l)	811.74
Petrol Sulphur Content (wt%)	0.0114
Petrol Density (kg/l)	756.37
BLCO Volumetric Flow rate (bpd)	90000
OCO Volumetric Flow rate (bpd)	10000
Jet Fuel Production (bpd)	9542.63
Diesel Production (bpd)	44699.51
Petrol Production (bpd)	33053.73

Table 4.1 summarizes the product results for the scenario. The maximum profit was R8 758 503 and resulted as expected to favor the use of BLCO, using 90 000 barrels for the day whilst using only 10 000 barrels of OCO. When considering product specifications, the density and sulphur content were well within the limits. If any of these variables were very close to the limit, it would be a point of concern, as for this particular model the assumption was that perfect blending takes place, whilst in reality this is not perfectly accurate. For the scenario in question, Table 4.1 also shows the maximum production case for each of the products.

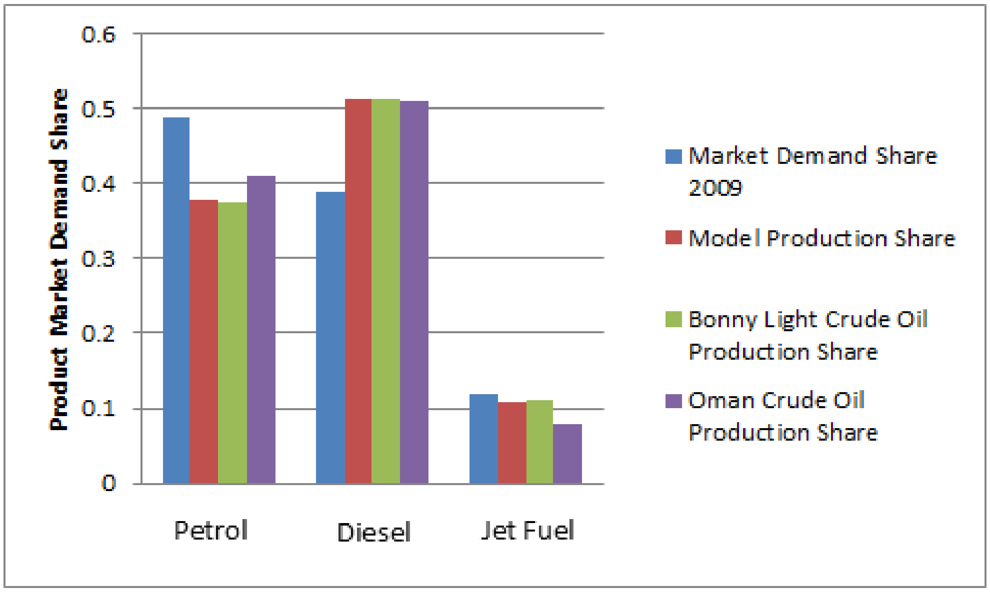

Figure 4.9: Product market demand share

Figure 4.9 shows the product market demand share for product in 2009 compared to the model production share. The production shares for petrol and diesel are similar however, different blends of crude yield different production market share, which the most noticeable when considering the share of jet fuel. If the refinery wants to maximize their profits need to evaluate blending different types of crude oils from light to heavy and from sweet to sour in order to perfectly match the market demand. They can also adjust the refinery configuration, or process unit parameters to deliver a slate which is closer to the desired slate.

For the scenario in question, a single period, linear programming model was formulated. By varying the crude oil blend, the model was able to calculate the maximum gross refinery profit, the effect the blend has on product quantities, and qualities like density, and sulphur content, and how the production share changes. Should the refinery increase the number and dissimilarity of crude oils being blended together, the refinery planner will have a greater understanding of what will be the optimal blend will be. Trying to find this optimal blend with a blend of many different crude oils without LP will be very difficult, and time consuming showing the necessity of using optimization methods in refinery scheduling. Varying the cut-point temperatures will also vary the effect on the variables discussed. A refinery planner may use the LP model as an economic decision making tool to discern how to operate the refinery given uncertainties like the ever changing crude oil and product sale price.

4.2 Scenario 2

This scenario comprises of variations of the cut-point temperatures in the CDU, whilst the flow rates remain constant. A base case consisting of the two crude oils described in scenario 1 each with a volumetric flow rate of 50 000 bpd, and predetermined cut point temperatures will be used as a reference to how the resulting Mixed Integer Linear Program (MILP) performs. Processing Unit Capacities will be previously stated.

Optimizing the process conditions of the CDU in a refinery is one of the greatest challenges for a refinery scheduler. It can have a profound effect on the gross refining profit achieved by producing the required range of distillates, at maximum yield, and at minimum cost. To achieve this goal, full real-time monitoring and control of each incoming stream of crude oil and outgoing distillate stream is an inevitable requirement (Shahvosky et al, 2012).

With reference to Figure 2.4, each stream of distillate is separated according to their boiling range. Table 4.2 summarizes the typical cut-point temperatures between the different distillate streams used in this model.

Table 4.2: Typical cut-point temperatures between distillate streams

Distillate Stream	CT_s^L Lower Cut-point Temperature Range °C	CT_s^U Upper Cut-point Temperature Range °C
LPG		15
LN	15	82-108
HN	82-108	165-193
KERO	165-193	215-271
DIE	215-271	343-375
ATMR	343-375	510-545
ATMD	510-545	

From the table it can be seen for the kerosene distillate stream, CT_s^L is between 165 and 193° C, which is the CT_s^U for the Heavy Naphtha distillate stream. Similarly the CT_s^U for the kerosene stream is the CT_s^L for the diesel stream. The cut-point temperatures are therefore interdependent on each other. The exact cut-point temperatures are determined with respect to the product quantities and quality specifications, or the physical properties of each of the streams to minimize quality give away and maximize profit.

Prediction of the yield of distillation can be made by using optimization techniques such as linear programming (LP). However, any unexpected discrepancy between the crude's actual properties and the LP model will directly impact distillation efficiency (Shahvosky et al, 2012).

For the base case, an equal blend of the two crudes will be used and will have their cut-point temperatures set as shown in Table 4.2. The model will then be set to optimize in the following modes:

- Maximum Gross Profit
- Maximum Jet Fuel Production
- Maximum Diesel Production
- Maximum Petrol Production

For each mode, they will be subject to the quality specifications for each of the products as shown in Table 2.9. Note, the cut-point temperatures vary as integers to reduce computation time. Another reason for this is controlling temperatures in the CDU to such accuracy is not realistic.

The base case for the scenario has the cut-point temperatures set as per Table 4.2, and results in products with results as shown in Table 4.3, 4.4 and 4.5.

Table 4.3:Scenario 2 base case cut-point temperatures between distillate streams

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	95
HN	95	180
KERO	180	243
DIE	243	359
ATMR	359	532
ATMD	532	

Table 4.4: Scenario 2 base case product slate

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Jet Fuel	10484.58	0.0789	808.99
Diesel	35114.06	0.0393	824.75
Petrol	34600.10	0.0346	785.66

Table 4.5:Scenario 2 base case gross refining profit

Gross refining profit (ZAR)	R 2502802.89

Maximum Gross Profit

Table 4.6: Maximum gross profit case cut-point temperatures between distillate streams

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	108
HN	108	165
KERO	165	231
DIE	231	375
ATMR	375	545
ATMD	545	

Table 4.7:Maximum gross profit case product slate

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Jet Fuel	10573.36	0.0603	796.83
Diesel	39345.15	0.0360	819.27
Petrol	32203.68	0.0379	776.58

Table 4.8:Maximum gross profit case gross refining profit

Gross refining profit (ZAR)	R 5166636.51

The results for setting the model to optimize the gross refining profit of the refinery by varying the cut-point temperatures whilst keeping the volumetric flow rates of the crude oils constant result in the total profit increasing from R 2 502 802.89 to R 5 166636.51. This was due to the total amount of product increases due to optimization. When considering the qualities of the products, the optimized case maintains the required sulphur content and density to be within the acceptable range for the relevant specifications.

Maximum Jet Fuel Production

Table 4.9: Maximum jet fuel production cut-point temperatures between distillate streams

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	108
HN	108	187
KERO	187	270
DIE	270	375
ATMR	375	545
ATMD	545	

Table 4.10: Maximum jet fuel production

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Jet Fuel	14956.94	0.0783	808.73

Since the refinery configuration shows jet fuel as a straight run stream from the CDU, as expected the maximum volumetric flow rate will be where the difference between the upper and lower cut-point temperatures for the stream are the greatest. Note, the theoretical maximum of the refinery would be when the kerosene lower cut-point is 165°C and the upper is 271°C, however in order for the other products to meet their product specification this is the maximum allowable cut-point temperature difference. At this point it is also important to note how bottlenecks in the model affect the cut-point temperatures. When a bottleneck in production occurs, in order for the process to continue the intermediate stream will either need to be stored, or limits the entire production stream. In this case the cut-point temperatures will change to accommodate this by increasing the production of other streams such that the variable being optimized is at a maximum. This results in a jet fuel production of 14956.94 bpd compared to the case study production of 10484.58 bpd. The sulphur content and density are within the product specification limits.

Maximum Diesel Production

Table 4.11: Maximum diesel production cut-point temperatures between distillate streams

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	107
HN	107	181
KERO	181	215
DIE	215	360
ATMR	360	545
ATMD	545	

Table 4.12: Maximum diesel production

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Diesel	40234.22	0.0355	817.16

The refinery configuration shows majority of the Diesel production coming from the diesel stream from the CDU, as expected the maximum Volumetric Flow rate will be where the difference between the upper and lower cut-point temperatures for the stream are the greatest. Once again, the theoretical maximum of the refinery would be when the Diesel lower cut-point is 215°C, which it is at, and the upper is 275°C; however it is limited to 270° C in order for the other products to meet their product specification. This results in a Diesel production of 40234.22 bpd compared to the case study production of 39345.15 bpd. The Sulphur content and density are within the product specification limits.

Maximum Petrol Production

Table 4.13: Maximum petrol production cut-point temperatures between distillate streams

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Petrol	37981.70	0.0330	784.84

Table 4.14: Maximum petrol production

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	108
HN	108	193
KERO	193	215
DIE	215	343
ATMR	343	539
ATMD	539	

Petrol is a light product, when considering how it is refined, it can be seen that it is blended with light streams and heavier distillate streams which are processed, this shows how sensitive the entire set of cut-point temperatures is on the production of petrol. It must be noted that for the case study refinery no stream or intermediate stream of kerosene from the CDU which is processed is blended into the petrol pool. For this reason the cut-point temperatures are set to minimize the distillation of kerosene. Note, the theoretical minimum of the refinery would be when the Kerosene lower cut-point is 181°C and the upper is 215°C, which it is. This results in a Petrol production of 37981.70 bpd compared to the case study production of 34600.58 bpd. The Sulphur content and density are within the product specification limits.

4.3 Scenario 3

This scenario comprises of variations of the cut-point temperatures, and the blend of crude oils in the CDU.

As per scenario 1, a base case consisting of the two crude oils previously described, optimized cut-point temperatures will be used as a reference to how the resulting MILP performs. Processing Unit Capacities will be previously stated. The results for this may be found on Table 4.15, 4.16 and 4.17. Note, these results may look the same as the results shown in Table 4.1, as for scenario 1 the optimal cut-point temperatures were used.

Table 4.15: Scenario 3 base case cut-point temperatures between distillate streams

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	108
HN	108	165
KERO	165	215
DIE	215	375
ATMR	375	545
ATMD	545	

Table 4.16: Scenario 3 base case product slate

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Jet Fuel	9542.63	0.0157	804.08
Diesel	44699.51	0.0110	811.74
Petrol	33053.73	0.0114	756.37

Table 4.17: Scenario 3 base case gross refining profit

Gross refining profit (ZAR)	R 8758503.13

Table 4.18: Scenario 3 base case volumetric flow rates

BLCO Volumetric Flow rate (bpd)	90000
OCO Volumetric Flow rate (bpd)	10000

This scenario describes the main economic function of the model presented, and as a result market demand constraints will be added. Given the country is hosting a major international event, such as the FIFA Football World Cup in 2010 and as a result the minimum amount of jet fuel produced will need to be 12 000 bpd. The crude oil participation will be a minimum of 10 000 bpd as per the base case.

Table 4.19: Minimum 12000 bpd jet fuel production cut-point temperatures between distillate streams

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	108
HN	108	165
KERO	165	228
DIE	228	375
ATMR	375	545
ATMD	545	

Table 4.20: Minimum 12000 bpd jet fuel production slate

Product	Volumetric Flow Rate (bpd)	Sulphur Content (wt %)	Density (kg/l)
Jet Fuel	12037.02671	0.017898875	808.8187848
Diesel	42205.1484	0.011645526	813.7057188
Petrol	33053.73564	0.011414366	756.3700054

Table 4.21: Minimum 12000 bpd jet fuel production gross refining profit

Gross refining profit (ZAR)	R 8457144.11

Table 4.22: Minimum 12000 bpd jet fuel volumetric flow rates

BLCO Volumetric Flow rate (bpd)	90000
OCO Volumetric Flow rate (bpd)	10000

When comparing this result of the addition of the minimum jet fuel production, it is clear that the model increased the upper cut-point temperature for kerosene, reducing the lower cut-point temperature for diesel. This resulted in the minimum jet fuel production to increase and the diesel production to decrease whilst still maintaining the quality specification for all the products. The economic effect of BLCO has already been established to be much higher than that of OCO, which is why there is no difference in the crude oil volumetric flow rates. Should many different crude oil been blended together, it may not have been as easy to identify the reasons why the cut-point point temperatures adjusted the way they have. The additional constraint as expected reduced the gross refining profit from R8758503.13 to R8457144.11. Combinations of various constraints on the product volumetric flow rates, product qualities, and crude oil participation may be similarly added to investigate the behavior of the model in the given situation.

The last case will be in the form of a sensitivity analyses on the gross refining profit, product volumetric flow rate, density, and sulphur content. The sensitivity analyses will be in the form of a tornado graph which shows the influence on the change in each variable compared to the variable to which the sensitivity is being tested. A similar sensitivity analyses may be performed on any of the outputs. For this scenario, the cut-point temperatures are varied from a base between their respective minimum and maximum range, whilst simultaneously varying the crude oils from a base of 50 000 bpd between 37500 and 62500 bpd.

Table 4.23: Base cut-point temperatures used for sensitivity analyses

Distillate Stream	Lower Cut-point Temperature °C	Upper Cut-point Temperature °C
LPG		15
LN	15	CT 2, 95
HN	CT 2, 95	CT 3, 179
KERO	CT 3, 179	CT 4, 243
DIE	CT 4, 243	CT 5, 360
ATMR	CT 5, 360	CT 6, 528
ATMD	CT 6, 528	

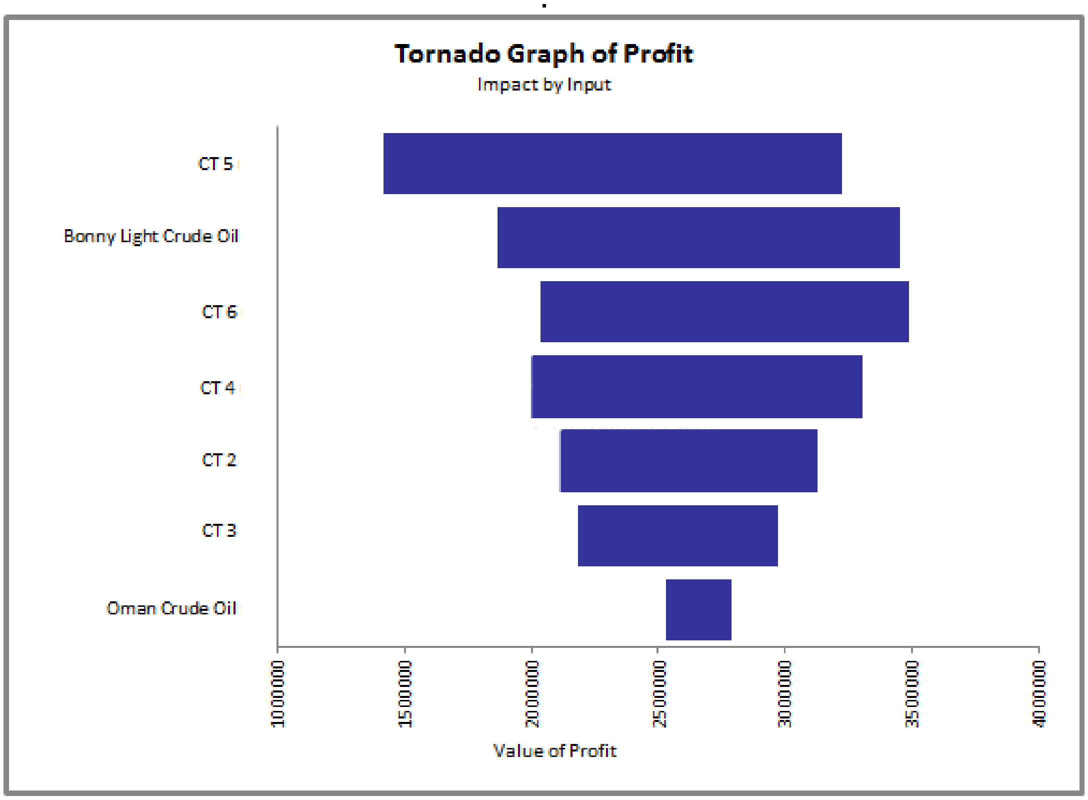

Figure 4.10: Sensitivity analyses for gross refining profit

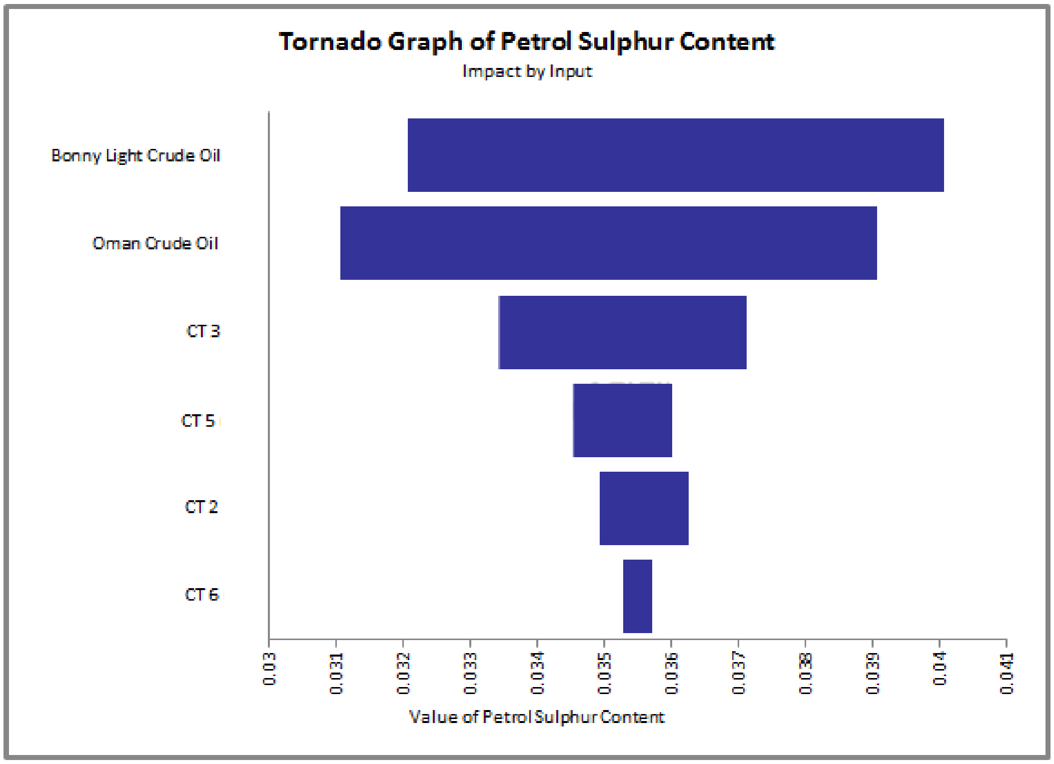

Figure 4.11: Sensitivity analyses on petrol sulphur content

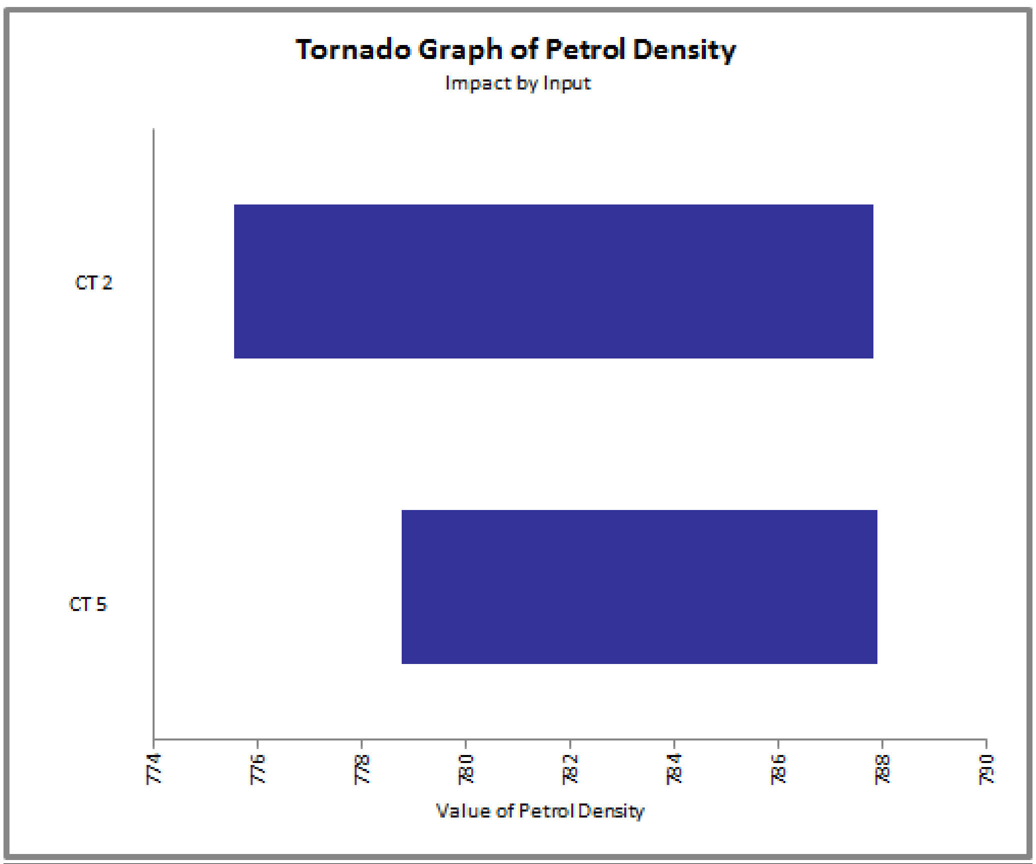

Figure 4.12: Sensitivity analyses on petrol density

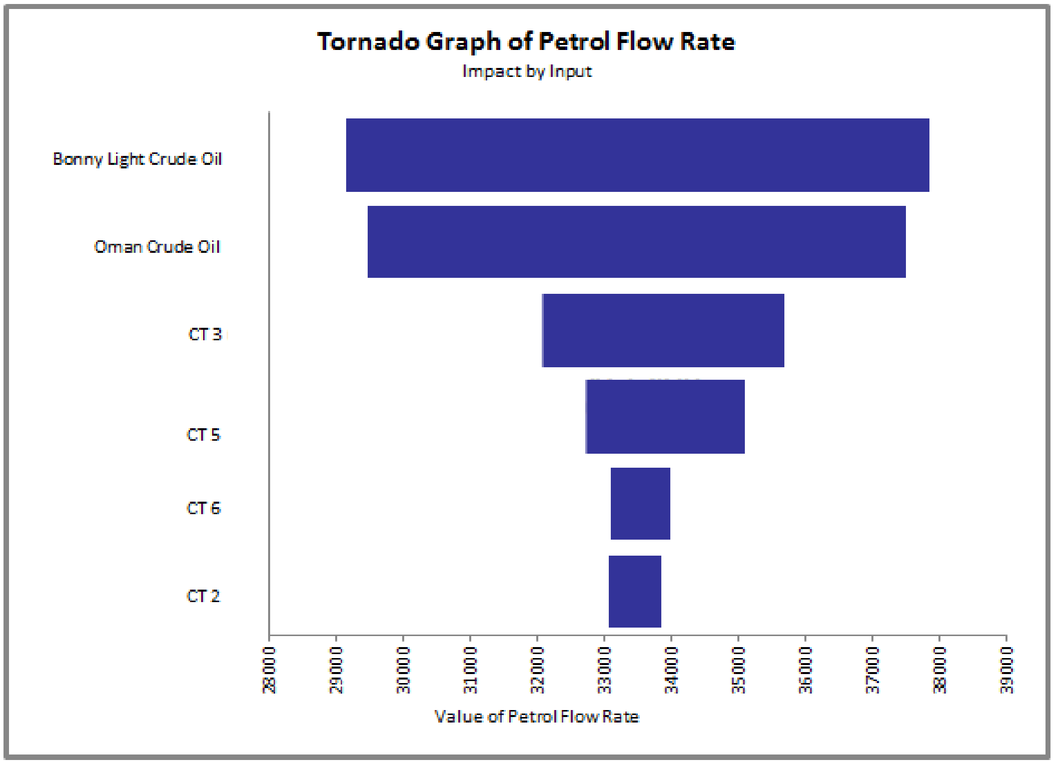

Figure 4.13: Sensitivity analyses on petrol flow rate

When considering the sensitivity analyses, the refinery planner will be able to ascertain which variables have the greatest impact on another. This becomes a useful tool when trying to make decisions on what strategy the refinery should follow. When considering the sensitivity on the gross refining profit, when referring to Table 4.23, cut-point temperature 5 (CT 5) is the cut-point separating diesel and atmospheric distillate. This is most likely due to the high sulphur content of this end of the crude fractions, having a pronounced influence on the sulphur content and density for which specifications have to be met. As expected the flow rate of BLCO is rated as the second most influential factor on the gross refining profit. This has been seen throughout the discussion of the results. For the sulphur content sensitivity the BLCO and OCO were most and second most influential on the variable. This is most likely due to there being so many different streams from both ends of the CDU making up the petrol blending pool that the different crude oil sulphur contents produced the highest impact.

CHAPTER 5: CONCLUSION AND RECCOMENDATIONS.

In this chapter a discussion around the most important conclusions with regards to work presented are discussed. The refining industry was investigated in detail in order to have a sufficient understanding of the model, the variables, the products, and how the economic function of the refinery is optimized.

In this study an efficient model has been developed to represent a case study refinery which would typically be found in South Africa. The objective of this study was to develop a tool to maximize the economic function or gross refining profit by investigating the influence of crude oil blending. Part of this involved the variation of the cut-point temperatures, which in turn would vary the physical properties, and flow rates of each stream.

A graphical representation of how optimization works with respect to the acceptable operational area when crude oil are blended with regard to the product specifications was presented. In addition, to test the model under different scenarios which a refinery planner would find themselves in, and finally a sensitivity analysis. The objectives were investigated, and a discussion provided.

5.1 Conclusion

It may be concluded that a refinery model is an absolute necessity to modern day refinery planners in order to ensure their investors reap the greatest reward from their investment whilst complying with product specifications and government regulations. The model was proven to be a very valuable tool in allowing the best refinery strategy to take place.

The model demonstrated how adjusting the blend of crude oil charged into the CDU make a significant influence on the quality specifications, quantity of final products, their effect on the other processing units, and of the gross refining profit.

The model demonstrated how a adjusting the CDU cut-point temperatures have a significant influence on the quality specifications, quantity of final products, their effect on the other processing units, and of the gross refining profit.

The model proved they have the required accuracy to base economic evaluations and decisions on by showing vast differences in gross refining profit from a base value of R 2502802.89 to an optimized value of R 8758503.13. This is especially true when considering the volatile crude oil market price that we are subject to.

The model demonstrated how the model may be utilized to minimize product quality give away.

5.2 Recommendations

In this study a crude oil blending optimization model was formulated, it illustrated how changing key variables can support economic decision making from an operational and planning level. There are several areas in which one could improve on the model.

The first would be to incorporate the maintenance, and running cost in terms of energy usage in the refinery.

Each processing unit modeled in this study made use of linear relationships of product yield, when in reality each unit has a number of its own variables which in most cases will not exhibit a linear relationship. In order to improve the accuracy of overall function, each processing unit should have their own sub model to more accurately determine the product quantities, and qualities of the full range of physical properties pertaining to the particular stream like vapor pressure, viscosity, smoke point, and corrosion. Calculation of these variables however makes the model exponentially more complex.

Since the CDU is regarded as the heart of the refinery, and is where all the initial property values are formed, more attention should be given to this unit. As an example of this, in the current model the average sulphur and density of streams are calculated using the mid-volume percent of each crude oil. This then gives a value which is an average of the entire temperature range between which it falls, but since no crude oil assay has a sulphur curve which resembles a straight line, the margin of error when calculating this value could be significant. Modeling this function by means of integration may lead to a more accurate result, but will however make the model far more complex.

The current model represents a single period for refining, in reality refineries may shut down certain parts of the refinery for maintenance reasons; in this case streams would be diverted between different units. Building a model where decision to divert intermediate streams would be useful. An interesting application of this would to build a model where there are multiple refinery site, with multiple refinery processing units and configurations. Intermediate streams from each site may be piped into the next creating a very complex refinery.

A multi-period model, where logistics of crude oil from shipping to being refined, to the logistics of moving the final product incorporating storage tanks, and their associated costs would too improve the model and make it more robust.

REFERENCES

Allen, D.H., *Linear programming models for plant operations planning*. British Chemical Engineering pg 16, 685–691, 1971

Alhajri, I. *Integration of Hydrogen and CO2 Management within Refinery Planning*. Ph.D. Ontario, Canada. University of Waterloo, 2008

Bodington C, Baker T, *A history of mathematical programming in the petroleum industry. Interfaces*, 1990, pg. 117–127.

Chung H., Kolbush S., de la Fuente E.,Christensen P, *FCC feed preparation for improved quality*. *Ultramar Incorporated, 1997*

Dechamps G. *Fuels and Refining.* South Africa: Total Professeurs Associes, 2013

Dunham C, Luhila M, Odunuga A, Refinery operations planning. 2009

Duissenov D, *Production and Processing of High Sulphur Crude and Associated Gas,* 2012. pg 14-23.

Environ Business (EB), *Crude DistillilationUnit*. Available at: http://www.environbusiness.com/uploads/images/images/fdistillation.gif Accessed 16/10/13, 2013.

ExxonMobile. 2005. *World Jet Fuel Specification Edition 5*. Available at: http://www.exxonmobil.com/AviationGlobal/Files/WorldJetFuelSpecifications2005.pdf. Accessed 17/08/13, 2005

Gary J, Handwerk G, Kaiser M, *Petroleum Refining: Technology and Economics Fifth Edition,* 2007, pg 1- 6

Gothe-Lundgren M, Lundgren J, Persson J, An optimization model for refinery production scheduling, International Journal of Production economics 78, 2002, pg 255-270.

International Council on Clean Transportation (ICCT).*Petroleum refining and the production of ultra low sulphur gasoline and diesel fuel.* Available: http://www.theicct.org/sites/default/files/publications/ICCT05_Refining_Tutorial_FINAL_R1.pdf. Last accessed 15/07/2013, 2011.

International Air Transport Association (IATA).*Aviation Jet Fuel Prices*. [ONLINE] Available at: http://www.iata.org/publications/economics/fuel-monitor/pages/price-analysis.aspx.Accessed 13/07/13, 2013.

Kelly J.D., J.L. Mann, *Crude Oil Blend Scheduling Optimization: an Application with Multimillion dollar benefits*, Hydrocarbon Processing, Vol. 82, No. 6, p. 42-80, 2003

Leiras A., Hamacher S., Elkamel A., *Petroleum refinery operational planning using robust optimization,* Engineering Optimization Vol. 42, No. 12, December 2010, pg 1119–1131, 2010

Mark A. Schulze. *Perceptive Scientific Instruments, Inc. Page 1 of 8 Linear Programming for Optimization* Available at: http://www.markschulze.net/LinearProgramming.pdf. Accessed 05 March 13, 1998.

McGraw Hill Financial: www.platts.com. C*rude oil market wire Volume 34*. Available at: http://www.platts.com/IM.Platts.Content/ProductsServices/Products/crudeoilmktwire.pdf. Accessed 16/08/13, 2013.

Nadkarni, R. A. "A Review of Modern Instrumental Methods of Elemental Analysis of Petroleum Related Material: Part 1-Occurrence and Significance of Trace Metals in Petroleum and Lubricants," *Modern Instrumental Methods of Elemental Analysis of Petroleum Products and lubricants, ASTM STP 1109.* R. A.Nadkarni, Ed., American Society for Testing and Materials, Philadelphia,1991, Pg 5 – 18.

OSHA Technical Manual (OTM) - Section IV: Chapter 2 - Petroleum Refining Processes. 2013. *OSHA Technical Manual (OTM) - Section IV: Chapter 2 - Petroleum Refining Processes*. Available at: https://www.osha.gov/dts/osta/otm/otm_iv/otm_iv_2.html. Accessed 08/06/2013, 2013.

OPEC.*World Oil Outlook 2012*. Available at: http://www.opec.org/opec_web/static_files_project/media/downloads/publications/WOO2012.pdf. Accessed 14/05/13, 2012

Palisade Tools: Evolver. *Evolver: Sophisticated optimization for spreadsheets.*. Available at: http://www.palisade.com/evolver/. Accessed 10/10/13, 2013.

South African Petroleum Industry Association (SAPIA). *2009 Annual Report.* Available: www.sapia.co.za/_literature_48396/SAPIA_2009_Annual_Report. Last accessed 19/06/2013, 2010.

Shahnovsky G, Cohen T, McMurray R,*Integrated monitoring for optimizing crude distillation*, 2012.

Shell.2006. *SANS 1598:2006*. Available at: http://s08.static-shell.com/content/dam/shell-new/local/country/zaf/downloads/pdf/others/southafrican-national-standard.pdf. Accessed 17/08/13, 2005

Shell.2006. *SANS 342:2006*. Available at: http://s04.static-shell.com/content/dam/shell-new/local/country/zaf/downloads/pdf/others/southafrican-national-standard2.pdf. Accessed 17/08/13, 2005

U.S. Energy Information Administration..*Country overview: South Africa*. Available at: http://www.eia.gov/countries/cab.cfm?fips=SF. Accessed 05/04/13, 2013

APPENDIX A: CRUDE OIL ASSAYS

A.1: Bonny Light Crude Oil Assay

TOTAL	**Crude** BONNY LIGHT **Country** Nigeria	TBP DISTILLATION

Assay 31-Jan-11

Assay Quality Good

Density at 15 °C, kg/m3	849.0
° API	35.09
Bbl/mt	7.42
Viscosity, cSt at 10 °C	8.7
Viscosity cst at 50°C	2.9
Pour Point, °C	-36.0
Wax content, wt%	
Wax Appearance Temp °C	
R V P at 37.8 °C, kPa	24.8
Water %vol	
BSW %vol	
NaCl mg/kg	
Sulphur, wt %	0.15
Mercaptan sulphur, mg/kg	2
Hydrogen sulphide, mg/kg	1
Acidity mg KOH/g	0.25
Nickel, mg/kg	3
Vanadium, mg/kg	0
Nitrogen, wt%	0.0980

	wt %	vol %
Ethane	0.02	0.05
Propane	0.21	0.35
Iso-Butane	0.28	0.42
n-Butane	0.61	0.89

°C	wt %	vol %	°C	wt %	vol %
015	1.12	1.37			
080	7.19	9.26			
150	20.19	23.80			
175	24.75	28.67			
230	35.42	39.65			
325	60.59	64.37			
350	66.13	69.63			
375	71.08	74.30			
550	92.43	93.68			
565	94.35	95.39			

PROPERTIES OF TBP CUTS

LIGHT NAPHTHA	Cut °C	Yield wt %	Yield vol %	Dens 15°C kg/m3	S wt %	RSH %wt	RON clear	RON 0,15g/l	MON clear	MON 0,15g/l	Napht %vol	Aro %Vol	RVP kPa			Benz %vol
	15-65															
	15-80	6.07	7.69	653	0.0005		77.3	83.6	76.0	82.6		2.1				2.1
HEAVY NAPHTHA	Cuts °C	Yield wt %	Yield vol %	Dens 15°C kg/m3	S wt %						Napht %vol	Aro %vol				
	80-150	13.00	14.54	759	0.0032						54.5	10.4				
	80-175	17.56	19.41	768	0.0035						50.6	11.7				
	100-150	9.29	10.38	759	0.0032						50.6	11.5				
KEROSENE	Cuts °C	Yield wt %	Yield vol %	Dens 15°C kg/m3	S wt %	RSH mg/kg	Smoke Point	Acid. mg/g	Cetane Calc	Freeze Pt °C	Naphtal. %vol	Aro. %vol	Saybolt Color	Visc cst 50 °C		Flash Point
	150-230	15.23	15.86	815	0.010		21		34.0	-65.0		15.5				
	175-230	10.67	10.98	825	0.012				36.0							
	150-250	20.53	21.06	828	0.036				34.0							
GASOIL	Cuts °C	Yield wt %	Yield vol %	Dens 15°C kg/m3	S wt %		Anilin Pt C	Cetane	Cetane Calc.	Cloud Pt °C	CFPP °C	Pour Pt °C	Visc cst 50 °C	Visc cst 100 °C	KUOP	Flash Point
	175-400	49.38	48.40	866	0.126				46.1	0	-1.8	-4				
	230-400	38.71	37.41	878	0.157				46.6	4	2.0	0				
	230-375	35.66	34.64	874	0.147				46.3	-5	-7.0	-9				
VACUUM DISTILLATE	Cuts °C	Yield wt %	Yield vol %	Dens 15°C kg/m3	S wt %	Conrad wt %	Anilin Pt C	Ni mg/kg	V mg/kg	Total N wt %	Bas N wt%	Pour Pt C	Visco cSt 100 °C	Visc cst 150°C	KUOP	Asp. C7 %wt
	375-550	21.35	19.38	935	0.28	0.20				0.1700	0.0732				11.73	
	375-565	23.27	21.09	937	0.28											
	375-580															
	400-565	20.22	18.32	937	0.28											
RESIDUE	Cuts °C	Yield wt %	Yield vol %	Dens 15°C kg/m3	S wt %	Conrad wt %	Asp C5 %wt	Ni mg/kg	V mg/kg	Total N wt %	Pene	Pour Pt °C	Visco cSt 100 °C	Visco cSt 150 °C		Asp. C7 wt %
	> 375	28.92	25.70	955	0.34							39	25	5		
	> 550	7.57	6.32	1017	0.52	16.0		65.1	4.7	0.7200		63	1973	119		0.3
	> 565	5.65	4.61	1041	0.60							65	3514	175		
	> 580															

* estimated value

Total DTS/AM Feb-11

A.2: Oman Crude Oil Assay

	Crude	**OMAN**	TBP
TOTAL	Country	Oman	DISTILLATION

Density at 15°C, kg/m3	869.2
°API	31.20
Bbl/mt	7.24
Viscosity, cSt at 10 °C	55.6
37,8 °C	
50 °C	11.8
Pour Point, °C	-39
Paraffins wt%	
Wax Appearance Temperature °C	
RVP at 37.8 °C, kPa	32
Water vol%	
RVP at 37.8 °C, kPa	
NaCl mg/kg	
Sulphur wt%	1.540
Mercaptan Sulphur, mg/kg	110
Hydrogen Sulphide, mg/kg	1
Acidity, mg KOH/g	0.51
Nickel, mg/kg	12.1
Vanadium, mg/kg	10.2

Assay Date 20-Dec-11

	%Pds	%Vol
Ethane	0.02	0.05
Propane	0.28	0.48
Iso-Butane	0.34	0.52
n-Butane	0.34	0.51

°C	wt%	vol%	°C	wt%	vol%
080	5.94	8.17	450	55.42	60.38
140	12.84	16.39	475	58.54	63.33
150	14.16	17.91	500	61.73	66.32
160	15.47	19.40	525	64.98	69.33
180	17.99	22.23	550	68.21	72.31
200	20.35	24.85	565	70.12	74.06
220	22.68	27.39	580	72.00	75.78
240	25.18	30.07			
250	26.56	31.53			
260	28.06	33.10			
300	35.02	40.29			
310	36.68	41.99			
320	38.10	43.43			
330	39.32	44.66			
340	40.50	45.84			
350	41.79	47.12			
360	43.21	48.54			
370	44.71	50.01			
380	46.21	51.48			
390	47.66	52.90			
400	49.05	54.26			

PROPERTIES OF TBP CUTS

LIGHT NAPHTHA	Cuts °C	Yield wt%	Yield vol %	Den 15°C kg/m3	S wt%	RSH mg/kg	RON clear	RON 0,15 g/l	MON clear	MON 0,15 g/l	Napht vol%	Aro vol%	RVP kPa			
	15-65															
	15-80	4.96	6.83	631	0.0321		75.9	82.6	72.9	80.2		1.8				
HEAVY NAPHTHA	Cuts °C	Yield wt%	Yield vol %	Den 15°C kg/m3	S wt%	RSH mg/kg					Napht vol%	Aro. vol%				
	80-150	8.22	9.74	734	0.0227						23.0	8.7				
	80-175	11.42	13.35	743	0.0299						23.3	9.9				
	100-150	5.92	7.00	735	0.0269											
KEROSENE	Cuts °C	Yield wt%	Yield vol %	Den 15°C kg/m3	S wt%	RSH mg/kg	Smoke Point	Acidity mg/g	Cetane calc	Freeze Pt °C	Naphta vol%	Aro. vol%	Saybolt Color	Visc cSt 50°C		Flash Point
	150-230	9.77	10.82	785	0.191		26			-58.1		15.2				
	175-230	6.57	7.21	792	0.240											
	150-250	12.40	13.62	791	0.230											
GASOIL	Cuts °C	Yield wt%	Yield vol %	Den 15°C kg/m3	S wt%		Anilin Point °C	Cetane	Cetane calc	Cloud Pt C	CFPP C	Pour Pt C	Visc cSt 50°C	Visc cSt 100°C	KUOP	Flash Point
	175-400	31.69	32.74	841	0.665				54	-4	-8	-13				
	230-400	25.12	25.53	855	0.805				54	-1	-3	-5				
	230-375	21.53	22.02	850	0.729				54	-5	-8	-11				
VACUUM DISTILLATE	Cuts °C	Yield wt%	Yield vol %	Den 15°C kg/m3	S wt%	Conrad. wt%	Anilin Point °C	Ni mg/kg	V mg/kg	Total N wt%	Bas N mg/kg	Pour Pt C	Visc cSt 100°C	Visc cSt 150°C	KUOP	Asp C7 wt %
	375-550	22.75	21.57	917	1.57	0.20				0.0688	0.0300				11.97	
	375-565	24.66	23.32	919	1.61											
	375-580	26.54	25.04	921	1.64											
	400-580	22.95	21.52	927	1.70											
RESIDUE	Cuts °C	Yield wt%	Yield vol %	Den 15°C kg/m3	S wt%	Conrad. wt%	AsphC5 wt%	Ni mg/kg	V mg/kg	Total N wt%	Pene	Pour Pt C	Visc cSt 100°C	Visc cSt 150°C		Asp C7 wt%
	> 375	54.54	49.26	962	2.50			22	19			21	86			
	> 550	31.79	27.69	998	3.17	18.2		38	32	0.3490		62	1260			0.0
	> 565	29.88	25.94	1001	3.24								1760			
	> 580	28.00	24.22	1005	3.32								2520			

* Estimated value

APPENDIX B: BLENDING CORRELATIONS

B.1 Average density

The average density of a blend of petroleum oils may be calculated by the following equation (Gary, 2004):

$$D_{BLEND} = (\sum_s F_s * PD_s)/(\sum_s F_s)) \qquad \forall i \in I, p \in PF_i$$

The average density property of the blend represented by D_{BLEND} is the product of the sum of all the volumetric flows of streams (s), and the density of streams (s) divided by the volumetric flow rate $\sum_s F_s$.

B.2 Average sulphur content

The average sulphur content of a of blend of petroleum oils may be calculated by the following equation (Gary, 2004)

$$S_{BLEND} = (\sum_s F_s * PD_s * PS_s)/(\sum_s F_s * \sum_s PD_s)$$

The average sulphur content of the blend represented by S_{BLEND} is the product of the sum of all the volumetric flows of streams (s), and the density of streams (s), and the sulphur weight percent of streams (s) divided by the total volumetric flow rate $\sum_s F_s$.