Planning and optimising of petroleum industry supply chain and logistics under uncertainty

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Planning and Optimising of Petroleum Industry Supply Chain and Logistics under Uncertainty

by

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A thesis submitted in partial fulfilment for the requirements of

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Preface

This thesis has been carried out in accordance with the regulations of the Sheffield Hallam University as a part of the requirements for the degree of Doctor of Philosophy. The contents of this research studying have been carried out by the author were supervised by Professor Sameh Saad between September 2013 to November 2017.

Elganidi H. Elsaghier

November 2017

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I sincerely thank my beloved family for their patience and support. They missed my attention and presence throughout the period of my study and for that I am truly indebted to them.

Dedicate

This thesis is dedicated to my late father (*Hussein*), my late mother (*Hawa*) and my late brothers and sister (*Husain, Mohamed* and *Fatima*).

Last but not least, to my darling wife (*Najat)* for her patience and sacrifice during my PhD journey. To my beloved children (*Hussein, Hawa, Mohamed, Mohanned, abdulbassit, Dareen and Fatima*) for their endless love.

Abstract

Petroleum industry has a major share in the world energy and industrial markets. In the recent years, petroleum industry has grown increasingly complex as a result of tighter competition, stricter environmental regulations and lower-margin profits. It is facing a challenging task to remain competitive in a globalised market, the fluctuating demand for petroleum products and the current situation of fluctuating high petroleum crude oil prices is a demonstration that markets and industries throughout the world are impacted by the uncertainty and volatility of the petroleum industry.

These factors and others forced petroleum companies for a greater need in the strategic planning and optimisation in order to make decisions that satisfy conflicting multi-objective goals of maximising expected profit while simultaneously minimising risk. These decisions have to take into account uncertainties and constraints in factors such as the source and availability of raw material, production and distribution costs and expected market demand.

The main aim of this research is the development of a strategic planning and optimising model suitable for use within the petroleum industry supply chain under different types of uncertainty. The petroleum supply chain consists of all those activities related to the petroleum industry, from the recovery of raw materials to the distribution of the finished product. This network of activities forms the basis of the proposed mathematical and simulation models.

Mathematical model of two-stage stochastic linear programming taking into consideration the effect of uncertainty in market demand is developed to address the strategic planning and optimisation of petroleum supply chain. GAMS software is used to solve the proposed mathematical models for this research.

Arena simulation Software is utilised to develop a model for the proposed petroleum supply chain starting from crude oil supply to the system, going through three stages of separation processes and finally reaching the distillation stage. The model took into account the following factors: Input Rate, Oil Quality, Distillation Capacity and Number of Failed Separators which are analysed against the performance measures: Total Products and Equipment Utilisation. The results obtained from the experiment are analysed using SPSS Programme.

Publications from the Thesis

Saad, S. M and Elsaghier E. (2015),“Petroleum logistics and supply chain management - A review”, ICMR, *International Conference on Manufacturing Research*, University of Bath, September 2015, UK.

Saad, S. M., Elsaghier E. and Ezaga. D. (2017), “Design and Planning of Petroleum Supply Chain: A Simulation Approach”. ICMR, *International Conference on Manufacturing Research*, University of Greenwich, September 2017, UK.

Saad, S. M and Elsaghier E. (2017), “Planning and optimising of petroleum supply chain and logistics under uncertainty of market demand.” *International Journal of Production Research,* (Under review, submitted August 2017).

Saad, S.M and Elsaghier E. (2017), “An integrated approach for petroleum industry supply chain optimisation”, *The Journal of Petroleum Science and Engineering.*

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List of Nomenclature

A. Nomenclature of the Mathematical Model

Sets

I = Set of raw material (i)

J = Set of products (j)

MD = Set of market demand (md)

T = set of time period in the planning horizon for one year (t)

S = set of scenarios (s)

Variables

$Q_{i,t}$ = Volume of crude oil produced during period time(t).

$V_{i,t}$ = Production volume of product (j) at the end of period time (t).

$TV_{j,t}^{s}$ = Volume of crude oil (i) transported at the end of time period (t) under scenario (s).

$SV_{j,t}^{s}$ = Volume of product (j) kept in stock at the end of period time (t) under scenario (s).

$F_{j,md,t}^{s}$ = Volume of product (j) shipped to source demand (md) at the end of period time (t) under scenario (s).

$VB_{j,d,t}^{S}$ = Backlog quantities of product (j) for demand source (md) at the end of period time (t) under scenario (s).

$DS_{j,md,t}^{s}$= Shortage amount of product (j) for demand source (md) at the end of period time (t) under scenario (s).

$D_{j,md,t}^{s}$ = Demand quantity of product (j) for demand source (md) at the end of period time (t) under scenario (s).

$Cp_{i,t}$ = Maximum capacity of crude oil production.

$SV_{j,t}^{max}$ = Maximum allowed stock volume of product (j) at the end of time period (t).

$TP_{j,t}^{max}$ = Maximum capacity of transportation of products (j) shipped to market demand (md) at the end of period time (t).

Parameters:

C_j = unit production cost for product (j) .

PS_j = price of product(j).

CB_j = Backlog penalty of product (j).

CO_i = unit production cost of crude oil (i) .

SC_i = unit storage cost of product (j).

TC_i = transportation cost of crude oil(i).

CT_j = transportation cost of product (j).

$\beta_{j,d}$= penalty of shortage below demand of product (j).

Scalar:

α= degree of uncertainty

δ = is expected shortage demand fraction of unserved cumulative demand at any time period for a given demand source.

γ = yield of product.

λ = maximum backlog allowed.

B. Nomenclature of the Simulation Model

PT	Processing time
OPV	Optimum production volume
C1	Distillation Capacity 1(Base)
C2	Distillation Capacity 2
C3	Distillation Capacity 3
C4	Distillation Capacity 4
C5	Distillation Capacity 5
C6	Distillation Capacity 6
C7	Distillation Capacity 7
C6	Distillation Capacity 8
C9	Distillation Capacity 9
F0	No Separator Failed
F1	1 Separator Failed
F2	2 Separators Failed
F3	3 Separators Failed
F4	4 Separators Failed
F5	5 Separators Failed
F6	6 Separators Failed
Q1	Quality of Crude Oil 1
Q2	Quality of Crude Oil 2
Q3	Quality of Crude Oil 3
Q4	Quality of Crude Oil 4
Q5	Quality of Crude Oil 5
R1	Input Rate 1
R2	Input Rate 2
R3	Input Rate 3

List of Abbreviations

PSC	Petroleum supply chain
API	American Petroleum Institute
BP	British Petroleum
EMMEU	Estimated Marginal Mean of Equipment Utilization
EMMTP	Estimated Marginal Mean of Total Products
LP	Linear programming
SP1	First-stage of separation
SP2	Second-stage of separation
SP3	Third-stage of separation
LPG	Liquid petroleum gas
MANOVA	Multivariate Analysis of Variance
MILP	Mixed integer linear programming
MTBF	Mean time between failure
MTBR	Mean time between repair
PVC	Polyvinyl chloride
SC	Supply Chain
PSI	Pound per square inch (1 Psi = 6 894.75729 Pascal's)
LPG	Liquid petroleum gas
bbl.	Barrel
DC	Distillation time
L1	Oil production line one
L2	Oil production line two
DOE	Design of experiment
CDU	Crude oil distillation unit
KPI	Key performance indicator

CHAPTER ONE

INTRODUCTION

1.1 Background

The supply and demand for crude oil and petroleum products are the key factor in determining the status of world economy. These days, the petroleum industry is facing a challenging task to remain competitive in globalised market due to the fluctuating demand for petroleum products as well as the fluctuating prices of crude oil. These lead to force petroleum companies to embrace every opportunity that increases their profit margin.

Petroleum is a vital source of energy that has, since 1990, met over 30% of the world’s energy demand (the five other main sources of energy are natural gas, nuclear energy, hydroelectricity, renewables and coal) (Cohen, 2016). It has contributed to the world’s economic, industrial and technological development with applications that span from powering vehicles and electricity generation to construction and the manufacture of plastics and other synthetics. All this depends on a supply chain (SC) made up of complex and expensive processes. The huge level of investment required to plan and operate the chain has driven organizations to look for safe, cheap and efficient ways of meeting customers' needs while ensuring things are done right the first time. This is important as errors in this context may not only necessitate extra spending on correction (depending on the stage of the project), but may also result in environmental damage and even fatal accidents.

The petroleum industry is a material flow intensive. Since supply chain cost amounts to 40% of total refining and distribution cost, effective management and optimisation of the chain are critical. Accordingly, there is a flourishing body of research in this area (Kemthose & Paul, 2012), and a number of quantitative models and mathematical programming techniques have been developed over the decades. Their use has significantly increased organisations’ ability to plan and control industry activities and increase profits. This has become even more crucial during the recent economic slowdown, which has forced many companies to abandon plans to build new refineries or expand capacity in existing plants and obliged them instead to optimise their existing facilities.

Detailed planning of the SC is vital if it is to be both robust enough to handle such uncertainties and flexible enough to adjust to internal and external changes in the petroleum industry.

However, from the last decades onward, the attention of researchers has focused on optimisation and planning of a part of petroleum supply chain and logistics under uncertainty, using various mathematical programming models. For example, both Escudero et al. (1999) and MirHassani (2008) presented modelling frameworks to solve real life supply/transportation/distribution scheduling problems under uncertain product demand. Al-Othman et al. (2008) used first a deterministic optimization model firstly and then proposed stochastic programing to identify the impact of uncertainties on the supply chain proposed, while Ribas et al. (2010) studied the impact of three sources of uncertainty demand for refinery products and market prices) over the investment decisions in the integrated oil supply chain using three formulations (a two-stage stochastic model with a finite number of realization, a robust min-max regret model and a max-min model). Al-Qahtani et al. (2008) applied a two-stage stochastic mixed integer nonlinear programming model (MINLP) to formulate the problem of the strategic planning, design and optimization of a network of petrochemical processes under uncertainty. Al-Qahtani and Elkamel (2010) utilised the sample average approximation method with statistical bounding techniques to develop a model to strategically integrate and coordinate petroleum refineries network planning under uncertainty. It enabled them understand the problems faced by chemical industries, economic considerations involved and the importance of process flexibility.

In addition, a few of authors have applied simulation approach in planning of a segment of petroleum industry supply chain and logistics. Cheng and Duran (2004) developed a decision support system to improve the combine inventory and transportation system in a representative world-wide crude supply problem based on the integration of discrete event simulation and stochastic optimal control of the inventory/transportation system. Schwartz et al. (2006) presented internal model control (IMC) and model predictive control (MPC) - based decision policies for inventory management in supply chains under conditions involving supply and demand uncertainty. Augusto et al. (2006) demonstrated how combined approach of templates and simulators, described as incremental modelling and used them to create a flexible refinery simulation toolset. They applied ARENA software on the proposed model. Pitty et al. (2008) presented two-part paper, in part 1 they proposed a dynamic model of an integrated refinery supply chain called Integrated Refinery In – Silico (IRIS) and demonstrated its application to provide decision support for optimal refinery supply chain design and operation based on a simulation – optimization framework, whereas the main objectives of part 2 is to demonstrate the application of simulation – optimisation method to support optimal design and operation such as investment and policy decisions in an integrated refinery supply chain to maximize the profit margin and customer satisfaction. Naraharisetti et al (2009) studied the extension of the process systems engineering (PSE) to the process systems engineering of enterprise (PSE2). They divided the various supply chain management decisions into five major groups which are system representation, modelling and simulation by using IRIS (Integrated Refinery in Silico) in Matlab/Simulink, synthesis and design, planning and scheduling and control and supervision. Chryssolouris, et al. (2005) proposed an integrated simulation - based approach uses a random - search formulation for dealing with short - term refinery scheduling problem involves the unloading of crude oil to storage tanks, the transfer and blending from storage tanks to charging tanks and crude oil distillation units.

Therefore, this research project focuses on the planning and optimisation of the whole petroleum industry logistics and supply chain, from the recovery of the raw materials to production and distribution, using mathematical and simulation modelling techniques. It creates a mathematical model and a simulation model which between them consider a range of parameters including crude oil production, transportation plans, production levels, operating conditions, products distribution plans and the prices of raw materials and products under significant sources of uncertainty (reflecting current market conditions). So far, there has been little investigation of the impact of uncertainty on these variables. Therefore, the aim and the objectives of this PhD thesis are as follows:

1.2 Research aims and objectives

The main aim of this research is the development of a generic model to aid practitioners in planning and optimising petroleum industry supply chains and logistics under different types of uncertainty. It seeks to offer a sustainable way of measuring performance. This involves investigating process parameters, variation and robust operation conditions and identifying those parameters that need more accurate estimation.

1.2.1 The objectives of the research programme

The following were the main objectives of this research

1- To carry out a comprehensive literature to establish the current knowledge and practice.

2- To identify the different supply chain functions involved in petroleum industry and decide up on the research project's scope.

3- To identify the different types of uncertainties and methods of evaluation.

4- To identify the key performance indicators concern the petroleum industry in today's market.

5- To develop of mathematical relationships between the key performance indicators and the uncertainty considered in this study.

6- To develop of an operational simulation model for planning and optimising petroleum logistics and supply chain.

7- To verify and validate the proposed model and take appropriate actions.

8- To design an experiment to investigate which variables impact on supply chain performance.

9- To conduct this experiment, collect data and analyse the results, and

10- To provide final conclusions, recommendations, limitation and future work.

1.3 Thesis's structure

The objectives mentioned in the previous section are addressed in nine chapters of this thesis. This chapter offers a brief introduction to the aims and objectives of the research. Chapter Two presents a comprehensive literature review discussing the various methodologies that have been employed by previous researchers to investigate petroleum industry supply chains and logistics under different types of uncertainty. This is followed in Chapter Three by a discussion of petroleum supply chain functions, key performance indicators (KPI) and sustainability issues in the petroleum industry.

Chapter Four addresses the methodology employed in the study, explaining why mathematical programming and simulation modelling were identified as suitable research methods and discussing the use of technical tools such as the GAMS software and ARENA simulation to address petroleum supply chain problems. The chapter explains that for the purpose of modelling, the supply chain network was defined as all those activities related to the petroleum industry, from the recovery of raw materials to final distribution.

Chapter Five presents the mathematical model of two-stage stochastic linear programming with recourse that was developed to investigate the effect of uncertainty in market demand on the supply chain. An operational simulation model for planning and optimising petroleum logistics and supply chains is presented in Chapter Six. The chapter also discusses input and output components and experimental factors.

Chapter Seven discusses the design of the experiments that were conducted to test the simulation model, and the issues surrounding its verification and validation. The results of these experiments are presented and discussed in Chapter Eight.

Chapter Nine summarises and discusses the main points obtained from the research before offering recommendations for further study in this area.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Supply chains have become the subject of increasing attention among business researchers since the 1990s. New competitive realities such as the downward pressure on prices, globalisation, shortening product life cycles, new sources of low cost competition and continued concentration of the market have led many to focus on SCs as a way of gaining competitive advantage. However, despite the fact that the petroleum industry plays a significant role in the global economy as one of its most important sources of energy, there is relatively little literature available on the petroleum supply chain. The purpose of this chapter is to review and analyse the literature that has been produced so far on petroleum logistics and supply chain management.

2.2 Petroleum industry overview

Historically, the modern petroleum industry began in 1859, when Edwin Drake drilled the first successful oil wells in Pennsylvania, US. Prior to that time, petroleum was only available in very small quantities via the natural seepage of subsurface oil in various areas throughout the world. With the discovery of "rock oil" in north-western Pennsylvania, crude oil became available in sufficient quantities to allow the development of large-scale processing systems. The earliest refineries employed simple distillation units to separate the various constituents of petroleum by heating the crude oil mixture in a vessel and condensing the resultant vapours into liquid fractions. Kerosene was the chief finished product; initially, this was used in light lamps instead of whale oil, but new applications were discovered with the development of the gasoline engine.

Today, the world is heavily dependent on petroleum, and demand continues to rise steadily year on year. According to the International Energy Agency 2013, oil and natural gas accounted for 36.1% and 26% respectively in 2013 of the total global energy consumption in the world. Oil accounted for the largest share of energy consumption since 1990, followed by Coal and natural gas as indicated in Figure 2.1. A rising global population and continued economic growth mean that worldwide demand for petroleum products will remain high. If it is to meet this demand, the petroleum industry must plan strategically and invest heavily in optimisation tools.

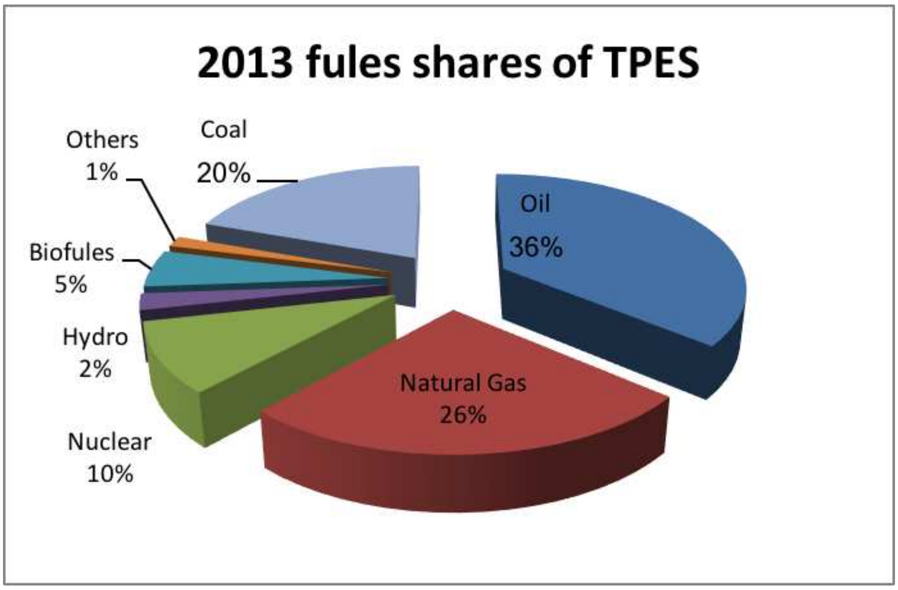


Figure 2.1 the total primary energy supply (TPES) in 2013

Source, International Energy Agency 2013

2.2.1 Crude oil production

World oil production grew steadily from about 400,000 barrels a day in 1900 to over 86 million barrels a day in 2013. The International Energy Agency (2013) expects this to rise to about 96 million barrels a day by 2035. However, almost all of the oil products humans consume are derived from non-renewable sources. As a limited natural resource, crude oil is subject to depletion, and several reports have indicated that production is already close to maximum level and that it will soon start to decline Nygren et al. (2009). Figure 2.2 shows the world production and consumption of petroleum over the last fifteen years.

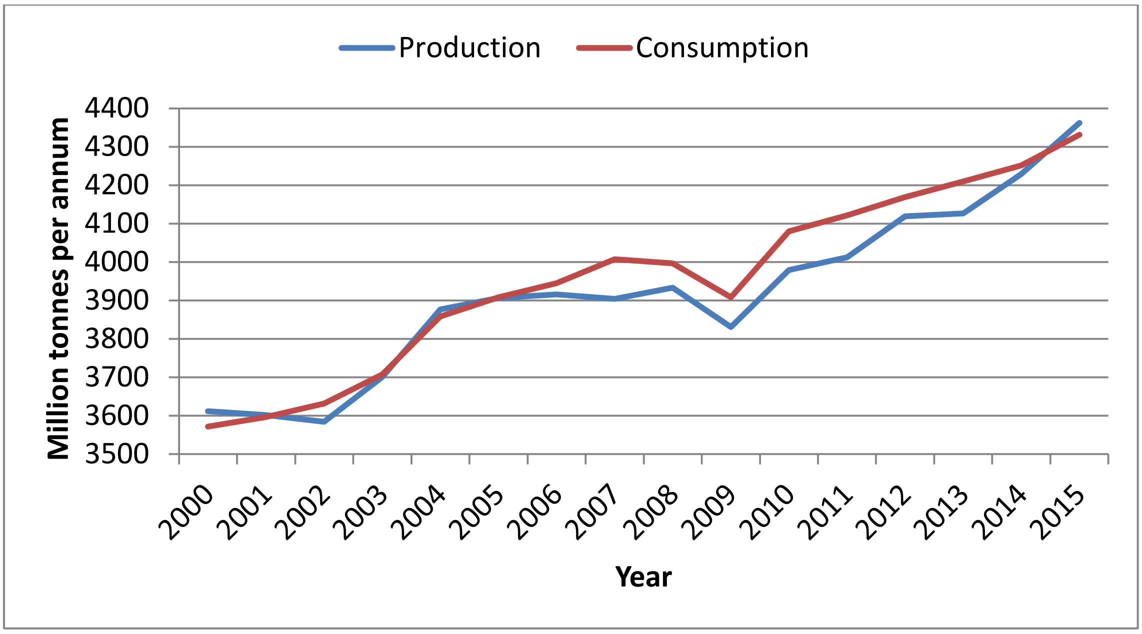


Figure 2.2 the World Production and Consumption of Petroleum

Source: BP Statistical Review of the World Energy (June 2011 - June 2016)

2.2.2 Prices of crude oil

The volatility of oil prices has a direct impact on the prices of petroleum products, which in turn have a negative impact on other goods and services. For example, in the United States, the cost of crude oil account for 53% of retail price of gasoline. Figure 2.3 shows the volatility of prices for several types of crude oil.

Oil price fluctuation considered a source of uncertainty affecting the cost of an essential input; this creates uncertainty regarding company profitability and valuations, which can have a knock-on effect on investment. This was demonstrated by Henriques and Sadorsky (2011) who developed a model showing how oil price volatility impacts on companies’ strategic investment decisions.

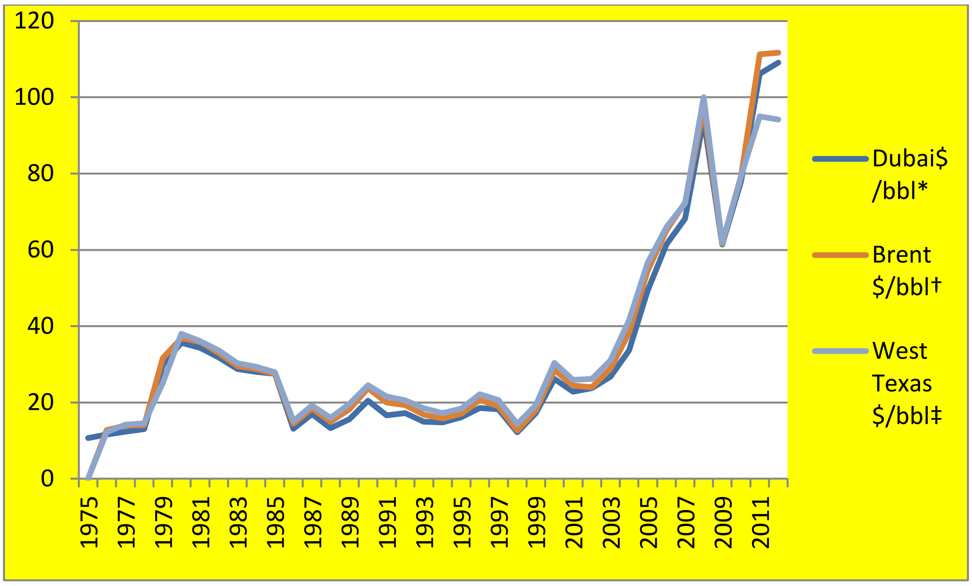


Figure 2.3 Oil Crude Prices (1975-2012)

Source: British Petroleum Statistical Review of World Energy (June 2013)

Further work carried out by Rafiq et al. (2009) found that demand and consumption are also influenced by changes in oil price (which raise or lower the cost of production and make products more or less expensive).

2.2.3 Types of crude oil

Crude oil is a complex liquid mixture of hydrocarbon compounds and small amount of organic compounds such as sulphur, oxygen, nitrogen and contains metals such as vanadium, nickel, iron and copper. Table 2.1 shows the elemental composition of crude oils (Roussel & Boulet, 1995).

Table 2.1 Elemental composition of crude oils

Element	Composition (wt. %)
Carbon	83.0 – 87.0
Hydrogen	10.0 – 14.0
Sulphur	0.05 – 6.0
Nitrogen	0.1 – 0.2
Oxygen	0.05 – 2.0
Ni	< 120 ppm (Part per million)
V	< 1200 ppm (Part per million)

Crude oil is classified into several types according to elemental composition, density and specific gravity, all of which can be easily measured in the field. Below are the major classifications:

2.2.3.1 Light/Heavy Crude oil

The classifications of crude oils as light or heavy depend on its density and specific gravity. American Petroleum Institute (API) gravity is the common measure of crude oil density; the heaviness of the crude oil is measured in comparison to water. It is calculated by the formula (2.1):

$$API\ gravity = \frac{141.5}{SG} - 131.5 \tag{2.1}$$

Where SG = Specific gravity of oil.

When oil has a higher gravity (more than 40 degrees), it is considered light oil. Light crude usually contain higher levels of naphtha (gasoline-range hydrocarbons). Otherwise, if oil has a gravity of less than 20 degrees, this is considered as heavier or thicker oil. Heavy crude oils are more viscous and higher densities and are usually rich in aromatics and contain more residual materials such as asphaltenes, sulphur, and nitrogen

2.2.3.2 Sweet/Sour Crude Oil

Crude oils is also categorised according to sulphur content. Oil containing less than 1% weight of sulphur is known as sweet crude while those with over 1% weight sulphur content are referred to sour crude oil. Sulphur compounds contained in petroleum can have harmful effect, including metal corrosion, air pollution and catalyst degradation.

2.2.3.3 Paraffinic/Naphthenic Crude Oils

Crude oil may be paraffinic, naphthenic and aromatics depending on the relative proportion of hydrocarbons that are present. Paraffin or Alkanes are presented by general formula ($C_n H_{2n+2}$), the simplest compound of Alkanes is Methane (CH_4). Other types of saturated hydrocarbons are Naphthalene or Cycloalkanes. These have at least one ring of carbon and are denoted by the general formula ($C_n H_{2n}$). A common example is Cyclohexane ($C_6 H_{12}$) Roussel and Boulet (1995b). Aromatics are unsaturated compounds classics according to Benzene rings. Light petroleum fractions contain mono- aromatics which have one benzene ring such as toluene (CH_3). The heaviest portion of the crude oil contains asphaltenes which are condensed Polynuclear aromatic compounds of complex structure. Table 2.2 shows properties of the some types of crude oil.

The quality of crude oil and other feed stocks dictates the level of processing and conversion necessary to achieve what a refiner sees as an optimal mix of products. Crude oil costs account for about 80% of a refinery's turnover Reddy et al. (2004). Light, sweet crude is more expensive than heavier, sourer crude because it requires less processing and produces a higher percentage of value-added products, such as gasoline, diesel, and aviation fuel. It is therefore important to take into account the product requirements of the market when determining refinery configuration and choosing crude grade.

Table 2.2 Properties of the some types of crude oils

Crude Source	Paraffin % vol.	Naphthenic % vol.	Aromatics % vol.	Sulphur % wt.	API gravity (˚API)
		Light Crudes			
Saudi Light	63	18	19	2.0	34
South Louisiana	79	45	19	0.0	35
Bery1	47	34	19	0.4	37
North Sea Brent	50	34	16	0.4	37
Lost Hills Light	50% Aliphatic		50	0.9	> 38
		Mid-range Crudes			
Venezuela Light	52	34	14	1.5	30
Kuwait	63	20	24	2.4	31
USA West Texas Sour	46	32	22	1.9	32
		Heavy Crudes			
Prudhoe Bay	27	36	28	0.9	28
Saudi Heavy	60	20	15	2.1	28
Venezuela Heavy	35	53	12	2.3	24

IARC, 1989; Mobil, 1997; OSHA, 1993 & International Crude Oil Market Handbook, 2004

2.2.4 Petroleum refinery overview

Refining petroleum is a complex chemical process. The refinery utilises several different techniques to take crude oil and transforms it into several valuable products such as gasoline, kerosene, diesel, naphtha, liquid petroleum gas, heavy gas oil, bitumen, coke, lubricating oil, waxes, and residue. A flow diagram showing the processes occurring within a typical modern refinery is presented in Figure 2.4 (Khor, 2007). Petroleum refining processes and operations may be grouped into four basic functions: distillation, conversion, cracking and treatment.

2.2.4.1 Distillation

This process involves the physical separation of crude oil at various boiling-point ranges into groups of hydrocarbon compounds called "frictions" through fractionation in atmospheric and vacuum distillation towers. No chemical reactions occur in these units:

2.2.4.1.1 Desalter

The purpose of this unit is to remove any salts from the crude oil before any other processes are started by forcing water into the crude oil stream; this process makes out the salts and prevents corrosion.

2.2.4.1.2 Atmospheric distillation

In this unit the crude oil complex mixture is separated into different fractions at atmospheric pressure and low boiling ranges, to produce heavy naphtha, kerosene, diesel and heavy gas oil.

2.2.4.1.3 Vacuum distillation

The atmospheric residues are distilled to produce vacuum gas oil, lube oil base stocks and asphalt.

2.2.4.2 Conversion processes

Conversion processes are employed to convert heavy feedstock from the distillation process into feeds suitable for coking and visbreaking units.

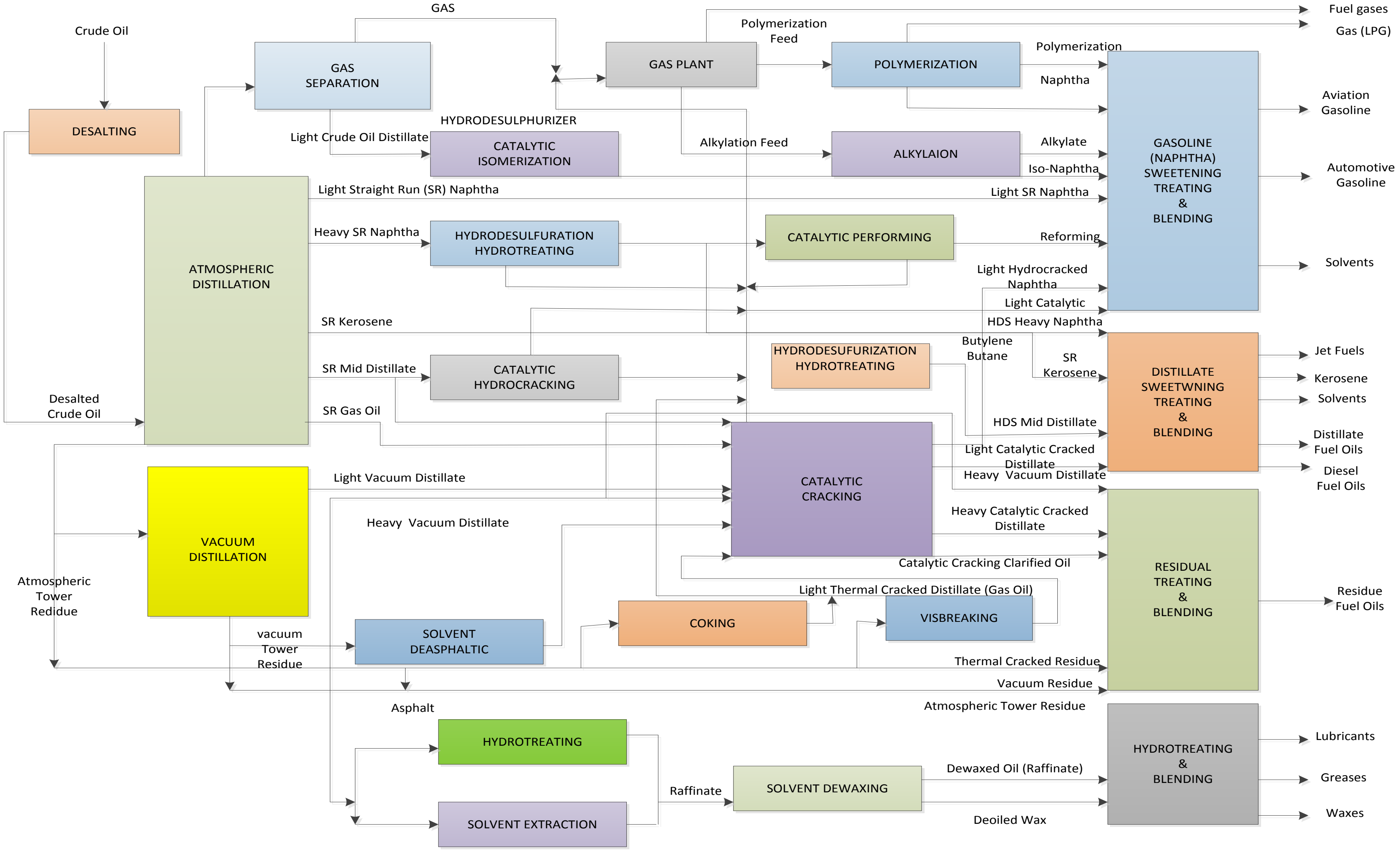


Figure 2.4 Flowchart summarises the processes in a modern refinery (Khor, 2007).

2.2.4.3 Catalytic cracking processes

There are used to crack heavy oil to produce lighter outputs that can be blended to produce high-value products, such as gasoline.

2.2.4.4 Treatment processes

Various treatment methods involving both chemical reaction and physical separation, (e.g. dissolution, absorption and precipitation) are employed to remove impurities and other constituents that would affect the properties of the finished products or reduce the efficiency of the conversion processes.

2.2.5 Petrochemicals

Petrochemicals are chemicals derived from petroleum or natural gas. The main feedstocks are natural gas, condensates (NGL) and other refinery by products such as naphtha, gasoil and benzene. Petrochemical plants are divided into three main primary product groups, depending on feedstock:

2.2.5.1 Olefins

Olefins include ethylene, propylene and butadiene. These are source of plastics such as (polyethylene, polyester, PVC).

2.2.5.2 Aromatics

Aromatics include benzene, toluene, and xylenes. There are also source of plastic such as (polyurethane, polystyrene, acrylates and nylon).

2.2.5.3 Synthesis gas

Synthesis gas is formed by steam reforming between methane and steam to create a mixture of carbon monoxide and hydrogen. It is used to make ammonia.

2.3 Petroleum supply chain

2.3.1 Overview

Supply chain management (SCM) is a term that has been defined as the planning and flow of materials and products to deliver goods and services to end consumers. Christopher and Gattorna (2005) define the supply chain as: “The network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer”.

Management of the supply chain involves planning the flow of materials and products so as to ensure that these products and services are delivered to end consumers in a timely and cost-efficient way. Christopher (2010) defines SCM as: “the management of upstream and downstream relationships with suppliers and customers with the aim of delivering superior customer value at less cost to the SC as a whole”. Lambert and Cooper (2000) add that it is: “the integration of key business processes from original supplier through to end user that provides products, services, and information that add value for customers and other stakeholders". The definitions characterize the SC as an integrated process in which a number of distinct business entities (e.g. customers, suppliers, manufacturers, distributors and retailers) collaborate to: (1) obtain raw materials, (2) process these raw materials into the required final products and (3) deliver these products to retailers/customers. Materials usually flow forwards along the chain, while information flow backwards (Beamon, 1998).

A typical petroleum supply chain involves oil exploration, oil production, oil transportation, crude oil storage (tanks are connected to the refinery by a network of pipelines), refinery operations, inventory of the finished products and distribution (via distribution centres). Strategic, tactical and operational decision making is required at all stages of the chain. Figure 2.5 displays the typical petroleum industry supply chain, from exploration and petroleum production, through processing and storage, to distribution and marketing of the refined products to consumers.

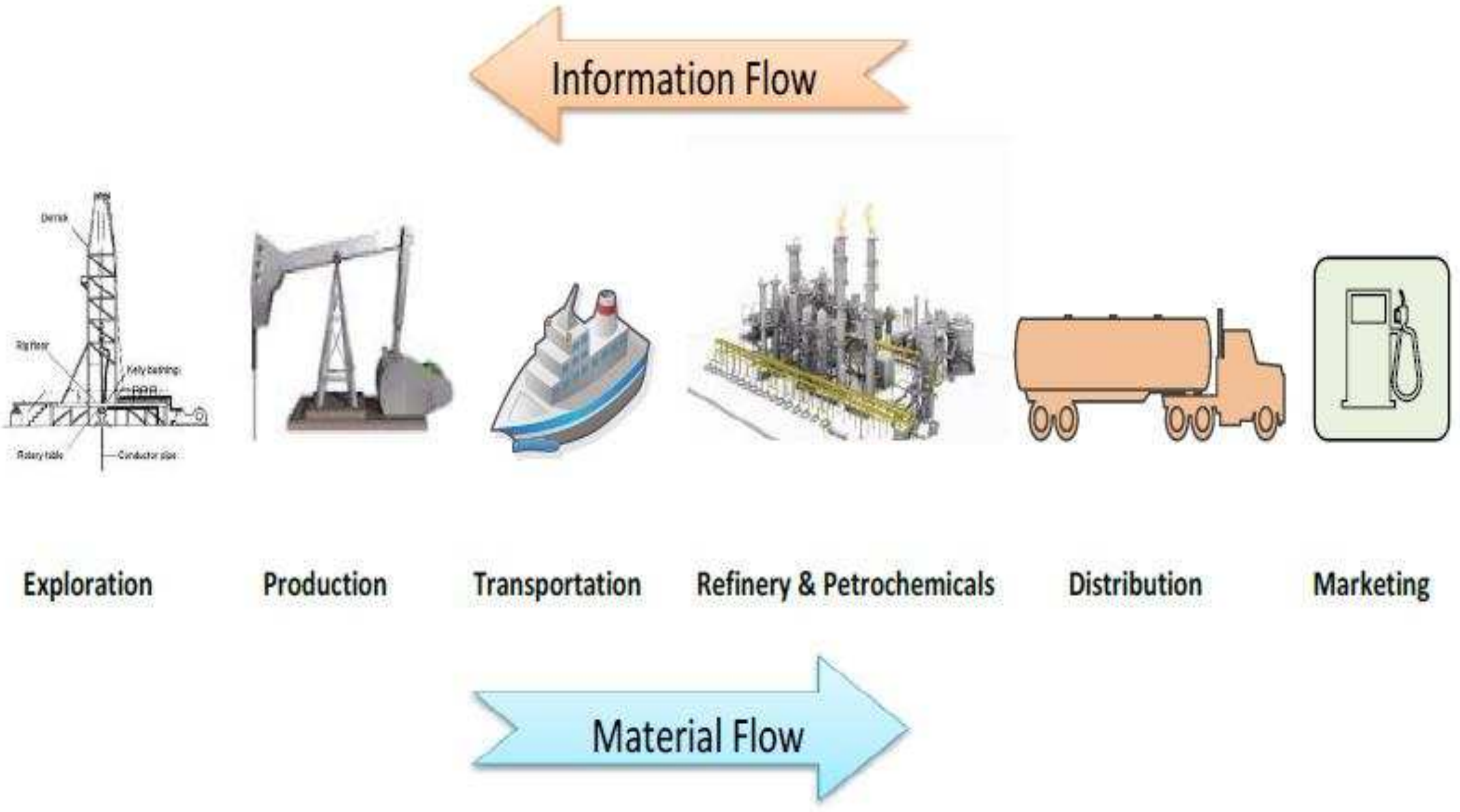


Figure 2.5 a typical petroleum SC

As in any other industry, the petroleum supply chain comprises multiple entities performing multiple functions. These functions may be classified as upstream, midstream and downstream, according to their position within the chain as shown in Figure 2.6. Upstream activities include all exploration activities (e.g. seismic, geophysical and geological investigations) and oil extraction operations such as drilling, production, facility engineering and reservoir maintenance. This is the highest level of the chain as activities at this stage have a significant influence on the operation of the SC as a whole. The midstream consists of the infrastructure used to transport crude oil and gas to refineries for conversion, along with the storage tanks. Finally, the downstream comprises the processing, transportation, marketing and distribution of petroleum products to end users. The recovered crude oil is transformed into higher value products such as gasoline, kerosene, diesel and naphtha in the refinery. These products are transported to distribution centres via pipeline, ships or rail, with trucks then being used for the last stage of the journey from the distribution centre to the retailer. Some petroleum companies are fully integrated; operating at all three levels of the chain, while others may be active at just one or two levels.

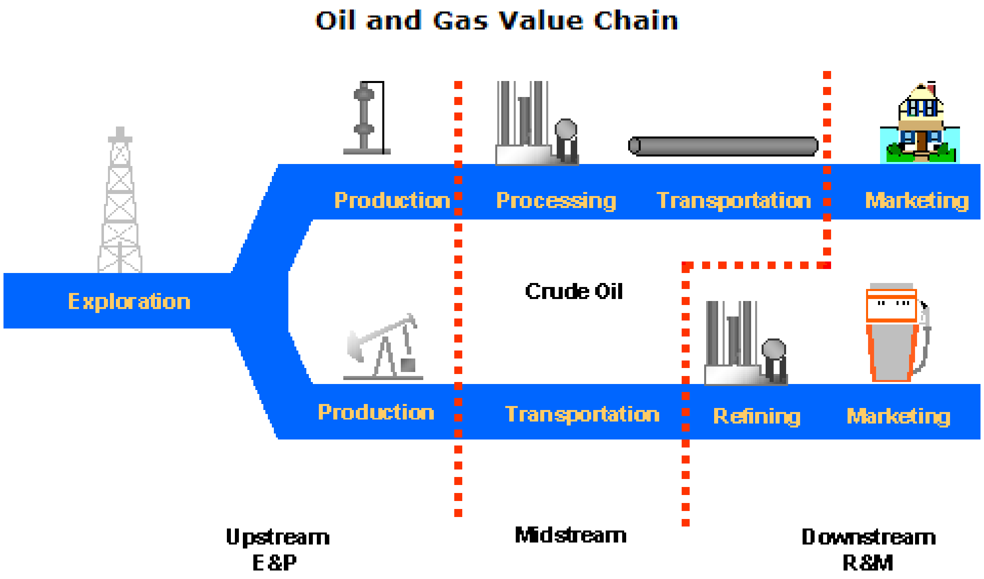


Figure 2.6 Upstream, Midstream, and Downstream Activities

(Source: Petro-Strategies, Inc.)

2.3.2 Logistics management in the petroleum industry

There have been many definitions of logistics management. Shapiro (1985) presents one of the simplest definitions in his seven Rs of logistics, which defines logistics as ensuring the availability of the right product, in the right quantity and the right condition, at the right place, to the right customer, at the right cost. The Council of Logistics Management (1998) defines logistics as: “the part of the supply chain process that plans, implements, and controls the efficient, effective flow and the storage of goods, services, and related information from the point of origin to the point of consumption in order to meet the customer's requirements”.

Sear (1993) was one of the first authors to focus specifically on the logistics of the petroleum supply chain, developing a linear programming model to investigate planning in one downstream petroleum company. Shah (1996) applied formal mathematical programming techniques to deal with the problem of scheduling the movement of crude oil from refinery tanks to harbour tanks and the connection of refinery tanks to crude distillation units. Jia and Ierapetritou (2003) investigated inventory management in a refinery delivering various types of crude oil by sea, while Pongsakdi et al. (2006) investigated the planning of crude oil purchasing and processing, employing an optimisation model to ensure that specification and demand could both be met while still realising the highest possible profit. The model, which was linear, was based on a discretisation of the time horizon. Relvas et al. (2006) developed a mixed-integer linear programming (MILP) approach to model the problem of oil derivations pipeline transportation scheduling and supply management. The mathematical model they developed covered pipeline scheduling and inventory management at distribution centres. Finally, Herrán et al. (2010) proposed a new, discrete mathematical approach to the short-term operational planning of multi-pipeline systems for refined products.

2.3.3 Petroleum industry supply chain (SC) under uncertainties

Uncertainty exists where those involved do not have the knowledge they need to accurately describe the current state of events or predict future outcomes. It can impact on decision making in the supply chain if decision makers are unclear about their objectives; if they lack information about the supply chain or its environment, or they lack the capacity to process this information; if they are unable to accurately predict the impact of possible control actions on supply chain behaviours; or if they lack effective control actions Van der Vorst et al. (2002). Uncertainty can be a long-term problem; for example, the effects of fluctuations in the price of raw materials, market demand and production rates may be felt for five to ten years Sahinidis et al. (1989). Mid-term uncertainties may affect operations for one to two years (Gupta & Maranas, 2003), while short-term uncertainties are day-to-day or week-to-week processing variations (e.g. equipment failure or a cancelled order) that require an immediate response Subrahmanyam et al. (1994).

It is extremely important that the petroleum processing industry plans for a high degree of uncertainty. As highlighted above, the industry is subject to a number of uncertainties, including variable reserves, production problems, and fluctuations in the price of raw materials, refined products and market demand. Investigating the effects of uncertainties in demand, market prices, raw material costs and production yields on planning decisions in the petrochemical supply chain, Lababidi et al. (2004) found the impact to be significant, with market demand being the most important. Figure 2.7 shows how the effects of market uncertainty are felt throughout the supply chain (Das, & Abdel-Malek, 2003).

Figure 2.7 the market uncertainty in supply chain

You and Grossman (2008) adopted a quantitative approach to investigate petroleum SC responsiveness under uncertainty, formulating the problem as a bi-criterion optimisation model that maximised net present value and maximised expected lead time. Responsiveness is defined as the ability of a supply chain to respond rapidly to changes in demand, both in terms of volume and mix of products (Christopher, 2000; Holweg, 2005). Al-Othman et al. (2008) studied the effect of uncertainties in market prices and market demand on the supply chain of one petroleum organisation owned by the producing country, concluding that uncertainty in market demand has a greater impact on supply chain planning than market prices. Ribas et al. (2010) studied the impact of three sources of uncertainty (crude oil production demand for refinery products and market prices) on investment decisions in the integrated oil supply chain. Ghatee and Hashemi (2009) presented a modelling framework for the optimisation of crude oil transportation under uncertainties in tank and pipeline capacity, oil field production, refinery demand and export terminal. Al-Qahtani and Elkamel (2008) formulated the problem of how to strategically plan, design and optimise a petrochemical processing network under uncertainties in process yield, raw material costs, product prices and lower product market demand.

Khor (2006) divided uncertainty factors into two categories: exogenous, or external, and endogenous, or internal (Maiti et al., 2001; Liu & Sahinidis, 1997). These are shown in Table 2.3.

Table 2.3 Uncertainty factors

Exogenous or External Uncertainty	Endogenous or Internal Uncertainty
• Location • Crude oil supply • Production costs • Distribution costs • Market demand • Processing investment costs Prices of crude oil and chemicals • Production demands (product volume & specification) • Budget available for capital investment in purchasing new equipment or replacing existing equipment and expanding capacity	• Product/process yield • Machine availabilities • Properties of components • Processing and blending options

2.3.4 Optimisation, planning, and designing techniques in the petroleum industry

The aim of supply chain design and planning is to determine the optimal way of deploying all of the functions (production, inventory and distribution) and resources within the chain so as to meet forecast market demand in an economically efficient manner. This process involves decision making at the strategic, tactical and operational levels (Grossmann et al., 2002). Strategic decisions may cover time horizons of one to several years, affect the whole organisation and focus on major investment. Tactical planning typically covers time horizons of between a few months and a year and addresses issues such as production, inventory and distribution. Production supply chain planning is a good example of tactical planning (McDonald & Karimi, 1997; Perea et al., 2000). Operational planning usually covers a horizon of one week to three months and involves decisions about day-to-day operations and resource allocation. Examples include the operational planning of utility systems (Lyer & Grossmann, 1998) and the planning of refinery operations (Moro & Pinto, 1998; McDonald, 1998), see Figure 2.8.

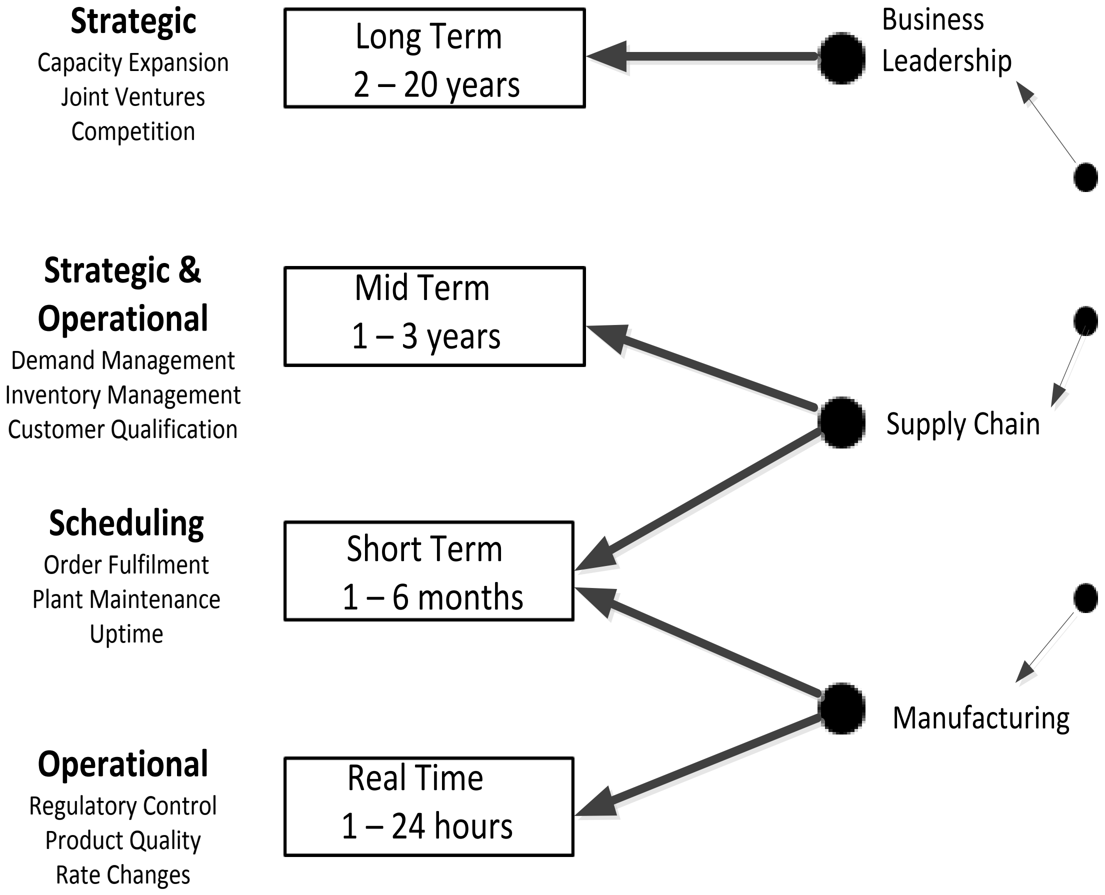


Figure 2.8 a typical functional hierarchy of corporate planning activities (Mc Donald, 1998)

Mathematical Programming techniques developed and applied in the late 1940s. Dantzig (1947) invented and developed of the simplex algorithm and really created the area of linear programming (LP) and Neumann developed the theory of duality as a linear optimisation solution. Optimisation techniques employed in applications such as processes, planning, operations, logistics operations, facilities design and so on, cover almost of subfields in mathematical programming such as linear programming, integer programming and non-linear programming.

However, from 50s onward, the attention of researchers has been directed to apply optimisation techniques in petroleum industry. Lee et al. (1996) presented a discrete mixed- integer linear programming for the crude oil scheduling. The objective was to find schedule that meets the predetermined crude slate for CDUs, while minimising total operating cost. Göthe-Lundgren et al. (2002) also formulated a mixed-integer linear programming model in oil refineries, this time to support shipment planning and strategic decision making in regard to new products and investment in storage capacity. Moro and Pinto (2004) focused on crude oil inventory management in a real-world refinery receiving several types of oil via pipeline. They formulated two responses: the first relied on a mixed-integer nonlinear programming model and the second adopted a discretisation procedure for the inventory levels of the tank farm, thus generating a mixed-integer linear programming problem. Neiro and Pinto (2004) proposed a general framework for modelling petroleum supply chains and applying mathematical model to processing units, storage tanks and pipelines. The same authors (Neiro & Pinto, 2005) later developed a model based on a nonlinear programming formulation to plan production over a single period. The model incorporated multiple planning periods and different crude oil types, and covered uncertainty related to prices and demand of the petroleum products as a set of discrete probabilities, crude oil handling added as constraints. The resulting models were mixed-integer nonlinear programming which was able to make predicative decisions in time period that required variable and high demands. Chunpeng and Gang (2009) framework for addressing short-term planning and scheduling problems combined a mixed-integer linear programming model and a lower-level simulation system. DeBrito, et al. (2009) offered what they called a "virtual refinery." This was a rigorous dynamic model incorporating every piece of equipment in the plant. Luo and Rong (2007) proposed a strategy for integration of production planning and scheduling in refineries that involved an upper level multi period mixed integer linear programming model and lower level simulation system. Li et al. (2010) applied the augmented lagrangian method to solve the full-space integration problems. They argued that to improve the quality of decision making in the process operations, it is essential to implement integrated planning and scheduling optimisation. Guajardo et al. (2013) proposed linear programming model for studying a problem of tactical planning in a divergent supply chain. Paolucci et al. (2002) developed a decision support system that facilitated the process of allocating the crude oil supply from tanker ships to port and then to refinery tanks. Bok et al. (1998) developed a multi period mixed integer nonlinear programming optimisation model that is both solution and model robust for any realisation of demand scenarios using the two - stage stochastic programming modelling frame work. Zhang et al. (2001) developed a new refinery optimisation approach by integration of the hydrogen network and the utility system with the material processing system. They used linear programming (LP) techniques to maximise the overall profit. This method considers the optimisation of refinery liquid flows, hydrogen flows, and steam and power flows simultaneously. Kim et al. (2008) modelled supply network and production planning, finding that distribution costs could be reduced by relocating distribution centres and reconfiguring their links to various markets. Finally, Herrán et al. (2010) proposed a mathematical formulation based on discrete-time MILP to model planning the transportation of multiple petroleum products in a multi-pipeline system.

Li and Hui (2004) presented an approach to determine plant revenue while planning refinery under uncertainty. They applied different loss functions to the planning model and upon comparison discovered that piecewise-linear approximation of the loss function gave accurate and improved solutions. Lasschuit and Thijssen (2004) developed a mixed-integer non-linear programming model to address scheduling and planning problems in chemical and oil industry. The model proved to be beneficial as it aided in strategic decision making. Ribas et al. (2012) developed a non-linear programming model to analyse the impact of uncertainties on operational planning of oil refineries using three mathematical models namely two-staged stochastic model, robust min-max regret model and a max-min model. Their study revealed that product specification constraints had a strong influence on the model decisions. Pongsakdi et al. (2006) addressed uncertainty in refinery operations planning as part of their investigation into financial risk management. They applied a stochastic model via a general algebraic modelling system (GAMS) to maximise profit, taking into account inventory and crude oil costs, unsatisfied demand and revenues. They found that the stochastic model yielded lower-risk, higher-profit solutions than a deterministic model would have done. Khor et al. (2008) proposed a hybrid of stochastic programming (SP) approach for an optimal midterm refinery planning under three sources of uncertainties: price of crude oil and saleable products, demands, and yields. Bok et al. (1998)

addressed long-term capacity expansion of a chemical processing network under uncertain demand forecast scenarios using a robust investment model. A multi-period mixed integer nonlinear programming optimisation model that is both solution and model robust for any realisation of demand scenarios was developed using the two-stage stochastic programming modelling framework. Dunne and Mu (2010) investigated the effect of uncertainty on US refinery investment decisions by constructing uncertainty measures from the commodity futures market and using data on actual capacity changes to measure investment episodes. Ejikeme-Ugwu et al. (2011) developed an integrated model covering three major refinery subsystems (product distribution, production and product blending and crude unloading). The model is designed to aid refinery planning in situations where there is uncertainty of final product demand. Benyoucef and Lantz (2012) employed a model based on a linear dynamic programming to analyse the development of Algerian refining industry by 2030 under uncertainties from petroleum products exportation and domestic demand. While comparing the result of the stochastic and deterministic models used in their research, they concluded that the stochastic model was more reliable as it took account of uncertainties. Guyonnet et al. (2008) investigated the benefits of integrating production planning for the SC (oil unloading, production and distribution) compared to planning for each part of the SC in isolation. They found that the integrated model yielded a plan that was more feasible across the SC and was more effective at optimizing profit. Tong et al. (2011) applied stochastic programming to optimize refinery planning under uncertainties of demand and product yield. Al-Qahtani and Elkamel (2009) presented a mixed-integer programming model for designing integration and coordination policy among multi-period refineries network and PVC petrochemical complex were integrated to illustrate the economic potential and trade-offs involved in the optimization of the network. You and Grossmann (2011) proposed a two-stage stochastic mixed-integer non-linear programming model for planning inventory-distribution in the industrial gas SC under uncertainties in demand and loss or addition of customers. The model was designed to aid decision making with regard to tank sizing, safe stock levels and route costing. Oliveira and Hamacher (2012) developed a two-stage stochastic model for optimising logistics infrastructure investment planning under uncertainties in product demand. Carneiro et al. (2010) worked on a two-stage stochastic model with fixed recourse to aid strategic planning in the oil SC under uncertainties while incorporating risk management. The model has already helped companies make huge financial savings. Yang et al. (2009) employed a stochastic programming model in a refinery with multiple operation modes for optimising multi-period SC problem under product yields uncertainty. Leiras et al. (2010) applied a robust mixed-integer linear model to address the problem of strategic planning in integrated multi-refinery networks under uncertainties in raw material costs, final product prices and product demand. Modelling of the uncertainties in process parameters provided a practical view of refinery industry helping with decision making trade-off evaluations.

Table 2.4 Recent works on planning and optimisation of petroleum industry supply chain under different uncertainties

	Authors Names	Problem	Uncertainties	Methodology
1	Ribas et al. (2012)	operational planning of oil refineries	oil prices, costs and demands	Two-stage stochastic model- robust min–max regret model- max–min model.
2	Benyoucef and Lantz (2012)	Refinery planning	domestic demand and the exportation of the petroleum products	Stochastic model
3	Oliveira and Hamacher (2012)	optimizing the investment planning process of a logistics infrastructure for the distribution of petroleum products	product demand	Sample Average Approximation (SAA)
4	Tong et al. (2011)	optimal refinery planning	Demand amount and product yield fluctuation	stochastic programming approach
5	You et al. (2011)	inventory-distribution planning for industrial gas supply chains	demand and customer presence	multi-period two-stage stochastic mixed-integer nonlinear programming (MINLP) model
6	Ugwu et a.l (2011)	Refinery planning	Final product demand	Two-stage stochastic linear programming (LP)
7	Carneiro et al. (2010)	Strategic planning of an oil supply chain.	internal demand for final products, oil supply, and prices of products	two-stage stochastic programming approach
8	Ribas et al. (2010)	strategic planning model for an integrated oil chain	crude oil production, demand for refined products and market prices	Two-stage stochastic model with a finite number of realizations, a robust min–max regret model, and a max–min model.
9	Leiras et al. (2010)	Strategic planning of integrated multi-refinery networks	Raw material costs, final product prices and product demand.	robust mixed-integer linear model
10	Yang et al. (2010)	optimization for the multi-period supply chain problem in a refinery with multiple operation modes	product yields	Chance Constrained Programming- Markov Chain of Product Yield Fluctuation
11	Ribas et al. (2009)	development of a strategic planning model for an integrated oil chain	crude oil production, demand for refined products and market prices	Two-stage stochastic model- robust min–max regret model- max–min model.
12	Guyonnet et al. (2009)	Refinery Planning, Oil Procuring, and Product Distribution	Crude oil and final products prices	multi-integer nonlinear programming (MINLP) model
13	Chunpeng and Gang (2009)	integration of production planning	plant wide management	multi-period mixed integer linear programming (MILP)
14	You and Grossmann (2008)	measure of process supply chain responsiveness	market demand	multi-period mixed-integer nonlinear programming (MINLP) model
15	Bagajewicz (2008)	refinery operations planning	product prices and demand	deterministic and stochastic model
16	Khor et al. (2008)	optimal midterm refinery planning	prices of crude oil and saleable	hybrid of stochastic programming

			products, demands, and yields	
17	Al-Othman et al. (2008)	optimization of petroleum organization operating in an oil producing country	market demands and prices	Two stage Stochastic linear programming
18	MirHassani (2008)	An operational planning model for petroleum products logistics	demand	mathematical linear programming model
19	Pongsakdi et al (2006)	Refinery production planning	product demand and price	Stochastic model
20	Neiro & Pinto (2005)	Production Planning of Petroleum Refineries	product prices & demand	nonlinear programming formulation
21	Lababidi et al. (2004)	optimization model for the supply chain of a petrochemical company operating	Demand, market prices, raw material costs and production yields.	two-stage stochastic programming approach
22	Li et al. (2004)	Refinery planning	Raw material & product demand	Stochastic programming
23	Sahinidis (2004)	production planning and scheduling, location, transportation, finance, and engineering design	the prices of fuels, the availability of electricity, and the Demand for chemicals.	stochastic programming, robust stochastic programming, probabilistic (chance-constraint) programming, fuzzy programming, and stochastic dynamic programming
24	Dempster et al. (2000)	strategic planning for logistic operations	product demands and spot supply costs	stochastic programming approach
25	Bok et al. (2000)	determining capacity expansion timing and sizing of chemical processing networks	demand forecast scenarios	A multi period mixed integer nonlinear programming optimization model
26	Escudero et al 1999	Supply, Transformation and Distribution (STD) logistics scheduling	product demand, spot supply cost and spot selling price	Stochastic model
27	Liu and Sahinidis 1996	process planning of chemical industry	prices and demand of chemical products and raw material	two-stage stochastic programming approach

2.4 Conclusion and Research Gaps

The concept of the supply chain has received increasing attention over the last twenty years. In the oil and gas sector, authors have focused their interest on the petroleum SC and its logistics. This literature review highlights the various methodologies that have been used to plan and optimise the SC and logistics in the petroleum industry under different types of uncertainty. The main points can be summarised as follows:

- Many authors have sought to address the problem by introducing solutions designed for segments of the supply chain; a few of them have taken a holistic view of the chain from exploration field to distribution centre.
- Most of the studies reviewed above treat the planning problem on the tactical and operational levels; few have considered the strategic level.
- Further research is required into how the petroleum SC might deal with different types of uncertainty such as resource availability, raw material prices, product demand etc.
- There are a small number of researches considered planning of petroleum supply chain problems with endogenous (internal) uncertainties such as product yield fluctuation, processing and blending options and machine availabilities.
- None of the authors in the literatures investigated significant factors within the SC that can influence the production output such as Input Rate, Distillation Capacity, Failure of Separators and Crude Oil Quality.
- Most of the approached used are quite complex and require a better understanding of mathematical programming to be adopted for use in any real life system.
- It is clear that oil and gas industry is complex in nature and it has proven that simulation is capable of handling such complexity, however simulation hasn't been utilised fully to capture clearly the influence of many factors involved and their interaction in designing and operating such environment.

CHAPTER THREE

PETROLEUM SUPPLY CHAIN FUNCTIONS

3.1 Introduction

Petroleum supply chains are global enterprises, engaged in managing activities across petroleum industry from crude oil production to refineries and petrochemical operations up to final product markets passing through all necessary logistics inclusive transportation, storages, and distributions. To remain competitive in today's dynamic global marketplace they must optimize every aspect of their operations – supply, manufacturing and distribution – and integrate these different decisions levels leads to creating substantial value to process (Grossmann, 2005).

The objective of optimising and planning petroleum supply chain is to minimise the production, operations, transportation, storage, and distributions costs as well as satisfying customer demands while preserving market share, along with maximising sales revenues. This chapter discusses in detail the functions within the petroleum supply chain.

3.2 Petroleum industry supply chain components

Literature review chapter reveals the range of optimisation models that have been developed to improve the planning and scheduling of several subsystems of the petroleum supply chain such as oil field infrastructure, crude oil supply, refinery operations, storage logistics, transportation of raw materials and final products and distribution to the markets and consumers have all featured in these models.

3.2.1 Oil field infrastructure design and operations

As in other supply chains, decisions arise at the strategic, tactical and operational levels in the petroleum SC. Decisions relating to oil field infrastructure investment and operation are generally strategic, with a long planning horizon (typically ten years). An oil field layout actually consists of a number of fields, each containing one or more reservoirs. Each reservoir contains one or more well sites. A network of pipelines connects the wells to the well platforms and the well platforms to the production platforms. The exploration phase involves significant investment; consequently, the key performance indicator here is return on investment. Iyer and Grossmann (1998) developed a multi-period mixed-integer linear programming (MILP) model for planning investment and operation in offshore oil fields. Decision variables include the choice of reservoirs to develop, selection from among candidate well sites , the well drilling and platform installation schedule, well and production platform capacity, and the fluid production rates from the chosen well for any given time period. The key performance indicator is calculated from the sum of discounted investment costs and the sum of discounted revenues from sale of oil. Van Den, et al. (2000), on the other hand, developed a multi-period mixed-integer nonlinear programming model for planning offshore oilfield infrastructure; incorporating nonlinear reservoir behaviour is incorporated directly into the formulation. Discrete decisions include the selection of production platforms, well platforms and wells to be installed/ drilled, and the drilling schedule over the planning horizon, while continuous decisions include the determination of platform capacities and the production profile for each well in each time period. Gupa and Grossmann (2012) proposed mixed integer nonlinear programming model for multi-field site includes three components (oil, water, and gas). The model focuses on long-term planning decisions related to FPSO (floating production, storage and offloading) installation and expansion, field-FPSO connections, well drilling, and production rates in each period.

3.2.2 Transportation and Distribution

Typically, the supply chain is composed of a network of nodes representing a range of facilities and activities (e.g. terminals, vendors, plants, distribution centres and international markets). These nodes are connected by transportation links. Oil transportation is the central operational function within the petroleum industry supply chain, linking upstream, where crude oil is produced, and downstream, where it is processed. Crude oil and petroleum products can be transported by rail or sea, via pipeline and in trucks. Which option is chosen will depend on factors such as distance, product type and cost; pipelines are considered the most economical option for covering long distances, though tankers are widely used to carry large volumes of crude oil across international waters from exporting to importing countries.

Relvas et al. (2006) used a mixed-integer linear programming approach to model the problem of oil derivatives pipeline transportation scheduling and supply management (see Figure 3.1). The system in their model comprises a pipeline that pumps oil derivatives to a single distribution centre located in a strategic local market. The distribution centre contains a tank farm in which each tank is reserved for a specific product. The process involves unloading oil derivatives from the pipeline into the right tank and then making them available to the local market. The main functions of the supply chain addressed by Relvas et al (2006) are: (a) the number of products to be transported, (b) the matrix of possible sequences between pairs of products in pipeline transit, (c) the maximum storage capacity for each product, (d) the pipeline capacity, (e) the time horizon and the total number of days to be considered, (f) the maximum number of allowable lots to be pumped through the pipeline during the time horizon, (g) the pumping rate, (h) the initial inventory of each product, (i) daily demand, and (j) the minimum settling period.

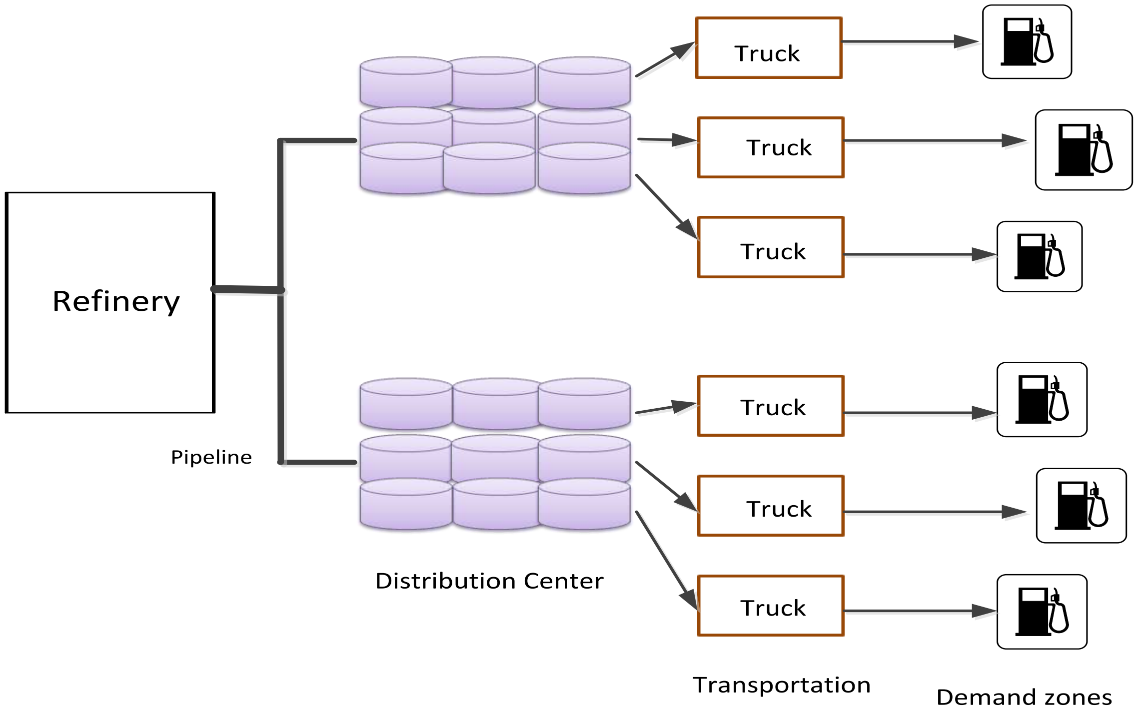


Figure 3.1 Product distribution systems

Source: Adapted from Relvas et al., (2006) Fernandes et al. (2013) developed a deterministic mixed integer linear programming (MILP) model for strategic design and planning of downstream petroleum supply chain network. The model aims to determine the optimal distribution network of connecting routes between refineries, depots and customer zones, including capacities for each depot and route. MirHassani (2008) presented a modelling framework for a real-life supply, transporting and distribution scheduling problem in oil industry. The system is characterised by the following elements: a set of petroleum refineries, oil product, pump station, depots, regions, import or export points, a network with origin nodes such as refineries, transhipment points such as pump stations, transportation points such as depots, and destination points.

Escudero et al. (1999) presented a modelling framework for the optimisation of a multi-period Supply, Transformation and Distribution (STD) scheduling problem to solve in the Hydrocarbon and Chemical sector under uncertainty on the product demand, spot supply cost and spot selling price. The model is characterised by the following elements: a set of oil products, a set of operators sharing a given STD system, the STD network with origin depots, transforming nodes, transhipment nodes, and destination depots. The goal is to minimise the total expected standard STD cost and product (expediting) spot supplying cost with demand and spot price uncertainty, subject to minimum/maximum product stock requirements, transportation capacity, supply limitations and product transforming constraints.

Dempster et al. (2000) formulated deterministic and stochastic models of strategic planning for logistic operations in the oil industry. Logistics planning for a consortium of oil companies encompasses supply, transformations, storage, and transportation activities over a complex network structure involving (continuous flow) pipelines and other (discrete) transport means such as trucks and ships over planning horizons on different time scales.

3.2.3 Crude Oil and Refinery Operation

Petroleum refining is an operationally complex, extremely competitive industry with low profit margins. Raw material prices and fluctuating demand are the biggest challenges facing refineries. Crude oil costs account for about 80% of a refinery's turnover Reddy et al. (2004), while supply chain costs amount to 40%

of total refining and distribution costs. Crude oil and logistics activity are therefore significant components of the total manufacturing cost, seriously impacting output, productivity and profitability.

The essential objective of a refinery is to generate maximum profit by converting crude oils into marketable products such as gasoline, naphtha, diesel and aviation fuel. This process may be broken down into four sub-processes: crude oil operations, production, inventory management and product blending. To achieve optimal refinery operation, decision makers must identify and plan for the refinery operation constraints the availability of resources (crude oil supply), the types of crude oils to process through several units in order to transform the different products from the crude distillation units into more valuable products.

Guyonnet et al. (2009) presented an integrated model for refinery planning, oil procurement and product distribution that covers three parts of crude oil supply chain (unloading, oil processing, and distribution) as shown in Figure 3.2. The problem involves a dock stations, a set of storage and charging tanks, set of distillation units (CDU) and set of production distribution centres.

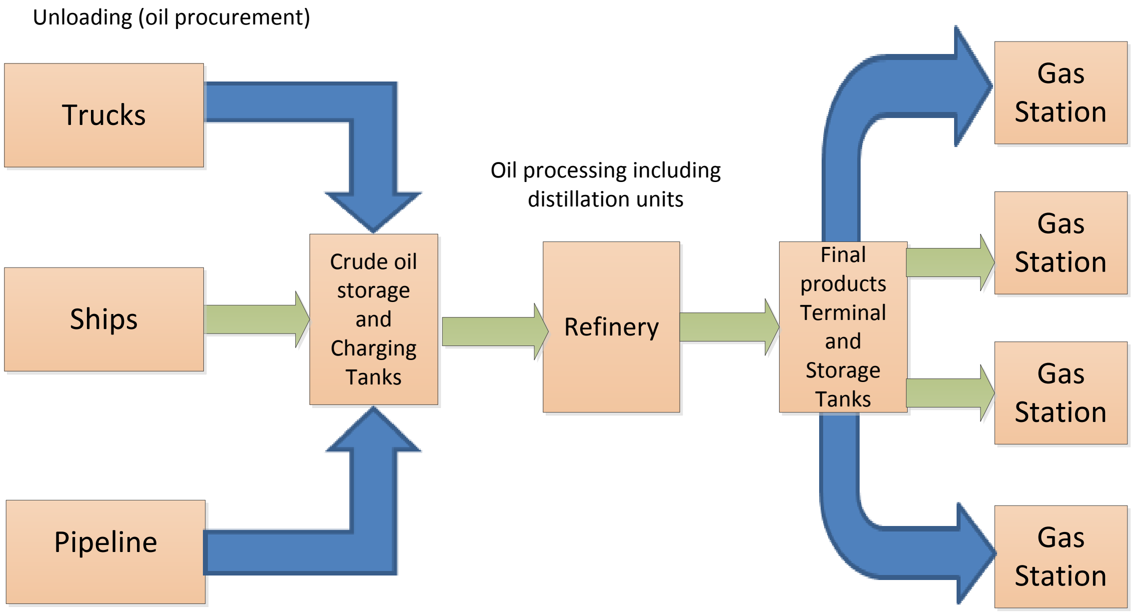


Figure 3.2 Overview of oil supply chain

Source: Adapted from Guyonnet et al., (2009)

Crude oil operations are sub-process of oil supply chain as shown in Figure 3.3. Whether coming from oil fields or international sources, crude oil is carried to the oil terminal by large tankers and transferred to storage tanks. Different types of crude oil are stored in different storage tanks and then left for the brine to separate out.

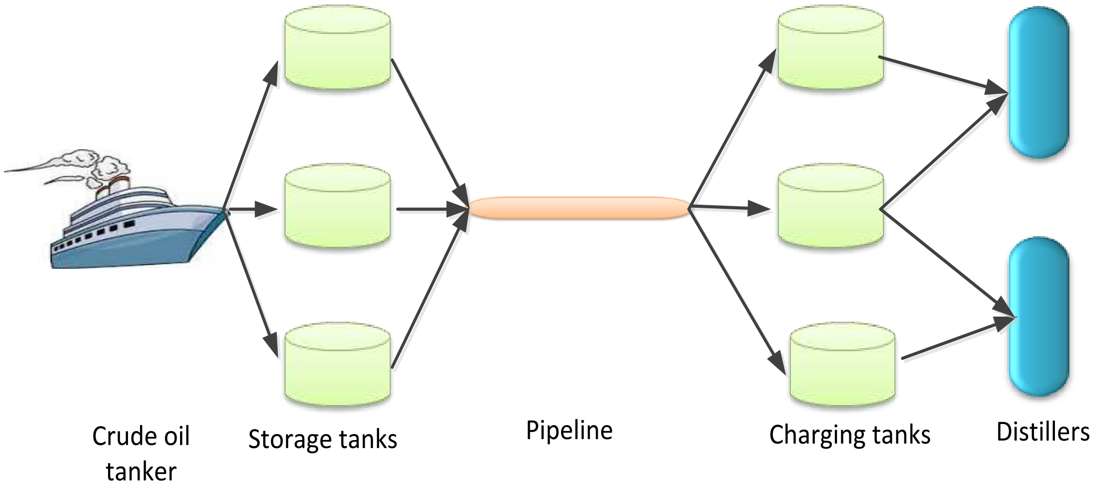


Figure 3.3 Processes of crude oil operations

Source: Adapted from Wu et al. (2005)

Wu et al. (2005) call this the residency time (RT) constraint). The oil is then piped to charging tanks in the refinery, where some of it may be mixed before being fed into the distillers. Planning at this stage must encompass the unloading and blending of the crude oil, the storage facilities (the storage and charging tanks) and the processing facilities (the crude distillation units). Information must be available on inventory levels and tank capacity, crude oil quantity and quality, crude oil arrival time, demand of crude - mix to be charged from a charging tank, flow rate of stream bounds and cost coefficient.

Ribas et al. (2010) developed strategic planning model for an integrated oil chain considering three sources of uncertainty: the crude oil supply, the Brazilian demand for final products, and the product and oil prices in the Brazilian and international market. The model considers the following functions: refinery operation and transportation costs, process unit capacity, maximum volume transported by transportation arc, investment in refining and transportation, export and import limits for products and oil, Brazilian production of crude oil, domestic consumption of products, and price of oil and refined products on the domestic and international markets.

Neiro and Pinto (2004) developed an MINLP model for the planning of multiple existing refineries, terminals and pipeline networks. They included a range of input functions: crude oil price (from all possible suppliers), inventory costs for petroleum and storage tanks of refineries products, transportation costs for crude oil and operation cost.

3.2.4 Petrochemical Operations

Petroleum feedstock, natural gas and tar are the main drivers of production in the petrochemical industry (Bell, 1990). This industry is a supply chain network of highly integrated production processes where one plant may be capable of producing various products of different grades. These products may have an end use or they may serve as the raw materials for other processes.

A number of authors have adopted the case study approach to demonstrate the performance of their optimisation models and illustrate the effect of variations in process yield, raw material and product prices and market demand on performance measurement of petroleum supply chain. Al-Qahtani et al., (2008), for example, addressed the strategic planning, design and optimisation of a network of petrochemical processes under uncertainties in process yield, raw material cost, product price and lower product market demand. These authors classified chemical inputs and outputs according to their function: primary raw materials (PR) are chemicals derived from petroleum or natural gas and other basic feedstock; secondary raw materials (SR) are chemicals used in only small amounts or as additives; intermediate (I) chemicals are those produced and consumed in the petrochemical network; and primary final product (PF) and secondary final product (SF) chemicals are the main final products and associated by products of the refining process respectively.

Lababidi et al. (2004) developed an optimisation model for the supply chain of a petrochemical company operating under uncertain operating and economic conditions. The model considers the functions of raw material procurement, production capacity, final product storage cost, lost demand cost, backlog penalty, transportation cost and storage cost for unshipped products under uncertainties of market demand and price, raw material costs and production yields. Figure 3.4 shows the supply chain network proposed by these authors. Hexane and catalysts are imported, while ethane is obtained from a local refinery. Two production plants produce the required amounts of ethylene and butane, and intermediate storage is provided for the hexane, ethylene and butane feed stocks. The production facility consists of two reactors, R1 and R2. R1 produces nine products (A1-A9), while R2 produces six products (B1-B6). Production volumes are directly shipped to demand sources, and excess volumes are kept in the warehouse. Demand sources represent retailers in different distribution countries. In the proposed network, eleven demand sources are considered (D1-D11). The network can be considered fairly typical, but it can be easily modified and extended to include more products and additional demand sources.

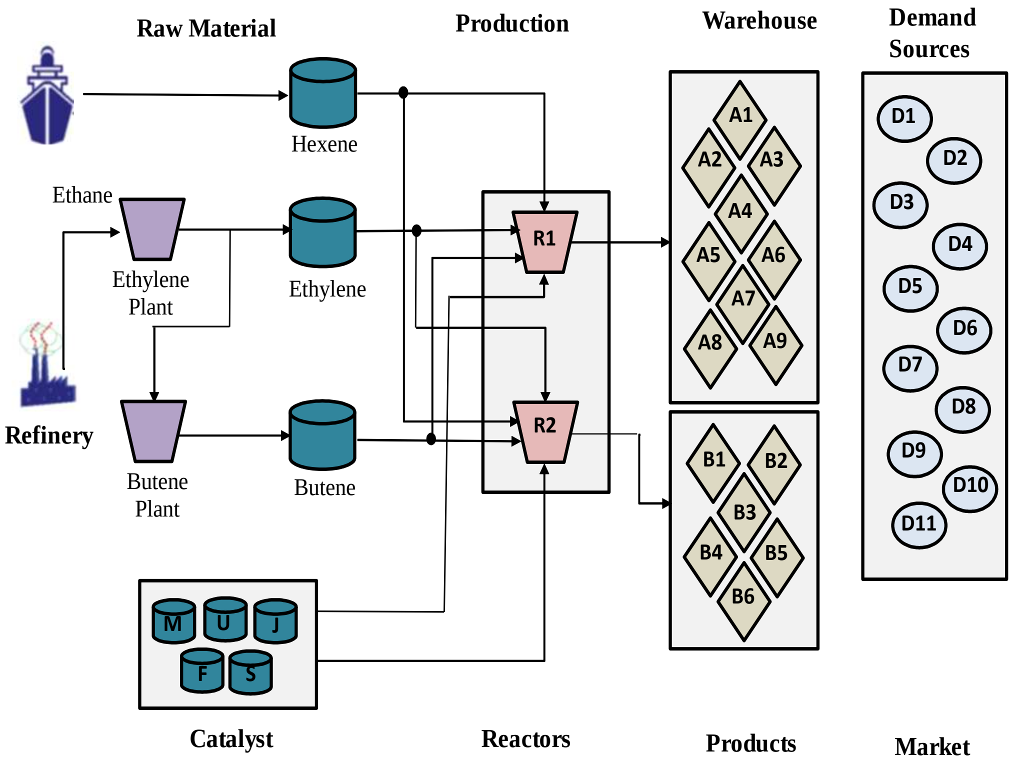


Figure 3.4 Network of supply chain proposed for a typical petrochemical company

Source: Adapted from Lababidi et al., (2004)

Tong et al. (2011) extended the work of Gu's short-time planning model by developing a two-stage stochastic programming approach for optimal refinery planning under uncertainties of demand and product yield. Purchasing, transportation, mode changeover costs, and the penalties related to demand dissatisfaction and inventory violation are the main function in the proposed model.

Kue and Chang (2008) presented a mathematical programming model for integrated planning and scheduling in typical conversion refineries. The main functions of the proposed model are: quantity and quality of crude oil, processing unit (reaction and separation) capacity, transport capacity from one unit to another with pumps and pipeline, and tank storage (in product distribution terminals and import/export terminals) for raw materials, intermediates and final products.

Al-Othman et al. (2008) developed and implemented a multi-period stochastic planning model for the supply chain of a petroleum organisation operating in an oil-producing country under uncertain market conditions. The proposed supply chain functions relate to crude oil production, processing, storage and transportation to demand sources. The authors divide the supply chain into four sectors: the crude oil sector, the refinery sector, the petrochemical sector and the downstream sector (see Figure 3.5). Different types of crude oil come from a number of sources, each requiring a specific processing approach and satisfying a particular market demand. The crude oil is exported to international markets or processed in local refineries. Each refinery processes a specific mix of different grades of crude oil. Refinery products are either exported to demand sources or fed to local petrochemical plants. Petrochemical products are, in turn, either exported or used by the downstream chemical industry.

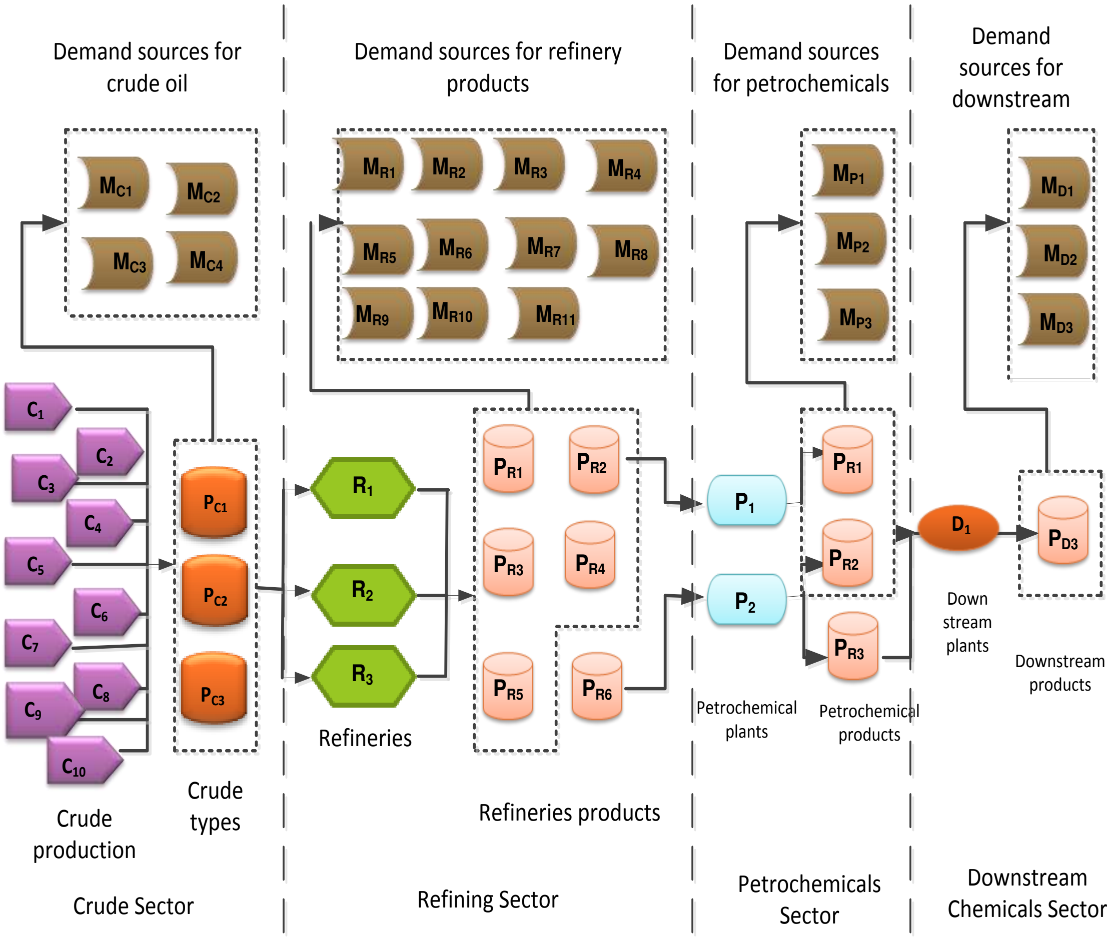


Figure 3.5 Supply chain network for petroleum organisation case study

Source: Adapted from Al-Othman et al., (2008)

Oliveira and Hamacher (2012) addressed the problem of optimising petroleum supply chain under uncertain demand for petroleum products. The problem defines as strategic planning of petroleum products distribution, the distribution of flows, determining of investments levels in logistics infrastructure, inventory policies, and the level of the external commercialisation of refined products. The authors developed two-stage stochastic model to deal with problem and the objective functions of the mathematical model was to minimise the cost related of investment, fright, inventory, operations, demurrage cost and penalties for unsatisfied demand of oil products and supply limit.

3.3 Key Performance Indicators (KPIs) and Sustainability Issues in Petroleum Industry

3.3.1 Performance Measurement definition

Neely et al. (1995) define performance measurement as: “a process of quantifying the effectiveness of actions” and “the set of metrics used to quantify both efficiency and effectiveness”. It should be noted that the terms measure, metric and indicator are generally regarded as synonymous in the literature. Performance measures may be defined as measuring points that give a good indication of the success or failure of a key factor or process. Bititci et al. (2002) define them as measurable characteristics (of products, services, processes and operations) that an organisation uses to track performance. They may address the type or level of activities conducted (process), the direct products and services delivered by a programme (outputs) and/or the results of these products and services (outcomes).

Performance measure identifies the gaps between used and required performance and provides indications to progress towards closing the gaps. Performance measurement identifies the gaps between actual and required performance and provides indicators of the organisation’s progress towards closing these gaps. Essentially, it gives managers the information they need to make intelligent decisions. Performance measurement may be used to determine the efficiency and/or effectiveness of an existing system, to compare competing alternative systems, or to design new systems. It helps organisations to set business goals and provides feedback on their progress towards these goals. As such, it is a key contributor to an organisation’s control capabilities.

Beamon (1998) suggested three types of measure for assessing supply chain performance (see Table 3.1). These are resource measures (generally cost), output measures (generally customer responsiveness) and flexibility measures.

Table 3.1 Performance measurement types and their associated KPIs

Performance measurement type	Key performance indicator
Resources	***Total cost.*** Total cost of resources used.
	Distribution cost. Total cost of Distribution including transportation and handling cost.
	Manufacturing cost. Total cost of manufacturing including labour, maintenance, and re-work costs.
	Return on investment. Measure the profitability of an organisation.
Output	***Sales.*** Total revenue.
	Profit. Total revenue less expenses.
	On-time delivers. Measure item, order, or product delivery performance.
	Back order/stock out. Measure item, order, or product availability performance.
	Costumer response time. Amount of time between an order and its corresponding delivery.
	Manufacturing lead time. Total amount of time required to produce a particular item or batch.
	Shipping errors. Number of incorrect shipments made.
	Customer complaints. Number of customer complaints registered.
Flexibility	Reduction in the number of backorders.
	Reduction in the number of lost sales.
	Reduction in the number of late orders.
	Increased customer satisfaction.
	Ability to respond to and accommodate demand variations.
	Ability to respond to and accommodate periods of poor manufacturing performance (machine breakdown).
	Ability to respond to and accommodate periods of poor supplier performance.
	Ability to respond to and accommodate periods of poor delivery performance.
	Ability to respond to and accommodate new products, new markets, or new competitors.

Source: Adapted from Beamon (1999)

Suitable quantitative performance measures include: (i) measures based on financial flow (cost minimisation, sales maximisation, profit maximisation, inventory investment minimisation and return on investment); and (ii) measures based on customer responsiveness (fill rate maximisation, product lateness minimisation, customer response time minimisation, and lead time minimisation), (Papageorgiou, 2009).

Most researchers studying supply chain performance have focused on discrete part manufacturing; supply chains in process industries like the petroleum industry have not received the same attention. Among those that have investigated petroleum SCs, Varma et al. (2007) used a combination of the analytical hierarchy process (AHP) and the balanced scorecard (BSC) to evaluate SC performance against a set of criteria within the BSC's four perspectives (customer, financial, internal business and innovation and learning).

Kumah and Markeset (2007), meanwhile, presented a framework for the development of performance-based service strategies for Norway's oil and gas industry. They found that the implementation of performance-based service strategies benefits all parties, leading to a better return on investment, improved service quality and enhanced customer satisfaction (and in turn, enhanced customer retention and loyalty).

3.3.2 KPI Definition and Composition

The central concern of this thesis is key performance indicators, defined here as those measurable characteristics (of products, services, processes and operations) that give a good indication of the success or failure of key factors critical to the execution of organisational strategy. This direct relationship with organisational strategy is what distinguishes KPIs from corporate performance measures (Kellen & Wolf, 2003).

Artley and Stroh (2001) explain that KPIs are composed of a number and a unit of measure. The number expresses magnitude (how much). KPIs are always tied to a goal or an objective (the target), but as the measure is used for the purpose of comparison, it need not represent an absolute value. For example, when measuring customer profitability, it may be more valuable (and easier) to know the distance in profitability between two customers than to know the absolute value for one customer's profitability. Many measures are normalised into a value that promotes comparison not just with itself, but also with other measures.

The unit of measure gives the number a meaning (what). KPIs can be represented by single-dimensional units like hours, metres, dollars, number of errors, number of certified employees or length of design time. They can show the variation in a process or deviation from design specifications. Single-dimensional units of measure usually represent very basic and fundamental measures of some process or product. More often, multidimensional units of measure are used. These measures are expressed as ratios of two or more fundamental units. They may be units such as miles per gallon (a KPI of fuel economy), number of accidents per million hours worked (a KPI in company safety programmes), or number of on-time vendor deliveries per total number of vendor deliveries. KPIs expressed this way almost always convey more information than single-dimensional or single-unit KPIs. Ideally, KPIs should be expressed in the units of measure that are most meaningful to those who must use or make decisions based on these measures. A specific KPI can be compared to itself over time, compared with a target or evaluated along with other measures.

3.4 Conclusion

This chapter discussed the petroleum supply chain and logistics functions. The chain encompasses a wide range of functions, including investment decision making, selection of crude oil types, refinery operations, transportation, management of production levels and capacities, production distribution and inventory management.

The main points mentioned above have been concluded as following:

- Planning and optimising these functions is evidently a very complex task, and it would be virtually impossible to develop an optimisation/planning model that considers them all.
- Most authors have limited themselves to investigating sub-problems within the supply chain rather than the performance of the chain as a whole. Al-Othman et al. (2008) study is one of the few that takes a more holistic view, presenting the chain as made up of four sectors: the crude oil sector, the refinery sector, the petrochemical sector and the downstream sector. However, their model ignores key functions such as raw material, crude oil transportation and final product transportation costs under conditions of internal uncertainty (product yield) and external uncertainty (raw material and final product prices and market demand).
- There were very few authors who focused on the new types of supply chain associated with sustainability for example environmental, social, and economic and their impact on the petroleum supply chain.

CHAPTER FOUR

RESEARCH METHODOLOGY AND PLANNING OF THE PROPOSED PETROLEUM SC FRAMEWORK

4.1 Introduction

As mentioned in the above two chapters, a range of methodologies have been deployed to plan and optimise the petroleum industry SC. Recent attempts have sought to address the challenge posed by market volatility by using stochastic programming, with the two-stage mathematical model being the most widely adopted option for planning under uncertainty. This model uses two types of decision variables; first-stage variables, often known as design variables or "here-and-now" (H-N) variables, must be decided before the actual realisation of the random variables, while in the second stage, "wait-and see" (W-S) variables, also known as control or operating variables, are applied to deal with uncertainty parameters.

This study employs a two-stage stochastic linear program with recourse to investigate the relationship between uncertainty of market demand and several key performance indicators within the supply chain. This set of relationships was fed into the proposed simulation model to replicate the different types of uncertainty and strategic indicators in today's petroleum industry. ARENA software and the GAMS program were used to build, verify and validate the model and to run experiments to investigate which variables have an impact on SC performance.

4.2 Research method

4.2.1 Linear Programming

This mathematical technique for the optimisation of a linear objective function, subject to linear equality and inequality constraints, has its origins in Dantzig's (1947) simplex algorithm. Linear programming has been successfully applied by managers and decision makers in many sectors to find optimal solutions to problems such as how to maximise profit and minimise cost. Numerous applications have been developed for use in the resource allocation, distribution and transportation functions.

4.2.1.1 Mathematical Model

Lawson and Marion (2008) defined mathematical model as a very precise language helps us to formulate ideas and identify underlying assumption. The main objectives of mathematical modelling are: developing scientific understand, test the effect of changes in a system; aid decision making including tactical decisions by managers and strategic decisions by planner. Figure 4.1 shows a flow chart of mathematical modelling for industrial process.

Managers are required to make decisions that affect all parts of the organisation, whether this is planning production, inventory, capital investment or materials requirements, forecasting sales or logistics management. They need to be able to choose the best option from a range of alternatives, or at least an option that offers substantial improvement. The main elements of any mathematical problem are:

- **Variables:** (also called decision variables) are a quantity that may change within the context of a mathematical problem or experiment. The goal is to find values of the variables that provide the best values of the objective function.
- **Objective function:** An equation to be optimised given certain constraints and with variables that need to be minimised or maximised using linear or nonlinear programming techniques.
- **Constraints:** are restrictions (limitations, boundaries) that need to be placed upon variables used in equations that model real-world situations.

Linear programming is the most widely used method of constrained optimisation. The largest optimisation problems may have millions of variables and hundreds of thousands of constraints, but recent advances in solution algorithms and computer power mean that these large problems can now be solved in practical amounts of time.

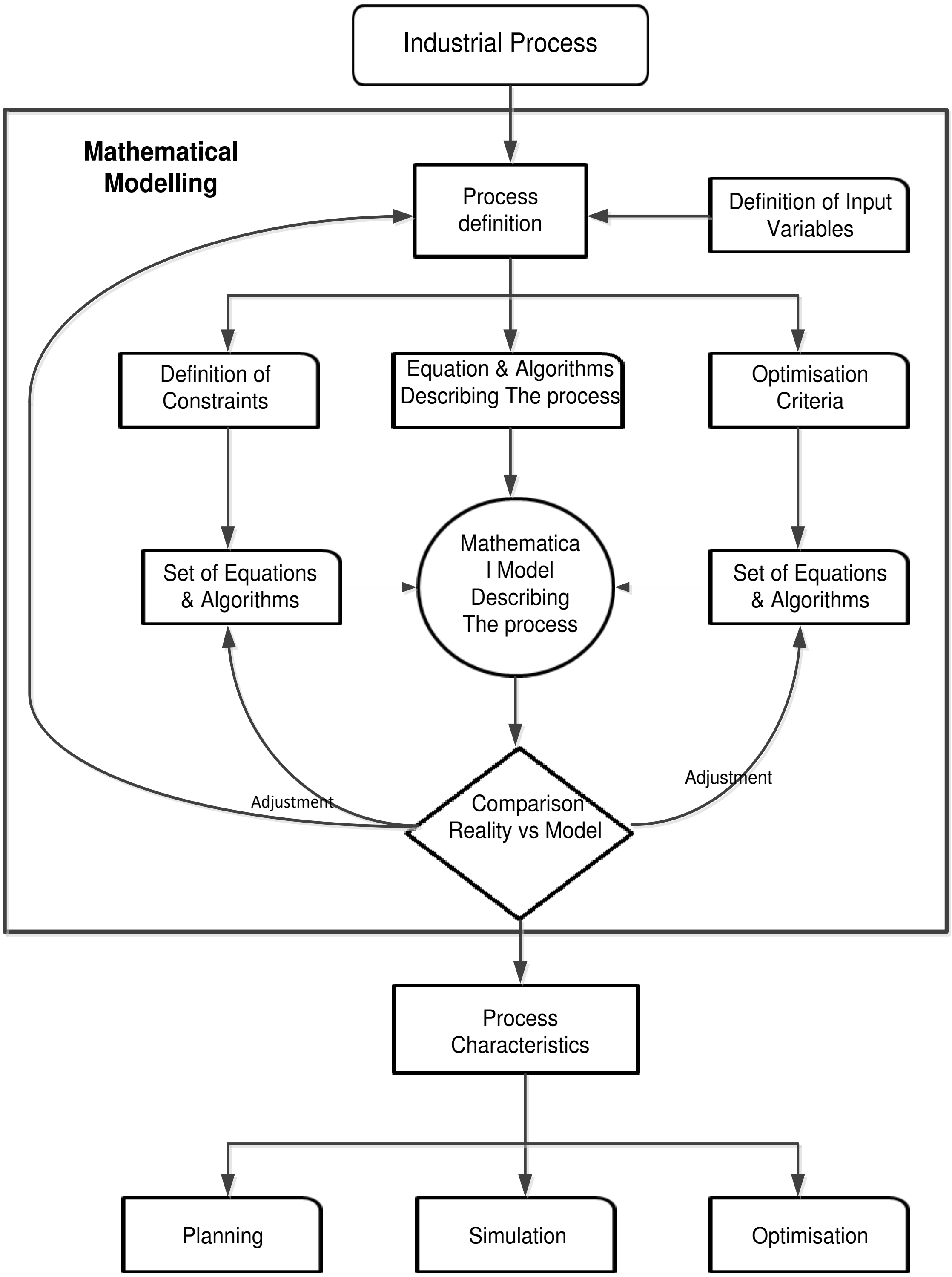


Figure 4.1 Flow chart showing application of mathematical modelling to the industrial process

Source: (Frankfurt Consulting Engineering GMBH)

4.2.1.2 Classifications of Models

4.2.1.2.1 Deterministic & Stochastic Models

Decision analysis can be approached in two ways. A deterministic solution may be appropriate if the optimisation of problems related to many variables and the outcome of decisions can be predicted with certainty. Figure 4.2 shows deterministic approach, where the situation represents the real problem under considerations. Deterministic information sometimes need to be assumed in order to develop the proposed the model mathematically in a form of algorithm. The model is then converted to a machine language in a form of computer program in order to identify the optimum decision which represented by vector x.

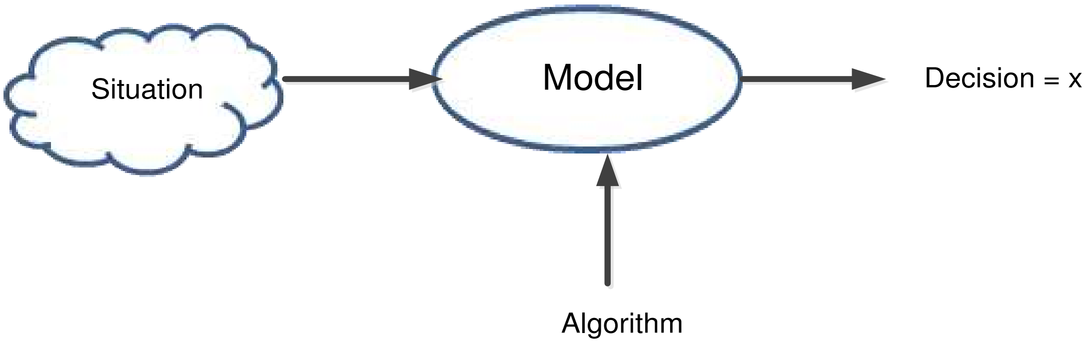


Figure 4.2 the deterministic Approach

Alternatively, a stochastic solution may be more appropriate if the situation has many variables and the decision outcome cannot be predicted with certainty (see Figure 4.3). The term stochastic are used to refer to things that are best modelled as random, for example, demand data is often particularly uncertain, so stochastic models of demand are often used to identify more realistic solutions (Leiras et al., 2011).

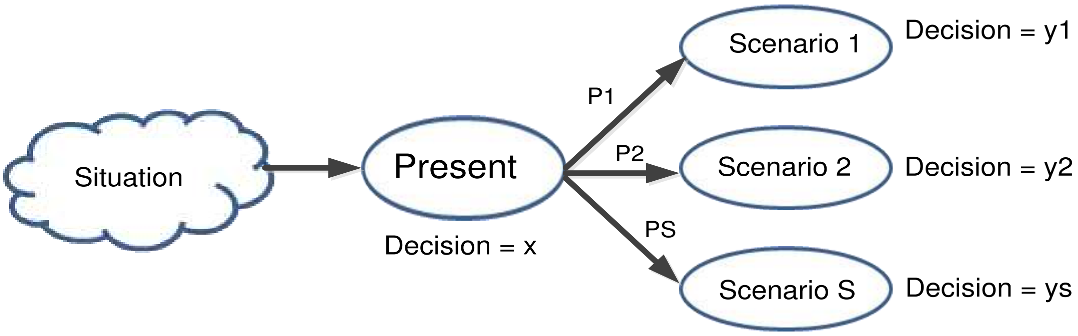


Figure 4.3 Decisions with uncertainty

4.2.2 Approaches to optimisation and planning under uncertainty

The oil industry is subject to uncertainties such as volatile market demand, unstable prices and fluctuations in oil production. Recent optimisation models have proposed a number of techniques for managing these uncertainties, as shown in Figure 4.4.

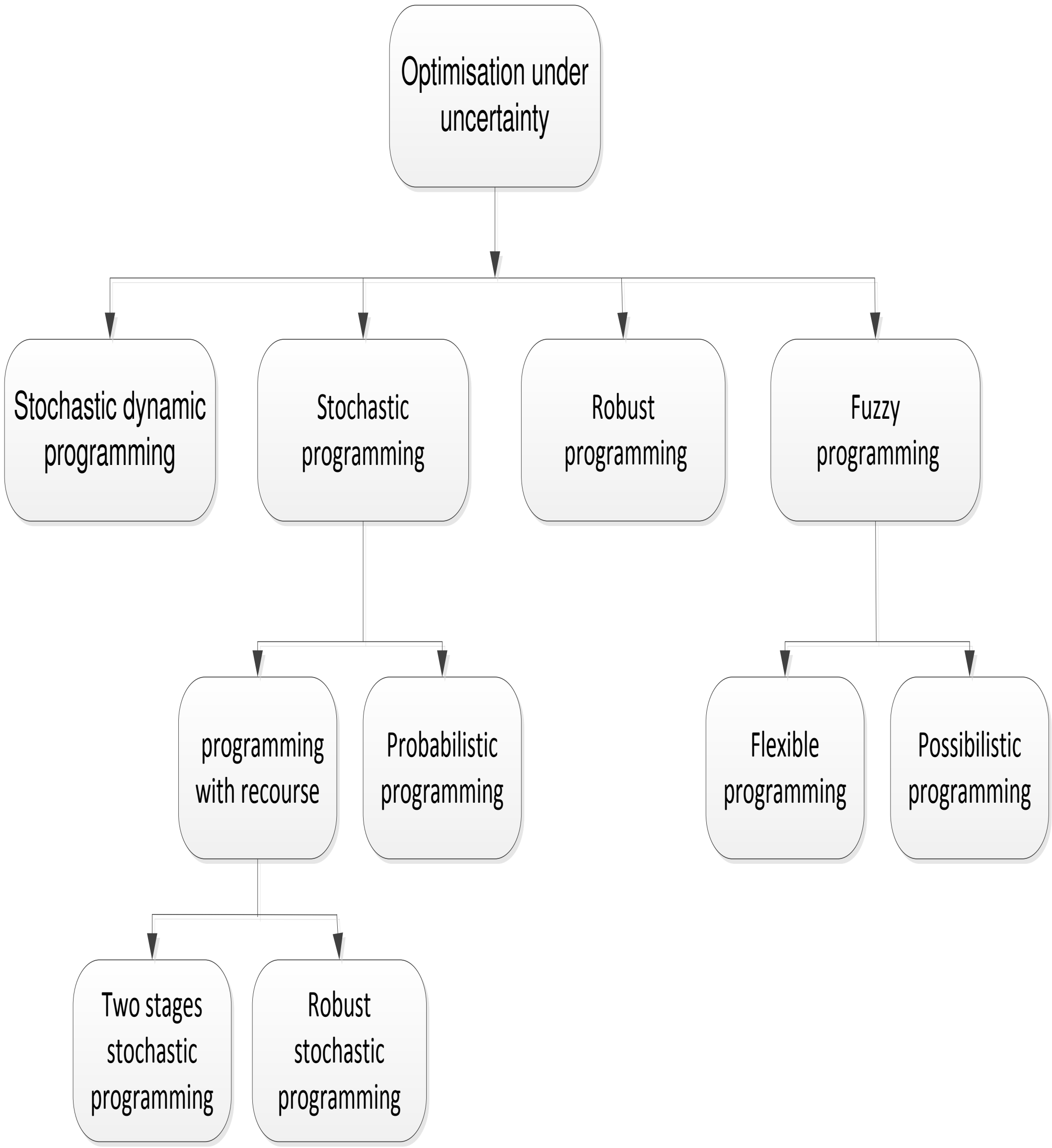


Figure 4.4 Approaches to optimisation under uncertainty

Source: Based on Sahinidis (2004), Khor and Elkamel (2008)

4.2.2.1 Stochastic linear programming

The stochastic programming approach is the main techniques for dealing with optimising and planning problems under uncertainty with parameters that assume a discrete or continuous probability distribution and can be divided into recourse models that can be extended to the multistage case such as (two-stage stochastic programming) and robust stochastic programming see Figure 4.4.

4.2.2.1.1 Two-stage stochastic linear program with recourse

Stochastic linear programming with recourse was introduced by Dantzig and Beale in 1950's, as a mathematical programming technique for dealing with uncertainty Valdimirou and Zenios (1997). The fundamental idea behind stochastic linear programming is the concept of recourse. Recourse is the ability to take corrective action after a random event has taken place. Recourse programs are those programs in which some decisions are recourse action can be taken once uncertainty is disclosed.

In two-stage recourse models, the decision variables are classified according to whether they are implemented before or after an outcome is observed. Decisions that are implemented before the actual realisation of random parameters are known as first-stage decisions. Once the uncertain events have presented themselves, further design or operational adjustments can be made through values of the second-stage or alternatively called recourse variables at a particular cost. Due to uncertainty, the second-stage cost is a random variable. The objective is to choose the first-stage variables in such a way that the sum of the first-stage costs and the expected value of the random second-stage costs is minimised. The concept of recourse has been applied to linear, integer, and non-linear programming (Sahinidis, 2004).

The standard formulation of the two-stage stochastic linear program with recourse is as follows Birge and Louveaux (1997):

$$
\begin{aligned}
&Min_x \; C^T x + E_\xi[\min q\,(\omega)^T \, y(\omega) && (4.1)\\
\text{s.t.}\quad &Ax = b\\
&T(\omega)x + Wy(\omega) = h(\omega)\\
&x \geq 0 \quad , \quad y(\omega) \geq 0
\end{aligned}
$$

Where

$x \in \mathcal{R}^{n1}$ represents the vector of first-stage decision variables (to be determined)

$c \in \mathcal{R}^{n1}$	Vectors of (known) coefficients
A	Is m x n constraint matrix
$b \in \mathcal{R}^{m1}$	Right hand vector.
E_{ω}	Expectation probability of occurrence of different scenarios.
$\omega \in \Omega$	Outcomes of random experiment.
Ω	Set of all outcomes of random experiment.
$y \in \mathcal{R}^{n2}$	Represents the vector of second-stage decision variables.
$q \in \mathcal{R}^{n2}$	Second stage-decision vector.
ξ	Random vector whose realisation provides information on the second-stage decision y.
$h \in \mathcal{R}^{m2}$	Fixed vector
$W \in \mathcal{R}^{m2 \times n2}$	fixed (recourse) matrix
$T \in \mathcal{R}^{m2 \times n1}$	random matrix with realisation (technology matrix).

First-stage decisions are represented by the vector x, while second-stage decisions are random events represented by the vector $y(\omega)$. The objective function in Equation) contains a deterministic term $C^T x$ and the expectation of the second-stage objective $q(\omega)^T\, y(\omega)$ taken over all the realisations of the random event ω. For each ω, the value of $y(\omega)$ is the solution of linear programming. The first constraint is for the deterministic problem, while the second constraint is defined for each realisation, and the function of the random events as well as the first-stage variables.

4.2.2.1.2 Robust stochastic programming with recourse

Robust stochastic programming, which was introduced by Mulvey et al. (1995), is powerful enough to achieve the optimal model solution for almost any scenario realisation.

4.2.2.1.3 Probabilistic programming

The probabilistic approach, also known as chance-constrained programming was proposed by (Charnes & Cooper, 1959). This approach is useful when the cost and benefits associated with the second-stage decision are difficult to measure.

4.2.2.2 Stochastic dynamic programming

Formally, a stochastic dynamic program has the same components as a deterministic one. Stochastic dynamic program deal with multistage decision processes (Bellman, 2013). In general, the result of a given action will be unknown. When events in the future are uncertain, the state does not evolve deterministically; instead, states and actions today lead to a distribution over possible states in the future.

4.2.2.3 Robust programming

The robust optimisation method developed by Mulvey et al. (1995) extends stochastic programming by replacing the traditional cost minimisation objective with one that explicitly addresses cost variability. A robust solution fits for all scenarios. Likewise, the objective function of a robust program contains no expectation or other stochastic component. The objective is a deterministic, linear function of the solution. Obviously, a robust model avoids the use of probability distributions (Liebchen et al., 2009).

4.2.2.4 Fuzzy programming

The fuzzy approach was originally proposed by Bellman and Zadeh (1970). Fuzzy programming models parameters as fuzzy numbers and constraints as fuzzy sets. Uncertainty parameters in mathematical models defined on a fuzzy set are associated with a membership function. The objective function may be a fuzzy goal or a crisp function and the constraints may allow some violations.

4.2.3 Simulation

Simulation is one of the decision maker’s most important techniques for solving problems. A simulation is an imitation of a process, a situation, or a real or proposed system. It is conducted in order to gain a better understanding of the system’s operational characteristics or to test its behaviour under different scenarios. Simulations, which are generally applied in situations where analytic or numerical methods alone would be insufficient, can be conducted via a computer or manually.

The simulation relies on the development of a model of the real system. This model takes the form of a set of hypotheses concerning how the system works. The hypotheses are expressed in the form of mathematical relationships or logical model between the system objects. Once the model has been developed, verified and validated, it can be used to run scenarios which might be too difficult or expensive to run on a real system, allowing the user to gather the data they need to identify which factors have a significant impact on the system, possible optimisation approaches and planning strategies.

Simulation is a useful tool for studying the behaviour of SCs because it allows the researcher to assess their efficiency and evaluate management solutions in a relatively short time (Iannone et al., 2007). However, while developments such as enhanced animation, advances in simulation software and increasingly powerful and affordable computers have facilitated the successful application of the simulation technique in several sectors (Franzese et al., 2006), its use is not widespread. There are two main reasons for this; developing simulation models takes a high level of skill, and the process is time-consuming (a system may require the integration of several models). Figure 4.5 summarises the sequence of steps that make up a simulation project (Banks & Carsen, 1984; Pegden et al. 1995; Law & Kelton, 1991).

4.2.3.1 Types of simulation

Simulation models are classified according to time and variability. Sturrock et al. (2009) classify simulations into the following groups based on these two characteristics:

4.2.3.1.1 Static and Dynamic

A static simulation is a model that is not time-based; it represents a system at a fixed moment in time. An example might be a Monte Carlo model. In contrast, a dynamic model evolves over time. An example in this category might be a model simulating the activities that occur in a bank over the course of its operating hours.

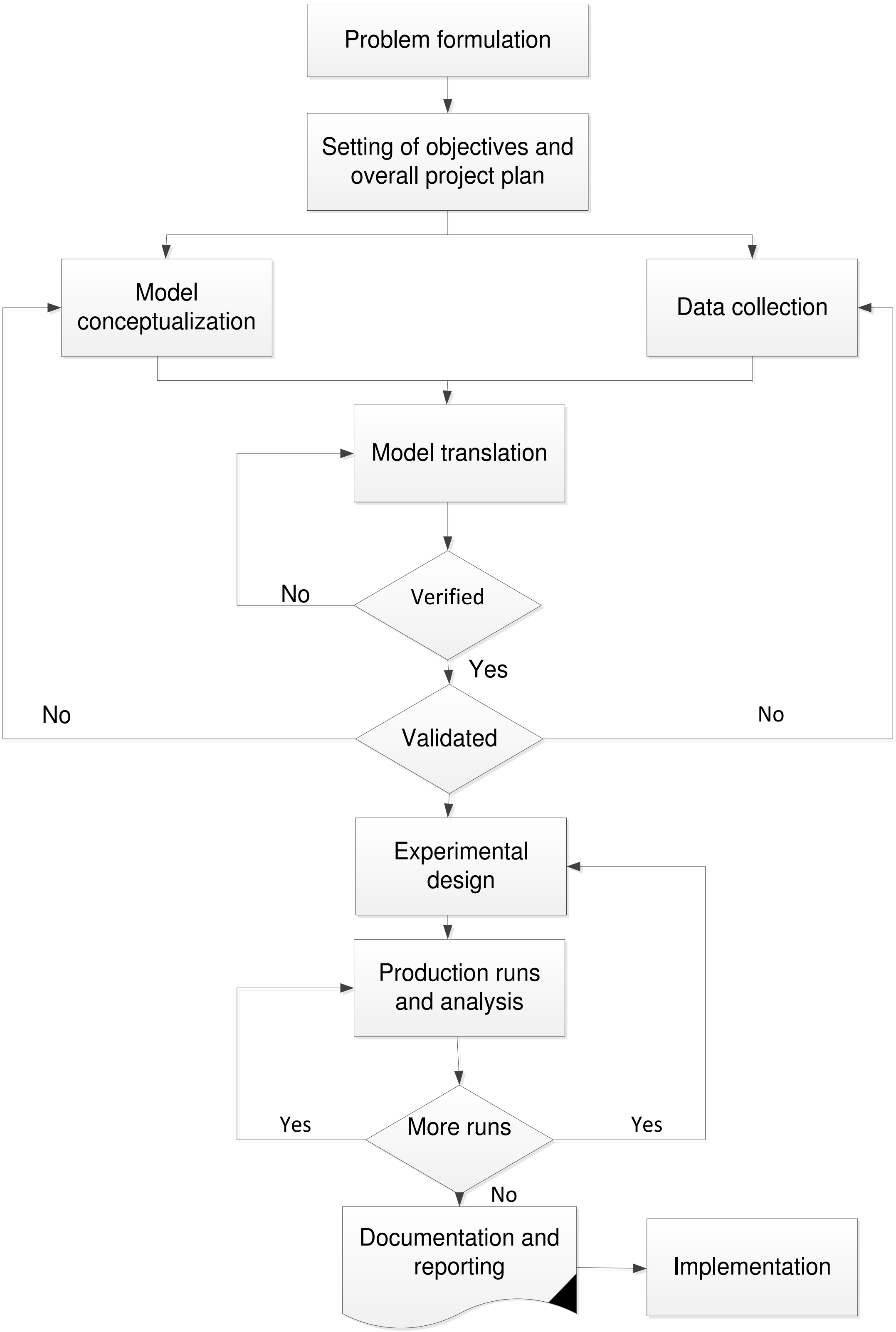


Figure 4.5 Simulation and model building flowchart

Source (Banks & Carsen, 1984)

4.2.3.1.2 Continuous and Discrete

In a discrete model, the state variables change only at a countable number of points in time. These points in time are the points at which an event/change in state occurs. In a continuous model, the state variables change in a continuous way. Continuous simulation is appropriate for systems with a continuous state that changes continuously over time. An example of such a system might be the amount of liquid in a tank and/or its temperature. This kind of system can be represented by differential equations.

4.2.3.1.3 Deterministic and Stochastic

Deterministic models are models where the outcomes are certain because the inputs are fixed. The model parameters for such systems are known or assumed. In contrast, stochastic simulation models contain one or more random variables as inputs, which results in random outputs. Since the outputs are random, they can be considered only as estimates of the true characteristics of the model. In a stochastic simulation, the output measures must be treated as statistical estimates of the true characteristics of the system (Gibb et al., 2002).

4.2.3.1.4 Terminating or Non-terminating Simulation

Terminating simulation models are models that start each time without any influence from the previous time period. These models usually have a natural terminating event. An example might be a store which starts in the morning empty of customers and stops at the end of the day. Non-terminating simulation models may begin/close with entities already in the system. Some non-terminating systems have no beginning and closing time at all; in other words, the system never stops. An example of such a system might be a power station (Chung, 2004).

4.2.3.2 Advantages of Simulation

Primarily, simulations provide a platform for carrying out experiments without having to disrupt the operations of the real system. They can be used to test concepts, designs and models and to demonstrate their capability before the real system is built; once built, the technique allows managers to retrieve information to improve real system performance. Simulation models allow managers to estimate the efficiency and effectiveness of systems and to assess the impact of changed input parameters on performance. They can be used to study and conduct experiments on the internal dynamics of any complex system or part thereof, or to investigate the impact of economic, financial, social and environmental changes. Unlike mathematical programming approaches, simulations do not require an understanding of complex maths, while the ability to incorporate animations makes it easier to communicate models to a wide audience. This relative user-friendliness makes simulations a useful staff training tool.

4.2.3.3 Simulation Disadvantages

Simulation models can be expensive to build; indeed, the whole process of modelling, data collection and analysis can be time-consuming, costly and cumbersome. The technique may not require advanced mathematical understanding, but the results can sometimes be difficult to interpret. In fact, they may not even be accurate; especially if the model is only a simplified version of the real system (it can be difficult for a modeller to gain a full understanding of a whole system).

4.2.4 Modelling and Simulation Tool

4.2.4.1 Mathematical GAMS Software

Although GAMS is the abbreviation of General Algebraic Modelling System, use of the software does not have to be restricted to mathematical models with algebraic equations. Those familiar with the methods of solving differential equations in partial derivatives know that the methods are always transformed to a system of algebraic equations. These algebraic equations are solved according to some iteration algorithm. That is, the applicability of GAMS is much wider.

GAMS facilitates the creation of mathematical models that represent real-world processes by designing algorithms for these mathematical models. Figure 4.6 shows high-level modelling system for mathematical programming and optimisation.

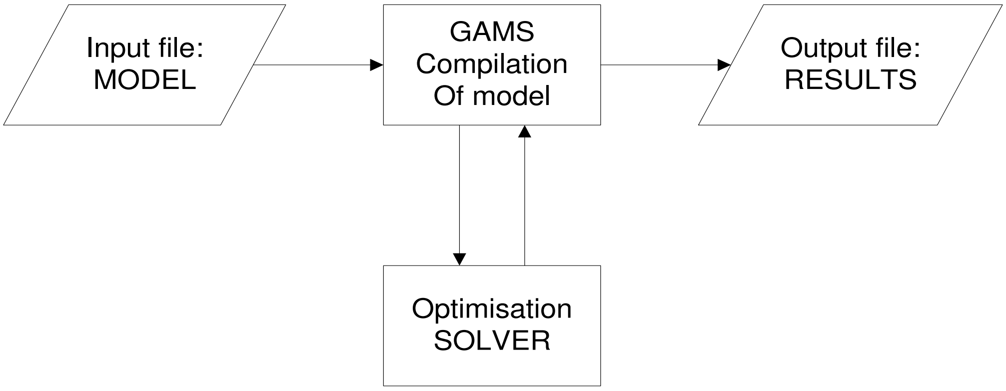


Figure 4.6 GAMS for mathematical programming and optimisation
Source (Rosenthal, 1992)

4.2.4.1.1 Motivation

Essential progress was made in the 1950s and 1960s with the development of algorithms and computer codes to solve large mathematical programming problems. However, in the 1970s, these tools were applied less frequently than might have been expected, mainly because the solution procedures formed only a small part of the overall modelling effort. Much of the time required to develop a model was taken up by data preparation and transformation and report preparation; many hours of analysis and programming time were needed to organise the data and write the programs that would convert it into the form required by the mathematical programming optimisers. Furthermore, it was difficult to detect and eliminate errors because the programs that performed the data operations were only accessible to the specialist who wrote them and not to the analysts in charge of the project (Rosenthal, 2012).

GAMS was developed in 1988 as part of a study funded by the World Bank. Since then, it has been applied in a variety of disciplines including finance, engineering, energy, environment, management, economics and mathematics. In recent years, it has been employed usefully in power systems (Chattopadhyay, 1999). The main advantage of GAMS software is that it offers high-level languages for compact formulation of large-scale and complex models. It allows modellers to build large, maintainable models and to adapt these quickly to suit new situations, to employ advanced algorithms and to identify errors easily. All this improves modellers' productivity. Finally, GAMS software allows separation between interface, data, model and solver. Its main disadvantages are that it is unsuitable for use with small problems, or for resolving very large-scale problems (1.000.000 x 1.000.000 variables matrix).

4.2.4.1.2 Structure of models in GAMS

Each model in the GAMS language has its own distinct characteristics. A model may in fact be made up of a group of models linked together by a small number of common variables or parameters. Figure 4.7 shows a typical GAMS structure. Most models have the following structure (Rosenthal, 1992):

- **Sets (indices)**

Sets are fundamental building blocks in any GAMS model. They allow the model to be succinctly stated and easily read.

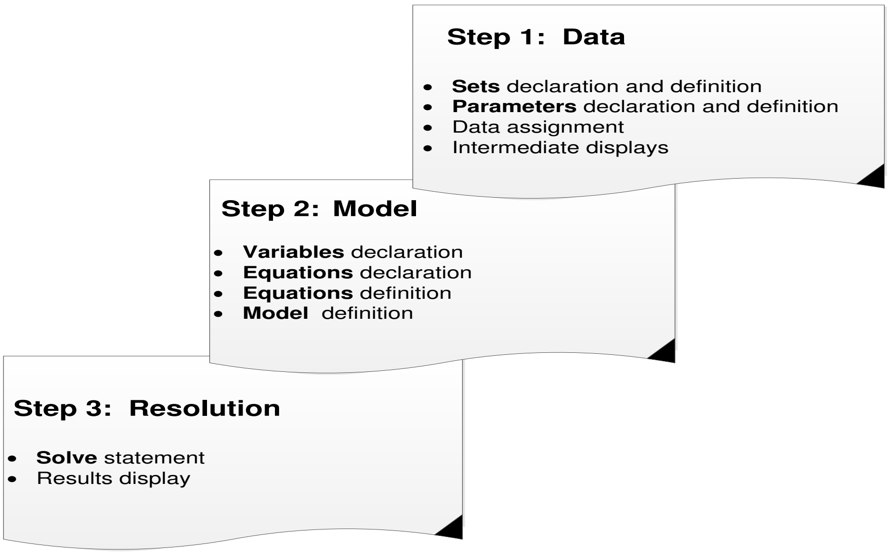


Figure 4.7 Chart of a typical GAMS structure

Source (Rosenthal, 1992)

- **Data**

One of the basic design paradigms of the GAMS language has been to use data in its most basic form, whether this is scalar, list oriented, or tables of two or more dimensions. Parameters are the elements that will not change after a simulation, such as elasticity, tax rates, distribution and scale coefficients. The scalar statement is used to declare and (optionally) initialize a GAMS parameter of dimensionality zero.

- **Variables**

They are the entities whose values are generally unknown until after a model has been solved. The declaration of a variable is similar to a set or parameter declaration, in that domain lists and explanatory text are recommended, and recommended, and several variables can be declared in one statement.

- **Equations**

In GAMS, equations are the symbolic algebraic relationships that will be used to generate the constraints in the model.

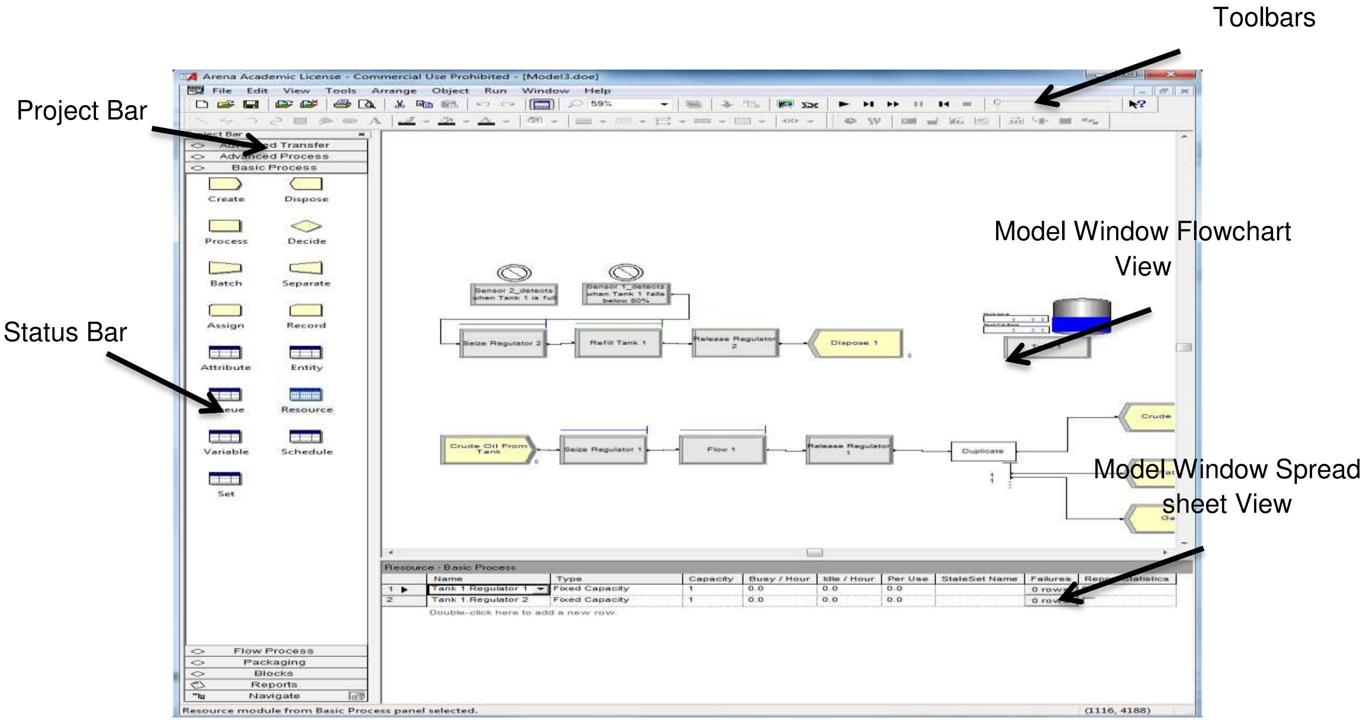
- **Model & Solvers**

The model statement is used to collect equations into groups and label them so that they can be solved. GAMS itself does not solve problems but passes problem definitions on to one of a number of separate solver programs.

4.2.4.2 Arena Simulation

ARENA simulation software, first developed in the mid-1990s, offers a powerful simulation environment comprising modelling object templates (modules) and transactions (entities). The software is designed to analyse the impact of changes involving significant and complex redesigns associated with supply chains, manufacturing, processes, logistics, distribution and warehousing, and service systems such as healthcare, ports and terminals, government and military, food and beverage, call centres, retail and customer service. Figure 4.8 presents a screen shot of ARENA Window.

Modules obtained from the templates (e.g. basic process, flow process, advanced transfer and advanced process) within the project bar are used to represent entities in the real system within simulation environment called the Model Window flowchart view. Some of the templates used in the current research are shown in Figure 4.9. The modules can be programmed or edited to suit the model's needs either by right clicking on them and selecting "edit via dialog" or through the spread-sheet view. The modules are connected by a connector line (through which entities flow) and can be accessed from the toolbar. To model dynamic processes, the software uses an entity-based, flowcharting methodology. The flowchart approach helps engineers and process designers to build a more accurate model and to analyse its results, and makes ARENA easier to understand, validate and verify than other simulation tools.



Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	Tank 1.Regulator 1	Fixed Capacity	1	0.0	0.0	0.0		0 rows	
2	Tank 1.Regulator 2	Fixed Capacity	1	0.0	0.0	0.0		0 rows	

Double-click here to add a new row.

Figure 4.8 Screen short of Arena Window displaying a simple model

ARENA has the ability to model both discrete and continuous events. In a discrete event simulation, the state of the system changes in discrete time intervals, making this kind of simulation suitable for problems where variables change in discrete times and by discrete steps. On the other hand, in a continuous simulation, system elements or processes change continuously over time. This kind of simulation is therefore suitable for systems in which the variables can be changed continuously. Some models have both discrete and continuous elements. The petroleum supply chain model in this research has continuous elements. In ARENA, each element of the system is modelled in a flowchart-like visual environment.

ARENA software contains criterion template panels for general purpose simulation models such as basic process, flow process, advanced transfer and advanced process. For example, the basic modules are used to model individual parts of the model comprised to create, assign, process, record, dispose etc. In the model of this study, two create modules create crude oil and other logical entities which run through the system. Figure 4.9 shows ARENA logic which used in simulation model of this research.

There are numerous advantages to using templates, chiefly that it reduces the time needed to produce a comprehensive simulation model and permits more scenarios. In programming idiom, a module is similar to an object. It enables the modeller to capture the characteristics of the process (logic, data and animation) and allows the reuse of the module.

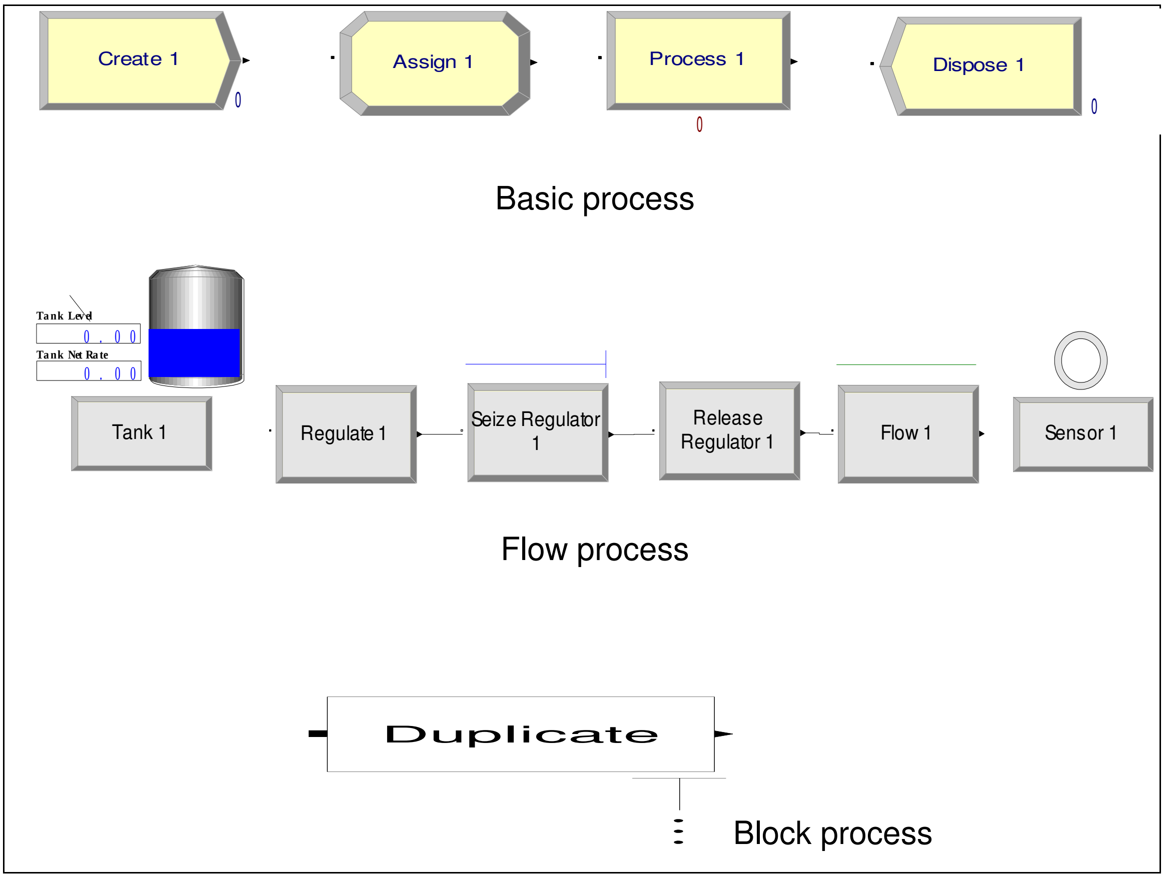


Figure 4.9 Template panels which are used in simulation model of this research

4.3 The Proposed Framework for Planning and Optimising Petroleum SC

Optimisation of the petroleum SC necessitates the consideration of a wide range of issues and functions, from crude oil selection, to process level targets, operating modes, inventory and distribution. The focus in this study is on developing a mathematical model for designing, planning and optimising an integrated petroleum SC and logistics network. The proposed model considers the full range of petroleum supply chain entities and activities, from crude oil production to market demand, and encompasses crude oil transportation, refinery operation, final products storage, and final product shipping to distribution centres. It accounts for uncertainty by using two-stage stochastic programming with recourse. The scenarios emerge from the assumption that market demand for final products will be ‘‘above average’’, ‘‘average’’, or ‘‘below average’’. Numerically, ‘‘above average’’ and ‘‘below average’’ scenarios are assumed as +20%, +10% and -20%, -10% of the average values respectively. The objective function is to optimise the petroleum SC by minimising total production and logistics costs, as well as lost demand and backlog penalties, and maximising sales revenues.

GAMS software was used to solve the proposed model and arrive at an optimal quantity for crude oil production, which was then fed into the simulation model. The simulation model focuses on the key areas of crude oil production and distillation unit processes. The results were analysed and their validity checked and the model run repeatedly to refine its performance.

Figure 4.10 displays the proposed framework for planning and optimising petroleum SC.

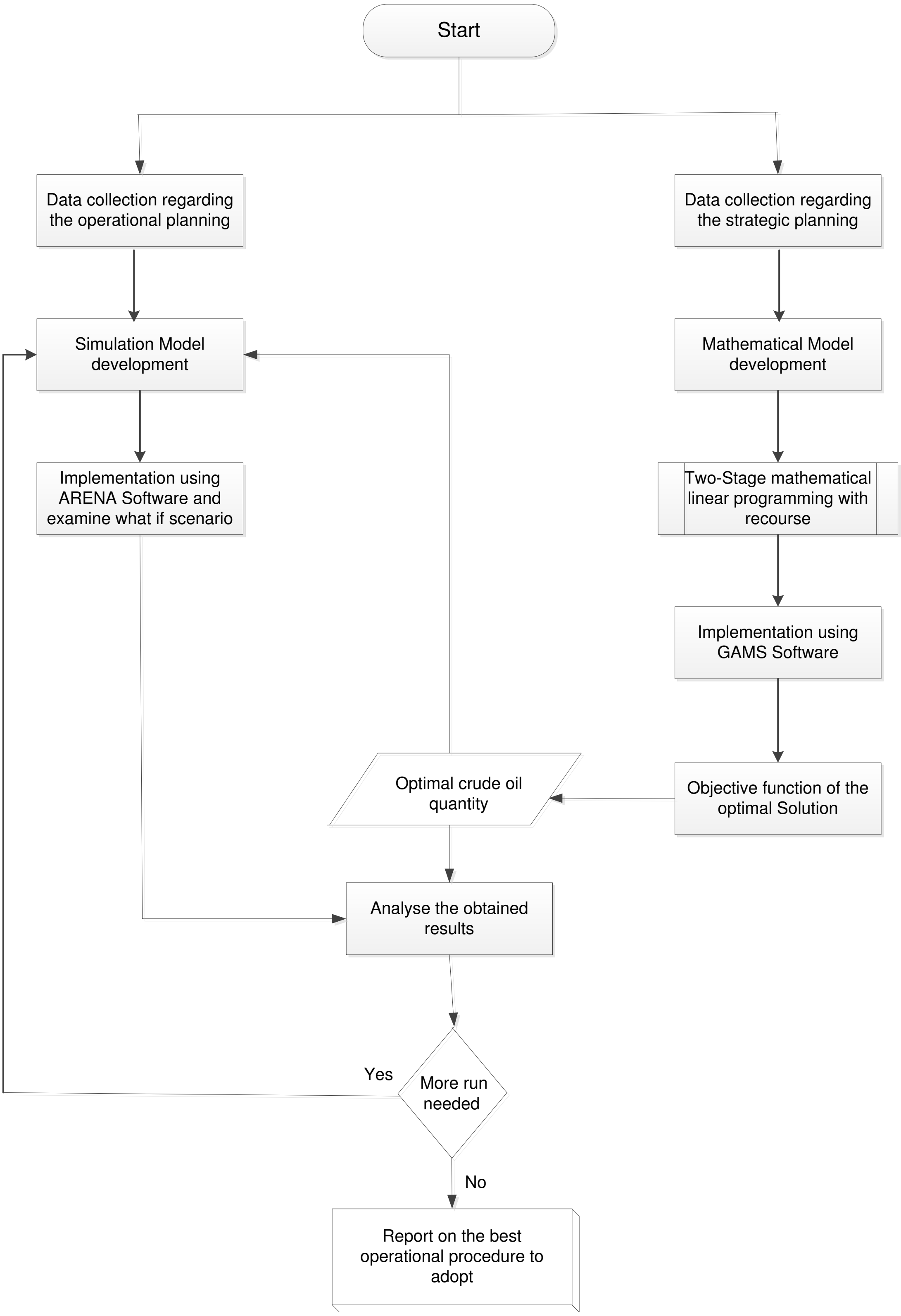


Figure 4.10 the Proposed Framework for Planning and Optimising Petroleum SC

4.4 Conclusion

This chapter presented the mathematical programming and simulation modelling methodologies that were employed in this research.

The following are the main points:

- It first presented an overview of the different types of linear programming methods, with particular emphasis on the two-stage stochastic linear program with recourse method used in this study. This method was chosen to show the relationship between uncertainty of demand and selected key performance indicators.
- The chapter then discussed the simulation modelling technique that was employed in the second stage of the study, highlighting the different classes of simulation model and the advantages and disadvantages of the technique.
- The modelling and simulation software employed in the study are then discussed. These included GAMS software, used for solving mathematical problems, and ARENA simulation software. This section discusses the types of module that were used in the simulation.
- The chapter concluded with a description of the study’s proposed framework for planning and optimising the petroleum SC.

The following chapter presents the results that were generated by the mathematical model part of this framework.

CHAPTER FIVE

DEVELOPMENT OF MATHEMATICAL MODEL OF PETROLEUM SUPPLY CHAIN

5.1 Petroleum supply chain network

The petroleum supply chain proposed in this research is illustrated in Figure 5.1. It includes majority of the activities related to raw materials supply to final product passing through a complex logistics network including oil production, transportation, storage of the refinery products which can be considered as distribution centres, and several conversion processes that take place in refinery plant.

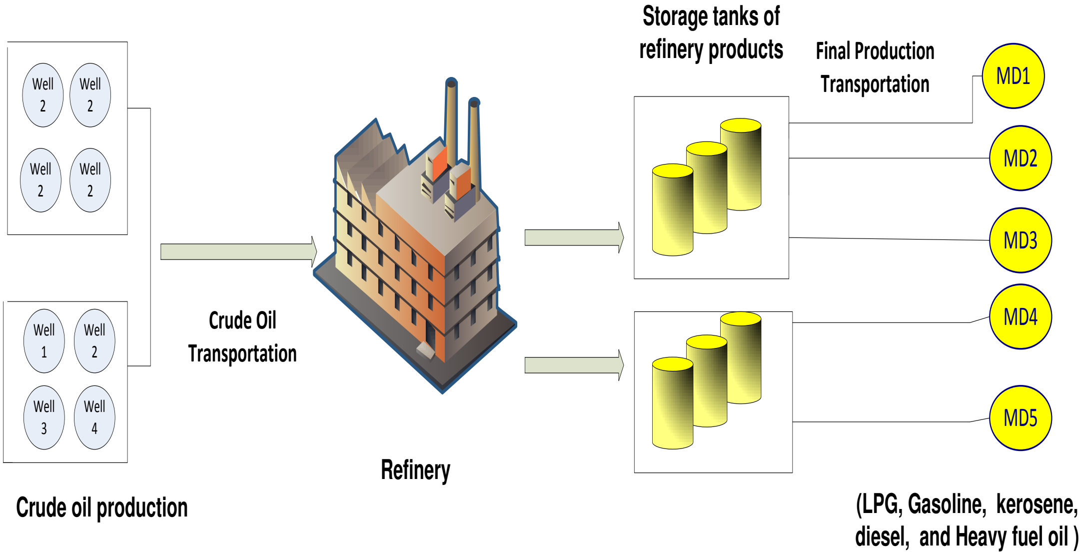


Figure 5.1 Petroleum supply chain network proposed

The network of petroleum supply chain proposed are designed to start from crude oil production which is considered the first variable of supply chain model. The amount of crude oil transported from production sites to the refinery is the second variable of the model of petroleum supply chain proposed.

The oil refinery activity is considered one of the most complex activities in the petroleum industry which carry different processes to transform crude oil into valuable refined products of higher aggregate value, in addition maximising the profit.

Oil refinery essentially involves two categories of processes: physical and chemical processes, the physical separation processes of crude oil into a range of homogeneous petroleum fractions. In distillation unit, crude oil entering the refinery undergoes primary separation by continuous atmospheric distillation to yield a variety of homogeneous fraction boiling over a wide range. A number of refinery products from distillation units such as LGP, Gasoline, Kerosene, Diesel and Heavy fuel oil are shipped to demand sources immediately.

Chemical conversion processes of certain fractions to alter the product yield and improve product quality. The refineries produce light fraction products such as naphtha, gasoline, LPG (liquid petroleum gas) and propylene, medium products as (aviation kerosene and diesel) and heavy fractions such as (paraffin, lubricants, light crude oil, gas oil, coke and fuel oil).

The volume of refinery production is one of the variables accounted in the model proposed. The storage capacity of final product is also considered in the model as a significant variable effect on supply chain optimisation.

The quantities of refinery products that shipped to distribution centres, quantities of backlog, shortage demand all of these variables taken into account too.

The problem is to develop an optimisation model for the planning of petroleum supply chain mentioned above that accounts for time periods of one year.

Decisions related to production quantities of crude oil, transportation plan, storage capacities, quantities of refinery production, shortage demand, backlog and amount of final production shipped are needed for planning purpose.

Choosing the best configuration for petroleum supply chain and the ideal design and plan for all activities and entities of the supply chain are difficult tasks due to the high number of variables and constraints present in a model. Mathematical programming plays a crucial role in solving this problem, assisting in the decision-making process and in the planning of all activities at the strategic level.

5.2 The proposed mathematical model

5.2.1 Deterministic Mathematical Model

The deterministic model proposed addresses the portfolio of the optimisation problem in the integration oil supply chain in order to satisfy market demand with the lowest cost.

The planning of petroleum supply chain is proposed at the strategic level, and the planning horizon (T) for one year is assumed. The planning horizon is usually divided into time periods at which items of the plan are scheduled.

5.2.1.1 The objective function

The objective function of the proposed mathematical model is to optimise the petroleum resources by minimising the total costs of raw materials production, refinery and petrochemical production, raw material and final products transport, storage of final products, and penalty of the amount of shortage and backlog products for demand source as well as maximising the sale revenues.

The objective function for the deterministic model is defined in plain English first then presented mathematically as follows:

$$\begin{aligned} Z = \min\{&[Production\ cost\ of\ crude\ oil] + [\ Production\ cost\ of\ final\ product] \\ &+ [Transportation\ cost\ of\ crude\ oil] + [Stoarge\ cost] \\ &+ [Transportation\ cost\ of\ final\ product] \\ &+ [Penalty\ of\ shortage\ products][Backlog\ penalty\ of\ product] \\ &- [\ Sale\ revenue]\} \end{aligned}$$

$$\begin{aligned} Z = \min\Bigg\{&\left[\sum_{i\in I}\sum_{t\in T} CO_i\ .\ Q_{i,t}\right] + \left[\sum_{j\in J}\sum_{t\in T} C_j\ .\ V_{j,t}\right] + \\ &\left[\sum_{i\in I}\sum_{t\in T} TC_i\ .\ \ TV_{i,t}\right] + \left[\sum_{j\in J}\sum_{t\in T} CS_j\ .\ \ SV_{j,t}\right] + \left[\sum_{j\in J}\ \sum_{md\in MD}\ \sum_{t\in T} CT_j\ .\ \ F_{j,\mathrm{md},t}\right] + \\ &\left[\sum_{j\in J}\ \sum_{md\in MD}\ \sum_{t\in T} \beta_{j,\mathrm{md}}\ .\ \ DS_{j,\mathrm{md},t}\right] + \left[\sum_{j\in J}\ \sum_{md\in MD}\ \sum_{t\in T} CB_{j,\mathrm{md}}\ .\ \ VB_{j,\mathrm{md},t}\right] \\ &- \left[\sum_{j\in J}\ \sum_{md\in MD}\ \sum_{t\in T} PS_{j,\mathrm{md}}\ .\ \ F_{j,\mathrm{md},t}\right]\Bigg\} \end{aligned} \tag{5.1}$$

5.2.1.2. Constraints

5.2.1.2.1 Material balance

Material balance for final products:

$$\sum SV_{j,t-1} + V_{j,t} = \sum F_{j,md,t} + \sum SV_{j,t} \quad \forall_j \in J\ , md \in MD, t \in T \tag{5.2}$$

Crude oil constraint:

$$Q_{i,t} \leq Cp_{i,t} \quad \forall_i \in I\ , \quad t \in T \tag{5.3}$$

5.2.1.2.2 Demand balance

$$F_{j,d,t} \leq D_{jm,d,t} \quad \forall_j \in J\ , d \in MD, \quad t \in T \tag{5.4}$$

$$VB_{j,t-1} + D_{j,md,t} = \sum F_{j,md,t} + DS_{j,md,t} + B_{j,md,t} \quad \forall_j \in J\ , md \in MD, \quad t \in T \tag{5.5}$$

$$DS_{j,md,t} = \delta \left(VB_{j,t-1} + D_{j,md,t} - \sum F_{j,md,t} \right) \quad \forall_j \in J\ , md \in MD, \quad t \in T \tag{5.6}$$

$$\sum VB_{jmd,t} \leq \sum(\lambda V_{j,t}) \quad \forall_j \in J\ , md \in MD\ , \ t \in T \tag{5.7}$$

$$\sum DS_{jmd,t} \leq \sum(\delta D_{j,md,t}) \quad \forall_j \in J\ , md \in MD\ , \ t \in T \tag{5.8}$$

5.2.1.2.3 Storage constraints

$$\sum SV_{j,t} \leq \sum SV_{j,t}^{max} \quad \forall_j \in J\ , \ t \in T \tag{5.9}$$

5.2.1.2.4 Transportation constraints

$$TV_{i,t} \geq Q_{i,t} \quad \forall_i \in I\ , \ t \in T \tag{5.10}$$

$$F_{j,d,t} \leq TP_{j,t}^{max} \quad \forall_j \in J\ , \ t \in T \tag{5.11}$$

5.2.1.2.5 Production yields

Production yield is defined as the final products that may be produced from processing the crude oil:

$$\sum V_{j,t} = \sum(\gamma\, Q_{j,t}) \quad \forall_j \in J\ , \quad t \in T \tag{5.12}$$

5.2.2 Stochastic Mathematical Model

The formulation of two-stage stochastic linear program is:

$$Min_x\ C^T x + E_\xi[\min q\,(\omega)^T\, y(\omega)] \tag{5.13}$$

s.t $Ax = b$

$$T(\omega)x + Wy(\omega) = h(\omega)$$

$$x \geq 0 \quad , \quad y(\omega) \geq 0$$

The objective function in equation (5.14) shown below includes first-stage decision (deterministic term) $C^T x$ which represented by vector x , and expectation of the second-stage objective, $q(\omega)^T\, y(\omega)$ taken over all realisation of the random events $\omega \in \Omega$, that represented by the vector $y(\omega)$.

For the petroleum supply chain optimisation problem presented in this study, the deterministic term corresponds to the crude oil quantity $Q_{i,t}$ and production volume $V_{i,t}$, during the planning horizon (T). The second-stage decision variables are represented by remaining terms for different scenarios.

In this section, the source of uncertainty in market demand for final product of refineries and petrochemicals plants is considered here in details. There will be a base model scenario (which represents the average demand) from which other scenarios will emerge from the assumption that market demand are assumed as 10%, 20% higher than the demand for the base model, and 10%, 20% lower than the demand for the based model in subsequent time periods.
We can define each scenario using superscript $S = 1{,}2{,}3{,}4 \; and \; 5$ representing:
1 = 10% lower than the base
2 = 20% lower than the base
3 = base
4 = 10% higher than the base
5 = 20% higher than the base
This assumption means that the five scenarios have equal probabilities of $\frac{1}{5}$, hence ($E_\xi = \left\{\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}\, , \frac{1}{5}\right\}$).

5.2.2.1 The objective function

The objective function of the stochastic optimisation model can be presented by modifying the equation (5.1) to account the uncertainty.

$$
\begin{aligned}
Z = \min\{\{&[Production\ cost\ of\ crude\ oil] + [\,Production\ cost\ of\ final\ product]\} \\
&+ \frac{1}{5}\{[Transportation\ cost\ of\ crude\ oil] + [Stoarge\ cost] \\
&+ [Transportation\ cost\ of\ final\ product] \\
&+ [Penalty\ of\ shortage\ products][Backlog\ penalty\ of\ product] \\
&- [\,Sale\ revenue]\}\}
\end{aligned}
$$

$$Z = \min\left\{\left[\sum_{i\in I}\sum_{t\in T} CO_i \,.\, Q_{i,t}\right] + \left[\sum_{j\in J}\sum_{t\in T} C_j \,.\, V_{j,t}\right] + \right.$$

$$\frac{1}{5}\sum_{S=1}^{5}\sum_{t\in T}\left[\sum_{i\in I} TC_i \,.\, TV^{S}_{i,t}\right] + \left[\sum_{j\in J} SC_j \,.\, SV^{S}_{j,t}\right] + \left[\sum_{j\in J}\sum_{md\in MD} CT_j \,.\, F^{S}_{j,md,t}\right] +$$

$$\left[\sum_{j\in J}\sum_{md\in MD} \beta_j \,.\, DS^{S}_{j,d,t}\right] + \left[\sum_{j\in J}\sum_{md\in MD} CB_{j,md} \,.\, VB^{S}_{j,md,t}\right]$$

$$\left. - \left[\sum_{j\in J}\sum_{md\in MD} PS_j \,.\, F^{S}_{j,md,t}\right]\right\} \tag{5.14}$$

5.2.2.2 Constraints

5.2.2.2.1 Material balance

The constraints used for the deterministic model are modified to the stochastic model formulation for each scenario $s \in \{1,2,3,4,5\}$.

5.2.2.2.2 Demand balance

To introduce uncertainty in market demand for final products, the demand balance represented by equations (5.4) to (5.6) becomes:

$\sum F^{s}_{j,md,t} \leq D^{s}_{j,md,t}$ $\forall_j \in J\ , md \in MD,\ t \in T \quad s \in \{1,2,3,4,5\}$ (5.15)

For the below average with 10%, 20% in product demand scenario $s = 1{,}2$:

$VB^{s}_{j,t-1} + (1-\alpha)D^{s}_{j,md,t} = \sum F^{s}_{j,md,t} + DS^{s}_{j,md,t} + B^{s}_{j,md,t}$ $\forall_j \in J\ , md \in MD,\ t \in T\ \ s \in \{1,2,3,4,5\}$ (5.16)

$DS^{s}_{j,md,t} = \delta\left(VB^{s}_{j,t-1} + (1-\alpha)D^{s}_{j,md,t} - \sum F^{s}_{j,md,t}\right)$ $\forall_j \in J\ , md \in MD,\ t \in T\ s \in \{1,2,3,4,5\}$ (5.17)

Where α is the degree of uncertainty. For each scenario assumed in final products demand $\alpha =$ 0.1, 0.2

For the average in product demand scenario $s = 3$:

$B^{s}_{j,t-1} + D^{s}_{j,md,t} = \sum F^{s}_{j,md,t} + DS^{s}_{j,md,t} + B^{s}_{j,md,t}$ $\forall_j \in J\ , md \in MD,\ t \in T,\ s \in \{1,2,3,4,5\}$ (5.18)

$$DS^{s}_{j,md,t} = \delta \left(VB^{s}_{j,t-1} + D^{s}_{j,md,t} - \sum F^{s}_{j,md,t} \right) \geq 0 \quad \forall_j \in J \ , md \in MD, \ t \in T, \quad s \in \{1,2,3,4,5\} \tag{5.19}$$

For the above average with 10%, 20% in product demand scenario $s = 4{,}5$:

$$B^{s}_{j,t-1} + (1+\alpha) D^{s}_{j,md,t} = \sum F^{s}_{j,md,t} + DS^{s}_{j,md,t} + B^{s}_{j,md,t} \quad \forall_j \in J \ , md \in MD, \quad t \in T \ \ s \in \{1,2,3,4,5\} \tag{5.20}$$

$$DS^{s}_{j,md,t} = \delta \left(VB^{s}_{j,t-1} + (1+\alpha) D^{s}_{j,md,t} - \sum F^{s}_{j,md,t} \right) \geq 0 \quad \forall_j \in J \ , md \in MD, \quad t \in T, \ s \in \{1,2,3,4,5\} \tag{5.21}$$

$$\sum VB^{s}_{j,md,t} \leq \sum (\lambda V_{j,t}) \qquad \forall_j \in J \ , md \in MD \ , \ t \in T \tag{5.22}$$

$$\sum DS^{s}_{j,md,t} \leq \sum (\delta D^{s}_{j,md,t}) \qquad \forall_j \in J \ , md \in MD \ , \ t \in T \tag{5.23}$$

5.2.2.2.3 Storage constraints

The stochastic formulation of storage constraint is:

$$\sum SV^{s}_{j,t} \leq \sum SV^{max}_{j,t} \qquad \forall_j \in J \ , \ t \in T \quad , s \in \{1,2,3,4,5\} \tag{5.24}$$

5.2.2.2.4 Transportation constraints

The stochastic formulation is as follows:

$$TV^{s}_{i,t} \leq Q_{i,t} \qquad \forall_i \in I \ , \ t \in T \quad , s \in \{1,2,3,4,5\} \tag{5.25}$$

$$F^{s}_{i,md,t} \leq TP^{max}_{j,t} \qquad \forall_j \in J \ , md \in MD \ , \ t \in T \tag{5.26}$$

5.2.2.2.5 Production yields

The stochastic formulation of yield products becomes:

$$\sum V^{s}_{j,t} = \sum (\gamma Q^{s}_{j,t}) \qquad \forall_j \in J \ , \ t \in T \tag{5.27}$$

5.3 Results and Discussion

To illustrate the key performance of the designed optimisation models, a number of case studies were carried out. Table 5.1 lists the case studies selected for analysis and discussion.

(Case 0) represents the solution of deterministic model before considering the effect of uncertainty of market demand on the proposed supply chain. The rest of the cases (case 1 to case 8) explain different scenarios considered changes in the key chosen parameters. The changes in optimal profitability of case studies compared with the optimal profitability of deterministic model (case 0) are showed in Table 5.1.

Table 5.1 the changes in optimal profitability of case studies compared with case 0

Case studies	Description	Change %
Case 0	Deterministic, base case	0.0
Case 1	Deterministic, - 20% market demand	-4.5
Case 2	Deterministic, - 10% market demand	7.7
Case 3	Deterministic, + 10% market demand	13.5
Case 4	Deterministic, + 20% market demand	-7.9
Case 5	Stochastic, - 20% market demand	8.4
Case 6	Stochastic, - 10% market demand	21.9
Case 7	Stochastic, + 10% market demand	21.9
Case 8	Stochastic, + 20% market demand	8.4

5.3.1 Deterministic base case (Case 0)

The deterministic base case results represent the considered to be optimal supply chain plan for which all parameters are considered at certain condition. The main points of Case 0 results are summarised in the following:

- The quantity of crude oil production and quantity of crude oil transported have the highest contribution in the overall quantities of the petroleum supply chain, which recorded 26.90% alike. Followed by volume of refinery productions and volume of refinery products shipped with 25.58% and 16.96% respectively. While the lowest contribution quantities represented by volume of backlog, volume of stored products and shortage product (below demand) with 1.79%, 1.72% and 0.09% respectively. The contribution of each parameters of supply chain is illustrated in Figure 5.2.

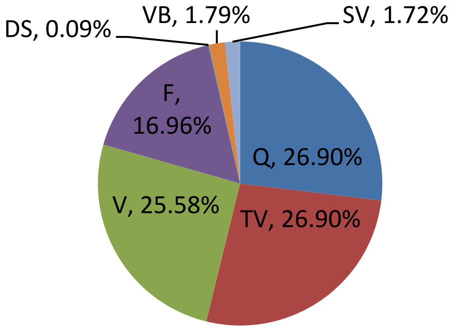


Figure 5.2 Optimal quantities of supply chain parameters (Case 0)

- The optimal quantity of crude oil production is accomplished for all time periods during the planning horizon that are shown in Table 5.2. The quantity gained from running the deterministic model Case 0 is 2.57E+07 tonnes of crude oil during time period of planning horizon which equivalent to 510,000 barrels/day. This quantity will be used in simulated model proposed in this research, which will be explained in the next chapter for calculating other key performance measures of petroleum supply chain.

Table 5.2 Optimal quantities of supply chain parameters during planning horizon (tonnes)

Items	Optimal Quantities(tonnes)
Quantity of crude oil (Q)	2.57E+07
Quantity of transported crude oil (TV)	2.57E+07
Quantity of products (V)	2.44E+07
Quantity of shipped products (F)	1.62E+07
Quantity of shortage demand (DS)	90000
Quantity of backlog (VB)	1.71E+06
Quantity of product kept in stock (SV)	1.65E+06

- The contribution of each cost items to the overall cost of the supply chain is shown in Figure 5.3. It is obviously that the cost of production quantity is the highest cost of overall supply chain and represents more than half of the total costs of supply chain items followed by crude oil production cost with about one third of the overall costs of items.

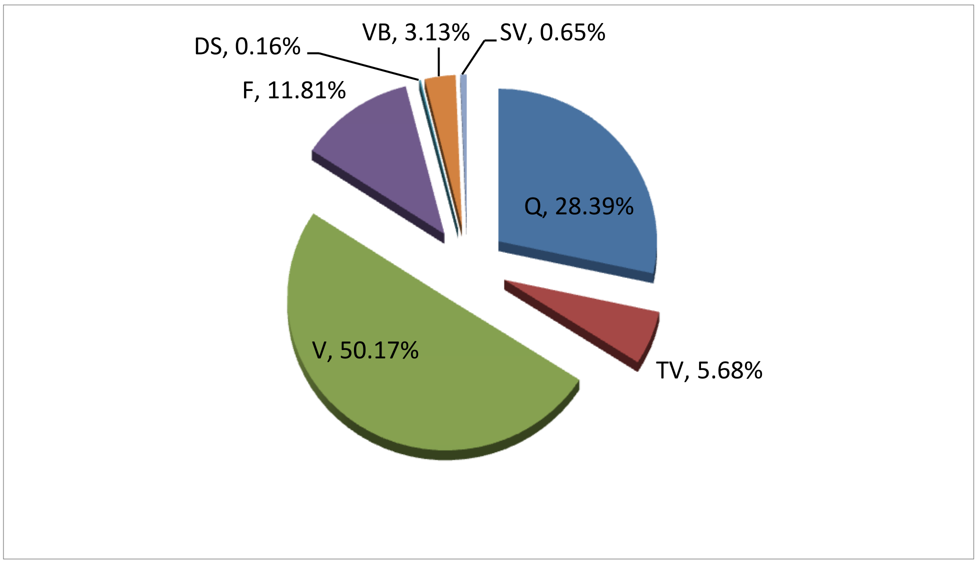


Figure 5.3 Contribution of each cost items of the supply chain

- The average of refinery products shipped in contrast with market demand is shown in Figure 5.4. For example, lack of kerosene was almost 8%, LPG, Gasoline, and diesel was 10% each while 11.4% was the reported lack for the heavy fuel oil. The reason for this is due to presence of backlog and shortage demand quantities.

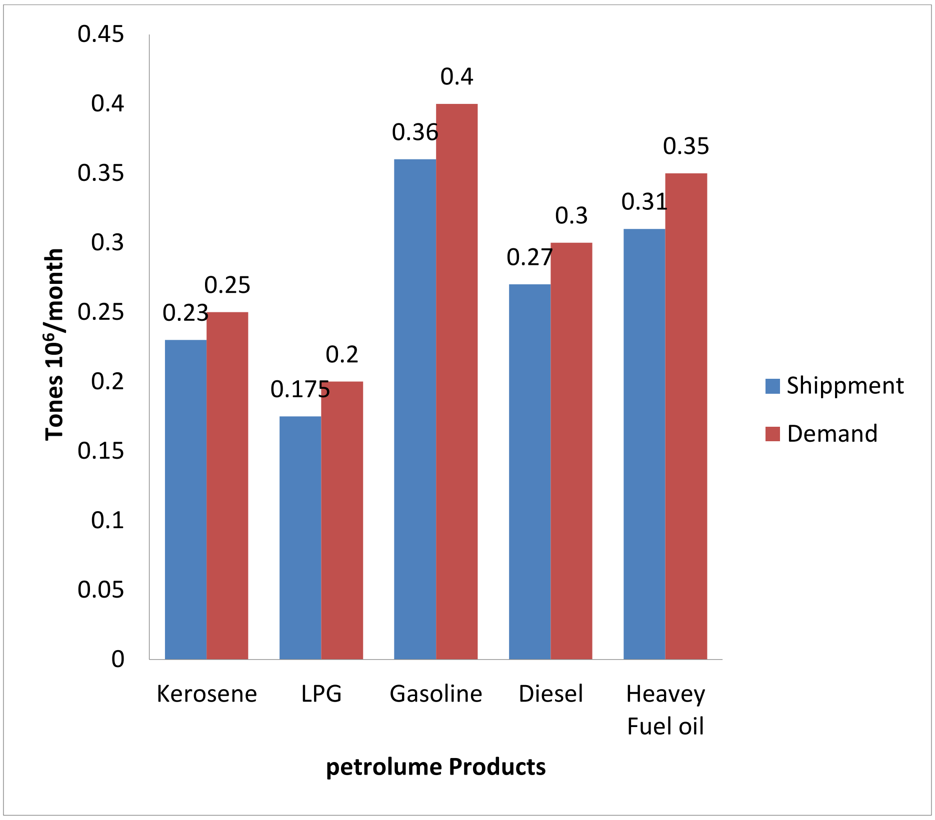


Figure 5.4 Average shipments of refinery products and corresponding market demand (Case 0) Tonnes/month

5.4 Sensitivity analysis

Uncertainty analysis and sensitivity analysis are essential parts of analyses for complex systems such as petroleum industry. Uncertainty analysis refers to the determination of the uncertainty in analysis of the results that derives from uncertainty in inputs values, and sensitivity analysis refers to the determination of the contributions of individual uncertainty of the inputs variables to the uncertainty in analysis of the results (Helton, et al., 2006).

Sensitivity analysis helps the decision maker by describing how changes in the state of nature probabilities and/or changes in the payoff affect the recommended decision alternatives.

Two approaches were applied in studying the effect of uncertainty of market demand on the supply chain. The first approach is based on introducing deviations in the deterministic model, and the scenario analysis stochastic approach is used for the second approach.

A measure tool known as Expected Value of Perfect Information (EVPI) is computed a maximum amount a decision maker should pay for additional information that gives a perfect signal as to the state of nature. In the other words, EVPI represents the loss of profit due to the presence of uncertainty or lack of information AL Othman et.al. (2008).

The expected value is simply the mean of a random variable, the average expected outcome is:

$$\boldsymbol{E(x) = \mu = \Sigma xp(x)} \tag{5.28}$$

Where:

$\boldsymbol{E(x)}$ Is the expected value or mean of the outcomes $\boldsymbol{x}$.

$\boldsymbol{\mu}$ Is the mean.

$\boldsymbol{\Sigma xp(x)}$ Is the sum of each random variable value multiplied by its own probability $\boldsymbol{p(x)}$.

In general, the expected value of perfect information (EVPI) is computed as follows:

$$\boldsymbol{EVPI = | EVwPI - EVwoPI |} \tag{5.29}$$

Where:

$\boldsymbol{EVPI}$ = Expected value of perfect information

$\boldsymbol{EVwPI}$ = Expected value with perfect information about the states in nature

$\boldsymbol{EVwoPI}$ = Expected value without perfect information about the states in nature

Mathematically, **EVPI** is calculated as the difference between the arithmetic average of optimum costs (value of objective function) of the five deterministic and stochastic plans (below 10%, 20%, average base and 10%, 20% above average).

The effect of uncertainty in market demand is studied through sets of cases studies and the results are shown in Table 5.1. The first set of cases (Case 1, Case 2, Case 3 and Case 4) is solved deterministic model for ±10% and ±20% uncertainty in market demand.

Sensitivity analysis results indicate clearly that the optimum petroleum supply chain plans are sensitive to changes in market demand.

Planning for a 20% decrease in market demand (Case 1) is about 4.5 less profitability than the base case (Case 0), as well as the assuming 20% increase in market demand (Case 4) reduces the profitability by about 7.9% deviated on base case. In contrast, (Case 2 and Case 3) showed positive deviations in profitability about 7.7% and 13.54% respectively. Such deviation in profitability for each case study that means the planning of supply chain under uncertain market demand is risky. Moreover, value of EVPI for both ±10% and ±20% deterministic plans (Case 1, Case 2, Case 3 and Case 4) are more than 1.5% as seen in Figure 5.5.

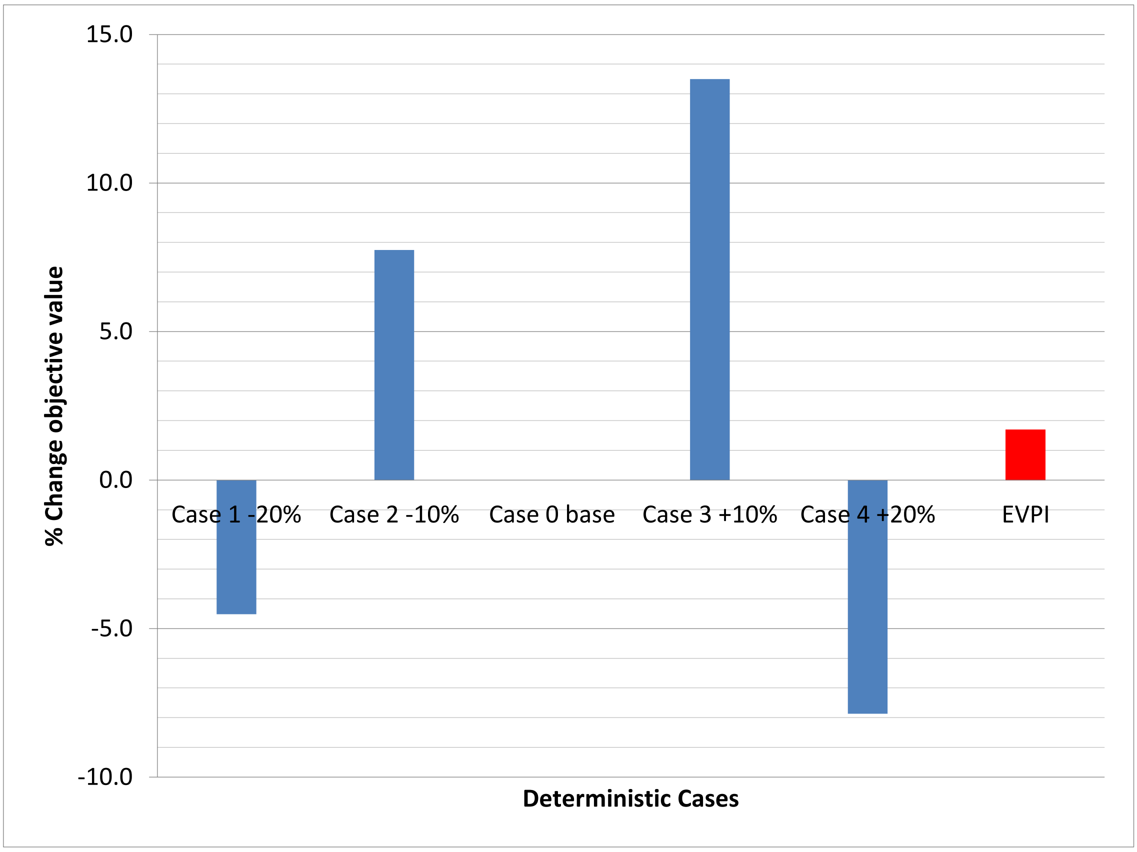


Figure 5.5 Percentages change of objective value obtained from deterministic cases.

Results of the stochastic model cases (Case 5, Case 6, Case 7 and Case 8) sensitivity analysis shows that the stochastic optimisation model outputted rigid optimum supply chain plans with more deviations of profitability with to that of base case (Case 0). For a ±20% uncertainty in market demand (Case 5 and Case 8), has increased in profitability by 8.4% compared with base case. Whilst, the profitability has more positive deviation with 21.9% for ±10% uncertainty in market demand (Case 6 and Case 7) as shown in Figure 5.6.

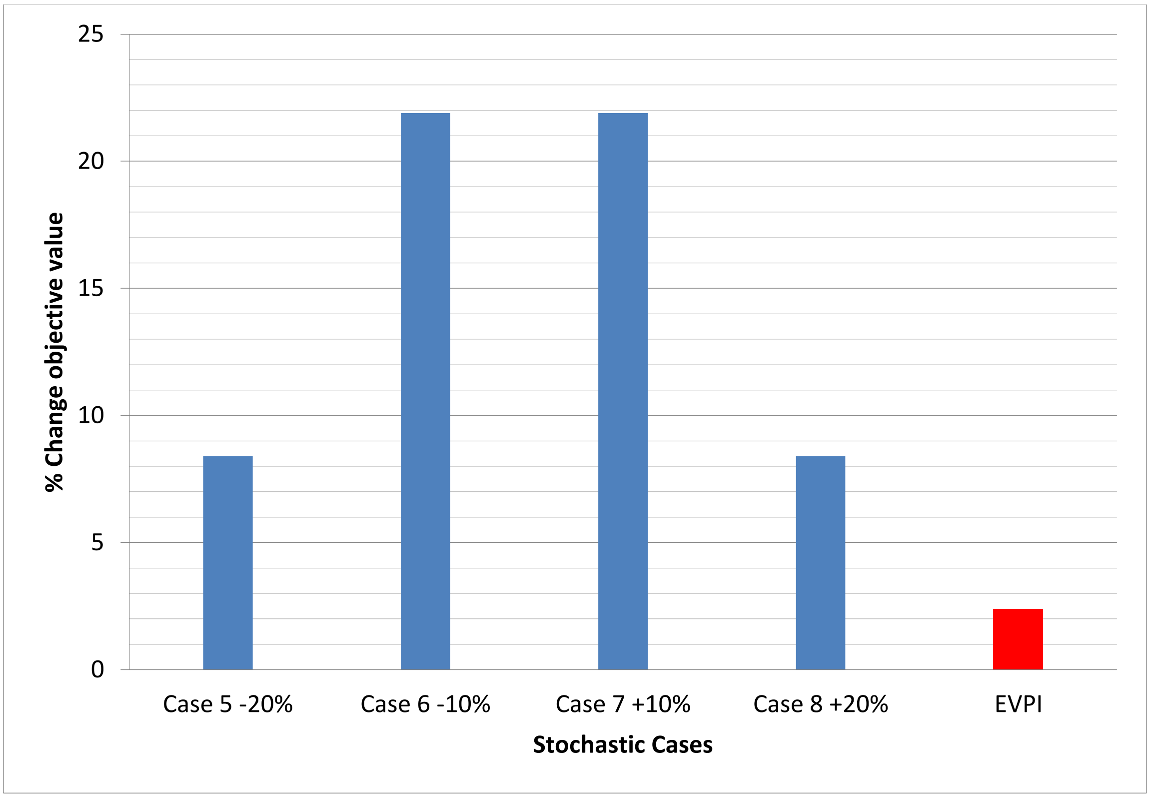


Figure 5.6 Percentages change of objective value getting from stochastic cases

Expected value of perfect information (EVPI), for both ±10% and ±20% stochastic model plan calculated 2.4% of the base case objective value, which is higher than the value calculated for deterministic model plan. It means the planning at stochastic cases is riskier than the planning at deterministic cases, although there is risk at both of them.

5.5 Conclusion

- The proposed network of petroleum supply chain consists of majority of the activities related to petroleum industry from raw materials to distribution centres was designed and used as the basis of the proposed mathematical and simulation modelling purposes.
- Mathematical model of two-stage stochastic linear programming with recourse to address the strategic planning and optimisation of petroleum supply chain have been developed and implemented to simulate and study the effect of uncertainty in market demand for valuable production on the supply chain proposed.
- Optimal planning results have illustrated the capabilities of the proposed mathematical model in developing a comprehensive one-year plans that ensure optimum operation of petroleum supply chain and maximum profitability.
- Sensitivity analysis results showed that planning in an uncertain of market demand is risky, it is important for petroleum companies to develop and resilient supply chain plans to be able capture the great benefit.
- The four cases which have been generated by the stochastic model appeared to have significant high EVPI, of course this indicate that the planning of supply chain in stochastic environment has more risk than if we are planning in deterministic situation, which is really expected.
- The key performance measures considered in the mathematical model is that the cost of quantities of crude oil, transportation of crude oil, refinery production, production storage, production shipped, backlog and shortage demand.
- The optimal quantity of crude oil presented into deterministic model which is (5.10E+05 bbl. /d) will be used in simulation model next chapter for calculating other performance measurement.

CHAPTER SIX

SIMULATION MODELLING AND ANALYSIS OF PETROLEUM (SC) AND LOGISTICS

6.1 Introduction

A mathematical model of two-stage stochastic linear programming with recourse to address the strategic planning and optimisation of petroleum supply chain and logistics have been developed and implemented in the previous chapter.

In this chapter, a schematic for the proposed system will be drafted serving as a guide to building the simulation model. Assumption considered while building the system will also discussed. The chapter will later be ended with the approach to building the model.

6.2 Objectives of Simulation Modelling

The main objectives of simulation modelling as mentioned in the introduction chapter are to design and develop an operational simulation model for planning and optimising petroleum logistics and supply chain. The proposed model focuses on two main production areas namely: crude oil separation and distillation unit. The crude oil input rate, quality, distillation processing time and a number of failed separators are all experimental factors considered in the simulation model. The output of total products and equipment utilisation were used to measure the designed model performance. The simulation model proposed in this research is discussed in detail in the next sections.

6.3 System Description

The process flowchart as shown in Figure 6.1 illustrates the processing stages considered for the simulation model proposed. It begins when crude oil arrives at first-stage of separation (SP1) which is then separated into oil, gas and water under high pressure of about 700 psi. The gas would flow to the gas- plant and the water flows to the water-treatment reservoir. The oil would then be transferred to the second stage of separation (SP2) with change of the flow -

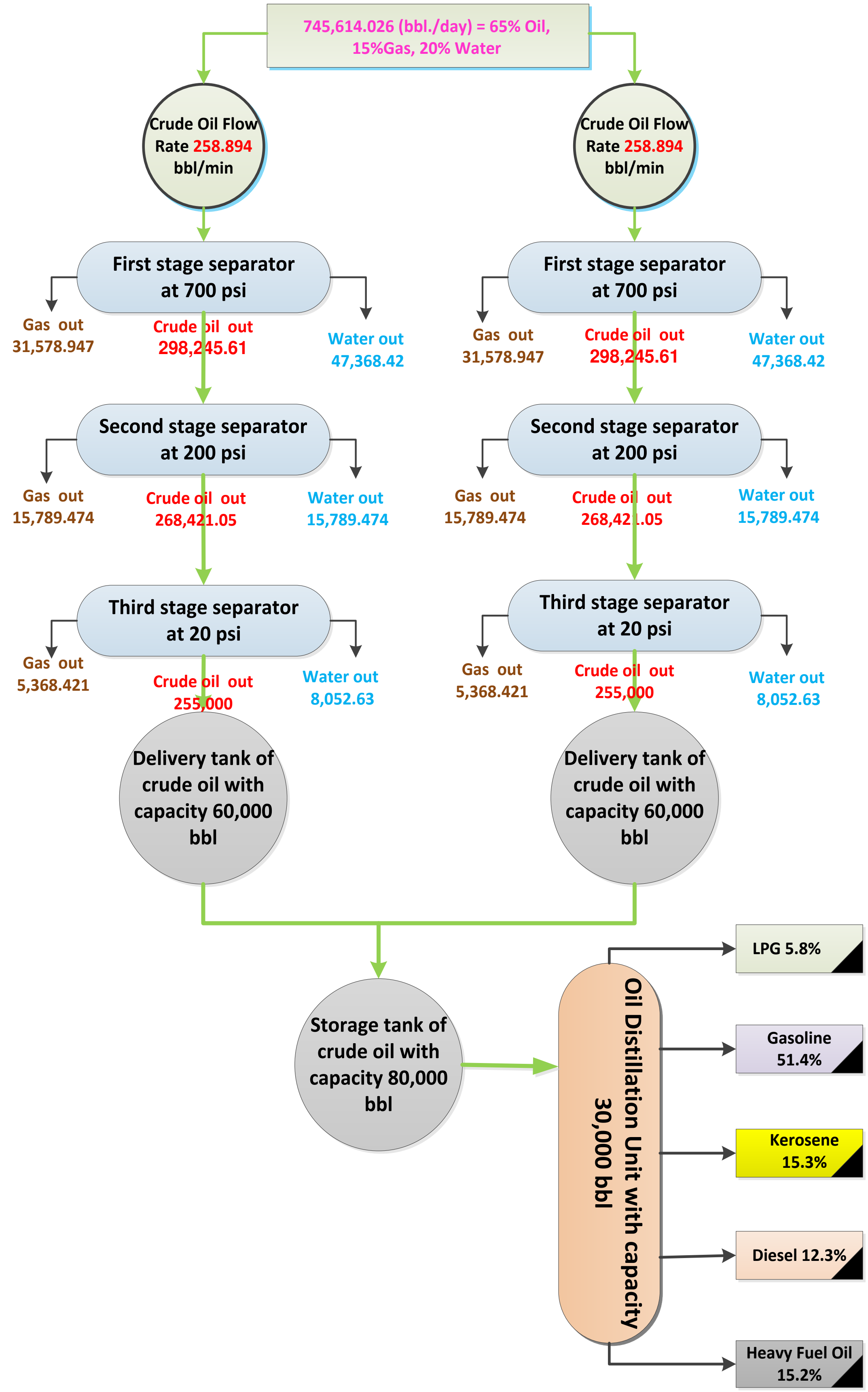


Figure 6.1 Process Flow Chart of the proposed model

pressure from 700 psi to 200 psi, separating the crude oil again into oil, gas, and water. At this stage, the percentage of water and gas separated are less than that of the first separation stage while the gas flows to the gas-plant and the water flows to the water-treatment reservoir. The crude oil still contains some amount of gas and water; therefore the oil is transferred to the third stage (SP3) at pressure 30 psi and separated further into oil, gas, and water. After this stage, the oil obtained contains little or no water depending on the quality of the crude oil from the well. However, it is assumed in this model that the amount of water and gas have been fully separated at this stage of the separation processes.

After the separation processes is completed, the oil separated is transferred to two delivery tanks with capacity of 60,000 barrels each. The two delivery tanks are connected with a storage tank of capacity 80,000 barrels which feeds the distillation unit to produce final products namely: liquid petroleum gas (LPG), gasoline, fuel oil, diesel, kerosene, and heavy fuel oil. The equipment specification for the model is show in Table 6.1.

Table 6.1 the equipment of the system and their capacities

Equipment	Capacity (barrels)
2 lines (3 Separators / line)	25,000 / separator
2 X Delivery Tank	60,000 / tank
1 X Storage Tank	80,000
1 X Distillation Tower	30,000

6.4 The Kind of Model Developed

Based on the kind of models described in the previous chapter, we can classify the model built in this project as dynamic because its state is constantly evolving. It also exhibits continuous and discrete characteristic in the following ways: Crude Oil flowing into tanks as continues event while Sensors used to detect the level of crude oil in order to trigger outflow or stop flow as discrete event. Without the introduction of an uncertainty called failure via a probability distribution, the model would have been considered deterministic model; however, it is a Stochastic Model. Finally, the model is a non-terminating system because refineries usually never stop except there is a problem and are considered to have no beginning and end. The interest of the project was on the steady state of the system.

6.5 Assumptions of Simulation Model

As mentioned in the literature review that crude oil is a complex liquid mixture of hydrocarbon compounds and small amounts of organic compounds such as sulphur, oxygen, nitrogen of different concentrations determines the types of crude oil and therefore, affects the quality. The variety of crude oil types vary in factors such as viscosity, density, amount of impurities and amount of water which have a significant effect on the oil production processes and the quality of final products produced. Other factors that affect crude oil processing are temperature, pressure, diameter of pipeline, etc. It is a complicated task to take all of these factors in account when designing and analysing simulation model of petroleum SC.

In this research, the proposed simulation model focus on two areas, separation of crude oil and distillation process. Therefore, the assumptions with regards to experimental factors are discussed in these areas. The experimental factors assumed in this model are crude oil flow rate which determines the quantity of crude oil flowing into the system. The oil, gas, and water ratio is used as a measure for crude oil quality. The distillation capacity, number of failed separators that affect the amount of crude oil to be processed and the amounts of final products were also taken into account. The experimental factors and the performance measures are listed in Table 6.2.

Table 6.2 The Input, Output Components and experimental factors

Components	**Details**
Independent (Experimental Factors)	• Crude oil flow rate • Oil, Gas, and Water Ratio in the content • Distillation Processing Time • Number of failed separators
Dependent (Performance Measures)	• Number of barrels of Final Products • Equipment Utilization

6.5.1 Oil Flow Rate

Petroleum industry is complicated and taking all influential factors into account is difficult task, so due to complexities and lack of data involved with these factors, the flow rate of oil was defined based on the case study's systems physical parameter (i.e. the pipes dimension) and is calculated by equation 6.1:

$$Flow\ rate = \frac{1}{4}\pi d^2 v \tag{6.1}$$

Where:

d = diameter of oil pipeline

v = velocity of oil

By estimating:

Velocity of oil = 1 m/s

Diameter of pipeline = 36.8 inch ≅ 0.9346 m

$$Flow\ rate = \frac{1}{4} * \pi * (0.9346)^2 * 1m/s = 0.686\ m^3/s$$

$$1\ m^3 = 6.28981\ barrels$$

$$Flow\ rate = 0.686 * 6.28981 = 4.31488\frac{bbl}{s} = 258.894\ bbl/min$$

$$\cong 372807\ bbl/day$$

6.5.2 Quality of Crude Oil

The data relating to quality of crude oil was presented based on its ratio of oil, gas and water content. Other refineries oil quality Mohammed et al. (2008); Karim et al. (2015) were also considered, however the data was collected from El-Sharara oil field which is one of the biggest Libyan oil fields. Five types of crude oil quality see Figure 6.2, considered as the proportion of oil, gas and water does not only vary between reservoirs but also throughout production because to facilitate the recovery of crude oil, refineries either inject gas or water into the reservoirs in either water flooding or natural gas injection processes. The crude oil proportion of oil, gas and water through each stage of separation process for the 5 types of crude oil are detailed in Table 6.3 to Table

6.7 where Q1, Q2 are lower quality while Q4, Q5 are higher quality crude when compared to the base Q3.

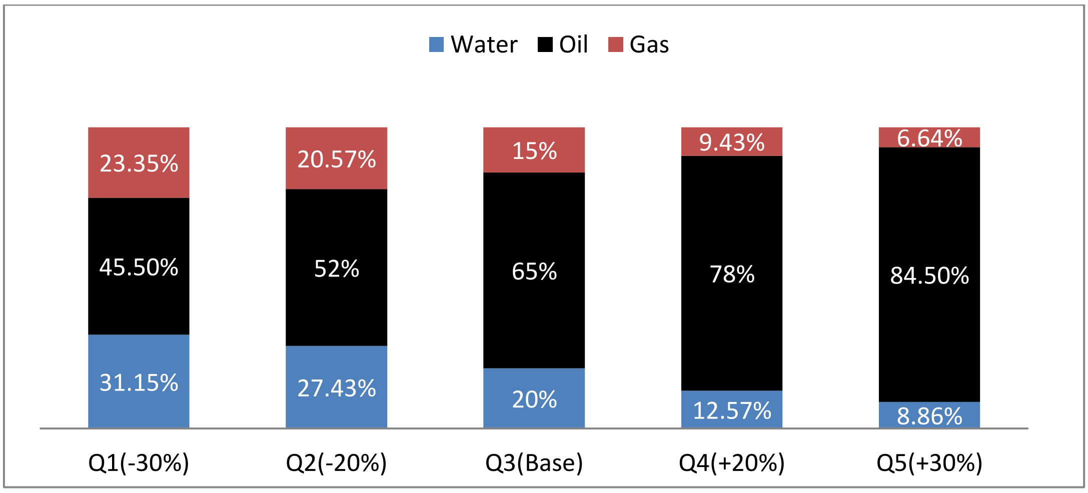


Figure 6.2 Crude Oil Quality Represented in Proportion of Oil, Gas and Water

Table 6.3 Crude Oil Quality Q3 (Base) and Proportion of Oil, Gas and Water at each Stage of Separation

Crude Oil Arrival Rate	372807.013 (bbl./day) Content of 65% Oil, 15% Gas, and 20% Water		
First Stage of Separation SP1	Outputs (bbl./day)		
	80% Oil	8% Gas	12% Water
	298,245.61	29,824.56	44,736.84
Second Stage of Separation SP2	Outputs (bbl./day)		
	90% Oil	5% Gas	5% Water
	268,421.05	14,912.28	14,912.28
Third Stage of Separation SP3	Outputs (bbl./day)		
	95% Oil	2% Gas	3% Water
	255,000	5,3687.421	8,052.63

Table 6.4 Quality of Crude Oil Q1 (-30%) and Proportion of Oil, Gas and Water at each Stage of Separation

Crude Oil Arrival Rate	372807.013 (bbl./day) Content of 45.5%Oil, 23.35%Gas, 31.15%Water		
First Stage of Separation SP1	Outputs (bbl/day)		
	68% Oil	14% Gas	18% Water
	253508.768	52192.98	67105.262
Second Stage of Separation SP2	Outputs (bbl/day)		
	84% Oil	7% Gas	9% Water
	212947.36	17745.61	22815.789
Third Stage of Separation SP3	Outputs (bbl/day)		
	93.5% Oil	2.35% Gas	4.15% Water
	199105.786	5004.262	8837.315

Table 6.5 Quality of Crude Oil Q2 (-20%) and Proportion of Oil, Gas and Water at each Stage of Separation

Crude Oil Arrival Rate	372807.013 (bbl./day) Content of 52%Oil, 20.57%Gas, 27.43%Water		
First Stage of Separation SP1	Outputs (bbl/day)		
	72% Oil	12% Gas	16% Water
	268421.049	44736.84	59649.122
Second Stage of Separation SP2	Outputs (bbl/day)		
	85% Oil	7% Gas	8% Water
	228157.89	18789.47	21473.68
Third Stage of Separation SP3	Outputs (bbl/day)		
	93% Oil	3.57% Gas	3.43% Water
	212186.839	8145.236	7825.815

Table 6.6 Quality of Crude Oil Q4 (+20%) and Proportion of Oil, Gas and Water at each Stage of Separation

Crude Oil Arrival Rate	372807.013 (bbl./day) Content of 78%Oil, 9.43%Gas, 12.57%Water		
First Stage of Separation SP1	Outputs (bbl/day)		
	88% Oil	5% Gas	7% Water
	328070.17	18640.35	26096.49
Second Stage of Separation SP2	Outputs (bbl/day)		
	94% Oil	3% Gas	3% Water
	308385.96	9842.11	9842.11
Third Stage of Separation SP3	Outputs (bbl/day)		
	96% Oil	1.43% Gas	2.57% Water
	296050.522	4409.92	7925.52

Table 6.7 Quality of Crude Oil Q5 (+30%) and Proportion of Oil, Gas and Water at each Stage of Separation

Crude Oil Arrival Rate	372807.013 (bbl./day) Content of 84.5%Oil, 6.64%Gas, 8.86%Water		
First Stage of Separation SP1	Outputs (bbl/day)		
	93% Oil	3% Gas	4% Water
	346710.522	11184.21	14912.28
Second Stage of Separation SP2	Outputs (bbl/day)		
	95% Oil	2% Gas	3% Water
	329374.995	6934.21	10401.315
Third Stage of Separation SP3	Outputs (bbl/day)		
	96.5% Oil	1.64% Gas	1.86% Water
	317846.87	5401.75	6126.375

6.5.3 Distillation Unit Process

The distillation unit process is one of the key elements for many processes of petroleum refineries as it is responsible for separating the crude oil into its useful constituents. It is important for operators to understand how distillation system is working. The distillation unit that is designed in the simulation model of this research is showed in Figure 6.3. The process of a distillation unit starts when oil is pumped from storage tank into boiler. The preheated oil in the boiler is heated and pressured just below boiling point. The pressure inside the distillation tower is lower than the pressure inside preheating, so when oil is fed into the tower it starts to boil. The vapour of the liquid such as LPG rises to the top of the tower and the remaining of liquid consists of a heaver component move down to the bottom of the tower. Five products were produced from distillation unit process and according to the data collected from real petroleum refineries, the percentage of final products are about (5.8% LPG, 51.4% Gasoline, 15.3% Kerosene, 12.3% Diesel and 15.2% Heavy Fuel Oil).

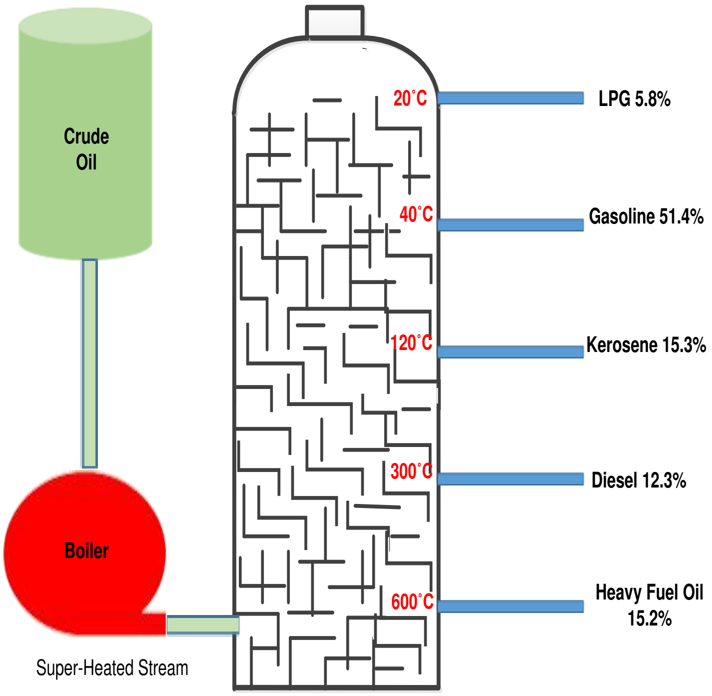


Figure 6.3 The distillation Column

In the model, the variation in boiling point of the various constituent of crude was used to determine what time each distillate is recovered from the distillation process. The temperature of recovery and the processing time are show in Table 6.8. Unlike the separation process where the time taken to complete separation was defined as 1 minute irrespective of the input rate, the distillation process time for completely raising the temperature of the base input rate R1 (258.894 bbl./min i.e. 372807.013 bbl./day) from 20 ˚C as initial temperature to 600˚C is 70 minutes. This implies that by 70 minutes, the heaviest hydrocarbon (Heavy Fuel Oil) will have been recovered from the distillation unit. It was on these bases that recovery timing for each distillate was determined and incorporated into the simulation:

Total time of distillation process = 70 min.

The highest temperature inside distillation unit = 600 c˚.

Time taken to rise the temperature inside distillation tower by one degree = 70min /600 c˚ = 0.117 min/ c˚.

To get the processing time for each product, it was done by multiplying each product recovery temperature by 0.117 min/ c˚ as shown in Table 6.8.

Table 6.8 The processing time needed for each product

Products	Temperature	Time (min.)
LPG	20˚C	2.33
Gasoline	40˚C	4.64
Kerosene	120˚C	13.92
Diesel	300˚C	34.8
Heavy Fuel Oil	600˚C	69.6

6.5.4 Failure of Separators

The failure of the separators is one factor that was considered to have impact on the production of crude. Separators failure is very common in both new and old crude oil production facilities but the tendency of failure occurring is high in a new facility, reduces when the facility grows older and again increases towards the end of the separators service life. As can be seen from the bathtub curve in Figure 6.4, failure is an uncertainty that could occur at any stage of a product life.

The simulation model has 6 separators, any of which can fail at any time with random occurrence. Based on this, it was decided that all possible combination of the number of separators (0 to 6) that can fail be considered. According to Kelton et al. (2008), Weibull distribution is suitable in reliability models to determine the lifetime of a device. Thus, Weibull distribution was used to depict the failure pattern of each separator. Furthermore, they stated that Gamma distribution can be used to represent time taken to complete a task, such as machining time or machine repair time. Therefore, Gamma distribution was used to represent time taken to repair a separator after failure.

In the proposed simulation model, the mean time between failure (MTBF) used with the Weibull distribution was 30 days; this was based on data collected from the oil field company and scale and shape parameters used to represent this time were 5 and 1 respectively. While the mean time between repairs (MTBR) used with Gamma distribution was 30 minutes for the six separators and generated randomly within the simulation software following Gamma distribution with scale parameter (0.5) and shape parameter (9). These values were also assumed based on the data collected from the company which is recently developed.

In this regard, the values of MTBF and MTBR were assumed based on the high tendency of failure that expected to occur at early age of a new facility, the assumed values have been tested and prove to give same trend as shown in the early part of the curve shown in Figure 6.4.

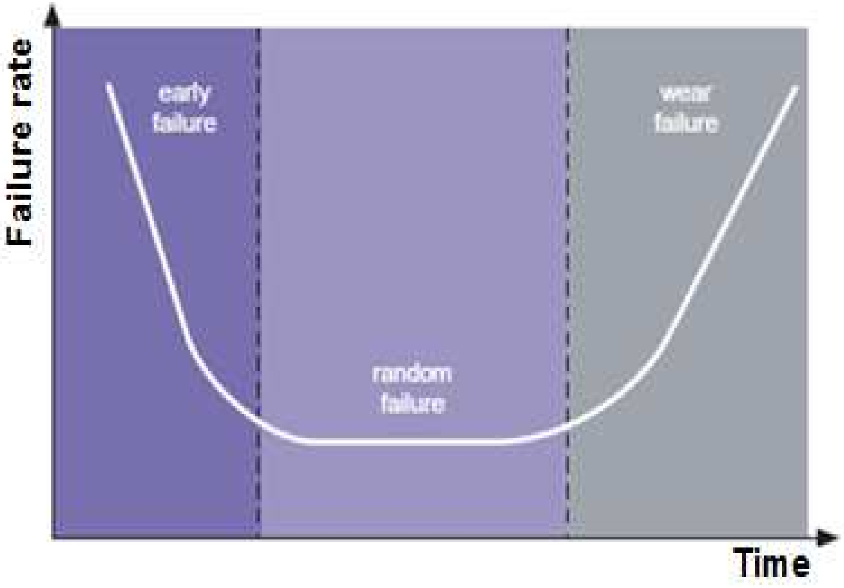
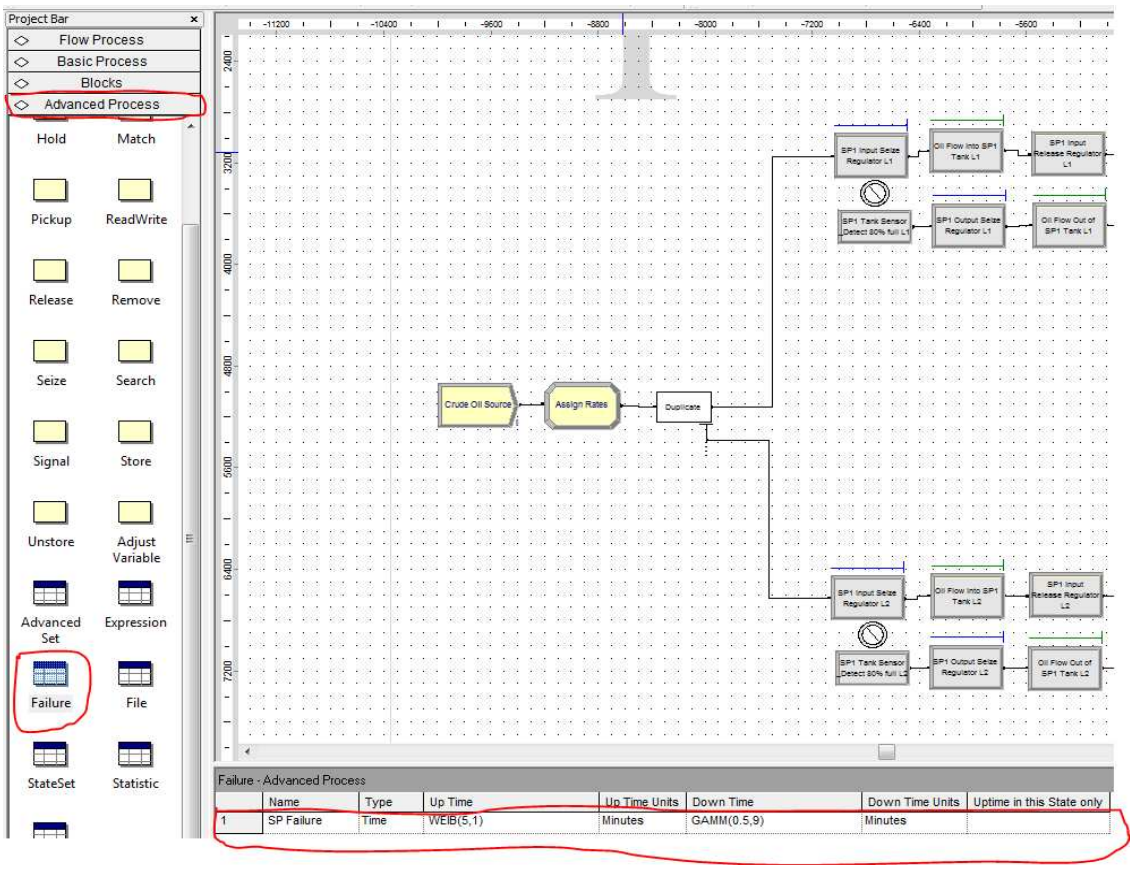


Figure 6.4 Bathtub Curve for Failure Frequency

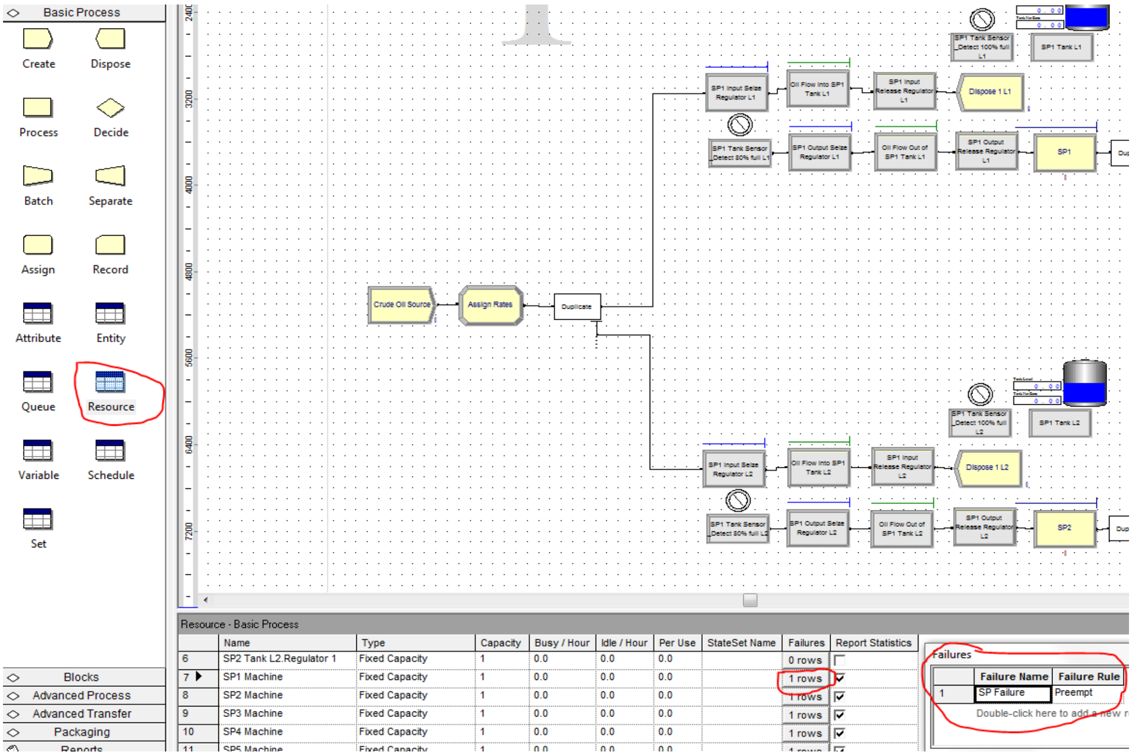
The values were inputted into Arena using the Failure and Resource modules as show in Figure 6.5 and Figure 6.6 respectively. Furthermore, since the separators selected to fail was predetermined, the sequence of selection was determined based on trials. The failure was first started from the first separator (SP1) failing to the last separator (SP6) failing and it was observed that due to failure staring at the beginning of the process the output when 3 & 6 numbers of separators failed is higher than 2 & 4 respectively see Figure 6.7. The failure was later tested starting from the last separator (SP6) to the first separator failing which provided a reasonable result showing that an increase in the number of separators failing is inversely proportional to the total barrels produced as indicated in Figure 6.8.



Failure - Advanced Process

	Name	Type	Up Time	Up Time Units	Down Time	Down Time Units	Uptime in this State only
1	SP Failure	Time	WEIB(5,1)	Minutes	GAMM(0.5,9)	Minutes	

Figure 6.5 Screenshot illustrating how failure was incorporated into the System



Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
6	SP2 Tank L2.Regulator 1	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☐
7	SP1 Machine	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
8	SP2 Machine	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
9	SP3 Machine	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
10	SP4 Machine	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
11	SP5 Machine	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑

Failures

	Failure Name	Failure Rule
1	SP Failure	Preempt

Double-click here to add a new r

Figure 6.6 Screenshot illustrating how failure was incorporated into the Recourse

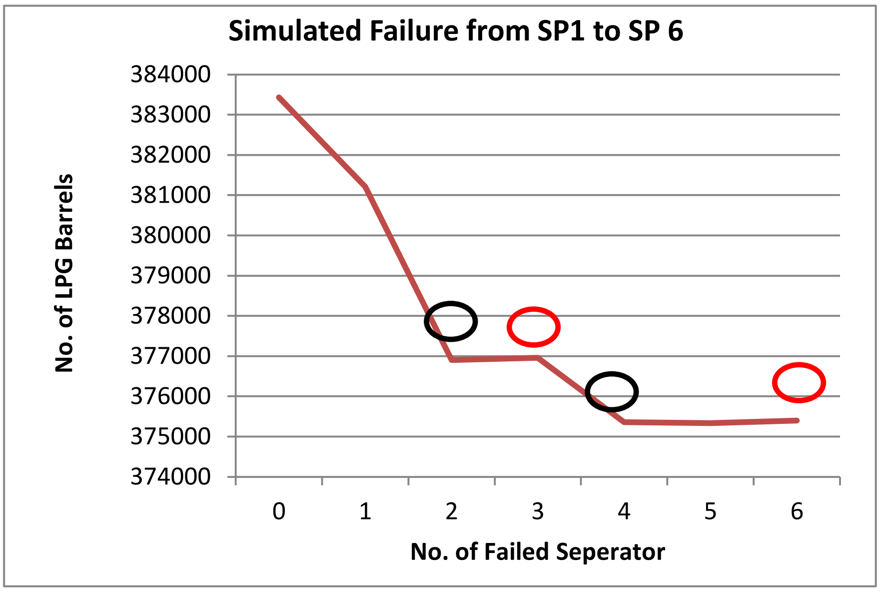


Figure 6.7 Simulated Failures from SP1 to SP6

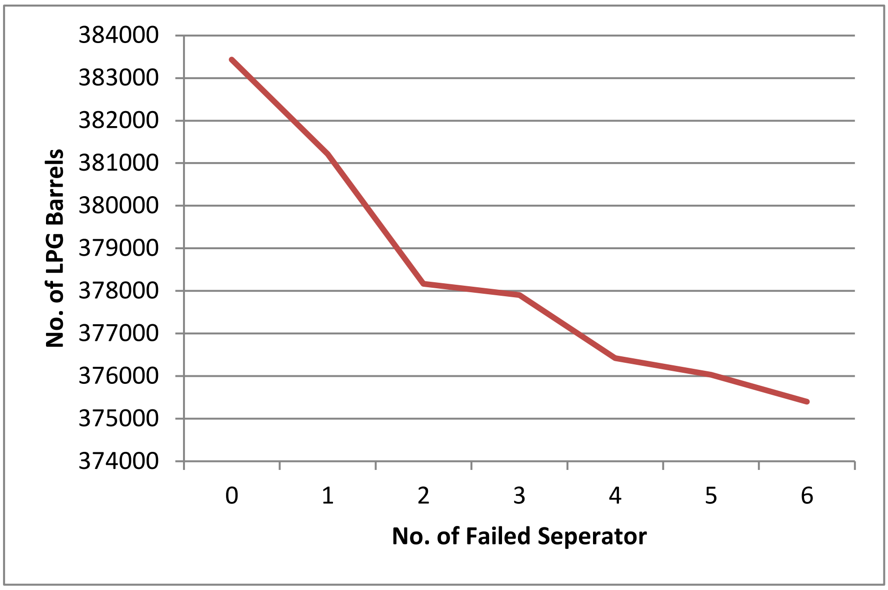


Figure 6.8 Simulated Failures from SP6 to SP1

6.5.5 Processing Time Affected by Quantity Change

As part of the distillation process, crude oil is heated to about 600 degrees Celsius before it is separated into fractions. As different quantity of crude will require different heating time, it is vital that this is considered in the simulation to get close results to the real system. To change the temperature of an object, heat energy is required. The amount required will depend on the mass of the object, the temperature change and the material it is made from. Furthermore, when a substance has reached it boiling point, it requires further energy to change its state from liquid to gas. This is related to the specific latent heat of the substance. For this research, the specific latent heat will not be considered because not all the distillates of crude oil are collected in gaseous state and also due to difficulties in obtaining the specific latent heat values for each distillate.

The equation for energy required to change in the temperature of an object is given below:

Where:

P = Power (Watt),

E = Energy (Joule),

Cp= Specific heat capacity (Joule/Kg/ ºC),

ΔT = Temperature change (ºC),

t = time (seconds) and

M = Mass (Kg).

Equation 6.2: Energy Relating to Specific Heat Capacity

$$\boldsymbol{E = M \times Cp \times \Delta T} \tag{6.2}$$

Also

Equation 6.3: Energy Relating to Power and Time

$$\boldsymbol{E = P \times t} \tag{6.3}$$

Combining both Equation 6.2 and Equation 6.3 while solving for time gives:

Equation 6.4: Time in Relation to Mass

$$\mathbf{t} = \frac{\boldsymbol{M \times Cp \times \Delta T}}{\boldsymbol{P}} \tag{6.4}$$

From Equation 6.4 it can be seen that the time required to change the temperature of an object is directly proportional to the mass of the object. Based on this equation the base value of the output after the third separation stage was divided with an Optimum Production Volume **(OPV)** which gave a value ($\boldsymbol{\frac{SP3\ Rate}{OPV}}$) used in adjusting the processing time when the Input Rate varies. More light will be thrown on this in further chapter.

6.6 Model-Building

The model representing activities from the crude oil source which flow through separation processes to distillation unit processes passing through delivery tanks and storage tank as showed in Figure 6.1, all of these activities were built using a hundred and thirty modules in Arena simulation software. In building the model, the system was divided into three phases (Production Line 1, Production Line 2 and Distillation) and each phase was further divided into sections as show in Figure 6.9.

This approach eased verification, validation and also helped in reducing the time for building the model as similar sectioned were copied rather than been built from the scratch. Since Phase 1 (Production Line 1) and Phase 2 (Production Line 2) are identical, explaining how of the phase was built was deemed sufficient.

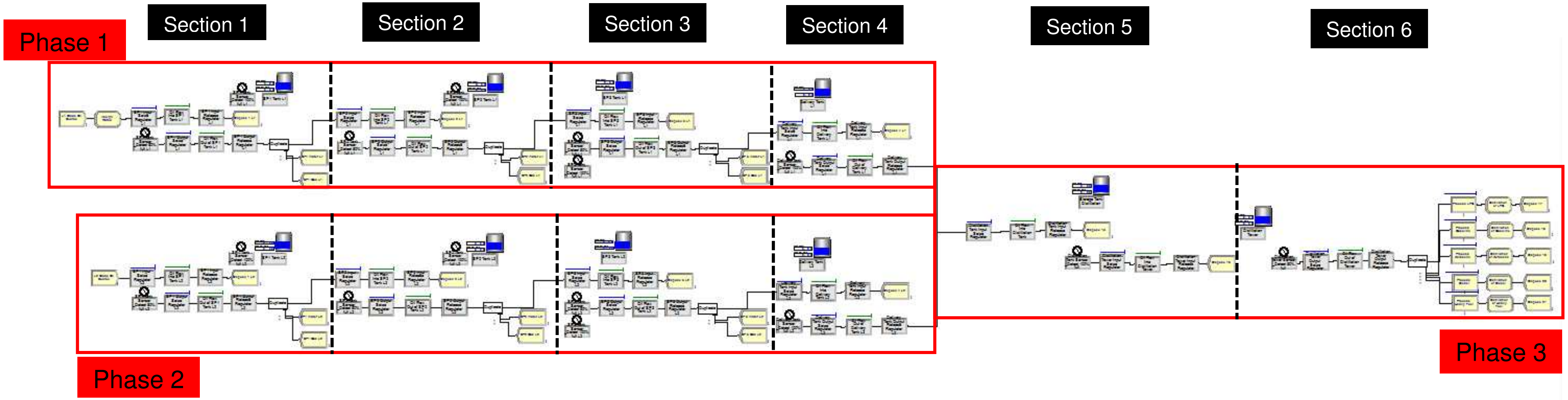


Figure 6.9 The Simulation Model Build-up in Phases and Sections

6.6.1 Phase1 (Production Line 1)

This phase was divided into 4 sections. Section 1 named "1st stage of separation" was responsible for processing crude from the oil well and separates it into water, gas and oil under pressure of 700 psi. Section 2 named "2nd stage of separation" receives oil from Sections 1 and further separates it into oil, water and gas under pressure of 200 psi. Section 3 named "3rd stage of separation" is responsible for processing oil from Section 2 under pressure of 20 psi with the aim of obtaining pure oil at this stage. The final section of this phase is responsible for transferring the oil from the 3rd stage of separation to the delivery tank

6.6.1.1 1st Stage of Separation (Section 1)

Figure 6.10 is a screenshot of the first stage of separation while Figure 6.11 illustrates a brief process description of the 1st stage of separation using a flow chart. The system starts with a Create Module named "Crude Oil Source" which is responsible for generating the entities named "Crude Oil" that flows to the 1st stage of separation.

In-between the Create Module and the 1st stage of separation an Assign Module was used to control the Input Rate (R1, R2 and R3), the Quality of Crude Oil (Q1, Q2, Q3, Q4 and Q5), the Separation Ratio of the separators used in the system, the Distillation Capacity and the Optimum Production Volume(OPV). Table 6.9 shows the variables used to store values defined in the Assign Module:

Table 6.9 Variables used in the Assign Module at the Beginning of the simulation

Variables	Purpose
Oil Source Rate	Controls the crude oil source Input Rate.
Separation SP1 ratio 1	Controls the Separator ratio of water, oil and gas in the1st Stage of Separation.
Separation SP2 ratio 2	Controls the Separator ratio of water, oil and gas in the 2nd Stage of Separation.
Separation SP2 ratio 3	Controls the Separator ratio of water, oil and gas in the 3rd Stage of Separation.
SP1 Rate	The value of oil that flows out after the 1st stage of separation.
SP2 Rate	The value of oil that flows out after the 2nd stage of separation.
SP3 Rate	The value of oil that flows out after the 3rd stage of separation.
Distillation time DC	Controls the capacity of the distillation unit.
Optimum production volume (OPV)	The optimum value which the system was design.

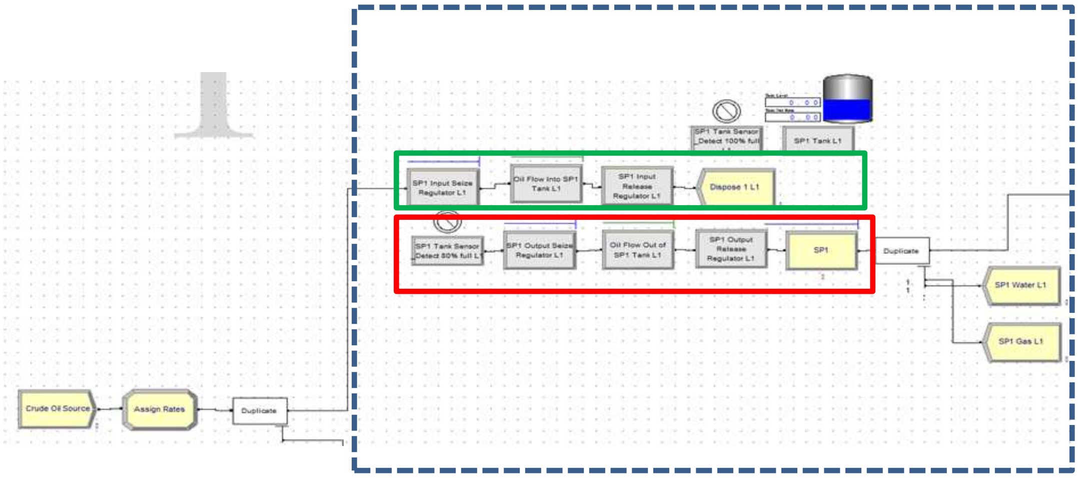


Figure 6.10 Screenshot from Crude Oil Source to the End of 1st Stage of Separation

The entities then flow from the Assign Modules to Duplicate Module which is responsible for supplying both Production Line 1 and 2 with crude oil. The entities then flow to the Input Seize Regulator which can be viewed as a regulator that controls the open valve to the Tank Module. After the Input Seize Regulator, the entities flow to the Flow Module responsible for adjusting flow of crude into the Tank Module. The capacity of the tanks for each separation stage was 25,000 barrels. Afterwards, the entities pass through the Input Release Regulator which releases the Tank that was initially engaged by entities via the Input Seize Regulator, allowing other regulators to make use of the Tanks in certain situation such as when the Tank is full. This chain of modules highlighted in green in Figure 6.10 responsible for the supply of crude oil into the SP1 Tank is then ended by a Dispose Module which serves as the ending point for entities in a simulation. A sensor was attached to the Tank Module to detect if the level of crude oil is 100% full upon which it sends a trigger to stops the crude oil flow, preventing overflow. Another chain of Modules highlighted in red in Figure 6.10 was used to coordinate the removal of crude oil from SP1 Tank, sending it to the 700 psi separator to be separated into Oil, Gas and water. This chain of modules started with a sensor which triggers flow out of SP1 Tank when the level of crude within reaches 80%. The sensor is followed by an Output Seize Regulator which can be viewed as a regulator of the SP1 Tank output valve after which a Flow Module coordinates the flow of crude oil out of the tank. An Out Release Regulator then follows which is responsible for disengaging SP1 Tank. This module can be viewed as responsible for closing the output valve of a Tank Module. The crude oil entities are then transferred to the Separator which is made up of the Process and Duplicate Module. The Process Module also allowed setting failures into the separators while the Duplicate Module enabled the separation of the Crude Oil entities into Oil, Water and Gas. Since Water and Gas were not the interest of this project, a Dispose Module was used to remove them out of the system while the Oil was transferred to the 2nd stage of separation.

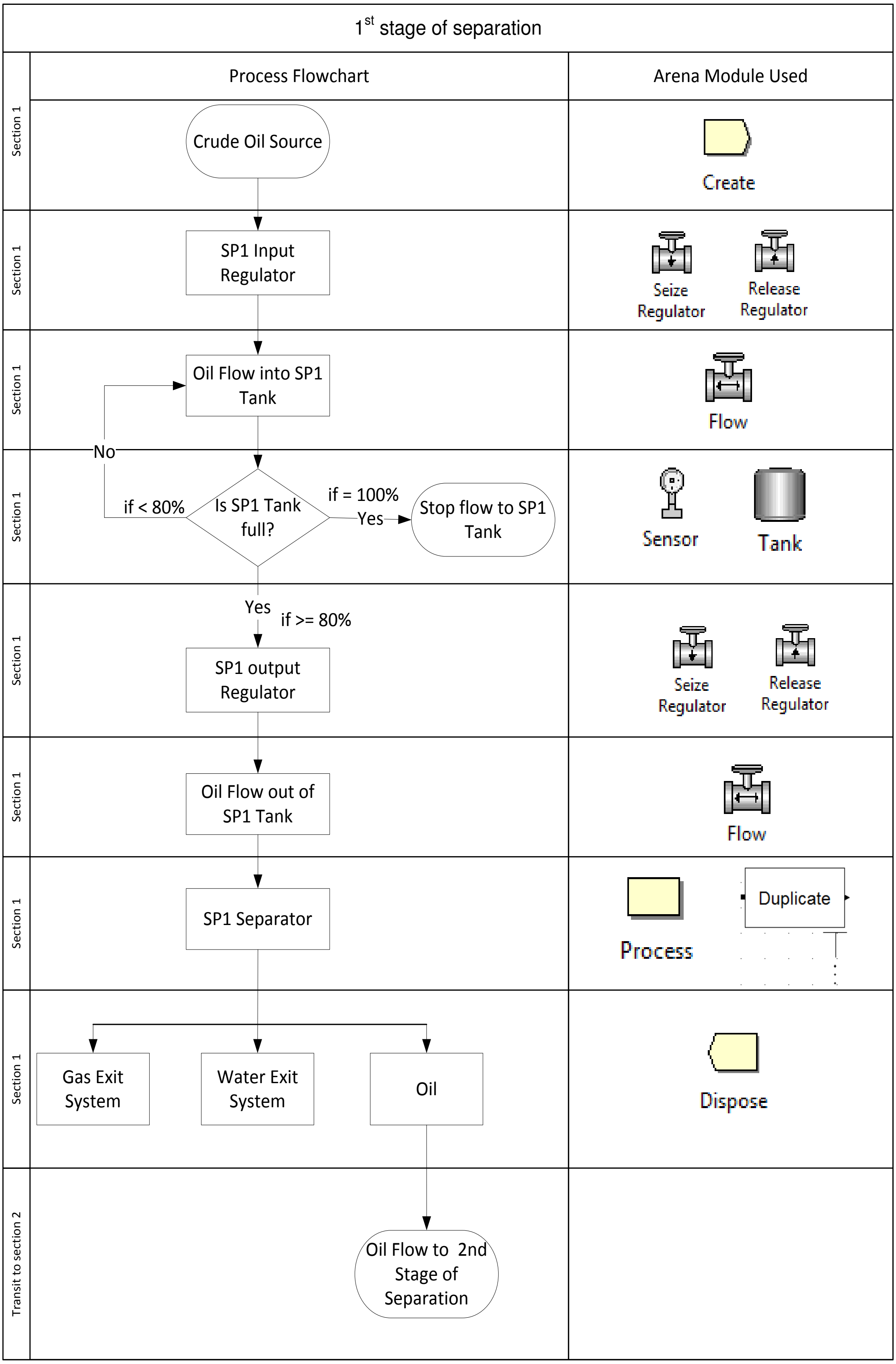


Figure 6.11 the 1st Stage of Separation Illustrated by a Process Flow Chart and Respective Arena Modules Used

The separation was controlled by Equation 6.5 containing variables used in the modules. Equation 6.5: Controlling Separator Ratio for 1st Stage of Separation.

$$\boldsymbol{SP1\ Rate = Source\ Rate\ \times Separation\ \ Ratio1} \tag{6.5}$$

After building Section 1 of Phase 1, the remaining Sections 2, 3, and 4 were built by copying and pasting Section 1 as indicated with the dotted line in Figure 6.6. The copied modules had to be renamed differently for each section as Arena Software requires each Module to be unique. Another thing that was done different was the facts that each section had different parameters and they were defined respectively. Rather than repeating the description of how Sections 2, 3, and 4 were built, as they are similar to Section 1, the explained build-up of the 1st stage of separation was deemed sufficient. Screenshots and flowcharts of Sections 2, 3, and 4 are presented

6.6.1.2 2nd Stage of Separation (Section 2)

The 2nd stage of separation receives the Oil from 1st stage of separation and further processes it under pressure of 200 psi. Equation 6.6 controls the ratio of Oil, Water and Gas for the 2nd Stage of Separation:

$$\boldsymbol{SP2\ Rate = SP1\ Rate \times Separation\ \ Ratio2} \tag{6.6}$$

Figure 6.12 is a screenshot of 2nd Stage of Separation while Figure 6.13 is a flowchart describing the process involved and the related Arena Modules used.

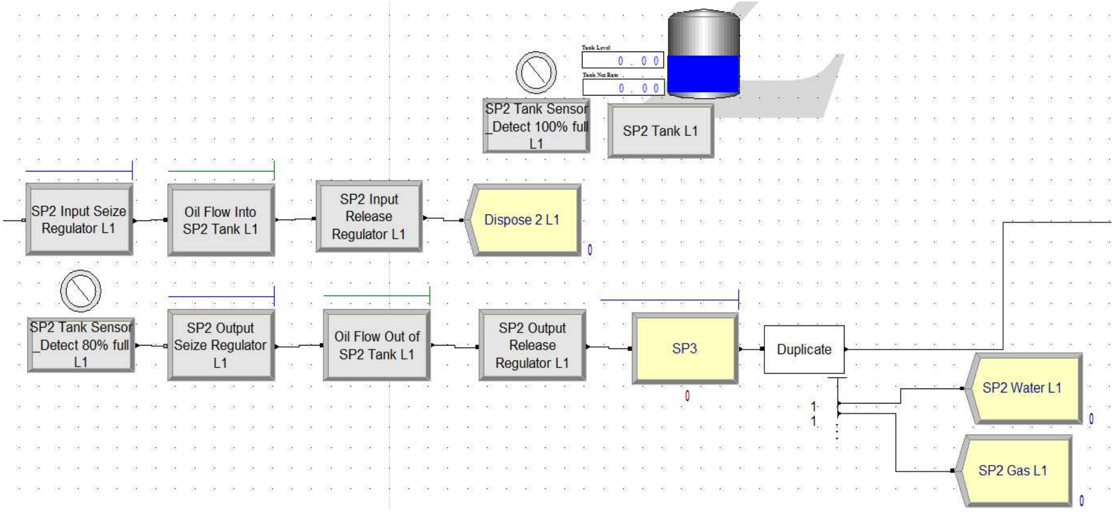


Figure 6.12 Screenshot of the 2nd Stage of Separation

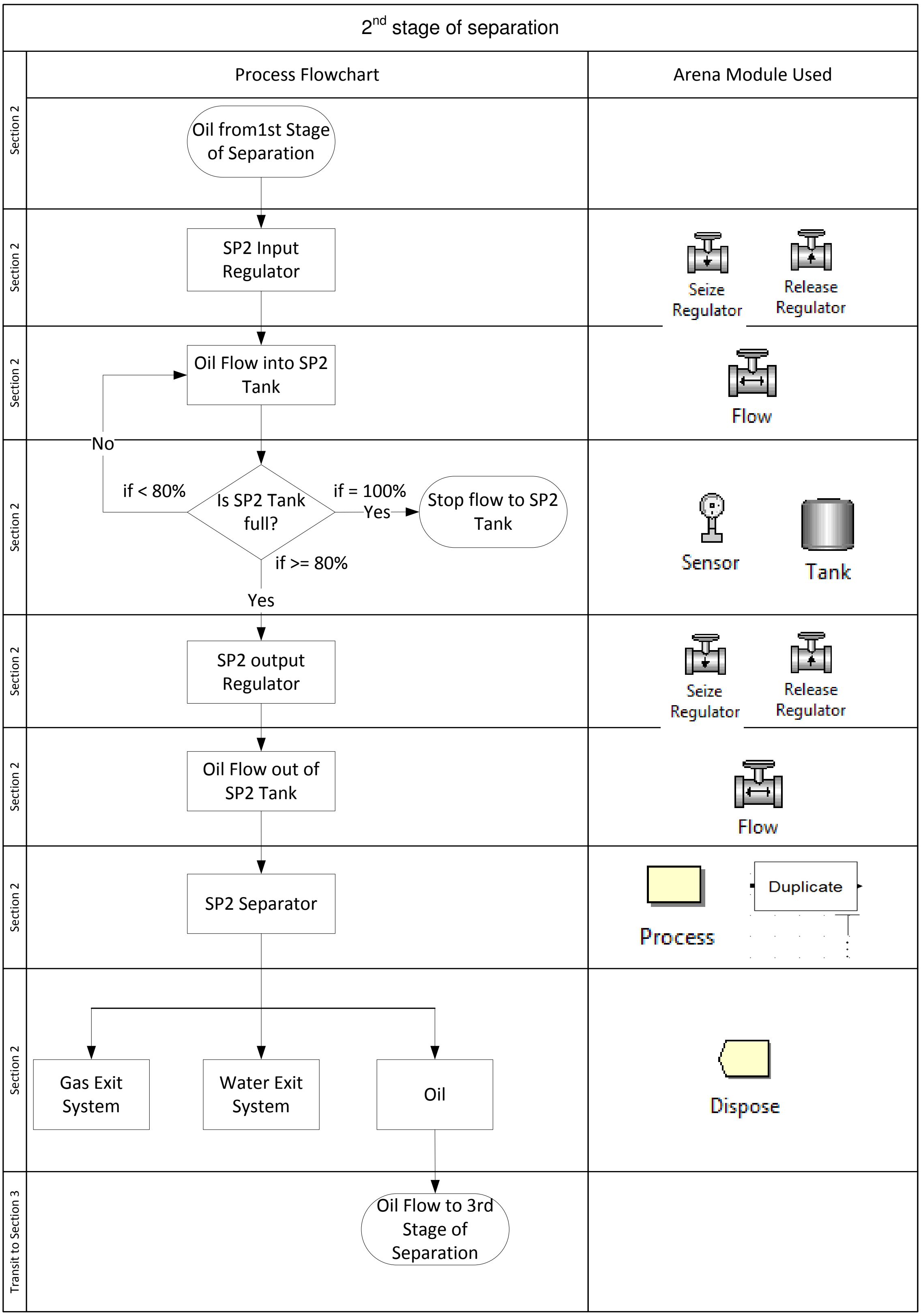


Figure 6.13 the 2nd Stage of Separation Illustrated by a Process Flow Chart and Respective Arena Modules Used

6.6.1.3 The 3rd Stage of Separation (Section 3)

The 3rd stage of separation (section 3) receives the Oil from 2nd stage of separation and further processes it under pressure of 20 psi. Equation 6.7 controls the ratio Oil, Water and Gas for 3rd Stage of Separation.

$$\boldsymbol{SP3\ Output\ Rate = SP2\ Input\ Rate \times Separation\ Ratio3} \tag{6.7}$$

Figure 6.14 is screenshot of 3rd Stage of Separation while Figure 6.15 is a flowchart describing the process involved and the related Arena Modules used.

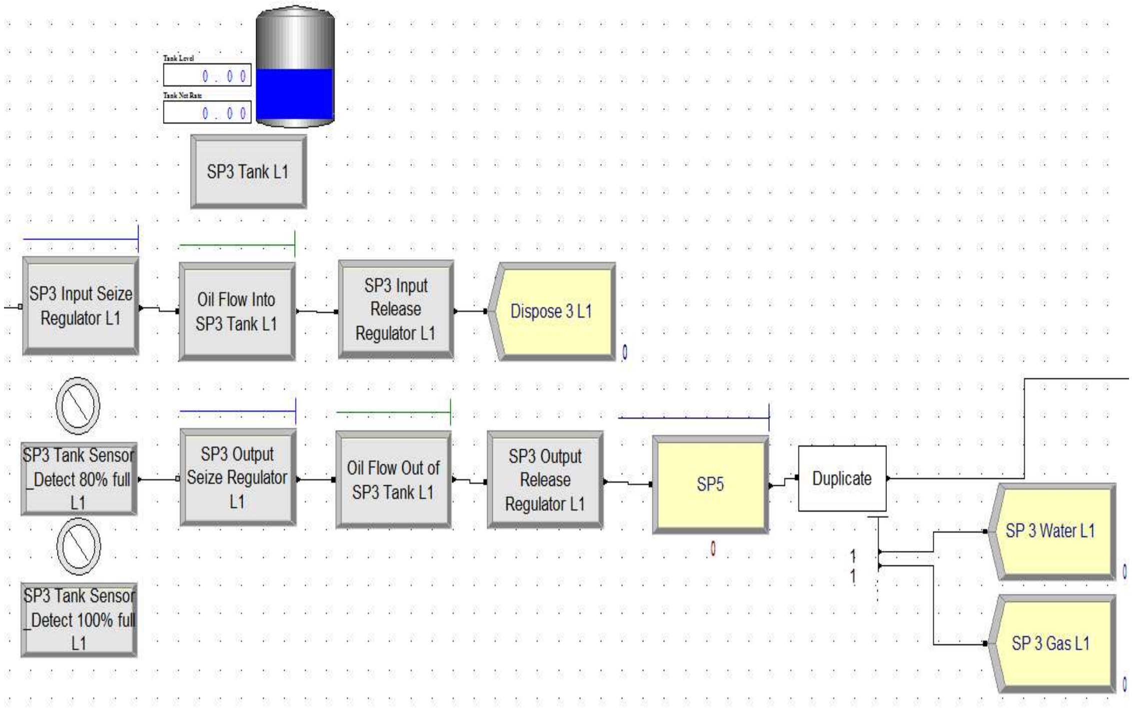


Figure 6.14 Screenshot of the 3rd Stage of Separation

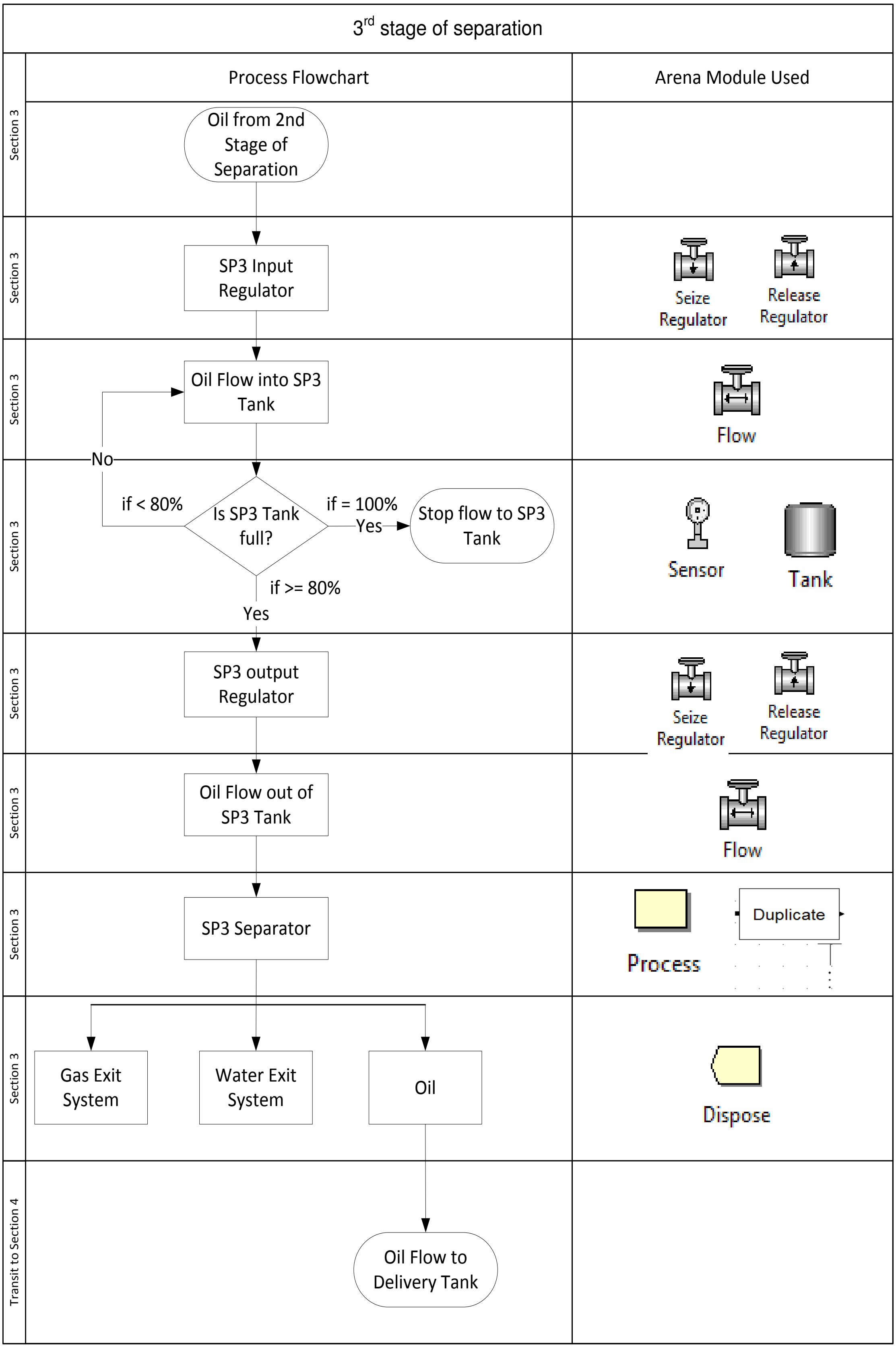


Figure 6.15 the 3rd Stage of Separation Illustrated by a Process Flow Chart and Respective Arena Modules Used

6.6.1.4 Deliver (Section 4)

Unlike Section 1, 2 and 3 which had separators (i.e. a Process and Duplicate Module), Section 4 had non as it was solely designed to collect all the oil that have completed in the three stages of separation process with each line having its own Delivery Tank. Rather than using a joint Delivery Tank for both lines, it was easier to collect the data about the oil contribution of each individual line arriving from the final stage of separation. The same chain of modules used to direct oils into and out of the Tanks during the separation was also used to deliver Oil to and out of the Delivery Tank as show with the blue and red highlights in Figure 6.16. The completion of section 4 marked of the end of the build-up of Phase 1(Production Line 1) of the simulation model.

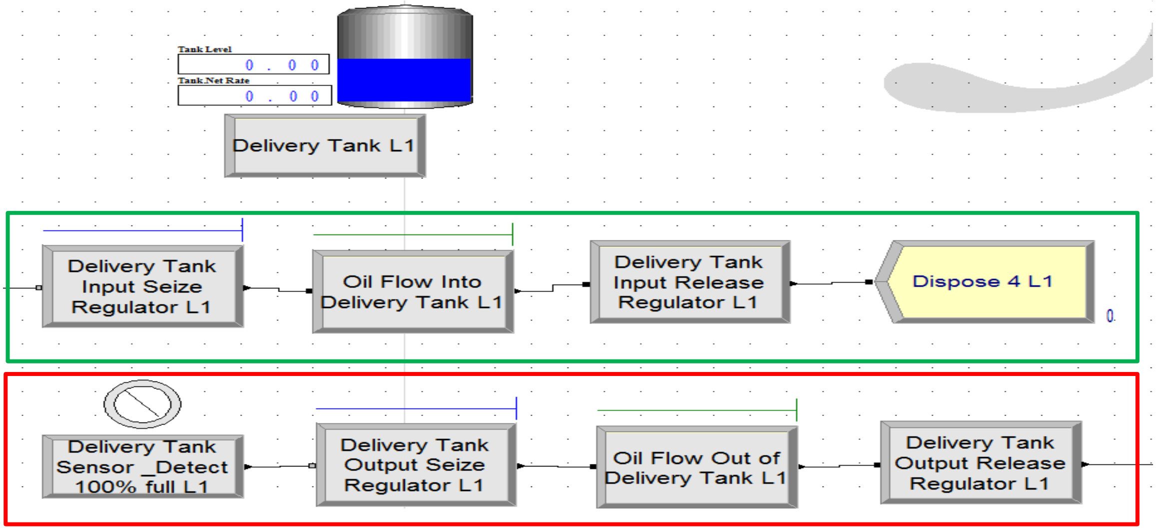


Figure 6.16 Screenshot of the Oil Delivery

6.6.2 Phase2 (Production Line 2)

Once Phase 1 was completed, Phase 2 was built by copying and pasting Phase 1 since both Phases were identical. Both shared variables defined in the Assign Module used in controlling the various setup for the model. It was also required to rename all the modules that were copied as Arena will trigger error if two modules share the same names. In Figure 6.17, Phase 1 is indicated by the black highlight while Phase 2 by the blue highlight.

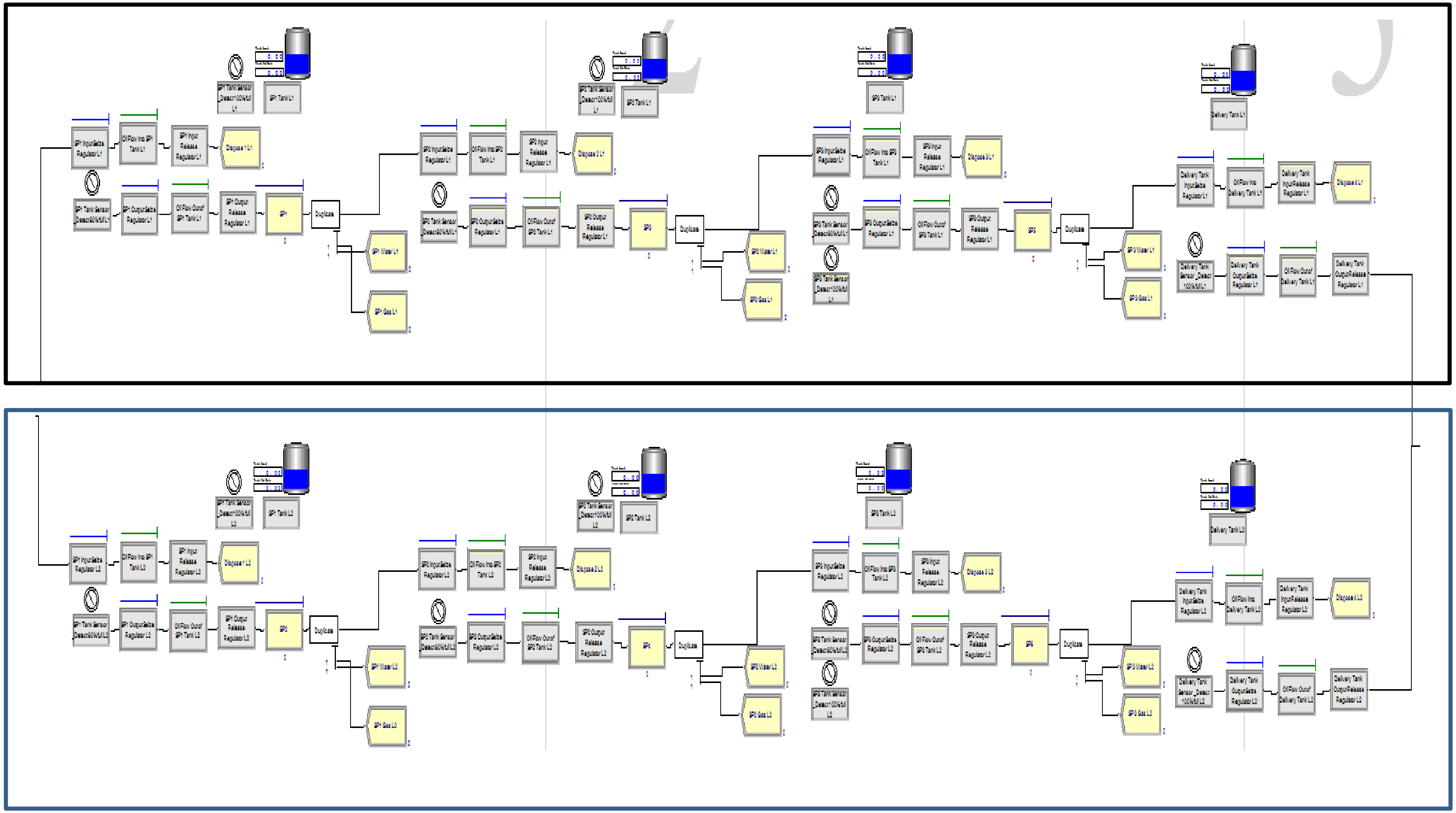


Figure 6.17 Indications of Line1 and Line 2 of the Model

6.6.3 Phase 3 (Storage and Distillation)

Upon completion of Phase 2, Phase 3 build-up was initiated. Phase 3 was divided into 2 sections. The first section named section 5 was responsible for storing Oil from the Deliver Tanks of Phase 1 and 2 before being transported to the Distillation Tower. The Second section named Section 6 was mainly responsible for distillation of Oil into its distillates (LPG, Gasoline, Kerosene, Diesel and Heavy Fuel).

6.6.3.1 Storage (Section 5)

Like the other Sections, a chain of modules consisting of Seize Regulator, Flow Module and Release Regulator was responsible for supplying the Oil into the Storage Tank having a capacity of 80,000 barrels. The flow into the Storage Tank is trigger by a Sensor Module on the condition that the Oil level in the Delivery Tanks reaches 100% of their 60,000 barrels capacity. The flow rate after the 3rd separation stage was maintained up to the delivery stage however the rate at which oil flow into the Storage Tank was allocated on the base of how much each individual line contribute. Figure 6.18 is a screenshot showing how the 3 phases are connected while Figure 6.19 is a flowchart giving a brief description of the transition from Phase 1 and 2 to Phase 3. Oil then flows out of the Storage Tank to the Distillation Tower which is trigger by a sensor that detects the Storage Tank with a capacity of 80,000 barrels is 100% full. The sensor is followed by Seize Regulator, Flow Module and Release Regulator coordinating oil flow into the Distillation Tower.

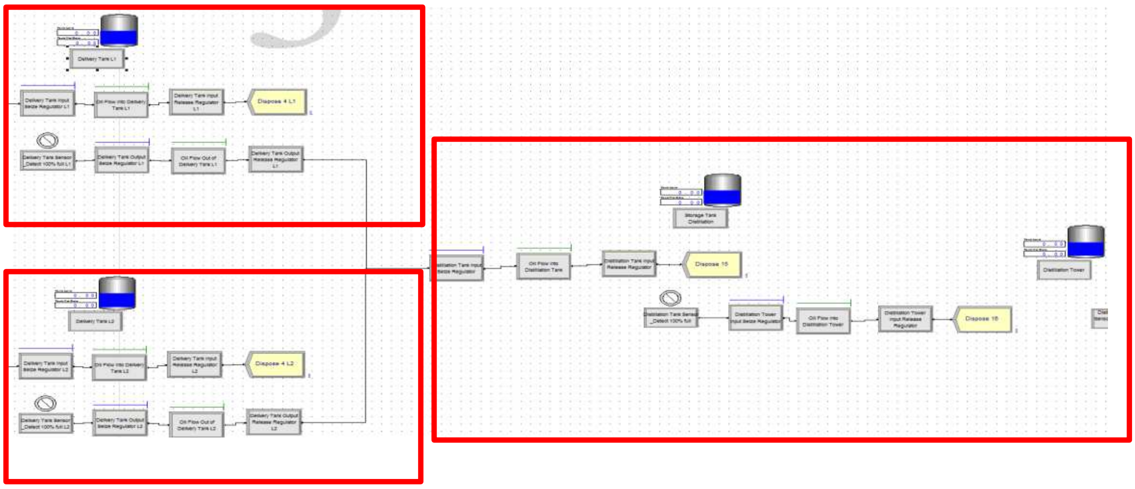


Figure 6.18 Screenshot Illustrating How Phase 1 (Section 4), 2 (Section 4) and 3 (Section 5) are connected

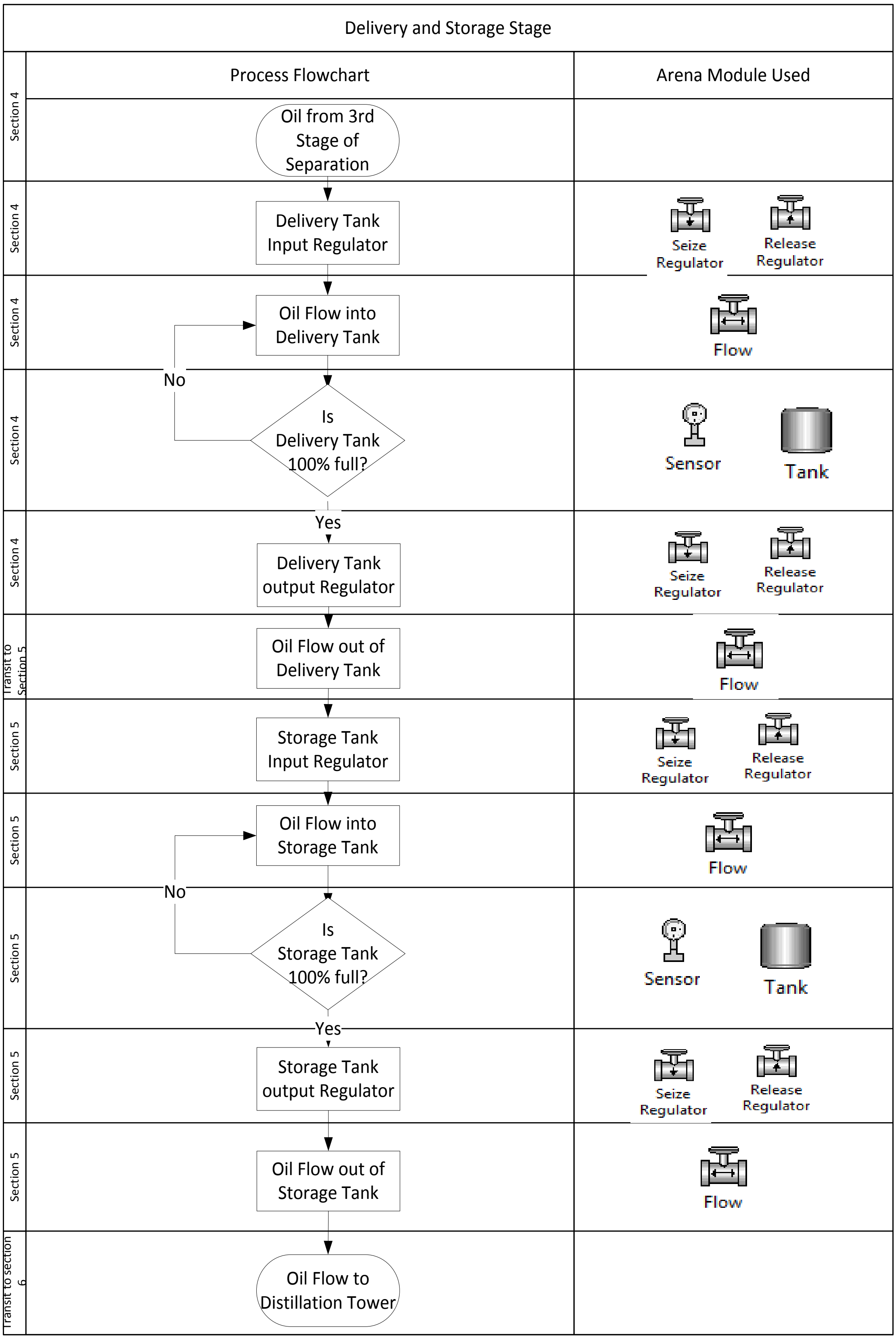


Figure 6.19 Deliveries and Storage Stage Illustrated by a Process Flow Chart and Respective Arena Modules Used

6.6.3.2 Distillation (Section 6)

The same chain of modules responsible for the supplying oil to the tanks in other sections was used to deliver oil from the distillation tower to the distillation area when the level of oil in the distillation tower reaches 80%. Figure 6.20 is a screen short of the distillation section while Figure 6.21 illustrates the distillation process using a flowchart. The distillation process started with the Assign Module where the setup of the distillation system was programmed. The variables defined in the Assign Module are PT LPG, PT Gasoline, PT Kerosene, PT Diesel and PT Heavy Fuel. The entities then flow into the Duplicate Module which was responsible for separating the entities into five distillates (LPG, Gasoline, Kerosene, Diesel and Heavy Fuel). However, to model the rate at which each distillate is recovered, 5 Process Modules (Process LPG, Process Gasoline, Process Kerosene, Process Diesel, and Process Heavy Fuel) were used; each allocated with the variables defined in the Assigned Module to Equation 6.8 to Equation 6.12 controlled the timing for each Process Module respectively.

Equation 6.8: Controlling the Process Time of Process Module for LPG

$$\boldsymbol{PT\ LPG = 2.33 \times \frac{SP3\ Rate}{OPV}} \tag{6.8}$$

Equation 6.9: Controlling the Process Time of Process Module for Gasoline

$$\boldsymbol{PT\ Gasoline = 4.64 \times \frac{SP3\ Rate}{OPV}} \tag{6.9}$$

Equation 6.10: Controlling the Process Time of Process Module for Kerosene

$$\boldsymbol{PT\ Kerosene = 13.92 \times \frac{SP3\ Rate}{OPV}} \tag{6.10}$$

Equation 6.11: Controlling the Process Time of Process Module for Diesel

$$\boldsymbol{PT\ Diesel = 34.8 \times \frac{SP3\ Rate}{OPV}} \tag{6.11}$$

Equation 6.12: Controlling the Process Time of Process Module for Heavy Fuel

$$\boldsymbol{PT\ Heavy\ Fuel = 69.6 \times \frac{SP3\ Rate}{OPV}} \tag{6.12}$$

The constant in each equation was explained earlier in Table 6.8. Furthermore, SP3 Rate/OPV in the equations was used to adjust the process time for each distillate when the input rates (R1, R2, and R3) varied at the Crude Oil Source. This enabled to vary the processing time with difference in input rate. After the entities for each distillate are processed by the Process Module, rather than using a Tank Module to store the distillates, an Assign Module was used to count the quantity of distillates processed as using a Tank Module might require fixing a capacity which might not be feasible since the quantity of the output varies with different system setup. The following variables named LPG Barrel, Gasoline Barrel, Kerosene Barrel, Diesel Barrel and Heavy Fuel Barrel were used to store the quantity of each distillate and the counting loop used in the Assign Module to achieve this are shown in Equation 6.13 to Equation 6.17.

.Equation 6.13: LPG Quantity Counting Loop

$$\boldsymbol{LPG\ Barrel = LPG\ Barrel + (SP3 \times 0.058 \times Number\ of\ Lines\,)} \tag{6.13}$$

Equation 6.14: Gasoline Quantity Counting Loop

$$\begin{aligned}&\boldsymbol{Gasoline\ Barrel =}\\ &\boldsymbol{Gasoline\ Barrel + (SP3 \times 0.514 \times Number\ of\ Lines\,)}\end{aligned} \tag{6.14}$$

Equation 6.15: Kerosene Quantity Counting Loop

$$\begin{aligned}&\boldsymbol{Kerosene\ Barrel =}\\ &\boldsymbol{Kerosene\ Barrel + (SP3 \times 0.153 \times Number\ of\ Lines\,)}\end{aligned} \tag{6.15}$$

- Equation 6.16: Diesel Quantity Counting Loop

$$\boldsymbol{Diesel\ Barrel = Diesel\ Barrel + (SP3 \times 0.123 \times Number\ of\ Lines\,)} \tag{6.16}$$

Equation 6.17: Heavy Fuel Quantity Counting Loop

$$\begin{aligned}&\boldsymbol{Heavy\ Fuel\ bbl}\\ &\qquad\boldsymbol{= Heavy\ Fuel\ bbl + (SP3 \times 0.153 \times Number\ of\ Lines\,)}\end{aligned} \tag{6.17}$$

After the entities are counted by the Assign Modules, they now flow into their individual final Dispose Module which is the end point of every entity out of the distillation area. This brings an end to the development of the simulation model.

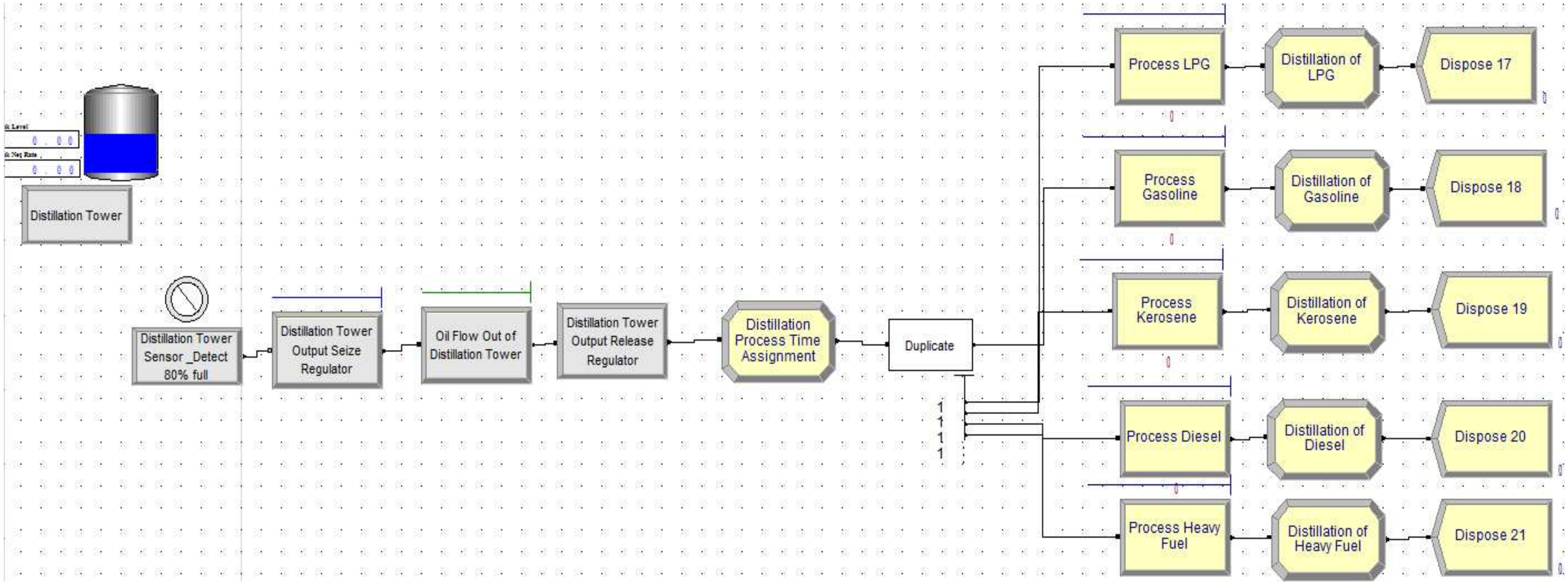


Figure 6.20 Screenshot of the Model Distillation Stage

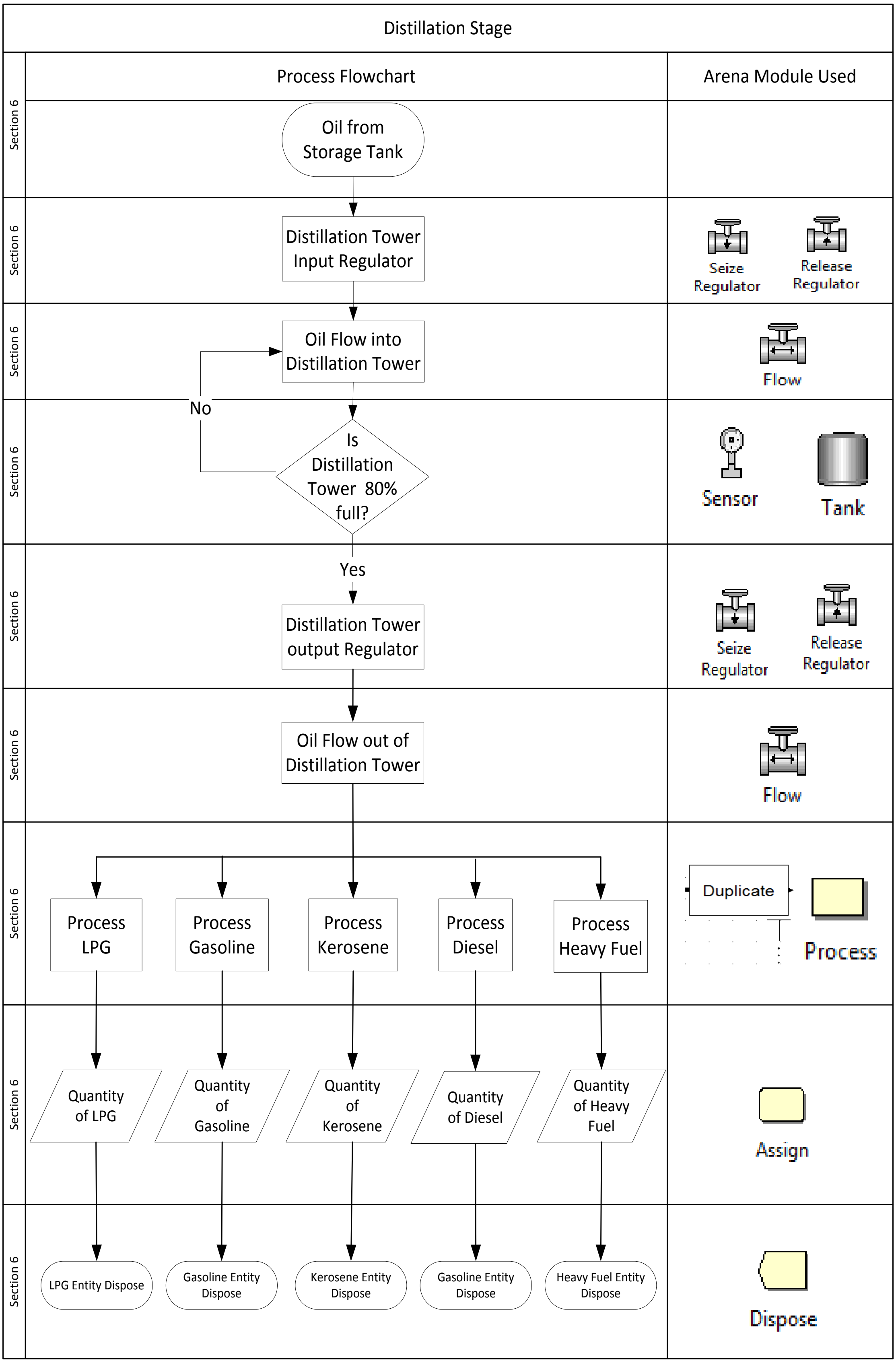


Figure 6.21 Distillation Stage Illustrated by a Process Flow Chart and Respective Arena Modules Used

6.7 Conclusion

The main points that were discussed in this chapter can be summarised as following:

- An operational simulation model for planning and optimising petroleum logistics and supply chain was designed and development.
- Classification of the model being built was explained.
- The input, output components and experimental factors were identified.
- Assumptions of model and calculations of input and output factors were carried out.
- The flow processes during the model-building were explained in detail by using both of discussion and flowcharts.

The design of experiments required to gather enough results and also the verification and validation of the proposed model to increase the author confident in the developed model all are provided in the next chapter.

CHAPTER SEVEN

DESIGN OF EXPERIMENTS, VERIFICATION AND VALIDATION OF THE PROPOSED MODEL

7.1 Introduction

Upon completion of a model, it is vital to test, verify and validate it. Without this, it is impossible to guarantee that the model is close enough to or mimics the real-world system and ensures that it meets customer requirement. It is also vital to ensure that the model is suitable for predicting outcomes especially in situation where experiments are required to be conducted to predict the behaviour of a real system. Experiments are useful in understanding processes within a system. It often involves conducting a series of test or trials with outcomes that are quantifiable. Such tests are carried out on assumptions that certain variables (factors) can influence outcomes (performance) of a system. Understanding the relationship of such factors and their outcomes is a key to comprehend the impact of variability on the process and the process behaviour. For this reason, it is essential that experiments should not be a guess work but designed to aid in understanding the relationship between the set of input variables and related output(s). This chapter deals with verification, validation and the design of experiment in relation to the research.

7.2 Verification and Validation

According to Ronald (2014), Verification deals with assuring through measurable facts and reproducible test data that the design or modelling inputs, the design or modelling procedure or method and the design or modelling outputs are essentially and numerically correct and free from computational and algorithmic errors". On the other hand, validation is the process of ensuring that the model is accurate enough to meet both the stated and implied customer requirements for use. The verification and validation steps used in the simulation are shown in in Figure 7.1.

The verification and validation will help to increase the reliance on the statistical output of the model to the point that it can be used for real life decision making about what the real system should look like and its desired performance.

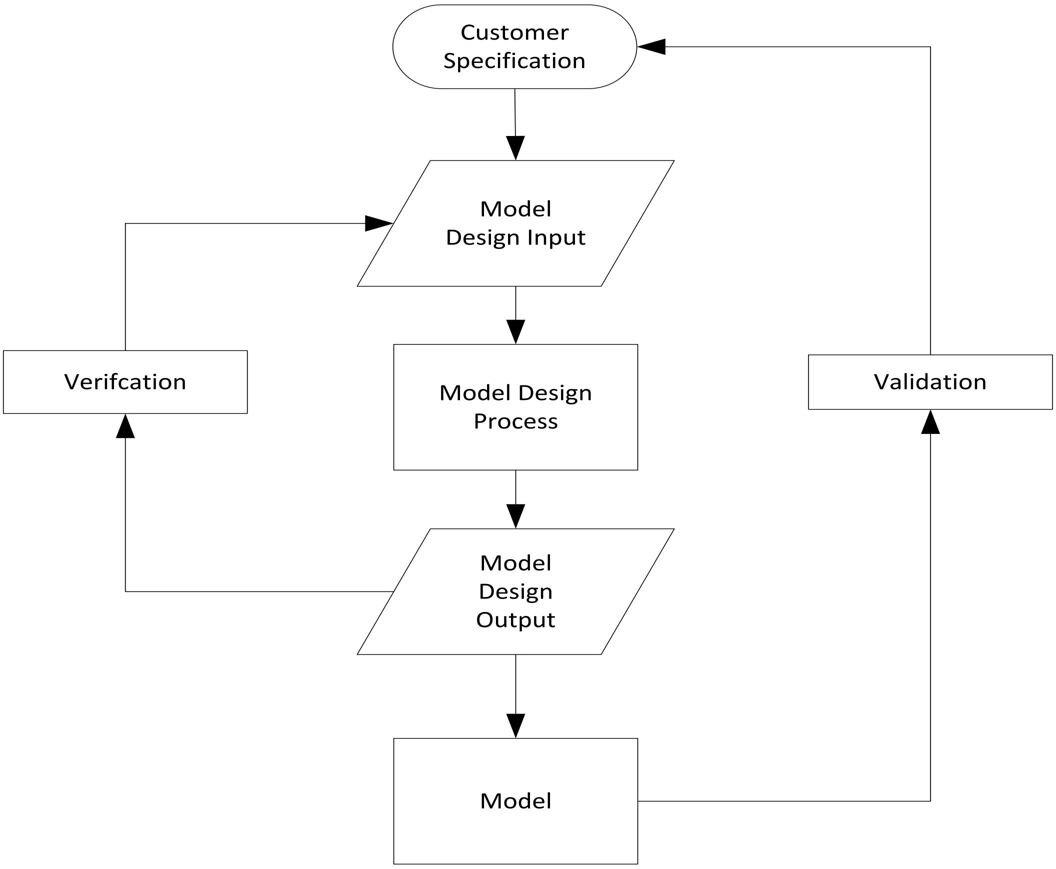


Figure 7.1 Flowchart Illustrating the Simulation Model Verification and Validation Steps

7.2.1 Methods of Verification

There are various approaches that can be used to verify and validate models; however visual inspection, model-logic, output reports and expert' assessment will be utilised here.

A visual inspection was carried out on the model by reducing the animation speed to a considerable level in which entities and their quantities can be seen as they move from one module in the model to another. This enabled comparison of the model to the concept agreed on, ensuring that events happen as expected and entities move along the right path. To obtain the best verification results, scenarios were considered, the entities were tracked overtime and the output report where compared with the documented expectations. At points where the output report deviated from the documented expectations, the model and the inputs underwent reviews until it finally depicted the real system.

The model logic represented in a flowchart was helpful in assessing how the model should behave at key points where more than one option could be taken for the flow of crude oil through the system. Among such critical points that were accessed was the crude oil flowing into and out of the tanks. Considering the risk of overflow, explosion or an empty system that can exist in a real system, it was checked through the logic that such risk should be avoided. At this point, the sensor was observed to ensure that when a tank is full, it stops flow into it and when empty, it stops flow out of it. The model logic helped in verifying that the appropriate quantity flow through each part of the system at their respective time and ensuring mitigation of any potential risk for the real system.

Finally, and after careful consideration of the outputs from the model, the author was satisfied with the outcomes of the model and proved to behave as expected which raised the author confidence to go ahead to the next stage.

7.2.2 How the Verification and Validation Was carried out in the Model

Verification and validation was carried out throughout the whole build phase of the system to eliminate errors which might be difficult to correct if it is differed till the model is completed. In addition to this, the model was built in 3 phases as was mentioned in in Figure 6.9. Each phase divided into sections ensuring that each section of the model functions as expected and mimics the real system before it is added to the whole block. It was through the understanding of how these modules work together and what role each module played that the verification check on entity pathway and output result compared to the expectations was based on. At a point, it was observed that entities queued at the seize module as a result of the Tank being busy and also due to the quantity specified in the flow module being higher than the regulator value. Upon adjusting the Regulator module quantity greater or equal to the Flow module, this issue was resolved. From this, it was understood that the Flow Module requires an entity per time to activate a continuous flow as in the real system. The sensor played a vital role in controlling when to refill and remover from the tank by triggering entities based on user specified tank levels. This verified that when the Tank level drops, the sensor triggers refilling and when full, the sensor stop the refilling process ensuring that no over flow occurs. Figure 7.2 illustrates Phase 1, Section 1 to 4 Verification.

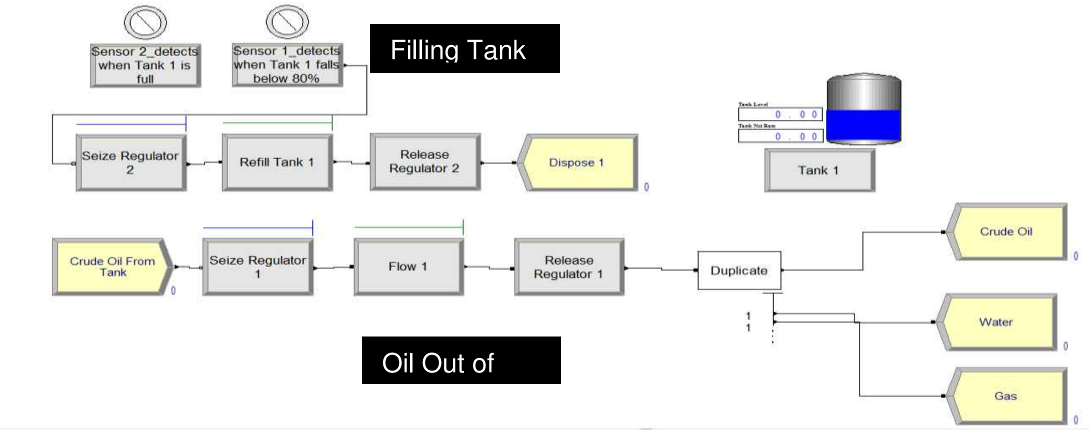


Figure 7.2 Section 1 to 4 model verification Build-up

After Phase1.section1 verification was completed, it was based on that the other sections of Phase 1 were built, guarantying little or no errors. Once Phase 1 was completed, it was duplicated to form Phase 2 which is the second line for the crude oil separation process but was renamed to avoid errors as each element of Arena must be unique and can't have the same name.

Phase 3 was then built up to mimic the distillation process as was shown in Figure 6.20. It consisted of the Duplicate, Process, Assign and Dispose modules in addition to other modules already discussed from Phase 1 and 2. When entities arrive from the Distillation Tower it is separated into the number of products expected by the Duplicate module and the Process module seize, process and release the entities base on the time required to process each product. We were able to verify the output by checking the number of barrels expected over a period of time with the number from the Output report prior to the introduction of the stochastic variable named separator failure. We also compare the percentage of each product with respect to each other and compare it with the customer specification which all matched. Verification and Validation helped to establish that our model was functioning accurately and will be able to meet the purpose it was designed for.

7.3 Design of Experiment

According to Anderson & Whitcomb (2000), a design of experiment is a systematic way to determining cause and effect relationships. An experiment in it basics form exists as a 2^k where k stands for the number of variables being studied and 2 represents the level of the variables. The purpose of the experiment designed for this context is to study how different selected levels of input (independent variables or factors) will affect the outputs (dependent or response variables). This information will guide decision making, enabling one determines what setup for the system being modelled will provide the optimum value suitable for meeting stakeholder's requirement. The factors to be analysed in the experiment were carefully selected. Starting from the dependent variables, a list of key performance indicators (KPI) in the petroleum industry were considered such as return on investment, production quantity, plant availability, injuries and uncertainties such as equipment breakdown. From these, equipment utilisation and the number of barrels of the final product were selected as the performance measures. Upon defining the performance measures, brainstorming was used to define the variables that could influence the output measures. The variables and their classification were mentioned in Table 6.2. These variables were further classified into controllable variables (does that can be influenced by a person) and uncontrollable variable (does that occur randomly due to uncertainties beyond ones control). Figure 7.3 summarises these in a systematic process flow. Table 7.1 gives further details of the experimental factors, their symbols, levels and the values.

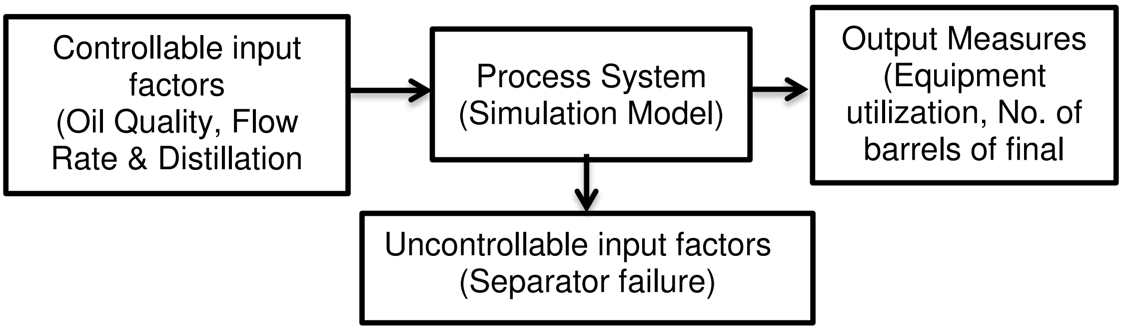


Figure 7.3 Flowchart of the model system and the classification of factors according to their controllability

Table 7.1 The Experimental Factors and Performance Measure with their Symbols, Levels and Values

Description	Symbol	Level	Value	Derived
Input-rate	**R**	**R1**	**258.894 bbl./min**	from calculation of systems physical parameter
		R2	**305.960 bbl./min**	
		R3	**387.231 bbl./min**	
Quality of Crude Oil	**Q**	**Q1**	**-30% (45.5%Oil, 23.35%Gas, 31.15%Water)**	from El-Sharara oil field Libya
		Q2	**-20% (52%Oil, 20.57%Gas, 27.43%Water)**	
		Q3	**Base (65%Oil, 15%Gas, 20%Water)**	
		Q4	**+20% (78%Oil, 9.43%Gas, 12.57%Water)**	
		Q5	**+30% (84.5%Oil, 6.64%Gas, 8.86%Water)**	
Distillation Capacity	**C**	**C1**	**Base Time (2.33, 4.64, 13.92, 34.8, 69.6)**	Experimentally determined with the aim of knowing the amount of capacity required to process all the distillates for the chosen crude type
		C2	**Base Time/3 (0.777, 1.547, 4.64, 11.6, 23.2)**	
		C3	**Base Time/6 (0.388, 0.773, 2.32, 5.8, 11.6)**	
		C4	**Base Time/9 (0.259, 0.516, 1.55, 3.87, 7.73)**	
		C5	**Base Time/12 (0.194, 0.387, 1.16, 2.9, 5.8)**	
		C6	**Base Time/24 (0.097, 0.19, 0.58, 1.45, 2.9)**	
		C7	**Base Time/48 (0.048, 0.096, 0.29, 0.72, 1.45)**	
		C8	**Base Time/72 (0.03, 0.06, 0.19, 0.48, 0.96)**	
		C9	**Base Time/96 (0.024, 0.048, 0.145, 0.36, 0.73)**	
No. of failed Separator	**F**	**F0**	**0**	Determined based on the number of separators in the system
		F1	**1**	
		F2	**2**	
		F3	**3**	
		F4	**4**	
		F5	**5**	
		F6	**6**	

The first factor in the table is the Input Rate (the amount of oil barrels/minute introduced into the system from the oil well). The first level of Input Rate (R1) was calculated based on the physical characteristics of the case study's system as mentioned earlier while the remaining two level R2 and R3 were defined by randomly selecting two other diameters for the pipes (40 inch and 45 Inch) and using them in Equation 6.1 to calculate their actual values. Secondly, the five levels of the Oil Quality were selected from the types of oil used by the case study. Thirdly, nine levels of distillation capacity were considered necessary as it was the interest of this work to determine how many distillation units or the size of the distillation unit necessary to process all the distillates from the process. Finally, separators failure was assigned seven levels based on the possibilities of all the six separators used in the model failing and a situation where none failed.

From the number of levels of variable mentioned above, it is clear that the number of experiment that needs to be conducted cannot be in a basic form 2^k. There are total of four independent variables with twenty-four levels. Giesbrecht, & Gumpertz, (2011) suggested that experiment with multiple variables and levels can be simplified by a pseudo factor method making it possible for the total number of experiments to be reduced while still offering a close estimate to the full experiments. However, as we are interested in getting a clear picture of the real system being modelled, a full scenario was considering necessary. This will lead to an experiments design with 945 runs (3 X 5 X 9 X 7 levels). The products output of experiments i.e. LPG, Gasoline, Kerosene, Diesel and Heavy Fuel Oil were summed up to get the total product while the individual distillates equipment utilisation were averaged to get percentage equipment utilisation (see Appendix B for details). This reduced the complexity for analysing the outputs of the experiment. Appendix A Table A.1 to A.30 shows the scenarios and results of experiment conducted for the proposed model.

7.3.1 Replication

This is the number of times an experiment is run with the same factors settings or levels conditions. Doing this can help increase the simulation model precision, enabling the model to better predict what the real system performance will look like. Aririguzo & Saad (2012) formulated an approach to determining the exact number of replications required for an experiment which was applied in this research as shown below in Equation 7.1:

Actual number of replication needed $(n\,*) \;\geq n\left(\frac{E}{\mathrm{E}*}\right)^2$ (7.1)

Where:

Initial number of replications (**n**) **= 10** (assumed)

Planned maximum error (**E***) **=** % of planned error × Mean

Maximum Error estimate $(\boldsymbol{E}) = \boldsymbol{t}_{\frac{t-\propto}{2n-1}} \times \boldsymbol{Mean} \div \sqrt{\boldsymbol{n}}$

Significant level (**α**) = 0.05

The initial number of replications **n** was randomly selected as 10 while % planned error was obtained based on the ratio of the standard deviation and the mean. Base on this value, the model was run for 7 scenarios with the values of input rate (R1 = 258.894), Quality of crude oil (Q3 = Base Q) and Distillation Capacity (C1 = Base T) remaining fixed while number of failed separated varied from 0 to 6 as indicated in the Table 7.2.

Gasoline was selected for calculating the number of replications because it had the highest value for standard deviation when compared to other distillates. Among all the scenarios, scenario 3 had the highest value of number of replications and it was concluded that 11 will be the number of replications used for all the experiments.

Table 7.2 Illustration of How the number of Replications Came About

Scenario No.	No. of Failed Separators	Gasoline Mean from replication	Gasoline Standard Deviation	% of planned Error	E*	E	n*
1	0(F0)	1694809.47	0	0	0	0	0
2	1(F1)	1687036.29	522.35	0.0003	506	373.64	5.45
3	2(F2)	1671562.73	2398.31	0.0014	2340	1715.53	10.5
4	3(F3)	1669196.19	1348.83	0.0008	1335	964.83	3.34
5	4(F4)	1665992.25	1354.28	0.0008	1333	968.73	3.38
6	5(F5)	1663425.46	1633.20	0.0010	1663	1168.24	4.93
7	6(F6)	1661022.51	1554.66	0.0009	1495	1112.06	4.48

7.3.2 Warm up period

Since we are more concerned about the steady state of the system, a warm up period was considered vital for the simulation. This is because any new production facility comes empty since nothing has been produced. Likewise, the tanks and pipes in the simulation were empty before any runs. If the simulation starts unfilled and idle but the system does not, then the statistical data collection for the whole simulation run will be unfair by the start-up for the simulation. Therefore, a warm up period of 917 minutes was defined for the simulation which represents the time taken for the simulation to reach steady state where crude oil will have flowed throughout the components of the simulation model. This warm up period was separate from the simulation run time 30 days (43200). Arena Simulation comes with a feature that allow modellers input the value of a warm up period for their model of interest. The value used here was determined by observing entities as they flow through the elements of the model during several pilot runs. Once the entity reached the final component, the model was paused and the time taken to reach the last component was noted as the warm up period. The warm up period was not considered as part of the experiment since it was the interest of this research to investigate the steady state of the system

7.4 Conclusion

The main points of this chapter are summarised in the following:

- Verification and validation of the proposed model, the approach to achieve this were discussed.
- The experimental design for the proposed simulation model was carried out.
- The levels and values of the experimental factors were defined and justified.
- Based on the levels of the factors the number of scenarios was calculated to be 945 and the number of replications was 11 for each experiment.
- The output of experiment which was the total of products and the percentage of equipment utilisation being the average of the individual utilisation have been recorded and listed in tables designed especially for results collection.
- Scenario replications and warn up period for the system was also calculated.

Next chapter provides a full analysis and detailed discussion for the obtained results, in addition, detailed Multivariate Analysis of Variance (MANOVA) is provided.

CHAPTER EIGHT

ANALYSIS OF RESULTS AND DISCUSSIONS

8.1 Introduction

The experimental design for the proposed simulation model was explained in the previous chapters. This chapter discusses the results obtained from a total of 945 runs of the experiment from the simulation model. The results were obtained from AERNA software output file after each run of experiment and were compiled into an Excel file. The experimental runs with dependent variables (Total Products & Equipment Utilization) and independent variables (Input Rate, Crude Oil Quality, Number of Failure Separators and Distillation Capacity) were later plotted graphically on Excel software.

SPSS software was used to further analyse the obtained results. Specifically, Multivariate Analysis of Variance (MANOVA) was applied to study the effect of input factors on the output factors to determine the significant factors.

8.2 The Effect of Input Rate, Quality of Crude, Distillation Capacity and Failure on the Output Performance Measure of Total Products

By analysing the sets of figures namely Figure 8.1 through Figure 8.5, Figure 8.6 through Figure 8.10 and Figure 8.11 through Figure 8.15 a lot can be deduced about the influence of the experimental factors on the performance measure. Each figure within the sets show the effect of the number of failed separators on the output at different distillation capacity while the Input Rates (R1, R2 & R3) and the Quality of Crude Oil (Q1, Q2, Q3, Q4 and Q5) were fixed for each graph. Irrespective of the distillation capacities, it can be noticed that the output was at the peak at F0 while it fell to the lowest points at F6. This clarifies the obvious that the number of failed separators had considerable impact on the system performance. The system was more effective and was at its highest output when no failure occurred in the separators (F0). It can be observed that the output performance sharply decreased from F0 to F1 and from F1 to F2 meaning the system had failure in one and two separators while from F2 to F3, F3 to F4, F4 to F5 and F5 to F6 the output had slightly dropped.

The reason for a sharp drop from F0 to F1 and from F1 to F2 is because a failure of one separator on a production line completely halts the production process of that line but the other line will continue supplying to the distillation tower however two separators failure, one on each line will cause the whole production system to halt for the duration of the downtime since the maximum production lines is two. Furthermore, slight drop in output from F2 to F3, F3 to F4, F4 to F5 and F5 to F6 is as a result of more than one separator failing alternatively or simultaneously on a line which frequently disrupts production, preventing the smooth flow of crude oil to other processing stages. About a 50% drop in the output can be observed from any of the graphs when comparing F0 output values to that of F6.

Another factor that had greater impact on the output was the distillation capacity as illustrated in the figures. The most significant effect within distillation capacity happened when the capacity was increased from C1 to C2 which had the highest gradient almost tripling the value a C1. The total product output slightly grew afterwards between C2 to C9. One reason for the sudden increase in output between C1 and C2 is due to the fact that over 55% of type of crude oil used is made up of light hydrocarbons (LPG and Gasoline) with lower boiling points enabling them to be recovered much quicker with lower distillation capacity (see Figure 8.3). There was no effect of distillation capacity on the output after C8 indicating that the distillation capacity was more than enough to process the crude oil.

Also Figure 8.1 through Figure 8.15 shows the effect of quality of crude oil on the output. For example, under the same setting of distillation capacity C9 and failure F0 the output was 11,885,000 bbl/30 days in Figure 8.1 but increased to 12,685,000 bbl/30 days, 15,300,000 bbl/30 days, 17,513,000 bbl/30, 18,645,000 bbl/30 days in Figure 8.2, Figure 8.3, Figure 8.4 and Figure 8.5 respectively. The output increases because the quality of crude oil increased from Q1 through Q5 respectively. From this It could be said that the lesser the water and gas content in the crude oil, the more oil could be extracted and therefore it had positively reflected on the output performance.

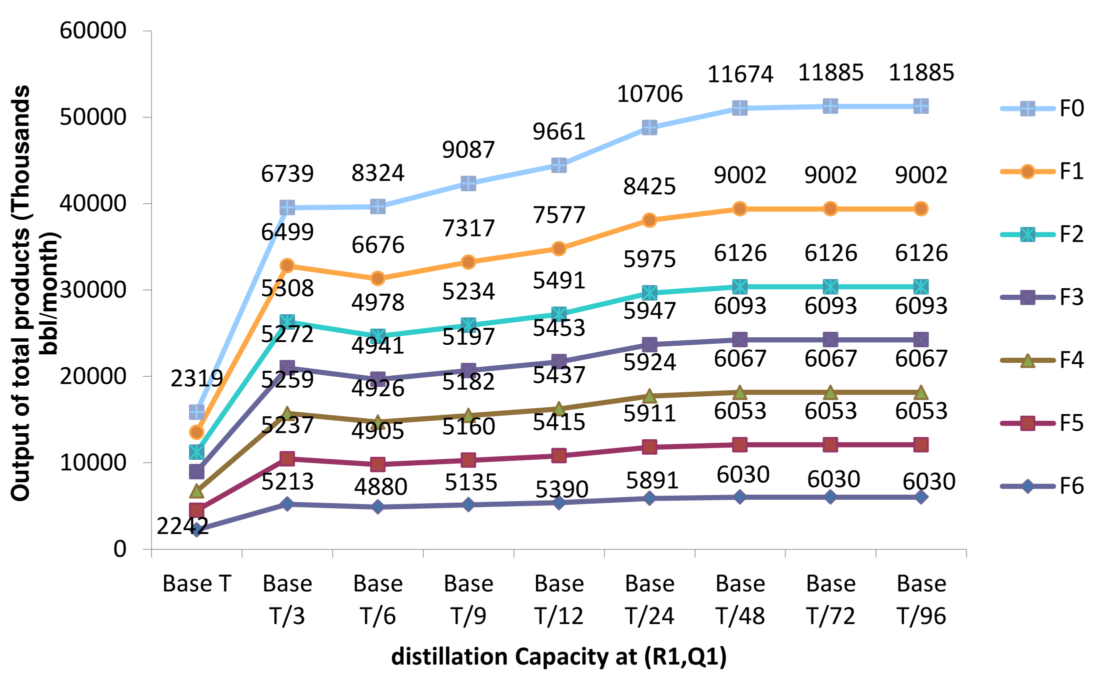


Figure 8.1 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R1, Q1)

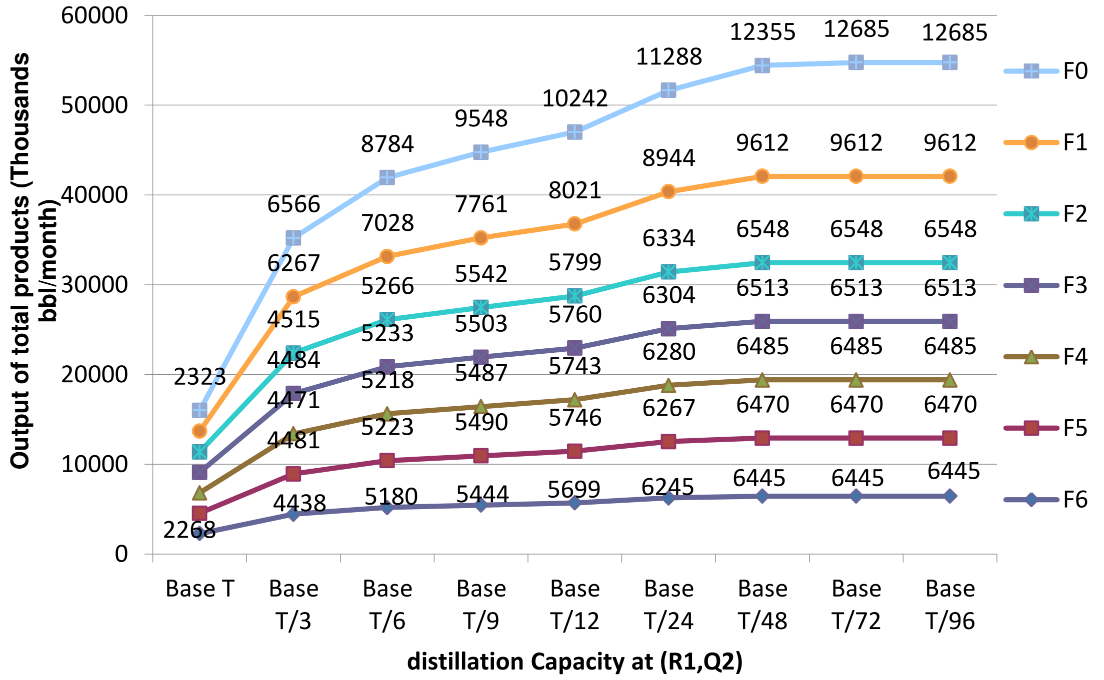


Figure 8.2 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R1, Q2)

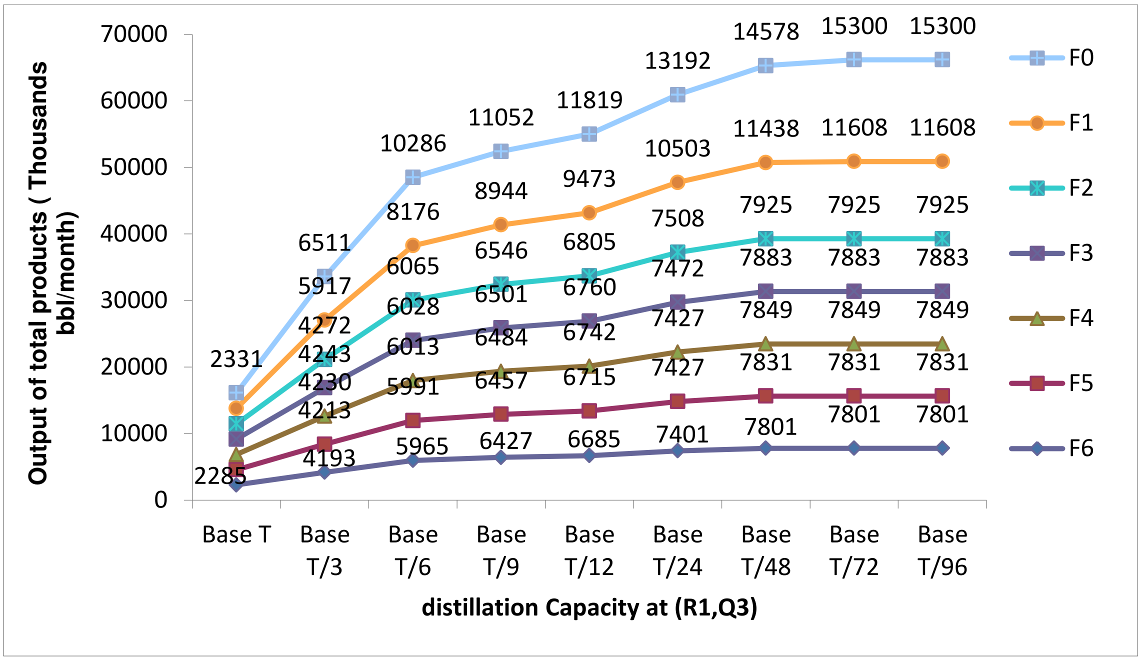


Figure 8.3 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R1, Q3)

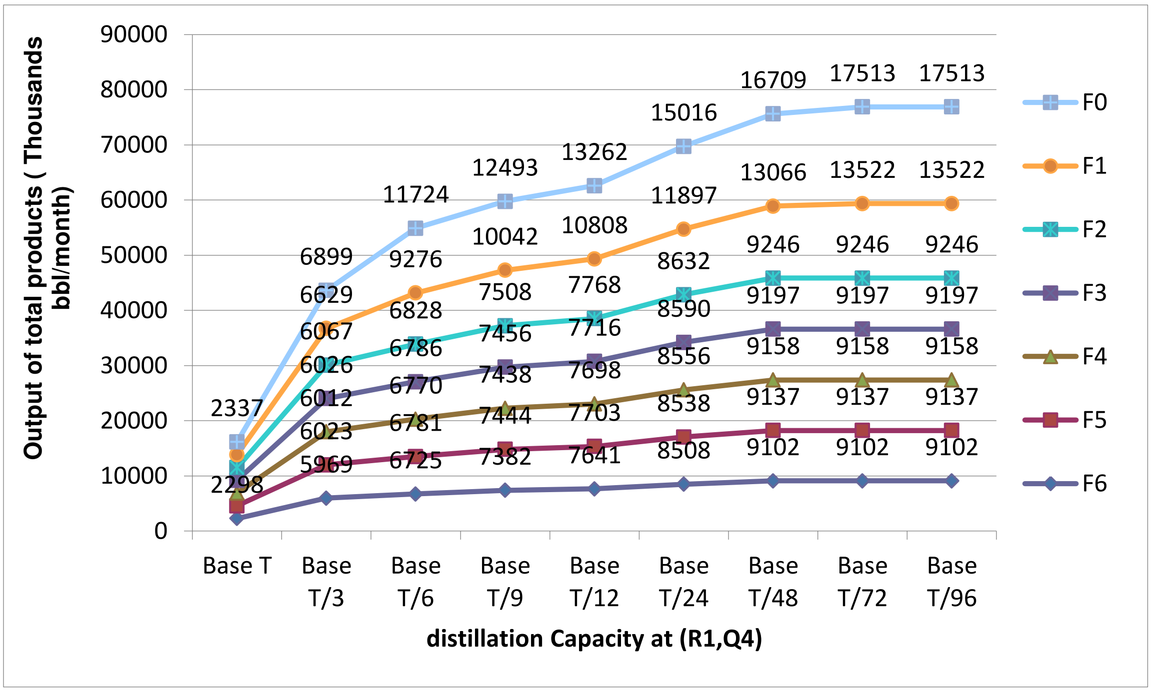


Figure 8.4 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R1, Q4)

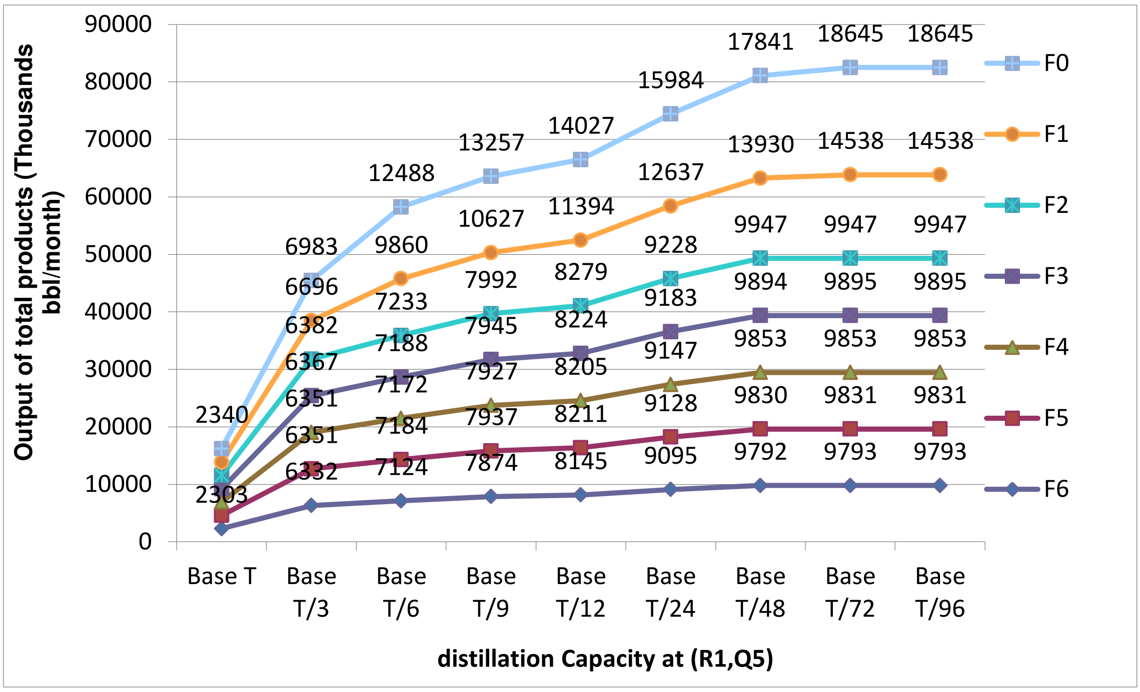


Figure 8.5 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R1, Q5)

Comparing the previous five figures set (Figure 8.1 through Figure 8.5) to the following Figure 8.6 through Figure 8.10 shows the effect of crude oil Input Rate. It was clear that when the crude oil input rate increased from R1 (258.89 bbl/min) in Figure 8.1 to R2 (306.96 bbl/min) in Figure 8.6 the output performance rose from 11,885,000 to 14,102,000 bbl/30 days under the same conditions. This increase in output was also reflected among the graphs between each set respectively.

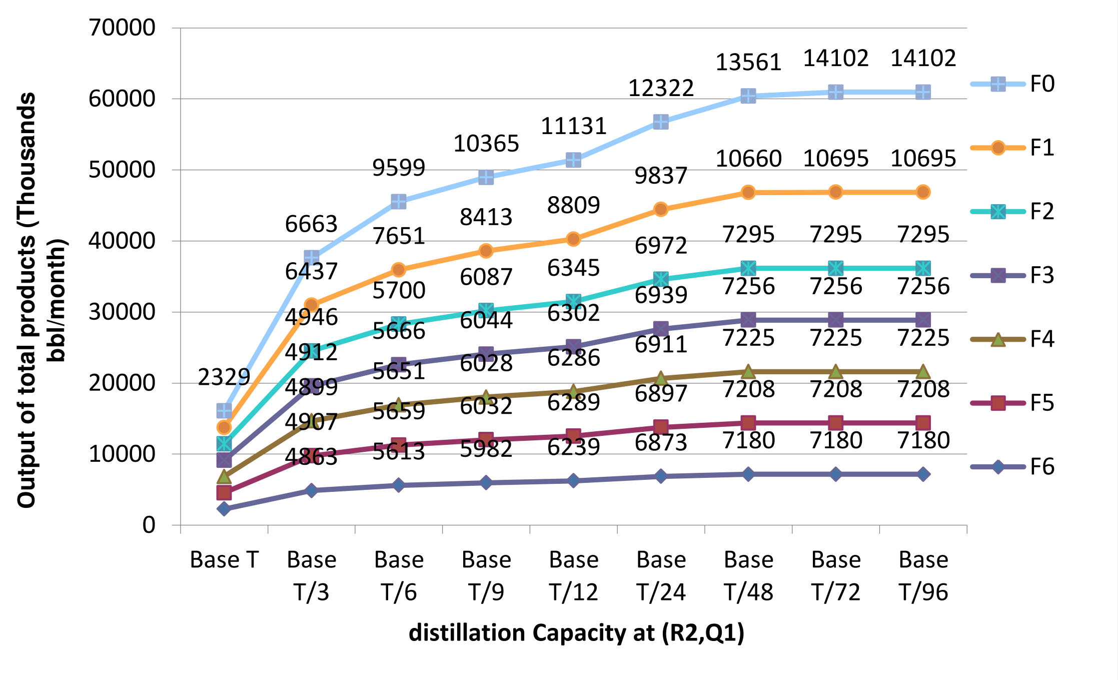


Figure 8.6 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R2, Q1)

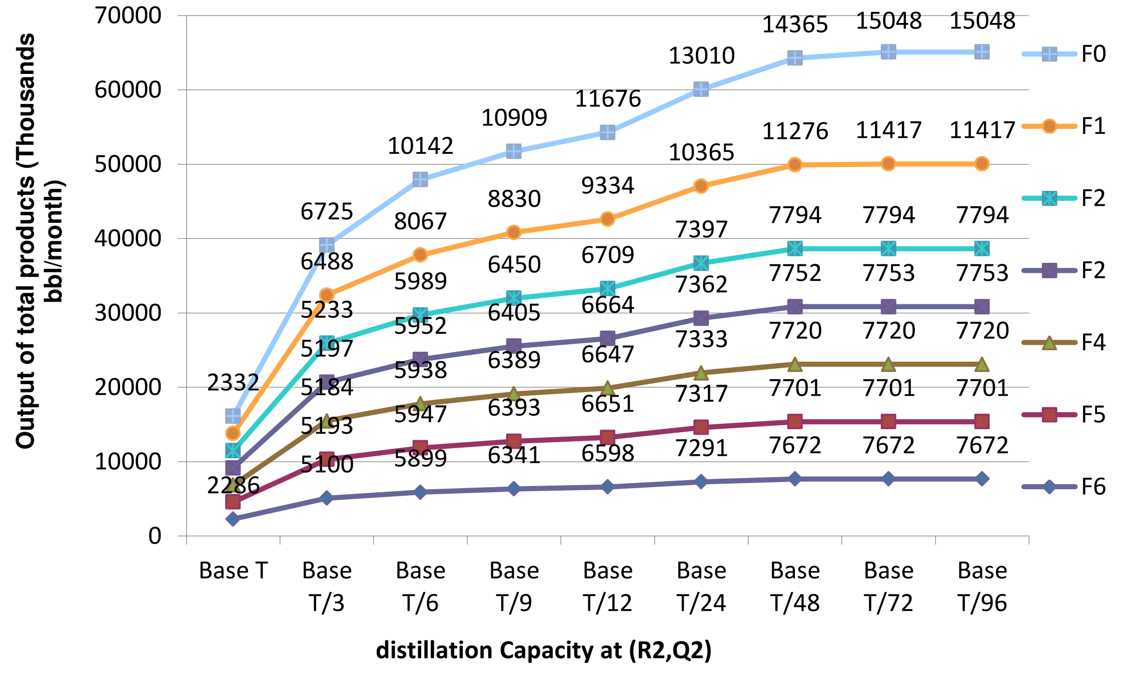


Figure 8.7 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R2, Q2)

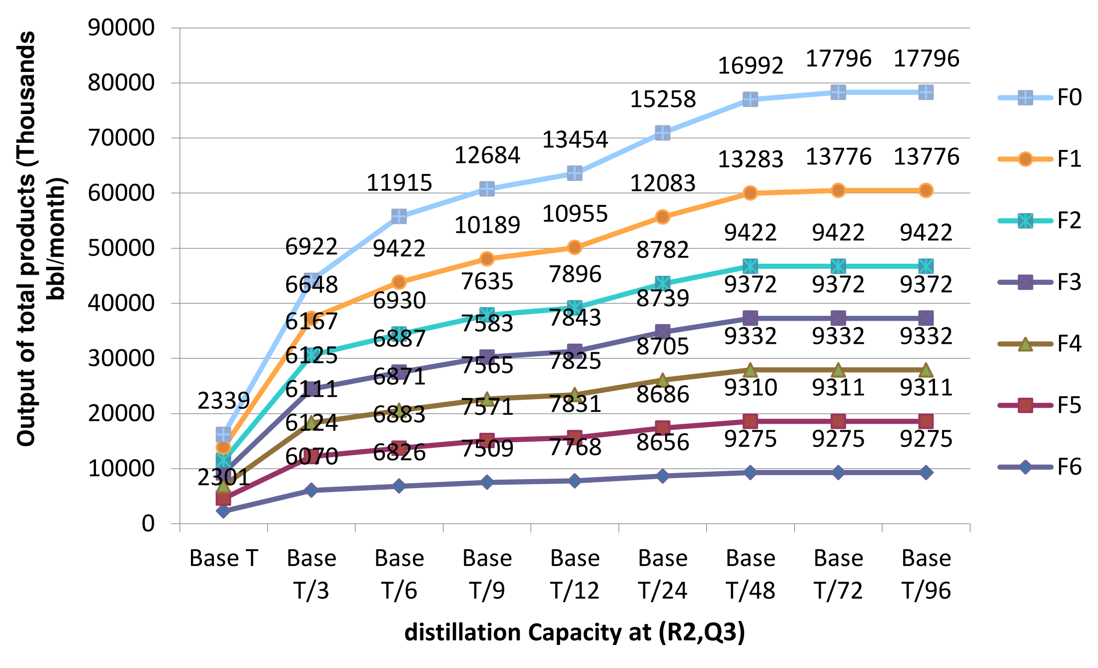


Figure 8.8 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R2, Q3)

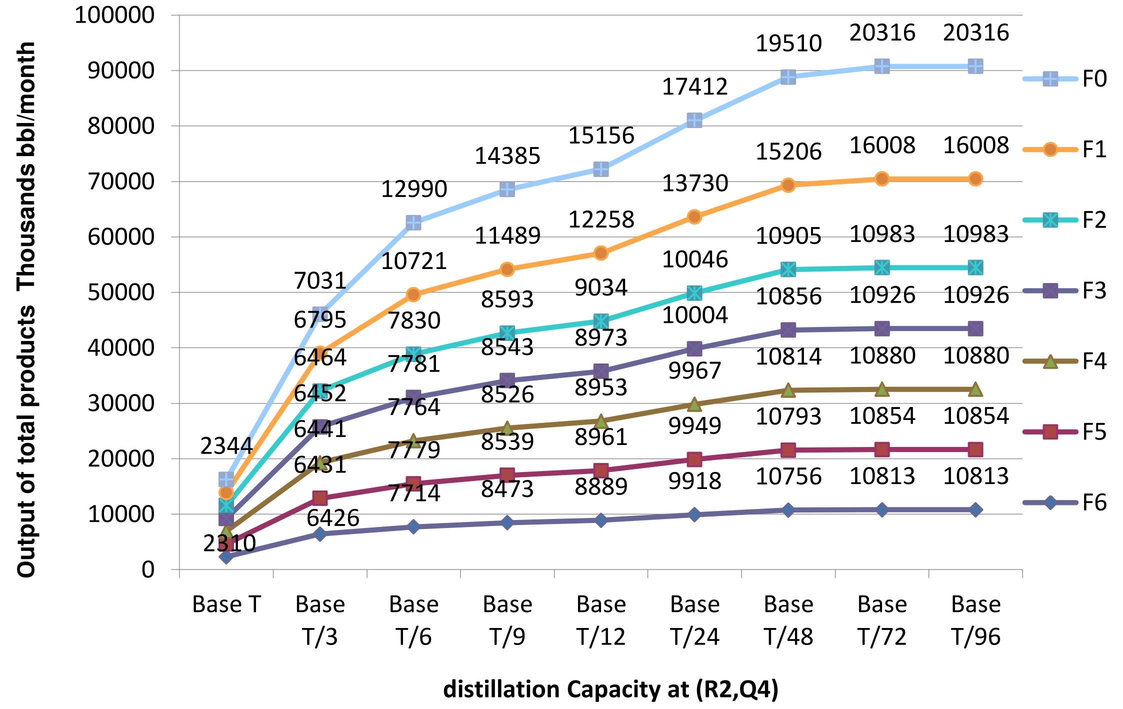


Figure 8.9 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R2, Q4)

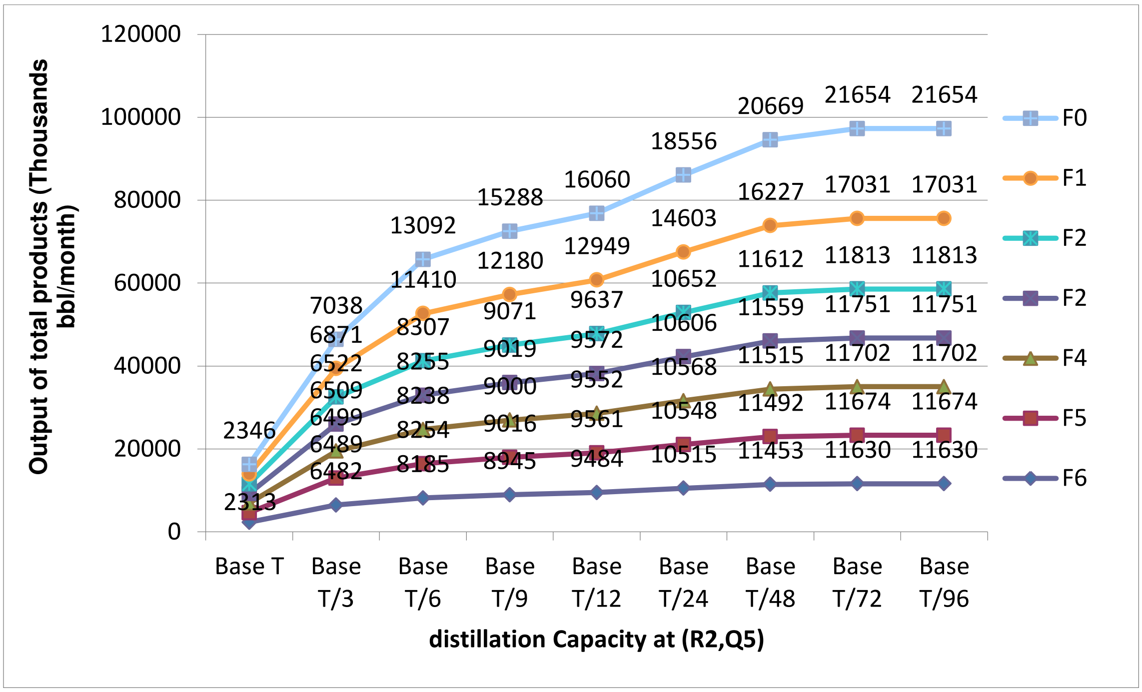


Figure 8.10 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R2, Q5)

Furthermore, the effect of Input Rate on the output performance can be noticed when it changed from R2 (306.96 bbl/min) in Figure 8.6 through Figure 8.10 to R3 (387.231bbl/min) in Figure 8.11 through Figure 8.15. For example comparing Figure 8.1, Figure 8.6 and Figure 8.11 at the same failure F0, Quality of Crude Oil Q1 and Distillation Capacity C8 but different Input Rate R1, R2 and R3 respectively resulted in the output rising from 11,885,000 bbl/30 days at R1 to 14,102,000 bbl/30 days at R2 and then 17,620,000 bbl/30 days for R3.This depicts that the Input Rate is directly proportional to output measure Total Product, which shows that it had impact of the system performance. This effect can also be notice in the sets of Figure 8.1 through Figure 8.5, Figure 8.6 through Figure 8.10 and Figure 8.11 through Figure 8.15 pointing to the fact that changes in the Input Rate significantly affects the performance of the system. Other Figures show the effect of the four input factors on the performance measurement of the output can be seen in Appendix D.

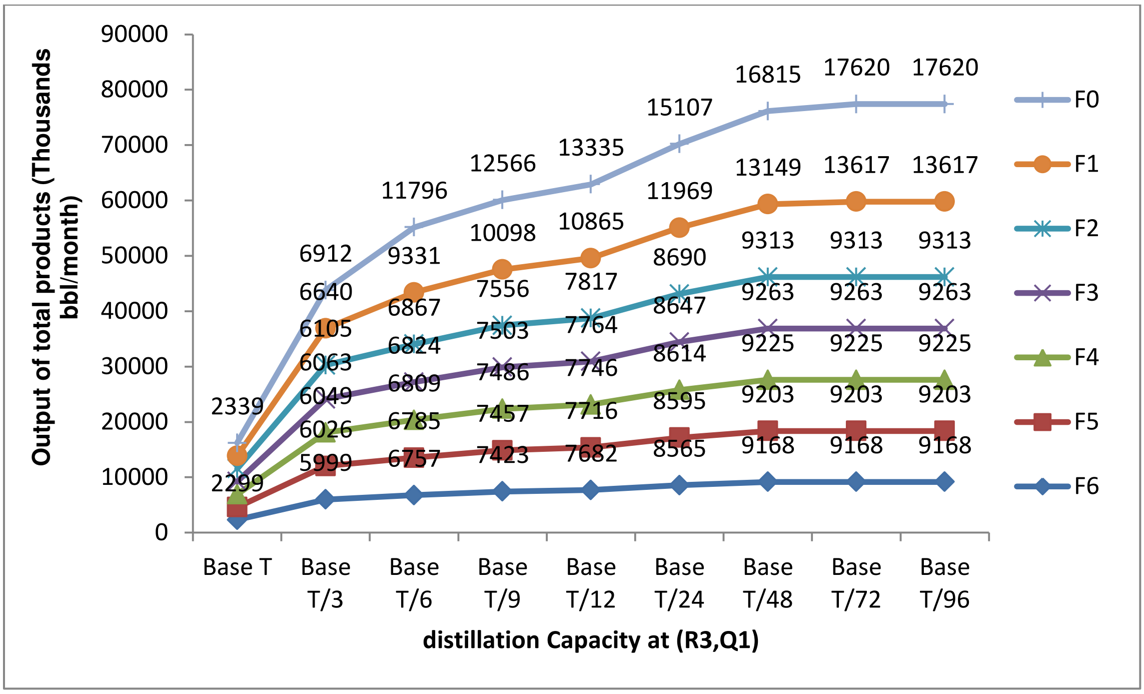


Figure 8.11 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R3, Q1)

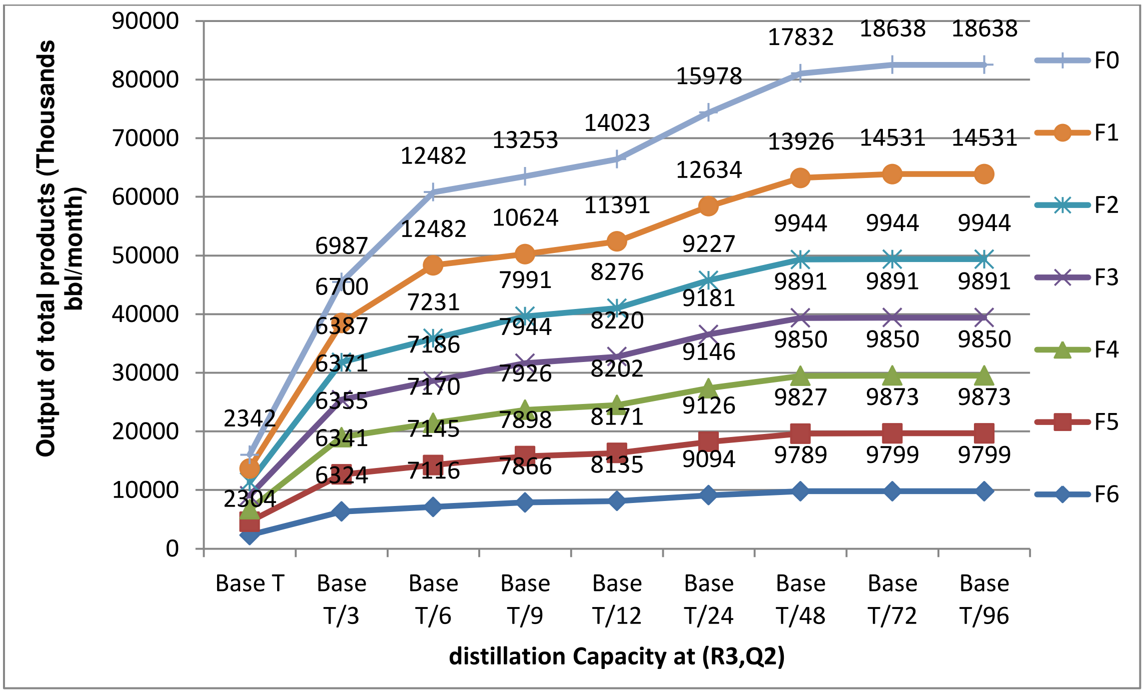


Figure 8.12 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R3, Q2)

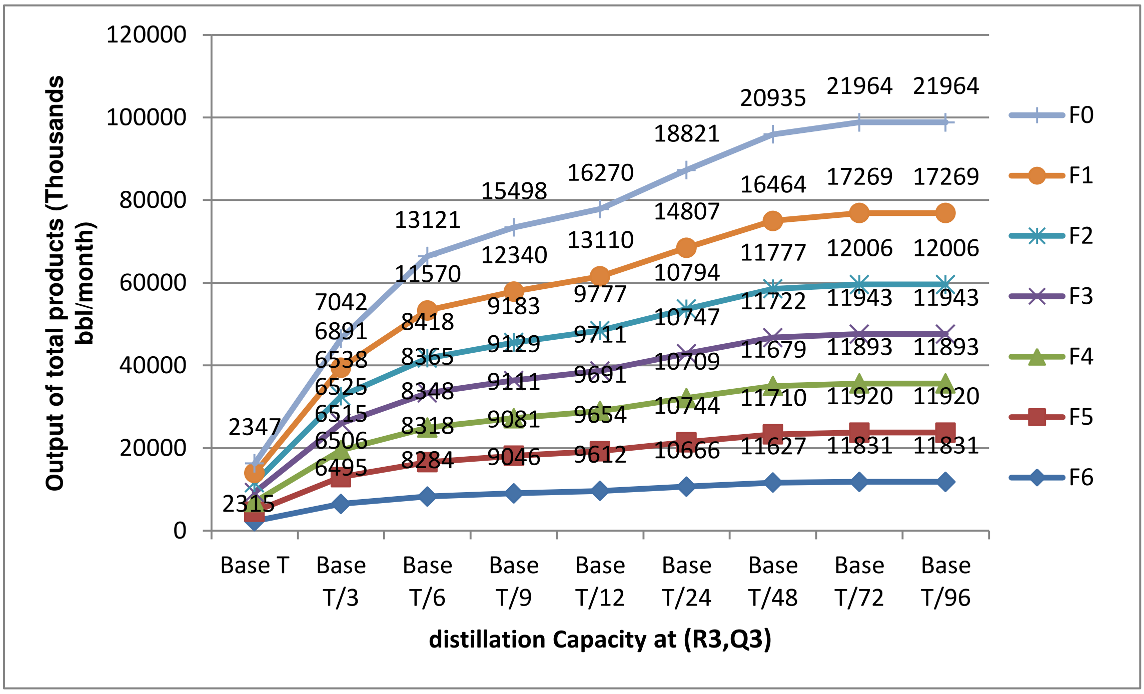


Figure 8.13 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R3, Q3)

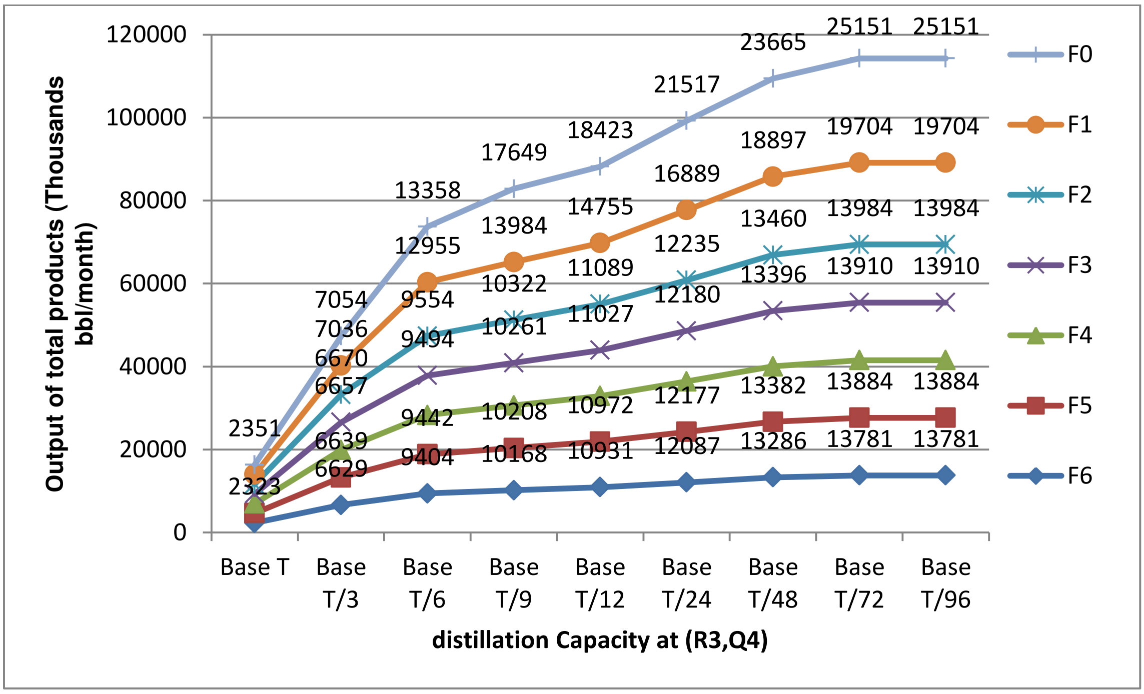


Figure 8.14 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R3, Q4)

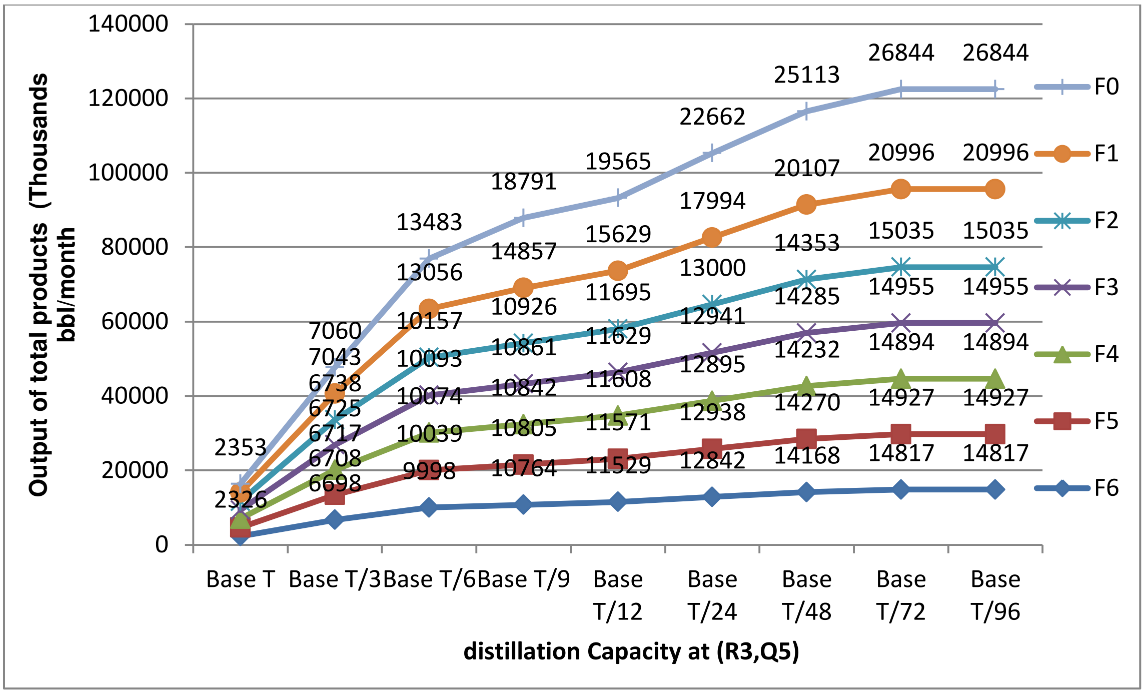


Figure 8.15 Graph of Total Product against Distillation Capacity Showing the Influence of the Number of Failed Separators at (R3, Q5)

8.3 The effect of input rate factors on the equipment utilisation

Upon analysing the set of Figure 8.16 through Figure 8.20, Figure 8.21 through Figure 8.25 and Figure 8.26 through Figure 8.30 it shared light on the influences on the experimental factors on the performance measure Equipment Utilisation.

Each figure within the sets shows the impact of the number of failed separators on the equipment utilisation. The equipment utilisation for each figure dropped suddenly from F0 (no failure) to F1 (one failure) and F1 to F2 (two failures) while from F2 to F6 (six failures) it remained approximately steady. The reason for the sudden drop of equipment utilisation from F0 to F2 was because a failure of one separator disrupts only one production line while the other line keeps supplying crude. However, one separator failing on each line simultaneously or alternative severely disrupt the utilisation of equipment since both line will be down. Utilisation remained steady after F3 since more than one separator failing on one line makes the failure redundant.

Each figure also illustrates the influence of the distillation capacity on the utilisation. It can be noticed that when the capacity was at its base C1, the utilisation was about 100% but an increase in the capacity from C1 through C9 resulted in a corresponding decrease in utilisation which is as a result of the capacity being more than what is necessary to process the crude oil.

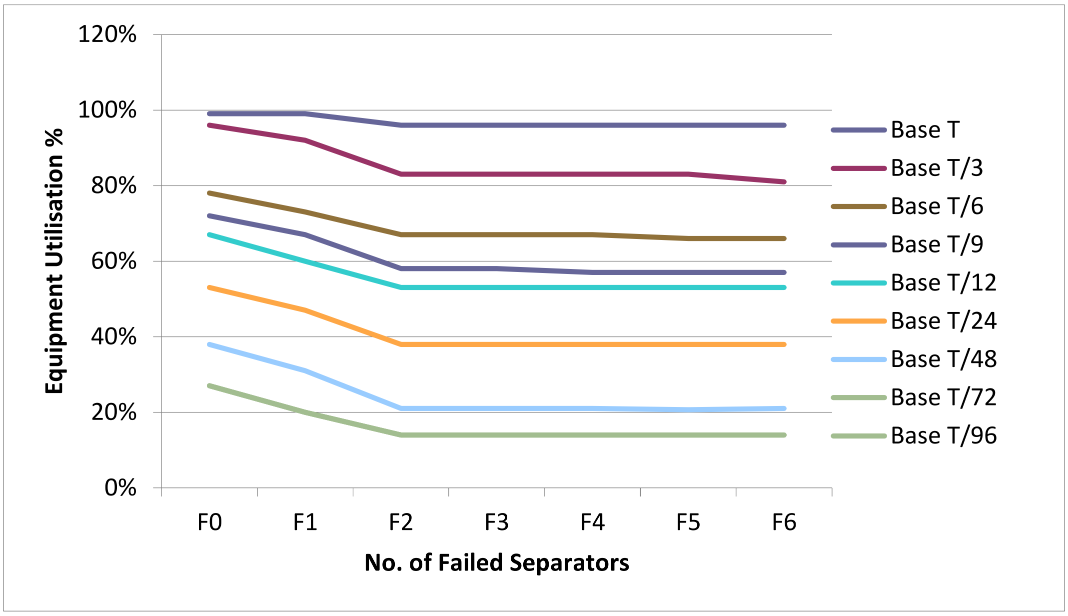


Figure 8.16 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R1, Q1)

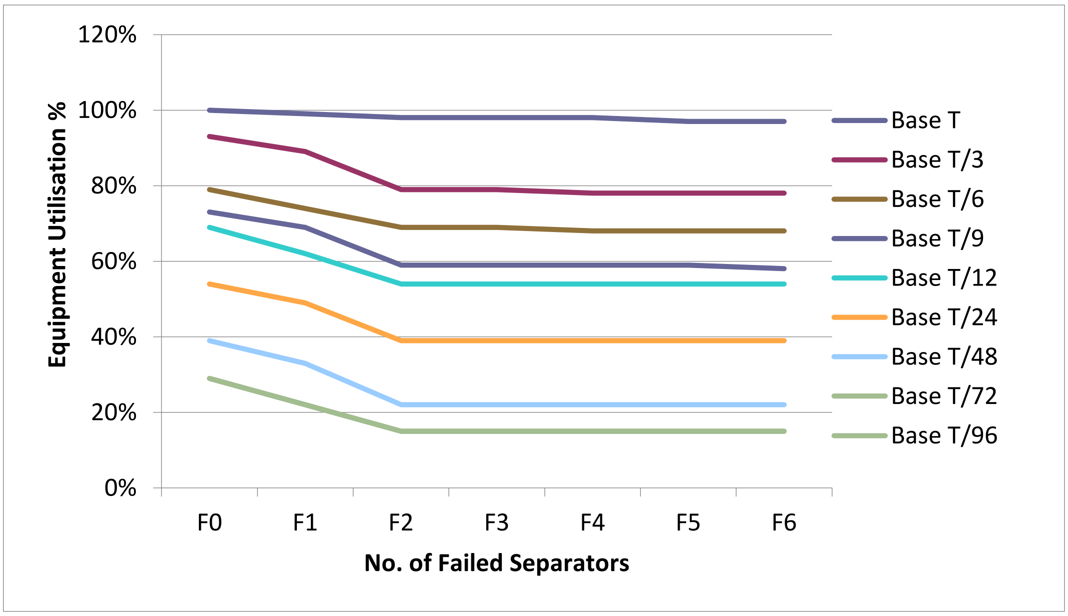


Figure 8.17 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R1, Q2)

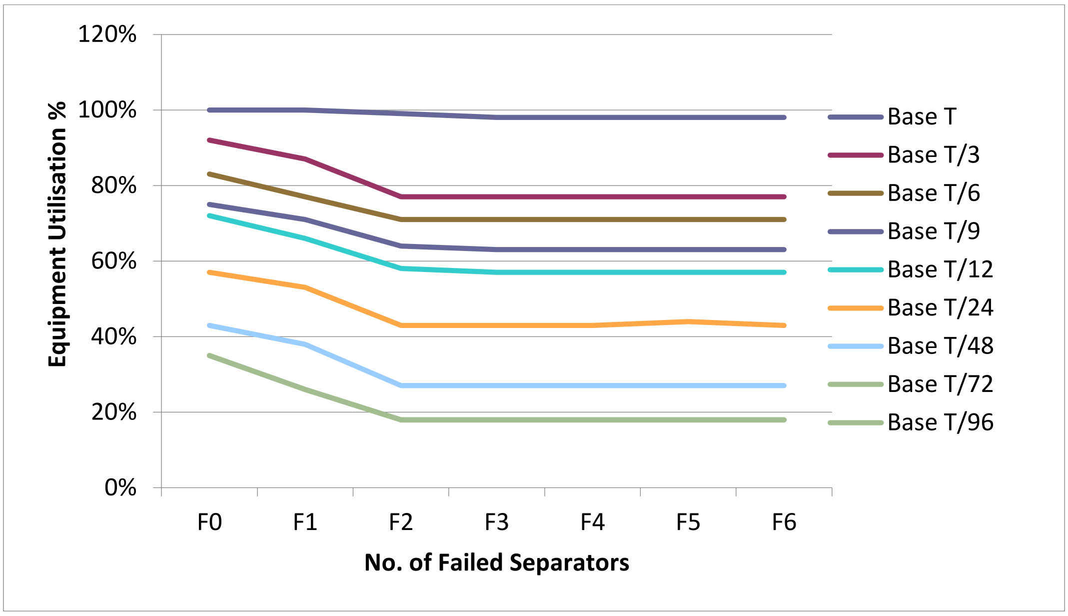


Figure 8.18 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R1, Q3)

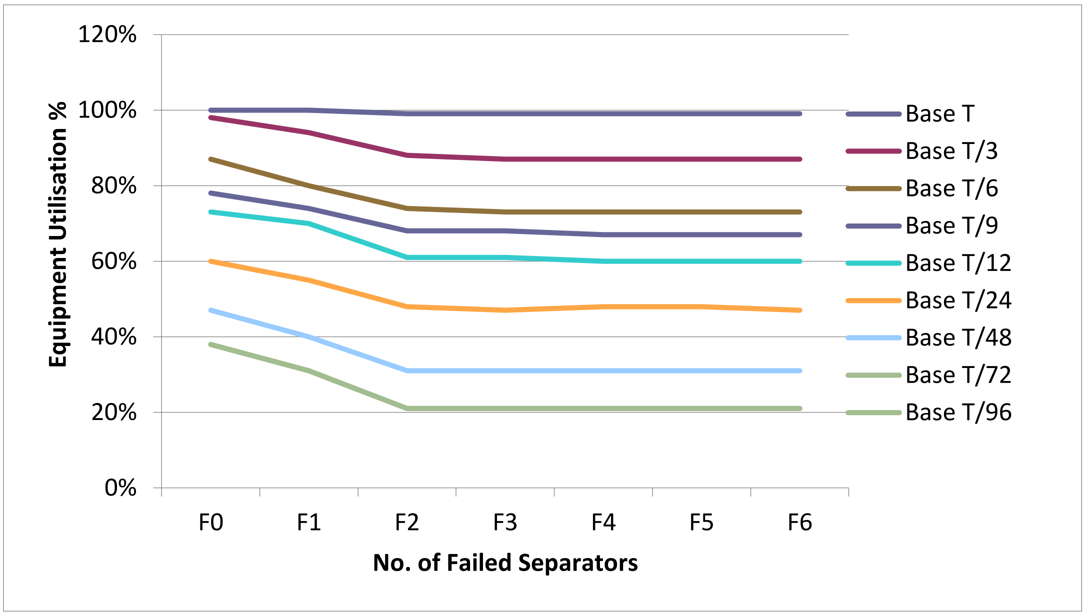


Figure 8.19 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R1, Q4)

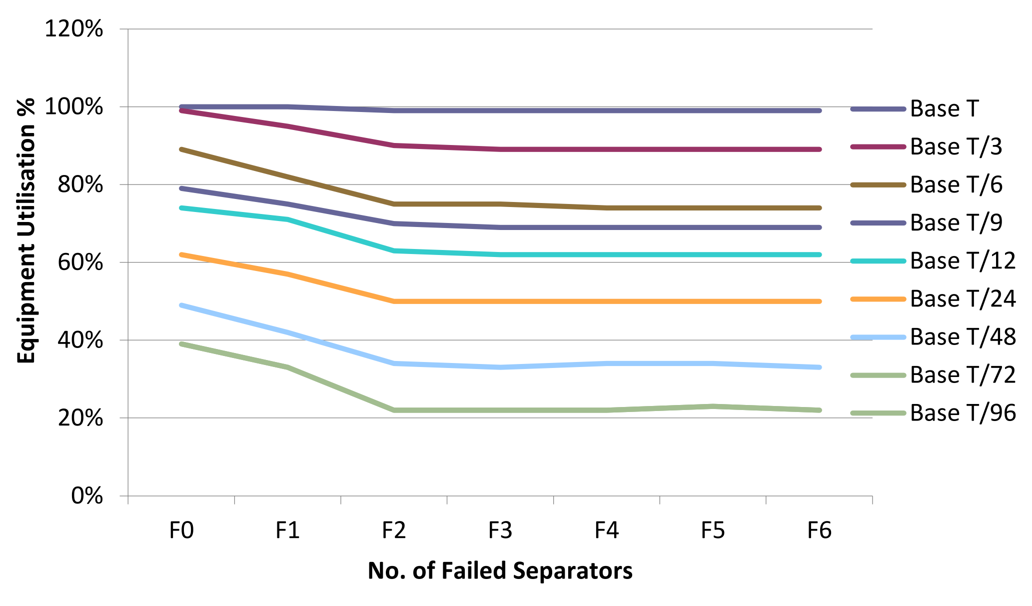


Figure 8.20 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R1, Q5)

Comparing the graphs within the sets of figures, the influence of the change in the quality of crude oil on the equipment utilisation can be noticed. For example, Figure 8.21 through Figure 8.25 show that equipment utilisation increases when the quality of crude oil increase from Q1 to Q5 respectively. This shows that the distillation unit had more crude to process as the quality of crude increased therefore increasing the utilisation of the equipment. This effect can also be observed in the set of Figure 8.26 through Figure 8.30.

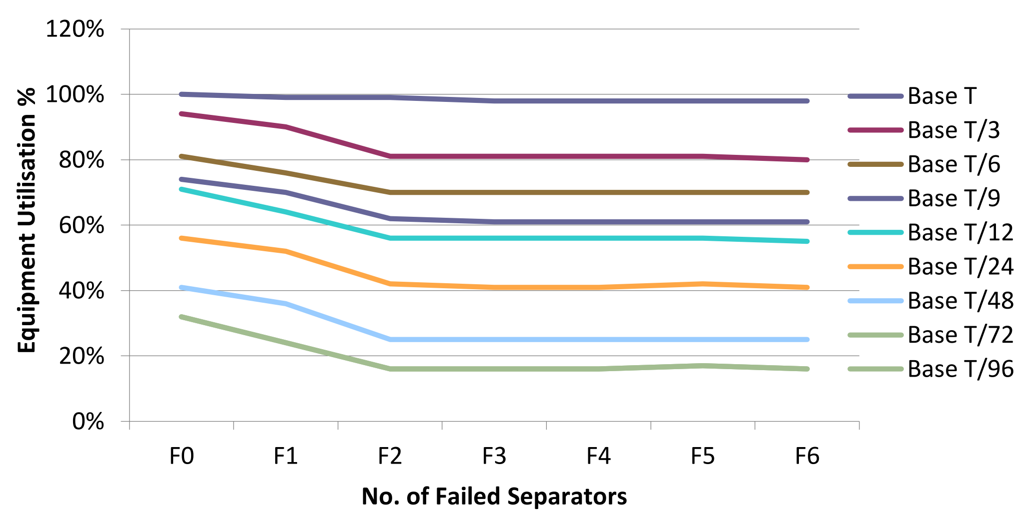


Figure 8.21 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R2, Q1)

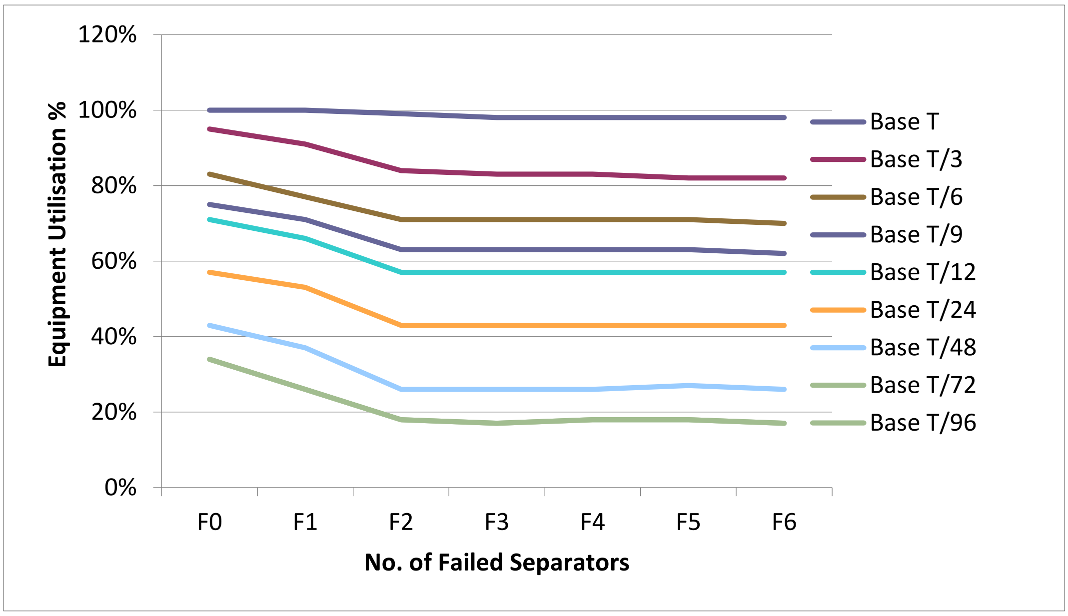


Figure 8.22 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R2, Q2)

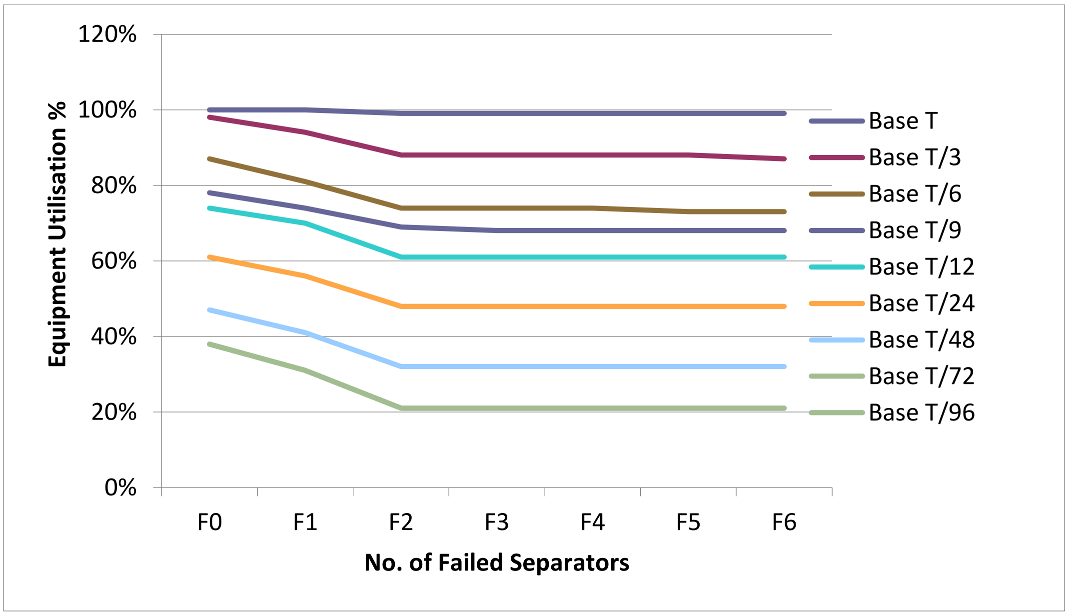


Figure 8.23 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R2, Q3)

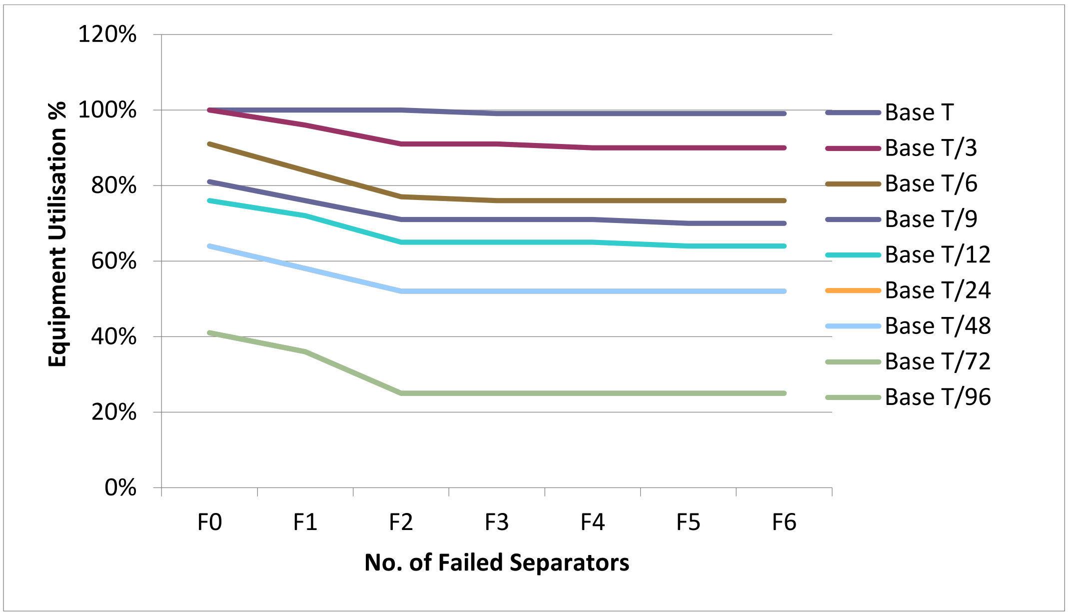


Figure 8.24 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R2, Q4)

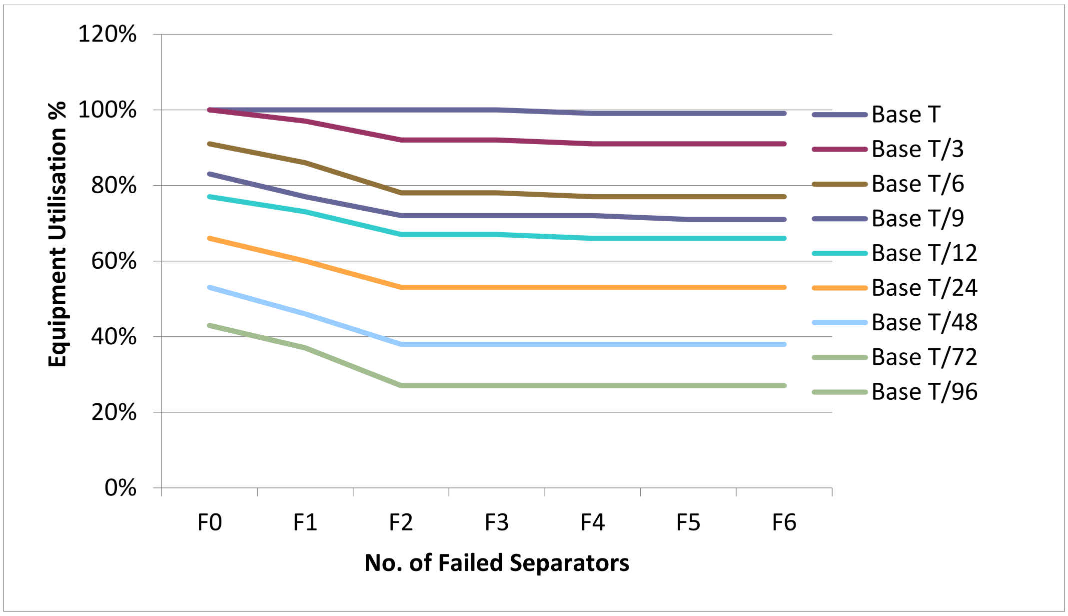


Figure 8.25 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R2, Q5)

Comparing the previous two sets of Figure 8.16 through Figure 8.20 and Figure 8.21 through Figure 8.25 to the following set of Figure 8.26 through Figure 8.30 respectively, the influence of a change in input rate can be noticed. For example, comparing Figure 8.16, Figure 8.21 and Figure 8.26 it can be observed that equipment utilisations were at the lowest in Figure 8.16 at input rate R1 but increased in Figure 8.21 at R2 and further increased in Figure 8.26 at R3. This shows that an increase in input rate increased the supply of crude to the distillation unit thereby increasing the amount of crude to be processed and resulted in the increased equipment utilisation.

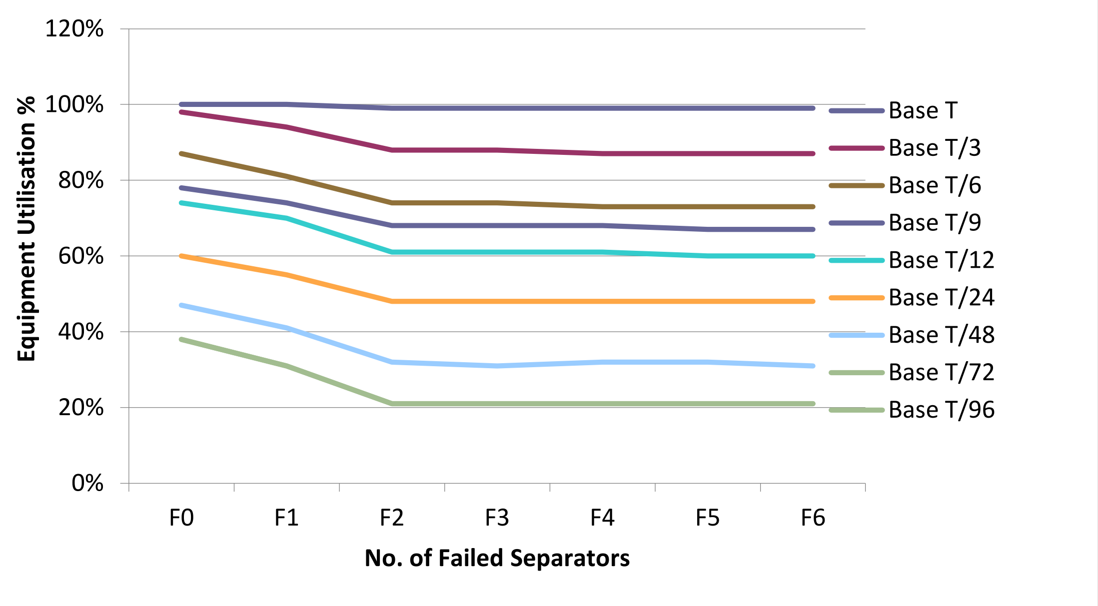


Figure 8.26 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R3, Q1)

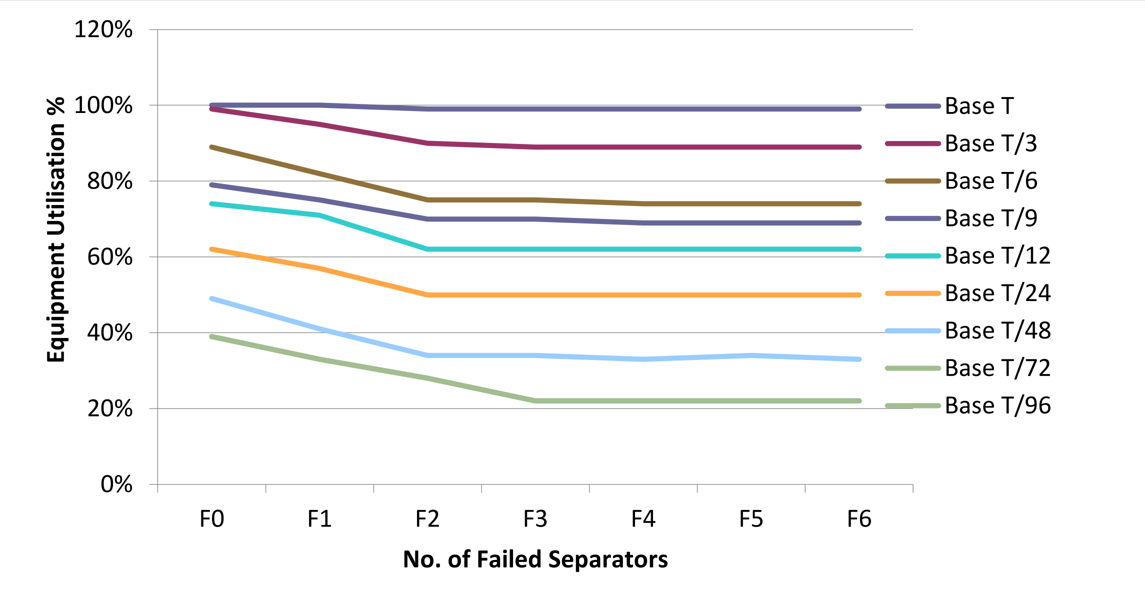


Figure 8.27 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R3, Q2)

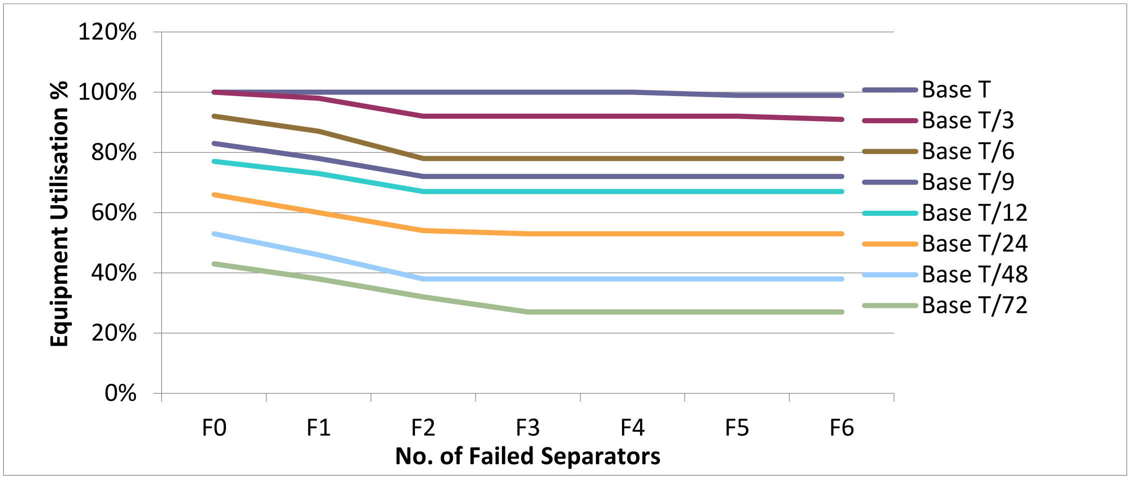


Figure 8.28 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R3, Q3)

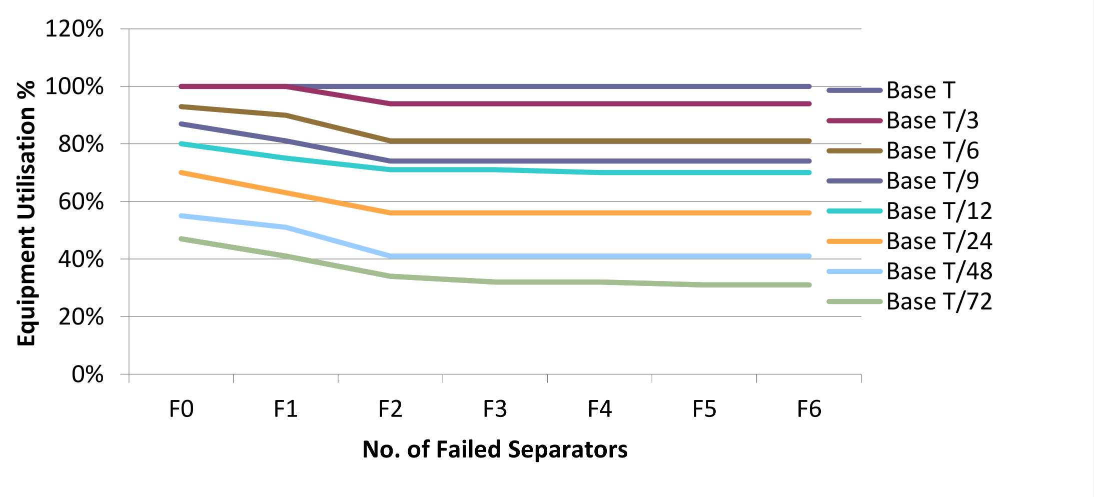


Figure 8.29 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R3, Q4)

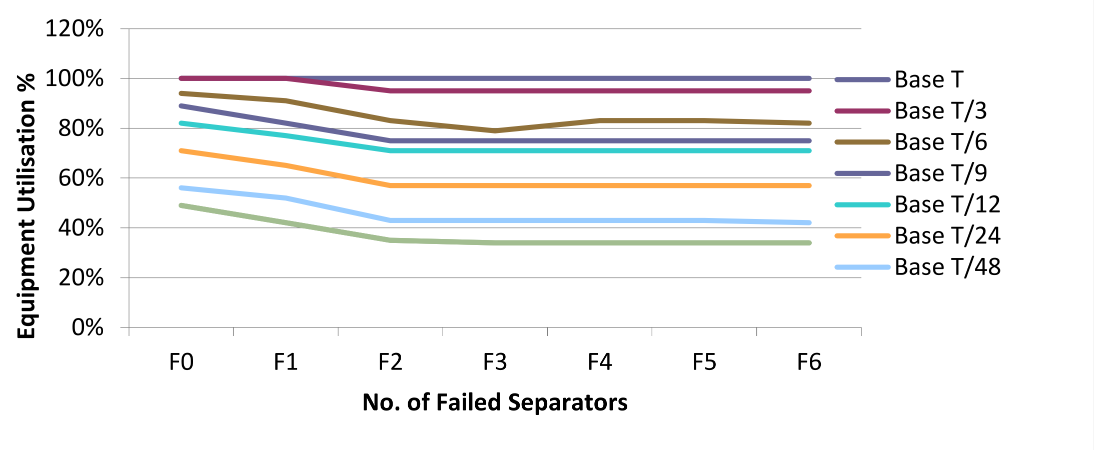


Figure 8.30 Graph of Equipment Utilisation against Number of Failed Separators Showing the Influence of the Distillation Capacity at (R3, Q5)

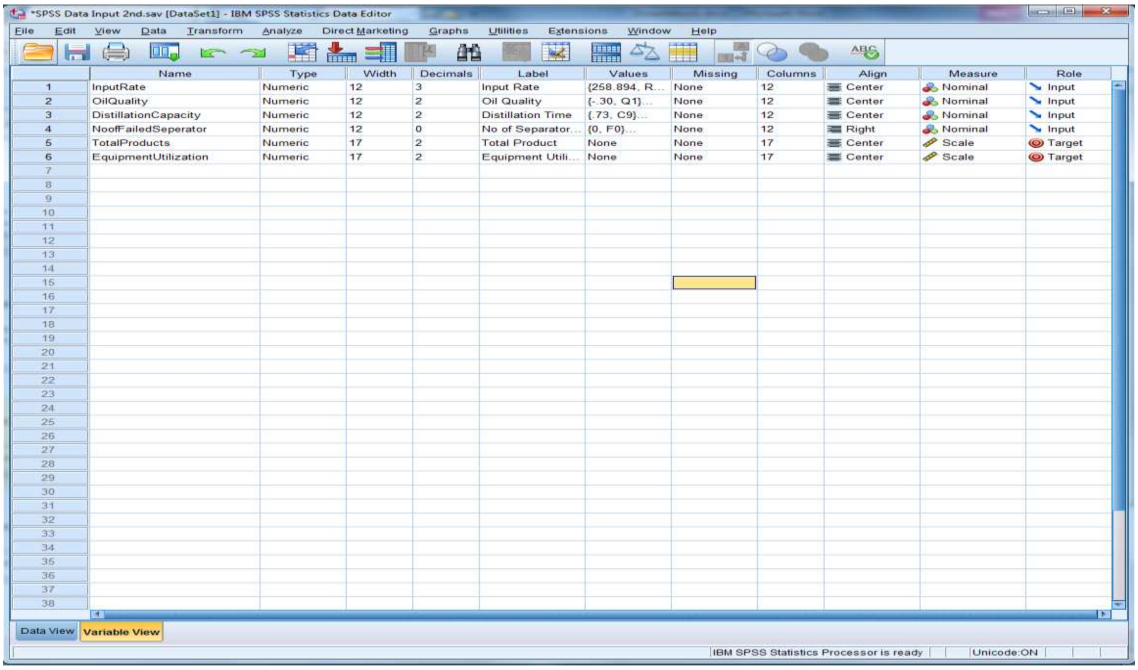
8.4 Results Analysis

8.4.1 Approach to analysis

There are several approaches to data analysis. The approach taken will depend on a number of factors such as: the nature of the data, the number of variable under consideration, the types of variables, the number of variables within each type and the purpose of the analysis. To further verify the significance of the experimental factors on the performance measures as explained in the previous section, SPSS software was used and MANOVA analysis technique was selected.

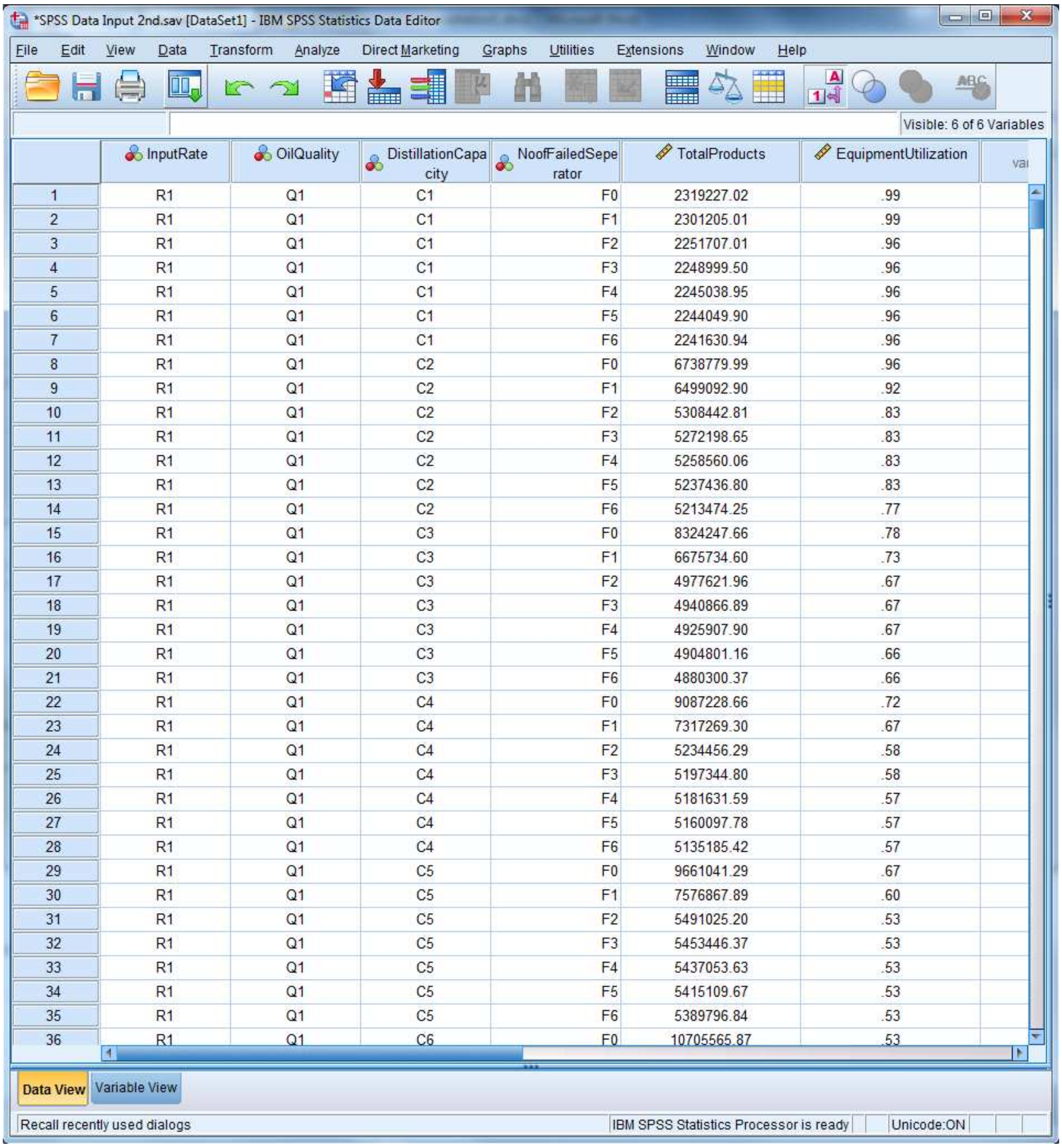
8.4.2 MANOVA Test

A MANOVA is a statistical technique used in measuring the strength between variables (Warne, 2014). It specifically involves measurement of the strength of independent variable(s) against more than one dependent variable. This technique was selected as the appropriate test for this research based on the general guideline for selecting statistical test developed by Leeper (2007) and summarised in of Appendix C. Prior to running MANOVA, the variables, their data types, labels, measure and role were initially defined under the variable view sheet as indicated in Figure 8.31 while the data from the design of experiment were imported into the data view sheet as indicated in Figure 8.32.



	Name	Type	Width	Decimals	Label	Values	Missing	Columns	Align	Measure	Role
1	InputRate	Numeric	12	3	Input Rate	{258.894, R...	None	12	Center	Nominal	Input
2	OilQuality	Numeric	12	2	Oil Quality	{-.30, Q1}...	None	12	Center	Nominal	Input
3	DistillationCapacity	Numeric	12	2	Distillation Time	{.73, C9}...	None	12	Center	Nominal	Input
4	NoofFailedSeperator	Numeric	12	0	No of Separator...	{0, F0}...	None	12	Right	Nominal	Input
5	TotalProducts	Numeric	17	2	Total Product	None	None	17	Center	Scale	Target
6	EquipmentUtilization	Numeric	17	2	Equipment Utili...	None	None	17	Center	Scale	Target

Figure 8.31 Screenshot of the SPSS Variable View Sheet



	InputRate	OilQuality	DistillationCapacity	NoofFailedSeperator	TotalProducts	EquipmentUtilization
1	R1	Q1	C1	F0	2319227.02	.99
2	R1	Q1	C1	F1	2301205.01	.99
3	R1	Q1	C1	F2	2251707.01	.96
4	R1	Q1	C1	F3	2248999.50	.96
5	R1	Q1	C1	F4	2245038.95	.96
6	R1	Q1	C1	F5	2244049.90	.96
7	R1	Q1	C1	F6	2241630.94	.96
8	R1	Q1	C2	F0	6738779.99	.96
9	R1	Q1	C2	F1	6499092.90	.92
10	R1	Q1	C2	F2	5308442.81	.83
11	R1	Q1	C2	F3	5272198.65	.83
12	R1	Q1	C2	F4	5258560.06	.83
13	R1	Q1	C2	F5	5237436.80	.83
14	R1	Q1	C2	F6	5213474.25	.77
15	R1	Q1	C3	F0	8324247.66	.78
16	R1	Q1	C3	F1	6675734.60	.73
17	R1	Q1	C3	F2	4977621.96	.67
18	R1	Q1	C3	F3	4940866.89	.67
19	R1	Q1	C3	F4	4925907.90	.67
20	R1	Q1	C3	F5	4904801.16	.66
21	R1	Q1	C3	F6	4880300.37	.66
22	R1	Q1	C4	F0	9087228.66	.72
23	R1	Q1	C4	F1	7317269.30	.67
24	R1	Q1	C4	F2	5234456.29	.58
25	R1	Q1	C4	F3	5197344.80	.58
26	R1	Q1	C4	F4	5181631.59	.57
27	R1	Q1	C4	F5	5160097.78	.57
28	R1	Q1	C4	F6	5135185.42	.57
29	R1	Q1	C5	F0	9661041.29	.67
30	R1	Q1	C5	F1	7576867.89	.60
31	R1	Q1	C5	F2	5491025.20	.53
32	R1	Q1	C5	F3	5453446.37	.53
33	R1	Q1	C5	F4	5437053.63	.53
34	R1	Q1	C5	F5	5415109.67	.53
35	R1	Q1	C5	F6	5389796.84	.53
36	R1	Q1	C6	F0	10705565.87	.53

Recall recently used dialogs

IBM SPSS Statistics Processor is ready

Unicode:ON

Figure 8.32 Screenshot of the SPSS Data View Sheet

This analysis was carried out with a confidence level of 95% and significant level (**α**) 0.05. The results from the MANOVA are indicated in Table 8.1, Table 8.2, Table 8.3 and Table 8.4. The result shows that the P-values for the experimental factors (Input Rate, Oil Quality, Distillation Capacity and Number of Failed Separators) are less than **α (**0.05**).** This indicates that the performance measures (Total Product and Equipment Utilisation) were influenced by the experimental factors each making significant impact on the performance.

Table 8.1 Result of MANOVA Indicating How Significant Input Rate is on Total Product and Equipment Utilisation

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig. (P-value)
Corrected Model	Total Products	1468067511000000.000[a]	2	734033755500000.000	44.616	.000
	Equipment Utilisation %	.979[b]	2	.490	7.169	.001
Intercept	Total Products	74267472330000000.000	1	74267472330000000.000	4514.077	.000
	Equipment Utilisation %	339.929	1	339.929	4976.357	.000
Input Rate	Total Products	1468067511000000.000	2	734033755500000.000	44.616	.000
	Equipment Utilisation %	.979	2	.490	7.169	.001
Error	Total Products	15498175280000000.000	942	16452415370000.000		
	Equipment Utilisation %	64.347	942	.068		
Total	Total Products	91233715120000000.000	945			
	Equipment Utilisation %	405.255	945			
Corrected Total	Total Products	16966242790000000.000	944			
	Equipment Utilisation %	65.326	944			

Table 8.2 Result of MANOVA Indicating How Significant the Oil Quality is on Total Product and Equipment Utilisation

Tests of Between-Subjects Effects						
Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig. (P-value)
Corrected Model	Total Products	1692581085000000.000[a]	4	423145271400000.000	26.042	.000
	Equipment Utilisation %	1.155[b]	4	.289	4.230	.002
Intercept	Total Products	74259541690000000.000	1	74259541690000000.000	4570.218	.000
	Equipment Utilisation %	339.915	1	339.915	4979.184	.000
Oil Quality	Total Products	1692581085000000.000	4	423145271400000.000	26.042	.000
	Equipment Utilisation %	1.155	4	.289	4.230	.002
Error	Total Products	15273661710000000.000	940	16248576280000.000		
	Equipment Utilisation %	64.171	940	.068		
Total	Total Products	91233715120000000.000	945			
	Equipment Utilisation %	405.255	945			
Corrected Total	Total Products	16966242790000000.000	944			
	Equipment Utilisation %	65.326	944			

Table 8.3 Result of MANOVA Indicating How Significant Distillation Capacity is on Total Product and Equipment Utilisation

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig. (P-value)
Corrected Model	Total Products	7903226711000000.000[a]	8	987903338800000.000	102.028	.000
	Equipment Utilisation %	60.300[b]	8	7.538	1403.764	.000
Intercept	Total Products	74267472330000000.000	1	74267472330000000.000	7670.113	.000
	Equipment Utilisation %	339.929	1	339.929	63307.111	.000
Distillation Capacity	Total Products	7903226711000000.000	8	987903338800000.000	102.028	.000
	Equipment Utilisation %	60.300	8	7.538	1403.764	.000
Error	Total Products	9063016081000000.000	936	9682709489000.000		
	Equipment Utilisation %	5.026	936	.005		
Total	Total Products	91233715120000000.000	945			
	Equipment Utilisation %	405.255	945			
Corrected Total	Total Products	16966242790000000.000	944			
	Equipment Utilisation %	65.326	944			

Table 8.4 Result of MANOVA Indicating How Significant the Number of Failed Separators is on Total Product and Equipment Utilisation

Tests of Between-Subjects Effects						
Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig. (P-value)
Corrected Model	Total Products	3748221502000000.000[a]	6	624703583700000.000	44.331	.000
	Equipment Utilisation %	1.985[b]	6	.331	4.899	.000
Intercept	Total Products	74267472330000000.000	1	74267472330000000.000	5270.296	.000
	Equipment Utilisation %	339.929	1	339.929	5033.902	.000
No. of Failed Separator	Total Products	3748221502000000.000	6	624703583700000.000	44.331	.000
	Equipment Utilisation %	1.985	6	.331	4.899	.000
Error	Total Products	13218021290000000.000	938	14091707130000.000		
	Equipment Utilisation %	63.341	938	.068		
Total	Total Products	91233715120000000.000	945			
	Equipment Utilisation %	405.255	945			
Corrected Total	Total Products	16966242790000000.000	944			
	Equipment Utilisation %	65.326	944			

In the follow sections, the effects of experimental factors on the estimated marginal means of the performance measures are briefly explained using graphs plotted with SPSS software.

8.4.3 The influence of the Experimental Factors on the Estimated Marginal Mean of Total Products

Figure 8.33 is a set of plots showing the effect of the four experimental factors on the performance-measure Estimated Marginal Mean of Total Products (EMMTP). As can be seen, an increase in Input Rate, Oil Quality and distillation capacity resulted in an increase in EMMTP. Each level of these factors had different effect on the EMMTP. Unlike the other factors, as the Number of Failed Separator increases EMMTP dropped. Sharp drop was experienced from F0 to F2 and then stayed relatively stable after F2 since the effect of an extra separator failing on a production line was almost redundant.

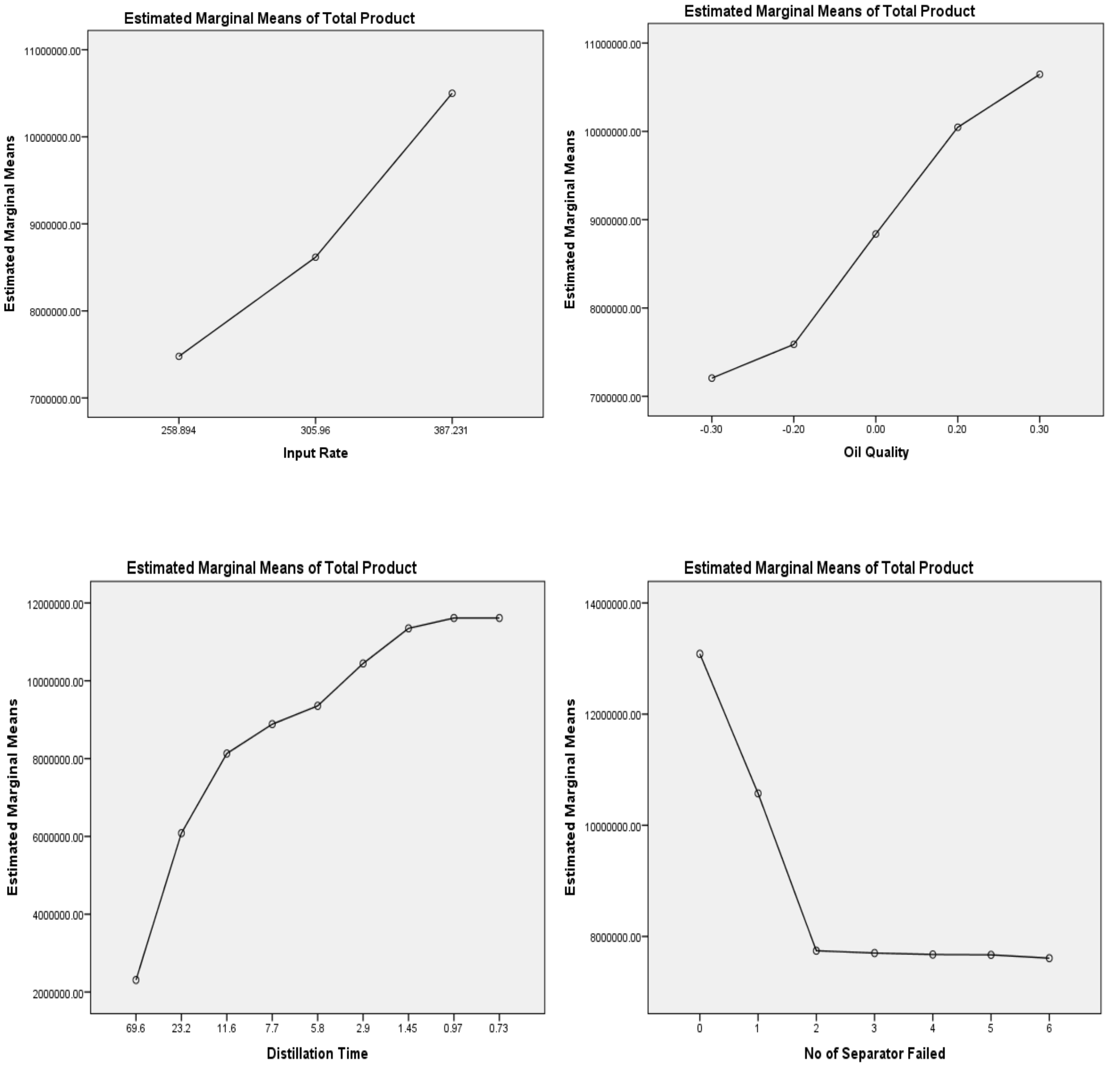
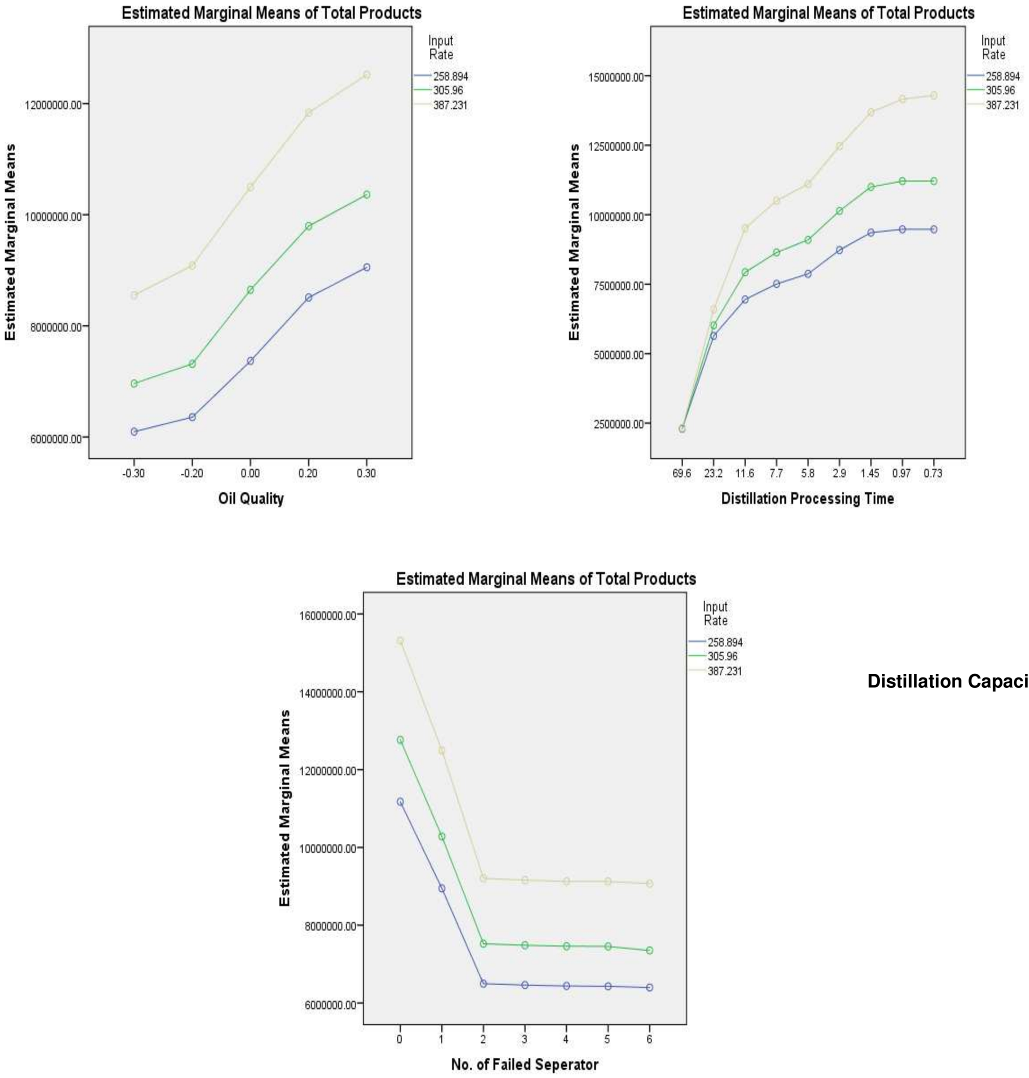


Figure 8.33 The Effect of the Experimental Factors on the EMMTP

8.4.4 The Influence of Input Rate and Other Factors on Estimated Marginal Mean of Total Products

In Figure 8.34 the interaction of the Input Rate and other factors with their effect on EMMPT can be seen as positive. For the same conditions in each graph the EMMPT increased when the Input Rate changed from R1 (258.894 bbl/min) to R2 (305.960 bbl/min) and to finally R3 (387.231 bbl/min).



Distillation Capacity

Figure 8.34 The Relationship between Input Rate and Other Experimental Factors on the EMMTP

The EMMPT were about the same for the three levels of Input Rate at Distillation Capacity C1 (69.6) due to the fact that the capacity was too low to process any of the distillates on time which resulted in a queue of oil through the system.

8.4.5 The Influence of Oil Quality and Distillation Capacity on Estimated Marginal Mean of Total Products

From Figure 8.35, the interaction between Distillation Capacity and Oil Quality can be seen as being positive on the EMMPT however, it can be noticed that the Oil Quality did not interact well at capacity C1 (69.6) because the base capacity was only able to process about 2500000 bbl/day therefore increasing the Oil Quality will only cause a queue of fluid in the system waiting to be processed and only result in the same output.

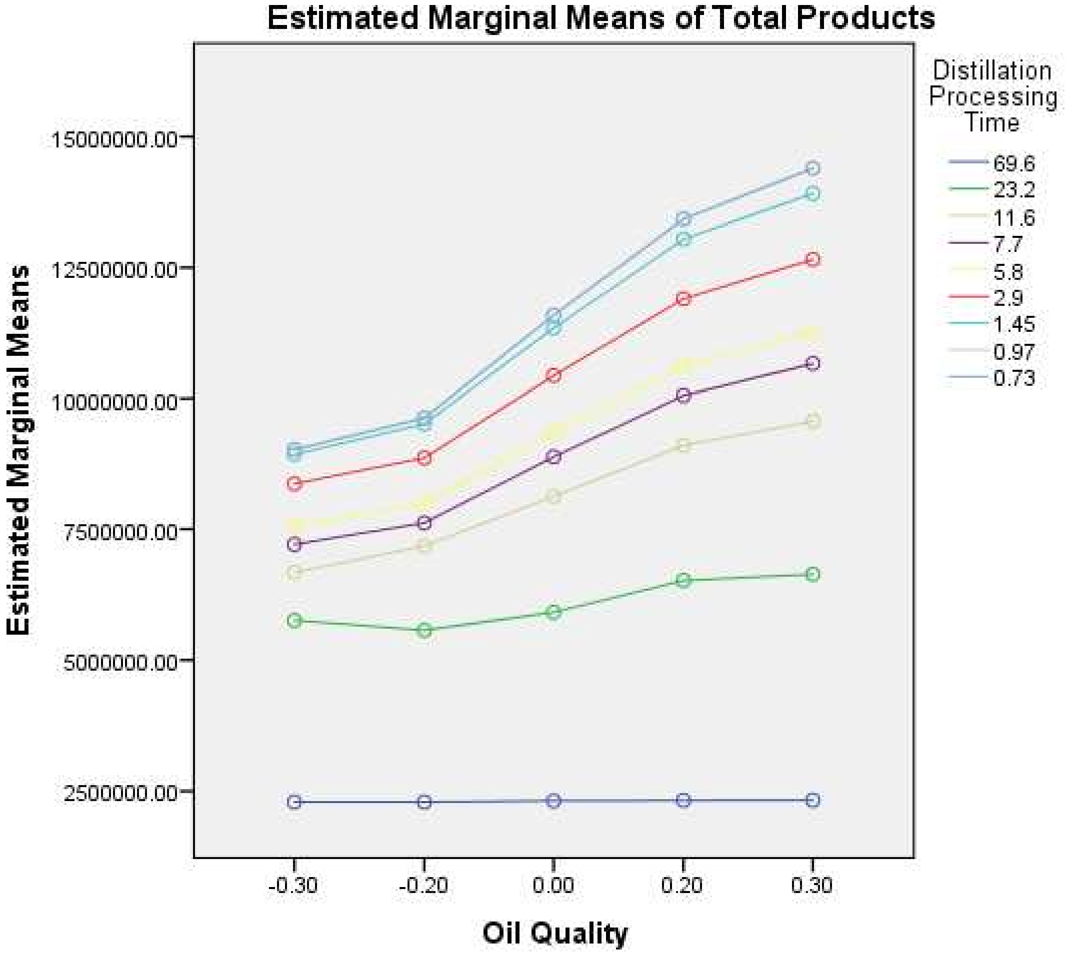


Figure 8.35 The Relationship between Oil Quality and Distillation Capacity on the Estimated Marginal Means of Total Product

8.4.6 The Influence of Oil Quality and Number of Failed Separators on Estimated Marginal Mean of Total Products

Figure 8.36 shows the impact of the interaction between oil quality and number of failed separators on EMMPT. It was clear that EMMPT decreased when the number of failed separators increased. Conversely, the EMMPT increase with quality of crude oil increase. When the number of failed separators increase beyond 2, their impact on EMMPT was about the same since multiple failure at once has a redundant impact on the system.

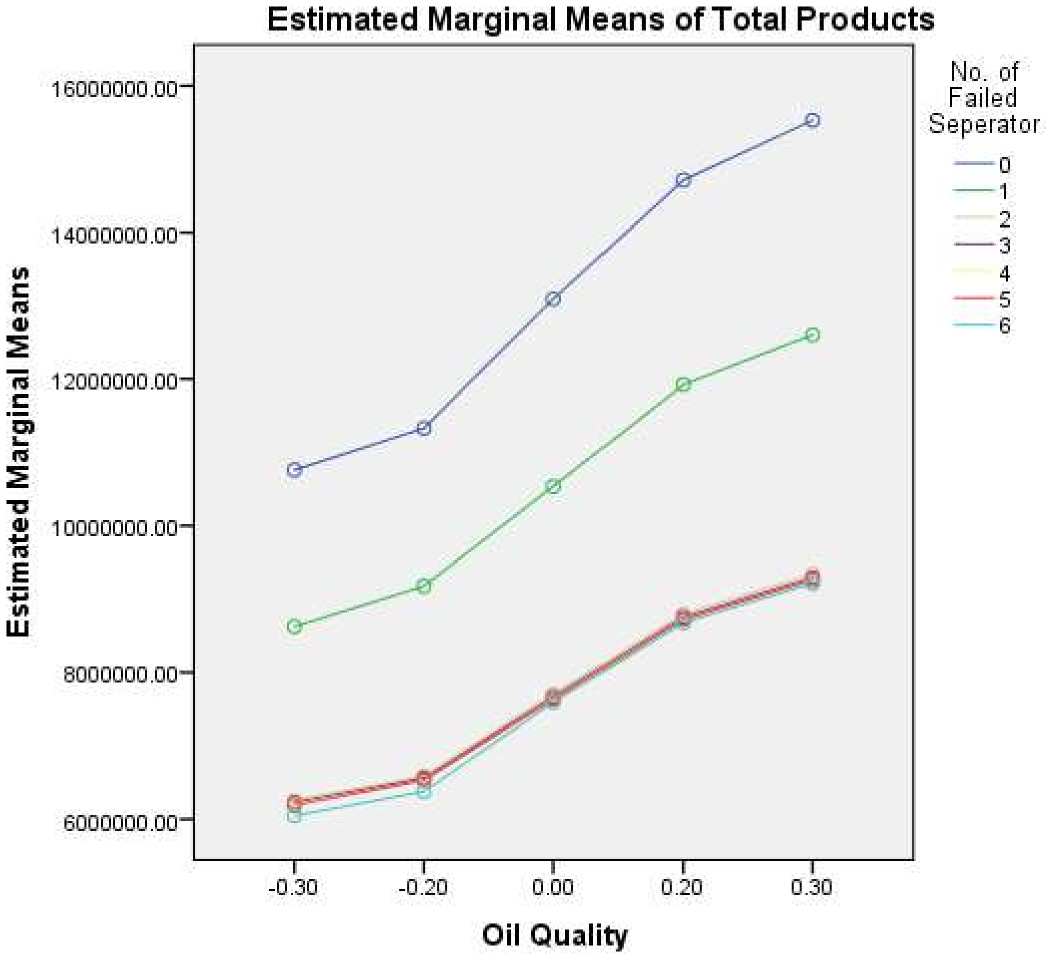


Figure 8.36 The Relationship between Oil Quality and Number of Failed Separator on the Estimated Marginal Means of Total Product

8.4.7 The Influence of the Experimental Factors on the Estimated Marginal Mean of Equipment Utilization (EMMEU)

Figure 8.37 is a set of plots showing the effect of the four experimental factors on the EMMEU. It can be seen that as the Input Rate and Oil Quality increased the EMMEU increased as well due to the fact that the system will be busier processing the increase quantity of crude supplied. Conversely the EMMEU decreased with increase in Distillation Capacity and the Number of Failed Separator. The inverse proportionality observed between the Distillation Capacity and EMMEU was based on the fact that as the capacity increases, the system becomes less busy while that observed between Number of Failed Separators and EMMEU was because failure will mean that the system will be down for repair thereby reducing its availability and the system Overall Equipment Effectiveness.

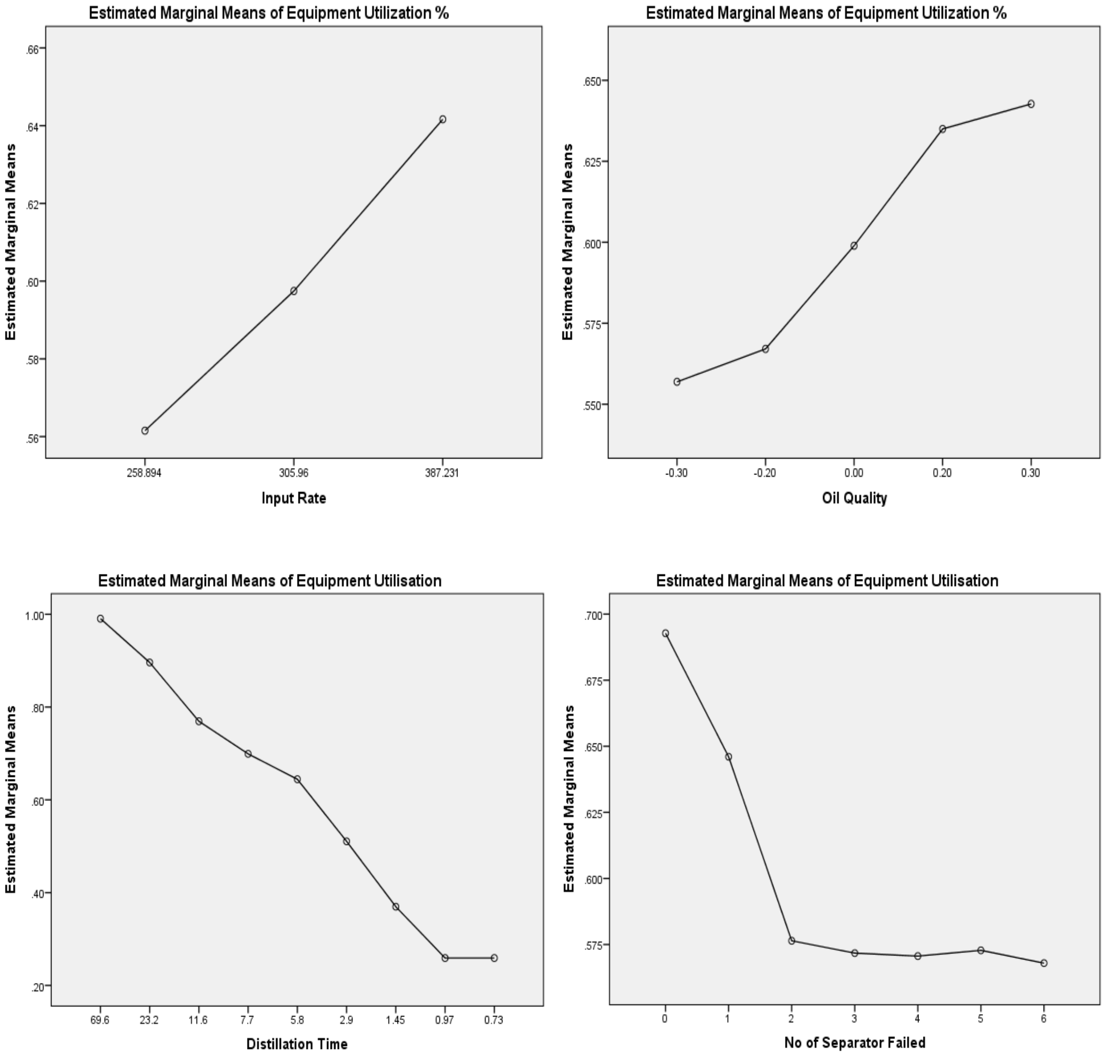


Figure 8.37 The effect of the Experimental Factors on the EMMEU

8.5 Conclusion

The main points of this chapter are summarised in the following:

- The results obtained from the 945 runs, when plotted on graphs by using Excel program, gave a picture of how changes in the levels of the experimental factors affected on the performance measures.
- MANOVA test was applied providing further analysis of the influence of the experimental factors on the output factors. The analysis showed that the performance measures were significantly influenced by all the experimental factors.

The next chapter will summarise the conclusions, recommendations, limitations, contributions to knowledge and future works.

CHAPTER NINE

CONCLUSIONS, RECOMMENDATIONS, CONTRIBUTIONS TO KNOWLEDGE AND FUTURE WORK

9.1 Introduction

Traditional approaches to planning, optimisation and management are insufficient to meet current and future challenges in the dynamic and complex environment of the petroleum industry. This was the motivation for developing a new mathematical model with two stage-stochastic linear programming and a simulation model for the planning and optimisation of the petroleum SC. This chapter summarises the findings of the research before discussing how it contributes to our knowledge and offering suggestions for further study. A comprehensive literature review highlighted the current knowledge and practices with details of the different SC functions involved in petroleum industry, different types of uncertainties, and decide up on the research project's scope were identified.

9.2 Summary of findings

- A comprehensive literature review revealed that while numerous authors have offered suggestions for optimising planning in segments of the petroleum supply chain, no one has taken an integrated approach and considered the chain as a whole. Furthermore, most of the reviewed studies treat the planning problem at the tactical and operational levels; few authors have addressed planning/optimisation at the strategic level.
- The different types of methodologies method used to deal with planning and optimising petroleum supply chain were introduced and discussed.
- In this study, the Proposed Framework for Planning and Optimising Petroleum Supply Chain has been developed and discussed.
- The petroleum supply chain encompasses a range of functions, including investment decision making; crude oil selection; refinery operations; the planning of transportation, production levels and capacities and product

distribution; and inventory management. Including all of these functions and their associated activities within a single planning model is virtually impossible. Accordingly, this study responds by proposing a two-part framework for petroleum SC optimization.

- The first part of this framework, a mathematical model of two-stage stochastic linear programming with recourse method to show the relationship between various supply chain functions and a range of KPIs (cost of crude oil, transportation of crude oil, refinery production, production storage, production shipped, backlog and shortage demand) under uncertainty of market demand.
- Optimal planning results revealed that the proposed mathematical model can be used to develop a comprehensive one-year plan that will deliver optimum SC operation and maximum profitability.
- Sensitivity analysis results showed that planning under uncertain market demand is risky. Petroleum companies therefore need to develop resilient supply chain planning if they are to capture the greatest available benefit from the market. The plans generated by the stochastic model had a high EVPI, indicating a higher level of risk than would have been produced in a deterministic plan.
- The optimal quantity of crude oil presented into deterministic model which was (5.10E+05 bbl./d) used in simulation model for calculating the performance measurement of simulation model of petroleum supply chain.
- GAMS software as a technique tool was used for solving mathematical problems with explaining its motivation and structure of the model has been introduced.
- The second part of the optimisation framework is an operational simulation model. Unlike the linear programming approach favoured by other researchers, the simulation approach used here allowed the combination of different types of petroleum SC system characteristics (continuous, discrete, dynamic, static, deterministic, stochastic and non-terminating) into one model, enabling it to mimic the behaviour of a real system. Furthermore, the

animation feature that comes with the Arena simulation software made the modelling process more interactive and easier for anyone to use.

- The system schematic served as a good blueprint for building the model. Unlike a real build, where errors might be costly to repair, building up the model within Arena mainly involved the drag and drop of entities called modules, which mimic the behaviour of real system entities. Module parameters could then be modified to fit the real system without incurring additional cost. The model was built in three phases in order to reduce the likelihood of mistakes and to facilitate the verification and validation process. In real life, building a new facility or modifying an existing one is often costly and might disrupt the regular operations of the SC. The simulation approach allows designers to confirm the feasibility of the proposed facility before it is actually built, without any disruption to any physical system.
- Verification and validation of the model was a vital part of this project, as the findings of the experiment would have been useless if the model did not perform as expected. It was necessary to ensure that the model behaved as expected and produced results that were similar to real-life systems. Four experimental factors (input rate, oil quality, distillation capacity and number of failed separators) and two performance measures (total products and equipment utilisation) were selected from a list of key performance indicators within the petroleum industry for consideration in the simulation. To avoid guess work, a standard approach was used to plan the experiment. Based on the levels of the experimental factors determined, a total of 945 runs were calculated and their performance measures were recorded. These runs represented the number of scenarios in which the proposed system could be set up. If the actual cost for setting up each scenario is known, the cost can be measured against the performance measures. This information may help guide companies' decision making in regard to system settings.
- The results obtained from the 945 runs, when plotted on graphs, gave a picture of how changes in the levels of the experimental factors affected the performance measures. The influence of the experimental factors was confirmed by further analysis using MANOVA in SPSS software. The

analysis showed that the performance measures were significantly influenced by all the experimental factors. This information may help companies attempting to optimise performance as it allows them to select the factor they need to achieve their target without compromising cost or increasing risk. For example, it became apparent that increasing distillation capacity raises output but reduces equipment utilisation – this means that companies must decide to what extent they are prepared to trade-off one effect against the other. Most will prefer to have an overall equipment effectiveness of about 95%, but others might choose a lower value to accommodate future increase in demand. Similarly, the pattern of failure observed among separators may aid in the development of equipment maintenance strategies that will increase equipment availability and, in turn, output. The findings may also guide equipment purchasing decisions, especially where the reliability and stability of the production process are important. Where this is the case, it is advisable to stick with brands and suppliers whose products have a reputation for reliability.

9.2 Contributions to Knowledge

The research's main contribution to knowledge is the development of a generic model for optimisation/planning framework that considers most of the activities and events within the petroleum supply chain. This has been done by designing and developing two models: a mathematical model and a simulation model. It is important to mention that the simulation model in particular can be considered as a major contribution to knowledge as it is a continues type of models, which is very rare to finding the literature.

9.3 Recommendations, limitation and future work

To provide built-in argumentations, the essence of recommendations and suggestions for future work are counted as following:

- The act of measuring performance provides information that aids intelligent decision making and proper management, so the identification of other key performance indicators (e.g. profitability, revenue, on-time deliveries, costumer response time and manufacturing lead time) should be considered in future research.

- The treatment of uncertainty requires further attention and research effort; more needs to be understood about the effects of uncertainties such as resource availability, raw material prices and product demand. There is little literature dealing with petroleum SC planning under endogenous uncertainties such as product yield fluctuation, processing and blending options and machine availability.
- The impact of sustainability dimensions on the petroleum supply chain has also received very little attention, given its global importance. Studies addressing the problem of sustainable petroleum SC optimisation would also be worthwhile. For example, factoring environmental impacts (e.g. carbon emission levels) into the system setup would help illustrate how green the refining process is.
- The experiment conducted here considered a range of factors. Introducing the cost of each factor into the simulation would allow researchers to assess the cost of setting up each scenario against the effect on performance measures.
- The energy consumption (coke and natural gas) of refineries is a major cost incurred in the industry. This factor can be linked with the SC process to determine the optimum amount of energy required.

References

Al-Othman, W. B., Lababidi, H. M., Alatiqi, I. M., & Al-Shayji, K. (2008). Supply chain optimisation of petroleum organization under uncertainty in market demands and prices. *European Journal of Operational Research, 189*(3), 822-840.

Al-Qahtani, K., Elkamel, A., & Ponnambalam, K. (2008). Robust optimisation for petrochemical network design under uncertainty. *Industrial & Engineering Chemistry Research*, 47(11), 3912-3919.

Al-Qahtani, K., & Elkamel, A. (2010). Robust planning of multisite refinery networks: Optimisation under uncertainty. *Computers & Chemical Engineering, 34*(6), 985-995.

Al-Sharrah, G., Elkamel, A., & Almanssoor, A. (2010). Sustainability indicators for decision-making and optimisation in the process industry: The case of the petrochemical industry. *Chemical Engineering Science*, 65(4), 1452-1461.

Anderson, M. J., & Whitcomb, P. J. (2000). *Design of experiments*. Kirk-Othmer Encyclopedia of Chemical Technology,

Anwar, K. (2010). *Marketing strategy: Supply chain management*. Retrieved 18 February 2017, from https://khairul-anwar.com/2010/02/22/marketing-strategy-supply-chain-management.

Aririguzo, J., & Saad, S. (2012). Simulating the integration of original equipment manufacturers and suppliers in fractal environment. *International Journal of Simulation and Process Modelling*, *7*(3), 148. http://dx.doi.org/10.1504/ijspm.2012.049151

Artley, W., & Stroh, S. (2001). Establishing an integrated performance measurement system. The Performance-Based Management Handbook, 2

Axsinvestor presentation. (2013). Retrieved 20 February 2017, from https://www.sec.gov/Archives/edgar/data/1214816/000121481613000036/axsinvestorpresentation.htm

Bagajewicz, M., Siemanond, K., Rangsunvigit, P., & Pongsakdi, A. (2006). Financial risk management in the planning of refinery operations. *International Journal Of Production Economics,* 103(1), 64-86. http://dx.doi.org/10.1016/j.ijpe.2005.04.007

Banks, J., & Carson, J. (1984). *Discrete-event system simulation* (1st ed.). [Englewood Cliffs, N.J.]: [Prentice-Hall].

Bansal, P. (2005). Evolving sustainably: A longitudinal study of corporate sustainable development. *Strategic Management Journal*, 26(3), 197-218.

Beamon, B. M. (1998). Supply chain design and analysis: Models and methods. *International Journal of Production Economics, 55*(3), 281-294.

Beamon, B. M. (1999). Measuring supply chain performance. *International Journal of Operations & Production Management, 19*(3), 275-292.

Bell, J. T. (1990). Modelling of the global petrochemical industry, Doctoral Dissertation, University of Wisconsin at Madison Madison, WI, USA.

Bellman, R. E., & Zadeh, L. A. (1970). Decision-making in a fuzzy environment. Management Science, 17(4), B-141-B-164.

Bellman, R. (2013). Dynamic programming Courier Corporation.

Bengtsson, J., Bredström, D., Flisberg, P., & Rönnqvist, M. (2013). Robust planning of blending activities at refineries. *Journal of the Operational Research Society, 64*(6), 848-863.

Benyoucef, A., & Lantz, F. (2012). Oil refining planning under petroleum products demand uncertainties: Case of Algeria. *Journal of Energy and Power Engineering, 6*(6), 858.

Beulens, A., & van der Vorst, J. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies. *International Journal of Physical Distribution & Logistics Managemen*t, 32(6), 409-430. http://dx.doi.org/10.1108/09600030210437951

Bloch, H., Salim, R., & Rafiq, S. (2009). Impact of crude oil price volatility on economic activities: An empirical investigation in the Thai economy. *Resources Policy*, 34(3), 121-132. http://dx.doi.org/10.1016/j.resourpol.2008.09.001

Boccalatte, A., Sacile, R., & Paolucci, M. (2002). Allocating crude oil supply to port and refinery tanks: A simulation-based decision support system. *Decision Support Systems*, 33(1), 39-54. http://dx.doi.org/10.1016/s0167-9236(01)00133-6.

Birge, J. R. (1997). State-of-the-art-survey-stochastic programming: Computation and applications. *INFORMS Journal on Computing, 9*(2), 111-133.

Bititci, U. S., Nudurupati, S. S., Turner, T. J., & Creighton, S. (2002). Web enabled performance measurement systems: Management implications. *International Journal of Operations & Production Management*, 22(11), 1273-1287.

Bodington, C. E., & Baker, T. E. (1990). A history of mathematical programming in the petroleum industry. *Interfaces*, 20(4), 117-127.

Bok, J., Lee, H., & Park, S. (1998). Robust investment model for long-range capacity expansion of chemical processing networks under uncertain demand forecast scenarios. *Computers & Chemical Engineering*, 22(7), 1037-1049.

Carneiro, M. C., Ribas, G. P., & Hamacher, S. (2010). Risk management in the oil supply chain: A CVaR approach. *Industrial & Engineering Chemistry Research, 49*(7), 3286-3294.

Charnes, A., & Cooper, W. W. (1959). Chance-constrained programming. Management Science, 6(1), 73-79.

Chattopadhyay, D. (1999). Application of general algebraic modelling system to power system optimization. *IEEE Transactions on Power Systems*, 14(1), 15-22.

Cheng, L., & Duran, M. A. (2004). Logistics for world-wide crude oil transportation using discrete event simulation and optimal control. *Computers & Chemical Engineering, 28*(6), 897-911.

Christopher, M. (2000). The agile supply chains. *Industrial Marketing Management*, 29(1), 37-44.

Christopher, M., & Gattorna, J. (2005). Supply chain cost management and value-based pricing. *Industrial Marketing Management*, 34(2), 115-121.

Christopher, M. (2010). *Logistics and supply chain management* (4th ed.). Harlow, England: Financial Times Prentice Hall.

Chryssolouris, G., Papakostas, N., & Mourtzis, D. (2005). Refinery short-term scheduling with tank farm, inventory and distillation management: An integrated simulation-based approach. *European Journal of Operational Research, 166*(3), 812-827.

Chung, C. (2004). Simulation modeling handbook (1st ed.). Boca Raton: CRC Press.

Chunpeng, L., & Gang, R. (2009). A strategy for the integration of production planning and scheduling in refineries under uncertainty. *Chinese Journal of Chemical Engineering*, 17(1), 113-127.

Cohen, B. (2016). BP statistical review of world energy 2016. Retrieved from http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf

Cooper, M., & Lambert, D. (2000). Issues in supply chain management. Industrial Marketing Management, 29(1), 65-83.

Dantzig, G. B. (1955). Linear programming under uncertainty. *Management Science, 1*(3-4), 197-206.

Das, S. K., & Abdel-Malek, L. (2003). Modelling the flexibility of order quantities and lead-times in supply chains. *International Journal of Production Economics*, 85(2), 171-181.

David Kelton, W., Sadowski, R. P., & Sturrock, D. T. (2008). Simulation with arena.

de Brito Cruz, C Chaimovich H, & Chaimovich, H. (2010). Industrial R&D still suffers from a lack of government support, even though the situation has improved radically over the past eight years. UNESCO Science Report, 103, 103-121.

Dempster, M., Pedron, N. H., Medova, E., Scott, J., & Sembos, A. (2000). Planning logistics operations in the oil industry. *Journal of the Operational Research Society*, 51(11), 1271-1288.

Dijkema, G. P., Grievink, J., & Weijnen, M. P. (2003). Functional modelling for a sustainable petrochemical industry. *Process Safety and Environmental Protection, 81*(5), 331-340.

Dunne, T., & Mu, X. (2010). Investment spikes and uncertainty in the petroleum refining industry. *The Journal of Industrial Economics, 58*(1), 190-213.

Ejikeme-Ugwu, E., Liu, S., & Wang, M. (2011). Integrated refinery planning under product demand uncertainty. EN Pistikopoulos, MCG Kokossis, AC (Eds.), Computer Aided Chemical Engineering, Elsevier, , 950-954.

Escudero, L. F., Quintana, F. J., & Salmerón, J. (1999). CORO, a modelling and an algorithmic framework for oil supply, transformation and distribution optimization under uncertainty. *European Journal of Operational Research, 114*(3), 638-656.

Fernandes, L. J., Relvas, S., & Barbosa-Póvoa, A. P. (2013). Strategic network design of downstream petroleum supply chains: Single versus multi-entity participation. *Chemical Engineering Research and Design*, 91(8), 1557-1587.

Franzese, L. A. G., Fioroni, M. M., Paz, D. P., Botter, R. C., Gratti, C. A., Martinez, A. O., & Bacigalupo, C. M. (2006). Supply-chain simulation and analysis of petroleum refinery systems: A reusable template with incremental approach. *Winter Simulation Conference: Proceedings of the 38 The Conference on Winter Simulation, 3*(06) 2306-2306.

Gibb, A., St-Jacques, M., Nourry, G., & Johnson, M. (2002). A comparison of deterministic vs stochastic simulation models for assessing adaptive information management techniques over disadvantaged tactical communication networks. 7th Iccrts,

Giesbrecht, F. G., & Gumpertz, M. L. (2011). Planning, construction, and statistical analysis of comparative experiments John Wiley & Sons.

Ghatee, M., & Hashemi, S. M. (2009). Optimal network design and storage management in petroleum distribution network under uncertainty. *Engineering Applications of Artificial Intelligence, 22*(4), 796-807.

Göthe-Lundgren, M., Lundgren, J. T., & Persson, J. A. (2002). An optimization model for refinery production scheduling. *International Journal of Production Economics, 78*(3), 255-270.

Grossmann, I. E., Van Den Heever, Susara A, & Harjunkoski, I. (2002). Discrete optimization methods and their role in the integration of planning and scheduling. *AIChE Symposium Series*, 150-168.

Grossmann, I. (2005). Enterprise-wide optimization: A new frontier in process systems engineering. *AIChE Journal*, 51(7), 1846-1857.

Guajardo, M., Kylinger, M., & Rönnqvist, M. (2013). Speciality oils supply chain optimization: From a decoupled to an integrated planning approach. *European Journal of Operational Research*, 229(2), 540-551.

Guillén-Gosálbez, G., & Grossmann, I. E. (2009). Optimal design and planning of sustainable chemical supply chains under uncertainty. *AIChE Journal, 55*(1), 99-121.

Gupta, A., & Maranas, C. D. (2003). Managing demand uncertainty in supply chain planning. *Computers & Chemical Engineering, 27*(8), 1219-1227.

Gupta, V., & Grossmann, I. E. (2012). An efficient multi-period MINLP model for optimal planning of offshore oil and gas field infrastructure. *Industrial & Engineering Chemistry Research*, 51(19), 6823-6840.

Guyonnet, P., Grant, F. H., & Bagajewicz, M. J. (2008). Integrated model for refinery planning, oil procuring, and product distribution. Industrial & Engineering Chemistry Research, 48(1), 463-482.

Helton, J. C., Johnson, J. D., Sallaberry, C. J., & Storlie, C. B. (2006). Survey of sampling-based methods for uncertainty and sensitivity analysis. Reliability Engineering & System Safety, 91(10), 1175-1209.

Holweg, M., Disney, S., Holmström, J., & Småros, J. (2005). Supply chain collaboration:: Making sense of the strategy continuum. European Management Journal, 23(2), 170-181.

Herrán, A., De la Cruz, J., & De Andrés, B. (2010). A mathematical model for planning transportation of multiple petroleum products in a multi-pipeline system. *Computers & Chemical Engineering, 34*(3), 401-413.

Henriques, I., & Sadorsky, P. (2011). The effect of oil price volatility on strategic investment. *Energy Economics, 33*(1), 79-87.

Lawson, D., & Marion, G. (2008). An introduction to mathematical modelling. Bioinformatics and Statistics Scotland, , 3-13.

Iyer, R. R., & Grossmann, I. E. (1998). A bi-level decomposition algorithm for long-range planning of process networks. Industrial & Engineering Chemistry Research, 37(2), 474-481.

Jia, Z., & Ierapetritou, M. (2003). Mixed-integer linear programming model for gasoline blending and distribution scheduling. *Industrial & Engineering Chemistry Research, 42*(4), 825-835.

Julka, N., Srinivasan, R., & Karimi, I. (2002). Agent-based supply chain management—1: Framework. *Computers & Chemical Engineering, 26*(12), 1755-1769.

Julka, N., Karimi, I., & Srinivasan, R. (2002). Agent-based supply chain management—2: A refinery application. *Computers & Chemical Engineering, 26*(12), 1771-1781.

Jung, J. Y., Blau, G., Pekny, J. F., Reklaitis, G. V., & Eversdyk, D. (2004). A simulation based optimization approach to supply chain management under demand uncertainty. *Computers & Chemical Engineering, 28*(10), 2087-2106.

Karim, A. R., Hamasalih, L. O., Tofiq, D. I., & Salih, D. M. (2015). A comparative elemental analysis of the different kurdistan crude oil fields. Technology, 2(2), 74-78.

Kellen, V., & Wolf, B. (2003). Business performance measurement. Information Visualization, 1(312), 1-36.

Khor, C. S. (2007). A hybrid of stochastic programming approaches with economic and operational risk management for petroleum refinery planning under uncertainty.

Khor, C., Elkamel, A., & Douglas, P. (2008). Stochastic refinery planning with risk management. *Petroleum Science and Technology, 26*(14), 1726-1740.

Kim, Y., Yun, C., Park, S. B., Park, S., & Fan, L. (2008). An integrated model of supply network and production planning for multiple fuel products of multi-site refineries. *Computers & Chemical Engineering, 32*(11), 2529-2535.

Koo, L. Y., Chen, Y., Adhitya, A., Srinivasan, R., & Karimi, I. A. (2006). Evaluating refinery supply chain policies and investment decisions through simulation-optimization. *Proceedings of the 2006 Winter Simulation Conference,*1431-1437.

Koo, L. Y., Adhitya, A., Srinivasan, R., & Karimi, I. A. (2008). Decision support for integrated refinery supply chains: Part 2. Design and operation. *Computers & Chemical Engineering, 32*(11), 2787-2800.

Kumar, R., & Markeset, T. (2007). Development of performance-based service strategies for the oil and gas industry: A case study. *Journal of Business & Industrial Marketing, 22*(4), 272-280.

Kuo, T., & Chang, C. (2008). Application of a mathematic programming model for integrated planning and scheduling of petroleum supply networks. Industrial & Engineering Chemistry Research, 47(6), 1935-1954.

Lababidi, H. M., Ahmed, M. A., Alatiqi, I. M., & Al-Enzi, A. F. (2004). Optimizing the supply chain of a petrochemical company under uncertain operating and economic conditions. *Industrial & Engineering Chemistry Research,43*(1), 63-73.

Lambert, D. M., & Cooper, M. C. (2000). Issues in supply chain management. *Industrial Marketing Management, 29*(1), 65-83.

Iannone, R., Miranda, S., & Riemma, S. (2007). Supply chain distributed simulation: An efficient architecture for multi-model synchronization. Simulation Modelling Practice and Theory, 15(3), 221-236.

Lasschuit, W., & Thijssen, N. (2004). Supporting supply chain planning and scheduling decisions in the oil and chemical industry. Computers & Chemical Engineering, 28(6), 863-870.

Law, A. M & Kelton, W. D. (1991). Simulation modelling and analysis McGraw-Hill New York.

Lee, H., Pinto, J. M., Grossmann, I. E., & Park, S. (1996). Mixed-integer linear programming model for refinery short-term scheduling of crude oil unloading with inventory management. *Industrial & Engineering Chemistry Research, 35*(5), 1630-1641.

Lee, J., Pati, N., & Roh, J. J. (2011). Relationship between corporate sustainability performance and tangible business performance: Evidence from oil and gas industry. International Journal of Business Insights & Transformation, 3

Leeper, N. J., Dewey, F. E., Ashley, E. A., Sandri, M., Tan, S. Y., Hadley, D., . . . Froelicher, V. (2007). Prognostic value of heart rate increase at onset of exercise testing. Circulation, 115(4), 468-474. doi:CIRCULATIONAHA.106.666388 [pii]

Leiras, A., Hamacher, S., & Elkamel, A. (2010). Petroleum refinery operational planning using robust optimization. *Engineering Optimization, 42*(12), 1119-1131.

Li, M., Li, Q., Guo, Q., Ding, R., & Xin, T. (2009). Scheduling optimization of refinery operations based on production continuity. *2009 IEEE International Conference on Automation and Logistics,* 1807-1811.

Li, Z., & Ierapetritou, M. G. (2010). Production planning and scheduling integration through augmented lagrangian optimization. *Computers & Chemical Engineering, 34*(6), 996-1006.

Li, W., Hui, C., Li, P., & Li, A. (2004). Refinery planning under uncertainty. *Industrial & Engineering Chemistry Research, 43*(21), 6742-6755.

Liebchen, C., Lübbecke, M., Möhring, R., & Stiller, S. (2009). The concept of recoverable robustness, linear programming recovery, and railway applications. Robust and online large-scale optimization (pp. 1-27) Springer.

Liu, M. L., & Sahinidis, N. V. (1996). Optimization in process planning under uncertainty. *Industrial & Engineering Chemistry Research, 35*(11), 4154-4165.

Liu, M. L., & Sahinidis, N. V. (1997). Process planning in a fuzzy environment. *European Journal of Operational Research, 100*(1), 142-169.

Luo, C., & Rong, G. (2007). Hierarchical approach for short-term scheduling in refineries. *Industrial & Engineering Chemistry Research, 46*(11), 3656-3668.

Iyer, R. R., & Grossmann, I. E. (1998). A bi-level decomposition algorithm for long-range planning of process networks. Industrial & Engineering Chemistry Research, 37(2), 474-481.

McDonald, C. M., & Karimi, I. A. (1997). Planning and scheduling of parallel semicontinuous processes. 1. Production planning. Industrial & Engineering Chemistry Research, 36(7), 2691-2700.

MirHassani, S. (2008). An operational planning model for petroleum products logistics under uncertainty. *Applied Mathematics and Computation, 196*(2), 744-751.

Mohammed, A., Attiya, H., & Khaliq Khudair, H. (2008). The Relationships between the Physical and Chemical Properties of Narrow Fractions Distilled From Mixed Kirkuk and Sharki-Baghdad Crude Oils. Iraqi Journal Of Chemical And Petroleum Engineering, 9(2), 1-8.

Moro, L., Zanin, A., & Pinto, J. (1998). A planning model for refinery diesel production. Computers & Chemical Engineering, 22, S1039-S1042.

Moro, L. F., & Pinto, J. M. (2004). Mixed-integer programming approach for short-term crude oil scheduling. *Industrial & Engineering Chemistry Research, 43*(1), 85-94.

Nam, P. H., Maiti, P., Okamoto, M., Kotaka, T., Hasegawa, N., & Usuki, A. (2001). A hierarchical structure and properties of intercalated polypropylene/clay nanocomposites. Polymer, 42(23), 9633-9640.

Naraharisetti, P. K, Adhitya, A., Karimi, I., & Srinivasan, R. (2009). From PSE to PSE 2—Decision support for resilient enterprises. *Computers & Chemical Engineering, 33*(12), 1939-1949.

Neely, A., Gregory, M., & Platts, K. (1995). Performance measurement system design: A literature review and research agenda. *International Journal of Operations & Production Management, 15*(4), 80-116.

Neiro, S. M., & Pinto, J. M. (2005). Multipored optimization for production planning of petroleum refineries. *Chem.Eng.Comm., 192*(1), 62-88.

Neiro, S. M., & Pinto, J. M. (2004). A general modelling framework for the operational planning of petroleum supply chains. *Computers & Chemical Engineering, 28*(6), 871-896.

Nygren, E., Aleklett, K., & Höök, M. (2009). Aviation fuel and future oil production scenarios. *Energy Policy, 37*(10), 4003-4010.

Paolucci, M., Sacile, R., & Boccalatte, A. (2002). Allocating crude oil supply to port and refinery tanks: A simulation-based decision support system. *Decision Support Systems, 33*(1), 39-54.

Papageorgiou, L. G. (2009). Supply chain optimisation for the process industries: Advances and opportunities. Computers & Chemical Engineering, 33(12), 1931-1938.

Paul, K. P. (2012). Supply chain management in Indian petroleum refineries.

Perea, E., Grossmann, I., Ydstie, E., & Tahmassebi, T. (2000). Dynamic modeling and classical control theory for supply chain management. Computers & Chemical Engineering, 24(2), 1143-1149.

Pegden, C. D., & Davis, D. A. (1992). Arena: A SIMAN/Cinema-based hierarchical modeling system. Proceedings of the 24th Conference on Winter Simulation, 390-399.

Pitty, S. S., Li, W., Adhitya, A., Srinivasan, R., & Karimi, I. A. (2008). Decision support for integrated refinery supply chains: Part 1. dynamic simulation. *Computers & Chemical Engineering, 32*(11), 2767-2786.

Pongsakdi, A., Rangsunvigit, P., Siemanond, K., & Bagajewicz, M. J. (2006). Financial risk management in the planning of refinery operations. *International Journal of Production Economics, 103*(1), 64-86.

Oliveira, F., & Hamacher, S. (2012). Optimization of the petroleum product supply chain under uncertainty: A case study in northern brazil. *Industrial & Engineering Chemistry Research, 51*(11), 4279-4287.

Rafiq, S., Salim, R., & Bloch, H. (2009). Impact of crude oil price volatility on economic activities: An empirical investigation in the thai economy. Resources Policy, 34(3), 121-132.

Reddy, P. C. P., Karimi, I., & Srinivasan, R. (2004). A new continuous-time formulation for scheduling crude oil operations. Chemical Engineering Science, 59(6), 1325-1341.

Relvas, S., Matos, H. A., Barbosa-Póvoa, A. P. F., Fialho, J., & Pinheiro, A. S. (2006). Pipeline scheduling and inventory management of a multiproduct distribution oil system. *Industrial & Engineering Chemistry Research, 45*(23), 7841-7855.

Ribas, G. P., Hamacher, S., & Street, A. (2010). Optimization under uncertainty of the integrated oil supply chain using stochastic and robust programming. *International Transactions in Operational Research, 17*(6), 777-796.

Ribas, G. P., Leiras, A., & Hamacher, S. (2012). Operational planning of oil refineries under uncertainty special issue: Applied stochastic optimization. *IMA Journal of Management Mathematics,* dps005.

Robichaud, V. (2010). An Introduction to GAMS.

Ronald, R. (2014). Verification and Validation. Distributed Generation & Alternative Energy Journal, 29(1), 5-6. http://dx.doi.org/10.1080/21563306.2014.10781512

Rosenthal, E. (2012). GAMS, A user's guide tutorial by richard E. Rosenthal, GAMS Development Corporation, Washington, DC, USA,

Rosenthal, R. E. (1992). A gams tutorial.

Roussel, J., & Boulet, R. (1995). Composition of crude oils and petroleum products. Characterization of Crude Oils and Petroleum Fractions: Petroleum Refining, 1, 1-84.

Saad, S. M., Lau, K. H., & Omer, A. (2009). Design and analysis of oil production area-A simulation approach. *Ecms,* 52-59.

Sahinidis, N., Grossmann, I., Fornari, R., & Chathrathi, M. (1989). Optimization model for long range planning in the chemical industry. *Computers & Chemical Engineering, 13*(9), 1049-1063.

Sahinidis, N. V. (2004). Optimization under uncertainty: State-of-the-art and opportunities. Computers & Chemical Engineering, 28(6), 971-983.

Sear, T. (1993). Logistics planning in the downstream oil industry. *Journal of the Operational Research Society, 44*(1), 9-17.

Shah, N. (1996). Mathematical programming techniques for crude oil scheduling. *Computers & Chemical Engineering, 20*, S1227-S1232.

Shapiro, J. F. (1985). Quantitative methods in distribution. *The Distribution Handbook, Eds., JF Robeson and RG House, Free Press, New York*, 373-409.

Schwartz, J. D., Wang, W., & Rivera, D. E. (2006). Simulation-based optimization of process control policies for inventory management in supply chains. *Automatica, 42*(8), 1311-1320.

Seuring, S., Sarkis, J., Müller, M., & Rao, P. (2008). Sustainability and supply chain management–an introduction to the special issue. Journal of Cleaner Production, 16(15), 1545-1551.

Subrahmanyam, S., Pekny, J. F., & Reklaitis, G. V. (1994). Design of batch chemical plants under market uncertainty. *Industrial & Engineering Chemistry Research, 33*(11), 2688-2701.

Sturrock, D., Sadowski, a., Swets, N., Sadowski, R., & Kelton, D. (2009). Simulation with arena (5th Ed.). Boston: McGraw-Hill Higher Education.

Tahmassebi, T., Ydstie, E., Grossmann, I., & Perea, E. (2000). Dynamic modeling and classical control theory for supply chain management. Computers & Chemical Engineering, 24(2-7), 1143-1149. (00)00495-6

The American Petroleum Institute Petroleum HPV Testing Group. (2011). HIGH PRODUCTION VOLUME (HPV) CHEMICAL CHALLENGE PROGRAM CRUDE OIL CATEGORY CATEGORY ASSESSMENT DOCUMENT crude oil category. Retrieved from http://www.petroleumhpv.org/petroleum-substances.

Tong, K., Feng, Y., & Rong, G. (2011). Planning under demand and yield uncertainties in an oil supply chain. *Industrial & Engineering Chemistry Research, 51*(2), 814-834.

Van Den Heever, Susara A, & Grossmann, I. E. (2000). An iterative aggregation/disaggregation approach for the solution of a mixed-integer nonlinear oilfield infrastructure planning model. Industrial & Engineering Chemistry Research, 39(6), 1955-1971.

Van der Vorst, Jack GAJ, & Beulens, A. J. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies. International Journal of Physical Distribution & Logistics Management, 32(6), 409-430.

Varma, V. A., Reklaitis, G. V., Blau, G., & Pekny, J. F. (2007). Enterprise-wide modelling & optimization—an overview of emerging research challenges and opportunities. Computers & Chemical Engineering, 31(5), 692-711.

Vladimirou, H., & Zenios, S. A. (1997). Stochastic linear programs with restricted recourse. *European Journal of Operational Research, 101*(1), 177-192.

Wang, J., & Rong, G. (2009). Robust optimization model for crude oil scheduling under uncertainty. *Industrial & Engineering Chemistry Research, 49*(4), 1737-1748.

Warne, R. (2014). A primer on multivariate analysis of variance (MANOVA) for behavioral scientists. Practical Assessment, Research & Evaluation, 19(17).

Whitcomb, P., & Anderson, M. (2007). DOE simplified: Practical tools for effective experimentation (2nd ed.). New York, NY: Productivity Press.

Wu, N., Zhou, M., & Chu, F. (2005). Short-term scheduling for refinery process: Bridging the gap between theory and applications. International Journal of Intelligent Control and Systems, 10(2), 162-174.

Yang, J., Gu, H., & Rong, G. (2009). Supply chain optimization for refinery with considerations of operation mode changeover and yield fluctuations. Industrial & Engineering Chemistry Research, 49(1), 276-287.

You, F., & Grossmann, I. E. (2008). Design of responsive supply chains under demand uncertainty. Computers & Chemical Engineering, 32(12), 3090-3111.

You, F., & Grossmann, I. E. (2011). Stochastic inventory management for tactical process planning under uncertainties: MINLP models and algorithms. AIChE Journal, 57(5), 1250-1277.

Zhang, X., Strømman, A. H., Solli, C., & Hertwich, E. G. (2008). Model-centred approach to early planning and design of an eco-industrial park around an oil refinery. Environmental Science & Technology, 42(13), 4958-4963.

Zhang, J., Zhu, X., & Towler, G. (2001). A simultaneous optimization strategy for overall integration in refinery planning. *Industrial & Engineering Chemistry Research, 40*(12), 2640-2653.

Zhou, Z., Cheng, S., & Hua, B. (2000). Supply chain optimization of continuous process industries with sustainability considerations. *Computers & Chemical Engineering, 24*(2), 1151-1158.

Appendix A

Table A.1 the output from different distillation processing time and No. of failed separator with (R1, Q1)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
1	1			1					1									1							2319227.020	99%
2	1			1					1										1						2301205.011	99%
3	1			1					1											1					2251707.009	96%
4	1			1					1												1				2248999.495	96%
5	1			1					1													1			2245038.948	96%
6	1			1					1														1		2244049.903	96%
7	1			1					1															1	2241630.942	96%
8	1			1						1								1							6738779.990	96%
9	1			1						1									1						6499092.897	92%
10	1			1						1										1					5308442.808	83%
11	1			1						1											1				5272198.645	83%
12	1			1						1												1			5258560.064	83%
13	1			1						1													1		5237436.803	83%
14	1			1						1														1	5213474.251	77%
15	1			1							1							1							8324247.658	78%
16	1			1							1								1						6675734.600	73%
17	1			1							1									1					4977621.957	67%
18	1			1							1										1				4940866.894	67%
19	1			1							1											1			4925907.902	67%
20	1			1							1												1		4904801.160	66%
21	1			1							1													1	4880300.366	66%
22	1			1								1						1							9087228.657	72%
23	1			1								1							1						7317269.303	67%
24	1			1								1								1					5234456.293	58%
25	1			1								1									1				5197344.800	58%
26	1			1								1										1			5181631.593	57%
27	1			1								1											1		5160097.779	57%
28	1			1								1												1	5135185.424	57%
29	1			1									1					1							9661041.285	67%
30	1			1									1						1						7576867.893	60%
31	1			1									1							1					5491025.204	53%

Table A.1 the output from different distillation processing time and No. of failed separator with (R1, Q1)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
32	1			1									1								1				5453446.365	53%
33	1			1									1									1			5437053.634	53%
34	1			1									1										1		5415109.667	53%
35	1			1									1											1	5389796.837	53%
36	1			1										1				1							10705565.87	53%
37	1			1										1					1						8425311.888	47%
38	1			1										1						1					5974766.865	38%
39	1			1										1							1				5946574.339	38%
40	1			1										1								1			5923542.756	38%
41	1			1										1									1		5911347.918	38%
42	1			1										1										1	5890903.379	38%
43	1			1											1			1							11674043.31	38%
44	1			1											1				1						9002053.485	31%
45	1			1											1					1					6126267.052	21%
46	1			1											1						1				6093379.145	21%
47	1			1											1							1			6067467.815	21%
48	1			1											1								1		6053101.037	55%
49	1			1											1									1	6029509.996	21%
50	1			1												1		1							11884967.33	27%
51	1			1												1			1						9002076.413	20%
52	1			1												1				1					6126281.633	14%
53	1			1												1					1				6093400.614	14%
54	1			1												1						1			6067480.913	14%
55	1			1												1							1		6053116.322	14%
56	1			1												1								1	6029524.603	14%
57	1			1													1	1							11884967.33	27%
58	1			1													1		1						9002076.413	20%
59	1			1													1			1					6126281.633	14%
60	1			1													1				1				6093400.614	14%
61	1			1													1					1			6067480.913	14%
62	1			1													1						1		6053116.322	14%
63	1			1													1							1	6029524.603	14%

Table A.2 the output from different distillation processing time and No. of failed separator with (R1, Q2)

Scenario No.	**Input Rate**			**Quality of Crude Oil**					**Distillation Processing Time**									**No. of Failed Separator**							**Total Products**	**Equipment Utilisation %**
	R1	**R2**	**R3**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**F0**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**		
64	1				1				1									1							2322642.629	100%
65	1				1				1										1						2309972.598	99%
66	1				1				1											1					2284809.466	98%
67	1				1				1												1				2280809.981	98%
68	1				1				1													1			2274754.024	98%
69	1				1				1														1		2270889.514	97%
70	1				1				1															1	2268364.729	97%
71	1				1					1								1							6565684.036	93%
72	1				1					1									1						6266805.225	89%
73	1				1					1										1					4515060.982	79%
74	1				1					1											1				4484311.223	79%
75	1				1					1												1			4471221.881	78%
76	1				1					1													1		4481279.386	78%
77	1				1					1														1	4438215.223	78%
78	1				1						1							1							8783907.066	79%
79	1				1						1								1						7027709.360	74%
80	1				1						1									1					5265772.236	69%
81	1				1						1										1				5233118.124	69%
82	1				1						1											1			5217612.208	68%
83	1				1						1												1		5223197.389	68%
84	1				1						1													1	5180145.791	68%
85	1				1							1						1							9548048.286	73%
86	1				1							1							1						7760978.678	69%
87	1				1							1								1					5541807.451	59%
88	1				1							1									1				5503166.584	59%
89	1				1							1										1			5487162.136	59%
90	1				1							1											1		5489743.825	59%
91	1				1							1												1	5444131.006	58%
92	1				1								1					1							10242390.28	69%
93	1				1								1						1						8021332.923	62%
94	1				1								1							1					5799079.304	54%
95	1				1								1								1				5760023.815	54%
96	1				1								1									1			5743370.213	54%

Table A.2 the output from different distillation processing time and No. of failed separator with (R1, Q2)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
97	1				1								1										1		5745542.692	54%
98	1				1								1											1	5699482.004	54%
99	1				1									1				1							11288456.16	54%
100	1				1									1					1						8944486.251	49%
101	1				1									1						1					6334463.232	39%
102	1				1									1							1				6304403.134	39%
103	1				1									1								1			6279963.501	39%
104	1				1									1									1		6266904.434	39%
105	1				1									1										1	6245131.472	39%
106	1				1										1			1							12354732.86	39%
107	1				1										1				1						9612457.527	33%
108	1				1										1					1					6547673.911	22%
109	1				1										1						1				6512602.528	22%
110	1				1										1							1			6484984.778	22%
111	1				1										1								1		6469675.510	22%
112	1				1										1									1	6444546.055	22%
113	1				1											1		1							12684827.52	29%
114	1				1											1			1						9612494.177	22%
115	1				1											1				1					6547680.502	15%
116	1				1											1					1				6512622.140	15%
117	1				1											1						1			6484996.218	15%
118	1				1											1							1		6469699.194	15%
119	1				1											1								1	6444568.157	15%
120	1				1												1	1							12684827.52	29%
121	1				1												1		1						9612494.177	22%
122	1				1												1			1					6547680.502	15%
123	1				1												1				1				6512622.140	15%
124	1				1												1					1			6484996.218	15%
125	1				1												1						1		6469699.194	15%
126	1				1												1							1	6444568.157	15%

Table A.3 the output from different distillation processing time and No. of failed separator with (R1, Q3)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
127	1					1			1									1							2331234.100	100%
128	1					1			1										1						2320607.416	100%
129	1					1			1											1					2299599.035	99%
130	1					1			1												1				2296186.185	98%
131	1					1			1													1			2291455.255	98%
132	1					1			1														1		2288313.439	98%
133	1					1			1															1	2284805.383	98%
134	1					1				1								1							6510628.964	92%
135	1					1				1									1						5917076.061	87%
136	1					1				1										1					4272213.254	77%
137	1					1				1											1				4242639.204	77%
138	1					1				1												1			4229813.813	77%
139	1					1				1													1		4212659.049	77%
140	1					1				1														1	4192821.030	77%
141	1					1					1							1							10285509.53	83%
142	1					1					1								1						8176470.176	77%
143	1					1					1									1					6065035.942	71%
144	1					1					1										1				6027966.764	71%
145	1					1					1											1			6012810.703	71%
146	1					1					1												1		5990652.921	71%
147	1					1					1													1	5965338.288	71%
148	1					1						1						1							11052460.27	75%
149	1					1						1							1						8943706.316	71%
150	1					1						1								1					6546319.135	64%
151	1					1						1									1				6500852.239	63%
152	1					1						1										1			6484052.424	63%
153	1					1						1											1		6457496.403	63%
154	1					1						1												1	6427191.332	63%
155	1					1							1					1							11819465.21	72%
156	1					1							1						1						9473280.306	66%
157	1					1							1							1					6805260.636	58%
158	1					1							1								1				6759549.365	57%
159	1					1							1									1			6742141.220	57%

Table A.3 the output from different distillation processing time and No. of failed separator with (R1, Q3)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
160	1					1							1										1		6715270.538	57%
161	1					1							1											1	6684502.538	57%
162	1					1								1				1							13192271.01	57%
163	1					1								1					1						10502783.89	53%
164	1					1								1						1					7507867.868	43%
165	1					1								1							1				7471863.992	43%
166	1					1								1								1			7426958.033	43%
167	1					1								1									1		7426958.033	44%
168	1					1								1										1	7400985.067	43%
169	1					1									1			1							14578269.89	43%
170	1					1									1				1						11437636.03	38%
171	1					1									1					1					7924715.592	27%
172	1					1									1						1				7882640.650	27%
173	1					1									1							1			7849380.023	27%
174	1					1									1								1		7830963.565	27%
175	1					1									1									1	7800748.065	27%
176	1					1										1		1							15300014.05	35%
177	1					1										1			1						11607946.41	26%
178	1					1										1				1					7924734.234	18%
179	1					1										1					1				7882694.548	18%
180	1					1										1						1			7849490.523	18%
181	1					1										1							1		7831032.112	18%
182	1					1										1								1	7800780.455	18%
183	1					1											1	1							15300014.05	35%
184	1					1											1		1						11607946.41	26%
185	1					1											1			1					7924734.234	18%
186	1					1											1				1				7882694.548	18%
187	1					1											1					1			7849490.523	18%
188	1					1											1						1		7831032.112	18%
189	1					1											1							1	7800780.455	18%

Table A.4 the output from different distillation processing time and No. of failed separator with (R1, Q4)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
190	1						1		1									1							2336978.127	100%
191	1						1		1										1						2327965.025	100%
192	1						1		1											1					2309793.561	99%
193	1						1		1												1				2306692.093	99%
194	1						1		1													1			2302366.200	99%
195	1						1		1														1		2298666.051	99%
196	1						1		1															1	2298002.740	99%
197	1						1			1								1							6899120.106	98%
198	1						1			1									1						6628612.099	94%
199	1						1			1										1					6067077.523	88%
200	1						1			1											1				6025576.809	87%
201	1						1			1												1			6011506.321	87%
202	1						1			1													1		6023324.617	87%
203	1						1			1														1	5969487.181	87%
204	1						1				1							1							11723852.56	87%
205	1						1				1								1						9276181.903	80%
206	1						1				1									1					6827848.979	74%
207	1						1				1										1				6785823.110	73%
208	1						1				1											1			6770220.448	73%
209	1						1				1												1		6780906.163	73%
210	1						1				1													1	6725209.326	73%
211	1						1					1						1							12493016.38	78%
212	1						1					1							1						10042207.62	74%
213	1						1					1								1					7507818.415	68%
214	1						1					1									1				7455990.424	68%
215	1						1					1										1			7438317.910	67%
216	1						1					1											1		7443745.284	67%
217	1						1					1												1	7382070.726	67%
218	1						1						1					1							13261905.95	73%
219	1						1						1						1						10807833.37	70%
220	1						1						1							1					7768122.686	61%
221	1						1						1								1				7716086.376	61%
222	1						1						1									1			7697850.805	60%
223	1						1						1										1		7702985.455	60%

Table A.4 the output from different distillation processing time and No. of failed separator with (R1, Q4)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
224	1						1						1											1	7640973.279	60%
225	1						1							1				1							15016085.87	60%
226	1						1							1					1						11897293.88	55%
227	1						1							1						1					8631805.810	48%
228	1						1							1							1				8589909.351	47%
229	1						1							1								1			8556321.043	48%
230	1						1							1									1		8538228.376	48%
231	1						1							1										1	8508020.018	47%
232	1						1								1			1							16709296.60	47%
233	1						1								1				1						13065876.58	40%
234	1						1								1					1					9245619.705	31%
235	1						1								1						1				9196684.339	31%
236	1						1								1							1			9157994.761	31%
237	1						1								1								1		9136719.549	31%
238	1						1								1									1	9101594.617	31%
239	1						1									1		1							17513279.70	38%
240	1						1									1			1						13521621.59	31%
241	1						1									1				1					9245691.437	21%
242	1						1									1					1				9196813.936	21%
243	1						1									1						1			9158130.040	21%
244	1						1									1							1		9136899.236	21%
245	1						1									1								1	9101758.043	21%
246	1						1										1	1							17513279.70	38%
247	1						1										1		1						13521621.59	31%
248	1						1										1			1					9245691.437	21%
249	1						1										1				1				9196813.936	21%
250	1						1										1					1			9158130.040	21%
251	1						1										1						1		9136899.236	21%
252	1						1										1							1	9101758.043	21%

Table A.5 the output from different distillation processing time and No. of failed separator with (R1, Q5)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
253	1							1	1									1							2339570.137	100%
254	1							1	1										1						2331183.788	100%
255	1							1	1											1					2314526.550	99%
256	1							1	1												1				2311238.116	99%
257	1							1	1													1			2307268.678	99%
258	1							1	1														1		2303403.424	99%
259	1							1	1															1	2302754.807	99%
260	1							1		1								1							6982723.490	99%
261	1							1		1									1						6695635.221	95%
262	1							1		1										1					6382309.149	90%
263	1							1		1											1				6366715.334	89%
264	1							1		1												1			6351193.316	89%
265	1							1		1													1		6350780.756	89%
266	1							1		1														1	6332315.682	89%
267	1							1			1							1							12487623.64	89%
268	1							1			1								1						9860007.840	82%
269	1							1			1									1					7232714.983	75%
270	1							1			1										1				7187698.433	75%
271	1							1			1											1			7171879.958	74%
272	1							1			1												1		7183569.911	74%
273	1							1			1													1	7124306.545	74%
274	1							1				1						1							13257294.97	79%
275	1							1				1							1						10626978.11	75%
276	1							1				1								1					7992378.501	70%
277	1							1				1									1				7945429.745	69%
278	1							1				1										1			7927141.614	69%
279	1							1				1											1		7936640.749	69%
280	1							1				1												1	7874303.616	69%
281	1							1					1					1							14027155.24	74%
282	1							1					1						1						11393926.30	71%
283	1							1					1							1					8279464.082	63%
284	1							1					1								1				8223702.050	62%
285	1							1					1									1			8205179.828	62%
286	1							1					1										1		8210825.588	62%

Table A.5 the output from different distillation processing time and No. of failed separator with (R1, Q5)

Scenario No.	**Input Rate**			**Quality of Crude Oil**					**Distillation Processing Time**									**No. of Failed Separator**							**Total Products**	**Equipment Utilisation %**
	R1	**R2**	**R3**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**F0**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**		
287	1							1					1											1	8144799.060	62%
288	1							1						1				1							15983986.62	62%
289	1							1						1					1						12637286.55	57%
290	1							1						1						1					9228294.823	50%
291	1							1						1							1				9183261.538	50%
292	1							1						1								1			9147499.678	50%
293	1							1						1									1		9127924.828	50%
294	1							1						1										1	9095481.260	50%
295	1							1							1			1							17840524.86	49%
296	1							1							1				1						13930206.63	42%
297	1							1							1					1					9947012.924	34%
298	1							1							1						1				9894288.179	33%
299	1							1							1							1			9853122.355	34%
300	1							1							1								1		9830224.638	34%
301	1							1							1									1	9792396.932	33%
302	1							1								1		1							18645335.07	39%
303	1							1								1			1						14538110.69	33%
304	1							1								1				1					9947396.106	22%
305	1							1								1					1				9894883.661	22%
306	1							1								1						1			9853387.268	22%
307	1							1								1							1		9830544.451	23%
308	1							1								1								1	9792825.143	22%
309	1							1									1	1							18645335.07	39%
310	1							1									1		1						14538110.69	33%
311	1							1									1			1					9947396.106	22%
312	1							1									1				1				9894883.661	22%
313	1							1									1					1			9853387.268	22%
314	1							1									1						1		9830544.451	23%
315	1							1									1							1	9792825.143	22%

Table A.6 the output from different distillation processing time and No. of failed separator with (R2, Q1)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
317		1		1					1									1							2328601.505	100%
318		1		1					1										1						2317080.050	99%
319		1		1					1											1					2294401.859	99%
320		1		1					1												1				2291005.329	98%
321		1		1					1													1			2285613.867	98%
322		1		1					1														1		2281741.295	98%
323		1		1					1															1	2279431.911	98%
324		1		1						1								1							6662849.894	94%
325		1		1						1									1						6437014.065	90%
326		1		1						1										1					4945507.346	81%
327		1		1						1											1				4911839.626	81%
328		1		1						1												1			4898760.419	81%
329		1		1						1													1		4907398.168	81%
330		1		1						1														1	4863438.331	80%
331		1		1							1							1							9598598.115	81%
332		1		1							1								1						7651103.685	76%
333		1		1							1									1					5700371.674	70%
334		1		1							1										1				5665692.569	70%
335		1		1							1											1			5650947.496	70%
336		1		1							1												1		5658556.182	70%
337		1		1							1													1	5613131.050	70%
338		1		1								1						1							10364955.88	74%
339		1		1								1							1						8413449.303	70%
340		1		1								1								1					6086702.827	62%
341		1		1								1									1				6044401.933	61%
342		1		1								1										1			6028336.432	61%
343		1		1								1											1		6031978.069	61%
344		1		1								1												1	5981989.847	61%
345		1		1									1					1							11131005.79	71%
346		1		1									1						1						8808788.480	64%
347		1		1									1							1					6345016.553	56%
348		1		1									1								1				6302375.451	56%
349		1		1									1									1			6285727.664	56%
350		1		1									1										1		6289003.809	56%

Table A.6 the output from different distillation processing time and No. of failed separator with (R2, Q1)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
351		1		1									1											1	6238601.817	55%
352		1		1										1				1							12321626.13	56%
353		1		1										1					1						9837034.049	52%
354		1		1										1						1					6971815.710	42%
355		1		1										1							1				6938525.128	41%
356		1		1										1								1			6911302.980	41%
357		1		1										1									1		6896541.388	42%
358		1		1										1										1	6872749.371	41%
359		1		1											1			1							13560879.30	41%
360		1		1											1				1						10660276.96	36%
361		1		1											1					1					7294773.867	25%
362		1		1											1						1				7256045.535	25%
363		1		1											1							1			7225157.091	25%
364		1		1											1								1		7207901.231	25%
365		1		1											1									1	7180203.545	25%
366		1		1												1		1							14102426.88	32%
367		1		1												1			1						10694532.93	24%
368		1		1												1				1					7294791.990	16%
369		1		1												1					1				7256114.165	16%
370		1		1												1						1			7225197.734	16%
371		1		1												1							1		7207940.151	17%
372		1		1												1								1	7180227.848	16%
373		1		1													1	1							14102426.88	32%
374		1		1													1		1						10694532.93	24%
375		1		1													1			1					7294791.990	16%
376		1		1													1				1				7256114.165	16%
377		1		1													1					1			7225197.734	16%
378		1		1													1						1		7207940.151	17%
379		1		1													1							1	7180227.848	16%

Table A.7 the output from different distillation processing time and No. of failed separator with (R2, Q2)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
380		1			1				1									1							2331659.874	100%
381		1			1				1										1						2320836.364	100%
382		1			1				1											1					2299542.787	99%
383		1			1				1												1				2296002.706	98%
384		1			1				1													1			2291534.776	98%
385		1			1				1														1		2287426.967	98%
386		1			1				1															1	2286110.720	98%
387		1			1					1								1							6725119.440	95%
388		1			1					1									1						6488388.227	91%
389		1			1					1										1					5232587.176	98%
390		1			1					1											1				5196786.073	83%
391		1			1					1												1			5183856.544	83%
392		1			1					1													1		5193150.849	82%
393		1			1					1														1	2300311.818	82%
394		1			1						1							1							10141689.78	83%
395		1			1						1								1						8066622.353	77%
396		1			1						1									1					5989228.818	71%
397		1			1						1										1				5952394.146	71%
398		1			1						1											1			5938038.915	71%
399		1			1						1												1		5946537.146	71%
400		1			1						1													1	5898689.785	70%
401		1			1							1						1							10908980.38	75%
402		1			1							1							1						8830263.513	71%
403		1			1							1								1					6450196.559	63%
404		1			1							1									1				6405238.121	63%
405		1			1							1										1			6389299.575	63%
406		1			1							1											1		6393451.109	63%
407		1			1							1												1	6340744.635	62%
408		1			1								1					1							11676102.41	71%
409		1			1								1						1						9334088.391	66%
410		1			1								1							1					6709132.199	57%
411		1			1								1								1				6663825.511	57%
412		1			1								1									1			6647385.094	57%
413		1			1								1										1		6651164.569	57%

Table A.7 the output from different distillation processing time and No. of failed separator with (R2, Q2)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
414		1			1								1											1	6598046.143	57%
415		1			1									1				1							13010177.55	57%
416		1			1									1					1						10364544.40	53%
417		1			1									1						1					7396837.406	43%
418		1			1									1							1				7361513.669	43%
419		1			1									1								1			7332534.430	43%
420		1			1									1									1		7316944.513	43%
421		1			1									1										1	7291483.634	43%
422		1			1										1			1							14365177.37	43%
423		1			1										1				1						11275786.40	37%
424		1			1										1					1					7793713.704	26%
425		1			1										1						1				7752442.700	26%
426		1			1										1							1			7719522.826	26%
427		1			1										1								1		7701187.003	27%
428		1			1										1									1	7671606.315	26%
429		1			1											1		1							15048446.03	34%
430		1			1											1			1						11416772.93	26%
431		1			1											1				1					7793736.849	18%
432		1			1											1					1				7752504.377	17%
433		1			1											1						1			7719585.453	18%
434		1			1											1							1		7701239.056	18%
435		1			1											1								1	7671640.004	17%
436		1			1												1	1							15048446.03	34%
437		1			1												1		1						11416772.93	26%
438		1			1												1			1					7793736.849	18%
439		1			1												1				1				7752504.377	17%
440		1			1												1					1			7719585.453	18%
441		1			1												1						1		7701239.056	18%
442		1			1												1							1	7671640.004	17%

Table A.8 the output from different distillation processing time and No. of failed separator with (R2, Q3)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
443		1				1			1									1							2338656.825	100%
444		1				1			1										1						2329641.073	100%
445		1				1			1											1					2312202.051	99%
446		1				1			1												1				2308812.949	99%
447		1				1			1													1			2304774.405	99%
448		1				1			1														1		2300868.808	99%
449		1				1			1															1	2300631.602	99%
450		1				1				1								1							6922337.177	98%
451		1				1				1									1						6647677.378	94%
452		1				1				1										1					6167261.961	88%
453		1				1				1											1				6125044.509	88%
454		1				1				1												1			6111313.450	88%
455		1				1				1													1		6124216.762	88%
456		1				1				1														1	6069730.638	87%
457		1				1					1							1							11914728.94	87%
458		1				1					1								1						9422195.993	81%
459		1				1					1									1					6929665.741	74%
460		1				1					1										1				6886768.177	74%
461		1				1					1											1			6871407.842	74%
462		1				1					1												1		6882606.083	73%
463		1				1					1													1	6826194.119	73%
464		1				1						1						1							12684220.31	78%
465		1				1						1							1						10188719.44	74%
466		1				1						1								1					7635441.164	69%
467		1				1						1									1				7582558.707	68%
468		1				1						1										1			7565217.474	68%
469		1				1						1											1		7571226.149	68%
470		1				1						1												1	7508710.612	68%
471		1				1							1					1							13453636.34	74%
472		1				1							1						1						10955122.68	70%
473		1				1							1							1					7896282.312	61%
474		1				1							1								1				7843106.031	61%
475		1				1							1									1			7825162.919	61%
476		1				1							1										1		7830809.507	61%

Table A.9 the output from different distillation processing time and No. of failed separator with (R2, Q3)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
477		1				1							1											1	7767966.547	61%
478		1				1								1				1							15258016.60	61%
479		1				1								1					1						12083237.35	56%
480		1				1								1						1					8781945.543	48%
481		1				1								1							1				8739382.631	59%
482		1				1								1								1			8705040.677	48%
483		1				1								1									1		8686206.084	48%
484		1				1								1										1	8655688.299	48%
485		1				1									1			1							16991768.51	47%
486		1				1									1				1						13282684.12	41%
487		1				1									1					1					9421620.939	32%
488		1				1									1						1				9371843.577	32%
489		1				1									1							1			9332307.339	32%
490		1				1									1								1		9310306.047	32%
491		1				1									1									1	9274735.259	32%
492		1				1										1		1							17796244.66	38%
493		1				1										1			1						13775687.83	31%
494		1				1										1				1					9421704.421	21%
495		1				1										1					1				9372076.064	21%
496		1				1										1						1			9332460.225	21%
497		1				1										1							1		9310508.475	21%
498		1				1										1								1	9274885.672	21%
499		1				1											1	1							17796244.66	38%
500		1				1											1		1						13775687.83	31%
501		1				1											1			1					9421704.421	21%
502		1				1											1				1				9372076.064	21%
503		1				1											1					1			9332460.225	21%
504		1				1											1						1		9310508.475	21%
505		1				1											1							1	9274885.672	21%

Table A.9 the output from different distillation processing time and No. of failed separator with (R2, Q4)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
506		1					1		1									1							2343739.970	100%
507		1					1		1										1						2336005.418	100%
508		1					1		1											1					2320939.949	100%
509		1					1		1												1				2317946.999	99%
510		1					1		1													1			2314047.563	99%
511		1					1		1														1		2311989.813	99%
512		1					1		1															1	2309857.981	99%
513		1					1			1								1							7031483.771	100%
514		1					1			1									1						6794718.166	96%
515		1					1			1										1					6464256.239	91%
516		1					1			1											1				6451950.383	91%
517		1					1			1												1			6440804.847	90%
518		1					1			1													1		6431010.646	90%
519		1					1			1														1	6425862.097	90%
520		1					1				1							1							12989969.61	91%
521		1					1				1								1						10720813.96	84%
522		1					1				1									1					7829580.420	77%
523		1					1				1										1				7780817.793	76%
524		1					1				1											1			7764310.118	76%
525		1					1				1												1		7778738.751	76%
526		1					1				1													1	7713850.525	76%
527		1					1					1						1							14385277.19	81%
528		1					1					1							1						11489383.28	76%
529		1					1					1								1					8593152.765	71%
530		1					1					1									1				8543278.058	71%
531		1					1					1										1			8525578.478	71%
532		1					1					1											1		8539106.368	70%
533		1					1					1												1	8473099.789	70%
534		1					1						1					1							15156364.93	76%
535		1					1						1						1						12257962.64	72%
536		1					1						1							1					9033543.122	65%
537		1					1						1								1				8972712.702	65%
538		1					1						1									1			8953358.388	65%
539		1					1						1										1		8961101.023	64%

Table A.9 the output from different distillation processing time and No. of failed separator with (R2, Q4)

Scenario No.	**Input Rate**			**Quality of Crude Oil**					**Distillation Processing Time**									**No. of Failed Separator**							**Total Products**	**Equipment Utilisation %**
	R1	**R2**	**R3**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**F0**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**		
540		1					1						1											1	8888855.904	64%
541		1					1							1				1							17412469.31	64%
542		1					1							1					1						13729576.01	58%
543		1					1							1						1					10046161.43	52%
544		1					1							1							1				10003755.56	52%
545		1					1							1								1			9967402.122	52%
546		1					1							1									1		9949097.556	52%
547		1					1							1										1	9917500.468	52%
548		1					1								1			1							19509831.52	64%
549		1					1								1				1						15205926.47	58%
550		1					1								1					1					10904858.21	52%
551		1					1								1						1				10855561.77	52%
552		1					1								1							1			10814164.60	52%
553		1					1								1								1		10792594.74	52%
554		1					1								1									1	10756253.14	52%
555		1					1									1		1							20316107.62	41%
556		1					1									1			1						16007708.79	36%
557		1					1									1				1					10983385.52	25%
558		1					1									1					1				10925787.13	25%
559		1					1									1						1			10879586.03	25%
560		1					1									1							1		10854153.98	25%
561		1					1									1								1	10813062.46	25%
562		1					1										1	1							20316107.62	41%
563		1					1										1		1						16007708.79	36%
564		1					1										1			1					10983385.52	25%
565		1					1										1				1				10925787.13	25%
565		1					1										1					1			10879586.03	25%
566		1					1										1						1		10854153.98	25%
567		1					1										1							1	10813062.46	25%

Table A.10 the output from different distillation processing time and No. of failed separator with (R2, Q5)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
568		1						1	1									1							2345981.344	100%
569		1						1	1										1						2338636.105	100%
570		1						1	1											1					2324686.502	100%
571		1						1	1												1				2321550.508	100%
572		1						1	1													1			2317980.309	99%
573		1						1	1														1		2315371.241	99%
574		1						1	1															1	2313479.429	99%
575		1						1		1								1							7038004.551	100%
576		1						1		1									1						6871223.124	97%
577		1						1		1										1					6522031.093	92%
578		1						1		1											1				6509100.672	92%
579		1						1		1												1			6498681.902	91%
580		1						1		1													1		6489252.530	91%
581		1						1		1														1	6482299.853	91%
582		1						1			1							1							13092189.67	91%
583		1						1			1								1						11410033.23	86%
584		1						1			1									1					8306556.370	78%
585		1						1			1										1				8254808.032	78%
586		1						1			1											1			8237739.271	77%
587		1						1			1												1		8253744.362	77%
588		1						1			1													1	8184655.879	77%
589		1						1				1						1							15288162.92	83%
590		1						1				1							1						12179576.10	77%
591		1						1				1								1					9071378.819	72%
592		1						1				1									1				9018571.174	72%
593		1						1				1										1			9000472.892	72%
594		1						1				1											1		9015513.294	71%
595		1						1				1												1	8945368.066	71%
596		1						1					1					1							16059976.41	77%
597		1						1					1						1						12949002.64	73%
598		1						1					1							1					9636690.508	67%
599		1						1					1								1				9572019.954	67%
600		1						1					1									1			9551957.010	66%
601		1						1					1										1		9560629.097	66%

Table A.10 the output from different distillation processing time and No. of failed separator with (R2, Q5)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
602		1						1					1											1	9483723.751	66%
603		1						1						1				1							18556059.76	66%
604		1						1						1					1						14603484.25	60%
605		1						1						1						1					10651876.13	53%
606		1						1						1							1				10606188.82	53%
607		1						1						1								1			10567695.89	53%
608		1						1						1									1		10548125.67	53%
609		1						1						1										1	10514584.08	53%
610		1						1							1			1							20669071.33	53%
611		1						1							1				1						16227033.54	46%
612		1						1							1					1					11611877.40	38%
613		1						1							1						1				11558732.69	38%
614		1						1							1							1			11514830.00	38%
615		1						1							1								1		11491821.39	38%
616		1						1							1									1	11453104.02	38%
617		1						1								1		1							21653744.27	43%
618		1						1								1			1						17030666.51	37%
619		1						1								1				1					11813115.97	27%
620		1						1								1					1				11751181.78	27%
621		1						1								1						1			11701764.39	27%
622		1						1								1							1		11674412.84	27%
623		1						1								1								1	11630078.18	27%
624		1						1									1	1							21653744.27	43%
625		1						1									1		1						17030666.51	37%
626		1						1									1			1					11813115.97	27%
627		1						1									1				1				11751181.78	27%
628		1						1									1					1			11701764.39	27%
629		1						1									1						1		11674412.84	27%
630		1						1									1							1	11630078.18	27%

Table A.11 the output from different distillation processing time and No. of failed separator with (R3, Q1)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
631			1	1					1									1							2339438.471	100%
632			1	1					1										1						2330307.993	100%
633			1	1					1											1					2312568.724	99%
634			1	1					1												1				2309114.747	99%
635			1	1					1													1			2305025.113	99%
636			1	1					1														1		2300311.818	99%
637			1	1					1															1	2299094.163	99%
638			1	1						1								1							6912067.581	98%
639			1	1						1									1						6639870.042	94%
640			1	1						1										1					6105228.802	88%
641			1	1						1											1				6062978.615	88%
642			1	1						1												1			6049416.178	87%
643			1	1						1													1		6025937.126	87%
644			1	1						1														1	5999168.528	87%
645			1	1							1							1							11795961.96	87%
646			1	1							1								1						9331341.411	81%
647			1	1							1									1					6867146.773	74%
648			1	1							1										1				6824219.305	74%
649			1	1							1											1			6809199.653	73%
650			1	1							1												1		6784766.947	73%
651			1	1							1													1	6756936.666	73%
652			1	1								1						1							12565623.21	78%
653			1	1								1							1						10098046.15	74%
654			1	1								1								1					7556166.595	68%
655			1	1								1									1				7503387.863	68%
656			1	1								1										1			7486355.167	68%
657			1	1								1											1		7456770.956	67%
658			1	1								1												1	7423071.316	67%
659			1	1									1					1							13335284.45	74%
660			1	1									1						1						10864520.88	70%
661			1	1									1							1					7816894.344	61%
662			1	1									1								1				7763828.109	61%
663			1	1									1									1			7746258.462	61%
664			1	1									1										1		7716400.397	60%

Table A.11 the output from different distillation processing time and No. of failed separator with (R3, Q1)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
665			1	1									1											1	7682311.994	60%
666			1	1										1				1							15107273.13	60%
667			1	1										1					1						11968938.82	55%
668			1	1										1						1					8690198.453	48%
669			1	1										1							1				8647432.935	48%
670			1	1										1								1			8614000.267	48%
671			1	1										1									1		8595333.515	48%
672			1	1										1										1	8565402.616	48%
673			1	1											1			1							16815356.09	47%
674			1	1											1				1						13148782.91	41%
675			1	1											1					1					9313142.499	32%
676			1	1											1						1				9263193.444	31%
677			1	1											1							1			9224781.072	32%
678			1	1											1								1		9202859.670	32%
679			1	1											1									1	9168093.082	31%
680			1	1												1		1							17620092.19	38%
681			1	1												1			1						13617230.87	31%
682			1	1												1				1					9313199.691	21%
683			1	1												1					1				9263354.567	21%
684			1	1												1						1			9224917.191	21%
685			1	1												1							1		9203047.227	21%
686			1	1												1								1	9168223.447	21%
687			1	1													1	1							17620092.19	38%
688			1	1													1		1						13617230.87	31%
689			1	1													1			1					9313199.691	21%
690			1	1													1				1				9263354.567	21%
691			1	1													1					1			9224917.191	21%
692			1	1													1						1		9203047.227	21%
693			1	1													1							1	9168223.447	21%

Table A.12 the output from different distillation processing time and No. of failed separator with (R3, Q2)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
694			1		1				1									1							2341642.503	100%
695			1		1				1										1						2333147.584	100%
696			1		1				1											1					2316542.679	99%
697			1		1				1												1				2313581.032	99%
698			1		1				1													1			2099649.464	99%
699			1		1				1														1		2306690.279	99%
700			1		1				1															1	2303801.523	99%
701			1		1					1								1							6987259.119	99%
702			1		1					1									1						6700053.683	95%
703			1		1					1										1					6386503.344	90%
704			1		1					1											1				6370528.012	89%
705			1		1					1												1			6354574.318	89%
706			1		1					1													1		6340549.133	89%
707			1		1					1														1	6324408.864	89%
708			1		1						1							1							12482171.04	89%
709			1		1						1								1						12482171.04	82%
710			1		1						1									1					7230775.417	75%
711			1		1						1										1				7185801.409	75%
712			1		1						1											1			7170302.614	74%
713			1		1						1												1		7144679.208	74%
714			1		1						1													1	7115582.596	74%
715			1		1							1						1							13252831.12	79%
716			1		1							1							1						10623737.78	75%
717			1		1							1								1					7990898.824	70%
718			1		1							1									1				7943797.510	70%
719			1		1							1										1			7925570.488	69%
720			1		1							1											1		7897734.823	69%
721			1		1							1												1	7865852.201	69%
722			1		1								1					1							14023332.07	74%
723			1		1								1						1						11391389.20	71%
724			1		1								1							1					8276143.414	62%
725			1		1								1								1				8220373.548	62%
726			1		1								1									1			8202139.153	62%
727			1		1								1										1		8170826.074	62%

Table A.12 the output from different distillation processing time and No. of failed separator with (R3, Q2)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
728			1		1								1											1	8135142.896	62%
729			1		1									1				1							15977528.29	62%
730			1		1									1					1						12634341.21	57%
731			1		1									1						1					9226781.553	50%
732			1		1									1							1				9181207.265	50%
733			1		1									1								1			9145696.637	50%
734			1		1									1									1		9125945.112	50%
735			1		1									1										1	9093965.154	50%
736			1		1										1			1							17832130.02	49%
737			1		1										1				1						13925859.04	61%
738			1		1										1					1					9944070.359	34%
739			1		1										1						1				9890715.277	34%
740			1		1										1							1			9849956.930	33%
741			1		1										1								1		9826696.655	34%
742			1		1										1									1	9789465.693	33%
743			1		1											1		1							18637731.30	39%
744			1		1											1			1						14531138.39	33%
745			1		1											1				1					9944410.290	28%
746			1		1											1					1				9891297.684	22%
747			1		1											1						1			9850218.841	22%
748			1		1											1							1		9872760.865	22%
749			1		1											1								1	9798771.991	22%
750			1		1												1	1							18637731.30	39%
751			1		1												1		1						14531138.39	33%
752			1		1												1			1					9944410.290	28%
753			1		1												1				1				9891297.684	22%
754			1		1												1					1			9850218.841	22%
755			1		1												1						1		9872760.865	22%
756			1		1												1							1	9798771.991	22%

Table A.13 the output from different distillation processing time and No. of failed separator with (R3, Q3)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
757			1			1			1									1							2347189.554	100%
758			1			1			1										1						2340279.248	100%
759			1			1			1											1					2326670.866	100%
760			1			1			1												1				2323367.361	100%
761			1			1			1													1			2320093.955	100%
762			1			1			1														1		2320093.955	99%
763			1			1			1															1	2314635.211	99%
764			1			1				1								1							7042404.580	100%
765			1			1				1									1						6891276.083	98%
766			1			1				1										1					6537958.366	92%
767			1			1				1											1				6524695.707	92%
768			1			1				1												1			6514798.820	92%
769			1			1				1													1		6505907.557	92%
770			1			1				1														1	6495240.777	91%
771			1			1					1							1							13120740.87	92%
772			1			1					1								1						11569841.24	87%
773			1			1					1									1					8417640.112	78%
774			1			1					1										1				8364764.575	78%
775			1			1					1											1			8348082.110	78%
776			1			1					1												1		8318380.084	78%
777			1			1					1													1	8284300.064	78%
778			1			1						1						1							15497554.63	83%
779			1			1						1							1						12339890.56	78%
780			1			1						1								1					9183132.481	72%
781			1			1						1									1				9129179.372	72%
782			1			1						1										1			9111493.402	72%
783			1			1						1											1		9080949.199	72%
784			1			1						1												1	9045818.046	72%
785			1			1							1					1							16269889.59	77%
786			1			1							1						1						13109900.05	73%
787			1			1							1							1					9776723.538	67%
788			1			1							1								1				9710689.650	67%
789			1			1							1									1			9690979.092	67%
790			1			1							1										1		9654073.193	67%

Table A.13 the output from different distillation processing time and No. of failed separator with (R3, Q3)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
791			1			1							1											1	9612083.118	67%
792			1			1								1				1							18820755.80	66%
793			1			1								1					1						14806710.74	60%
794			1			1								1						1					10794109.39	54%
795			1			1								1							1				10746729.92	53%
796			1			1								1								1			10708588.26	53%
797			1			1								1									1		10743524.51	53%
798			1			1								1										1	10665513.10	53%
799			1			1									1			1							20935410.49	53%
800			1			1									1				1						16464296.28	46%
801			1			1									1					1					11777381.38	38%
802			1			1									1						1				11722403.63	38%
803			1			1									1							1			11678725.59	38%
804			1			1									1								1		11710196.39	38%
805			1			1									1									1	11627025.57	38%
806			1			1										1		1							21963559.93	43%
807			1			1										1			1						17268541.86	38%
808			1			1										1				1					12006386.89	32%
809			1			1										1					1				11942502.51	27%
810			1			1										1						1			11893110.39	27%
811			1			1										1							1		11920294.94	27%
812			1			1										1								1	11831374.85	27%
813			1			1											1	1							21963559.93	43%
814			1			1											1		1						17268541.86	38%
815			1			1											1			1					12006386.89	32%
816			1			1											1				1				11942502.51	27%
817			1			1											1					1			11893110.39	27%
818			1			1											1						1		11920294.94	27%
819			1			1											1							1	11831374.85	27%

Table A.14 the output from different distillation processing time and No. of failed separator with (R3, Q4)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
820			1				1		1									1							2351125.612	100%
821			1				1		1										1						2345020.523	100%
822			1				1		1											1					2333224.808	100%
823			1				1		1												1				2330592.846	100%
824			1				1		1													1			2327715.943	100%
825			1				1		1														1		2325399.594	100%
826			1				1		1															1	2322690.700	100%
827			1				1			1								1							7054232.313	100%
828			1				1			1									1						7035689.607	100%
829			1				1			1										1					6669686.063	94%
830			1				1			1											1				6657190.746	94%
831			1				1			1												1			6648280.320	94%
832			1				1			1													1		6639327.011	94%
833			1				1			1														1	6628503.681	94%
834			1				1				1							1							13358352.83	93%
835			1				1				1								1						12955215.73	90%
836			1				1				1									1					9553930.594	81%
837			1				1				1										1				9493700.135	81%
838			1				1				1											1			9475564.062	81%
839			1				1				1												1		9442207.788	81%
840			1				1				1													1	9403719.483	81%
841			1				1					1						1							17648997.21	87%
842			1				1					1							1						13983743.09	81%
843			1				1					1								1					10321681.64	74%
844			1				1					1									1				10260649.60	74%
845			1				1					1										1			10241886.16	74%
846			1				1					1											1		10207547.83	74%
847			1				1					1												1	10167938.92	74%
848			1				1						1					1							18422640.50	80%
849			1				1						1						1						14755326.43	75%
850			1				1						1							1					11088865.10	71%
851			1				1						1								1				11026955.32	71%
852			1				1						1									1			11007058.09	70%
853			1				1						1										1		10971692.58	70%

Table A.14 the output from different distillation processing time and No. of failed separator with (R3, Q4)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
854			1				1						1											1	10931224.56	70%
855			1				1							1				1							21517138.02	70%
856			1				1							1					1						16888502.71	63%
857			1				1							1						1					12234948.51	56%
858			1				1							1							1				12179884.74	56%
859			1				1							1								1			12136568.95	56%
860			1				1							1									1		12176931.36	56%
861			1				1							1										1	12086684.18	56%
862			1				1								1			1							23664576.15	55%
863			1				1								1				1						18897267.43	51%
864			1				1								1					1					13459880.06	41%
865			1				1								1						1				13395964.91	41%
866			1				1								1							1			13346015.01	41%
867			1				1								1								1		13382364.14	41%
868			1				1								1									1	13286093.06	41%
869			1				1									1		1							25151394.38	47%
870			1				1									1			1						19703511.31	41%
871			1				1									1				1					13984042.37	34%
872			1				1									1					1				13909851.53	32%
873			1				1									1						1			13852480.98	32%
874			1				1									1							1		13883906.40	31%
875			1				1									1								1	13780785.18	31%
876			1				1										1	1							25151394.38	47%
877			1				1										1		1						19703511.31	41%
878			1				1										1			1					13984042.37	34%
879			1				1										1				1				13909851.53	32%
880			1				1										1					1			13852480.98	32%
881			1				1										1						1		13883906.40	31%
882			1				1										1							1	13780785.18	31%

Table A.15 the output from different distillation processing time and No. of failed separator with (R3, Q5)

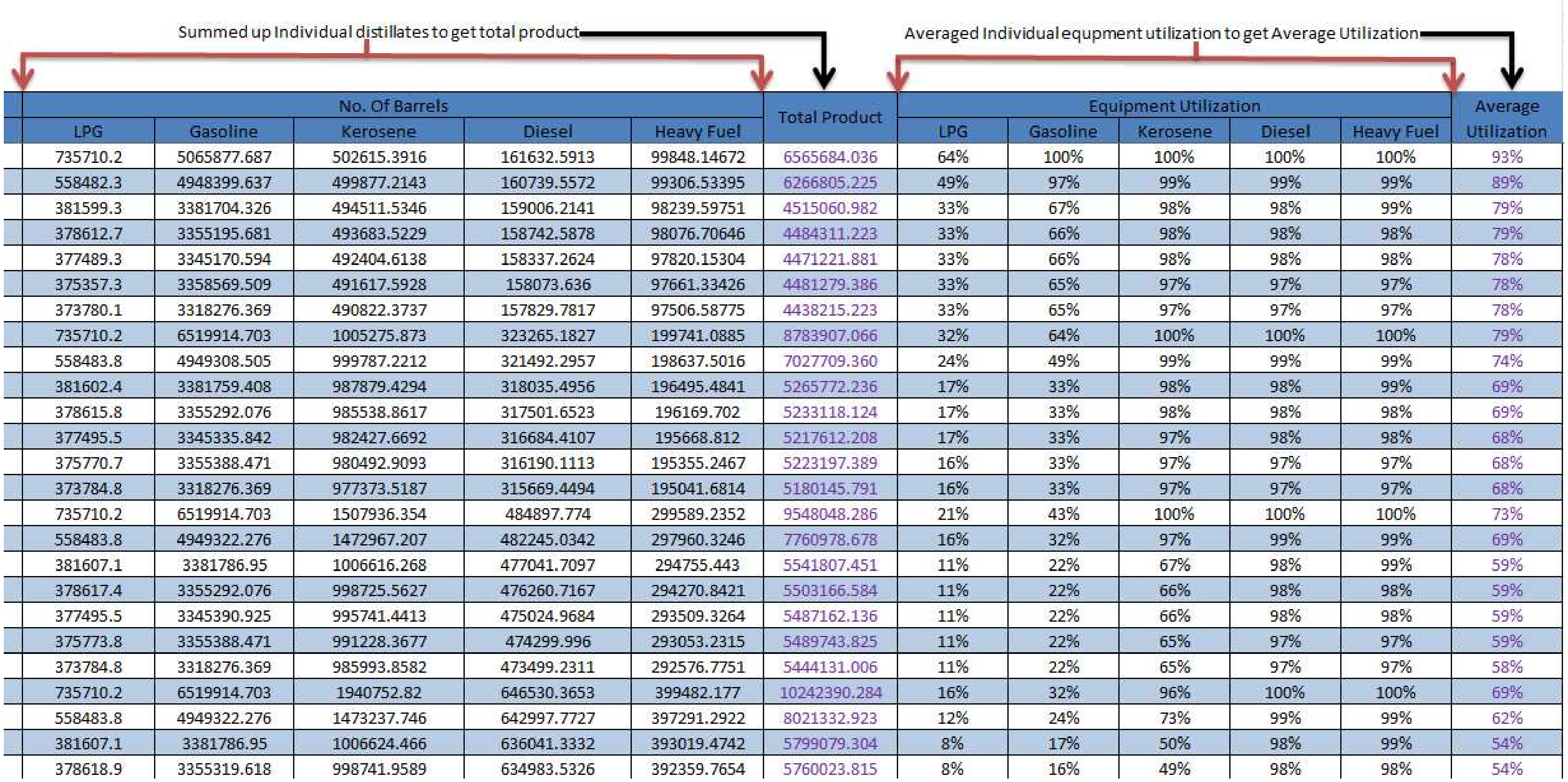
Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
883			1					1	1									1							2352960.538	100%
885			1					1	1										1						2347362.129	100%
886			1					1	1											1					2336196.944	100%
887			1					1	1												1				2333634.663	100%
888			1					1	1													1			2331038.647	100%
889			1					1	1														1		2328709.688	100%
890			1					1	1															1	2326448.799	100%
891			1					1		1								1							7059560.391	100%
892			1					1		1									1						7042591.868	100%
893			1					1		1										1					6738195.275	95%
894			1					1		1											1				6725270.120	95%
895			1					1		1												1			6717267.899	95%
896			1					1		1													1		6707758.659	95%
897			1					1		1														1	6698011.894	95%
898			1					1			1							1							13482614.85	94%
899			1					1			1								1						13055730.11	91%
900			1					1			1									1					10157455.35	83%
901			1					1			1										1				10092775.86	79%
902			1					1			1											1			10074150.73	83%
903			1					1			1												1		10038720.95	83%
904			1					1			1													1	9998217.391	82%
905			1					1				1						1							18791344.67	89%
906			1					1				1							1						14856963.28	82%
907			1					1				1								1					10926255.08	75%
908			1					1				1									1				10860804.25	75%
909			1					1				1										1			10841699.63	75%
910			1					1				1											1		10805250.42	75%
911			1					1				1												1	10763830.86	75%
912			1					1					1					1							19565485.18	82%
913			1					1					1						1						15629260.74	77%
914			1					1					1							1					11694742.25	71%
915			1					1					1								1				11628590.85	71%
916			1					1					1									1			11608252.46	71%
917			1					1					1										1		11571187.08	71%

Table A.15 the output from different distillation processing time and No. of failed separator with (R3, Q5)

Scenario No.	Input Rate			Quality of Crude Oil					Distillation Processing Time									No. of Failed Separator							Total Products	Equipment Utilisation %
	R1	R2	R3	Q1	Q2	Q3	Q4	Q5	C1	C2	C3	C4	C5	C6	C7	C8	C9	F0	F1	F2	F3	F4	F5	F6		
918			1					1					1											1	11528888.01	71%
918			1					1						1				1							22662245.29	71%
919			1					1						1					1						17993988.89	65%
920			1					1						1						1					12999862.64	57%
921			1					1						1							1				12941014.76	57%
922			1					1						1								1			12894821.13	57%
923			1					1						1									1		12937860.92	57%
924			1					1						1										1	12841666.85	57%
925			1					1							1			1							25113385.50	56%
926			1					1							1				1						20106662.50	52%
927			1					1							1					1					14353361.56	43%
928			1					1							1						1				14285013.56	43%
929			1					1							1							1			14231632.32	43%
930			1					1							1								1		14270350.70	43%
931			1					1							1									1	14167593.97	42%
932			1					1								1		1							26844210.63	49%
933			1					1								1			1						20996447.68	42%
934			1					1								1				1					15034670.43	35%
935			1					1								1					1				14954766.29	34%
936			1					1								1						1			14893746.48	34%
937			1					1								1							1		14927180.38	34%
938			1					1								1								1	14816649.59	34%
939			1					1									1	1							26844210.63	49%
940			1					1									1		1						20996447.68	42%
941			1					1									1			1					15034670.43	35%
942			1					1									1				1				14954766.29	34%
943			1					1									1					1			14893746.48	34%
944			1					1									1						1		14927180.38	34%
945			1					1									1							1	14816649.59	34%

Appendix B

Table B.1 Screenshot of How the Performance Measures Values Were Derived



Summed up Individual distillates to get total product

Averaged Individual equpment utilization to get Average Utilization

No. Of Barrels					Total Product	Equipment Utilization					Average Utilization
LPG	Gasoline	Kerosene	Diesel	Heavy Fuel		LPG	Gasoline	Kerosene	Diesel	Heavy Fuel	
735710.2	5065877.687	502615.3916	161632.5913	99848.14672	6565684.036	64%	100%	100%	100%	100%	93%
558482.3	4948399.637	499877.2143	160739.5572	99306.53395	6266805.225	49%	97%	99%	99%	99%	89%
381599.3	3381704.326	494511.5346	159006.2141	98239.59751	4515060.982	33%	67%	98%	98%	99%	79%
378612.7	3355195.681	493683.5229	158742.5878	98076.70646	4484311.223	33%	66%	98%	98%	98%	79%
377489.3	3345170.594	492404.6138	158337.2624	97820.15304	4471221.881	33%	66%	98%	98%	98%	78%
375357.3	3358569.509	491617.5928	158073.636	97661.33426	4481279.386	33%	65%	97%	97%	97%	78%
373780.1	3318276.369	490822.3737	157829.7817	97506.58775	4438215.223	33%	65%	97%	97%	97%	78%
735710.2	6519914.703	1005275.873	323265.1827	199741.0885	8783907.066	32%	64%	100%	100%	100%	79%
558483.8	4949308.505	999787.2212	321492.2957	198637.5016	7027709.360	24%	49%	99%	99%	99%	74%
381602.4	3381759.408	987879.4294	318035.4956	196495.4841	5265772.236	17%	33%	98%	98%	99%	69%
378615.8	3355292.076	985538.8617	317501.6523	196169.702	5233118.124	17%	33%	98%	98%	98%	69%
377495.5	3345335.842	982427.6692	316684.4107	195668.812	5217612.208	17%	33%	97%	98%	98%	68%
375770.7	3355388.471	980492.9093	316190.1113	195355.2467	5223197.389	16%	33%	97%	97%	97%	68%
373784.8	3318276.369	977373.5187	315669.4494	195041.6814	5180145.791	16%	33%	97%	97%	97%	68%
735710.2	6519914.703	1507936.354	484897.774	299589.2352	9548048.286	21%	43%	100%	100%	100%	73%
558483.8	4949322.276	1472967.207	482245.0342	297960.3246	7760978.678	16%	32%	97%	99%	99%	69%
381607.1	3381786.95	1006616.268	477041.7097	294755.443	5541807.451	11%	22%	67%	98%	99%	59%
378617.4	3355292.076	998725.5627	476260.7167	294270.8421	5503166.584	11%	22%	66%	98%	98%	59%
377495.5	3345390.925	995741.4413	475024.9684	293509.3264	5487162.136	11%	22%	66%	98%	98%	59%
375773.8	3355388.471	991228.3677	474299.996	293053.2315	5489743.825	11%	22%	65%	97%	97%	59%
373784.8	3318276.369	985993.8582	473499.2311	292576.7751	5444131.006	11%	22%	65%	97%	97%	58%
735710.2	6519914.703	1940752.82	646530.3653	399482.177	10242390.284	16%	32%	96%	100%	100%	69%
558483.8	4949322.276	1473237.746	642997.7727	397291.2922	8021332.923	12%	24%	73%	99%	99%	62%
381607.1	3381786.95	1006624.466	636041.3332	393019.4742	5799079.304	8%	17%	50%	98%	99%	54%
378618.9	3355319.618	998741.9589	634983.5326	392359.7654	5760023.815	8%	16%	49%	98%	98%	54%

Appendix C

Table C.1 A Guideline to Selecting Statistical Test. Source: Leeper (2017)

Number of Dependent Variable	**Number of Independent Variable**	**Nature of Dependent Variable(s)**	**Test(s)**
1	0 IVs (1 population)	interval & normal	one-sample t-test
		ordinal or interval	one-sample median
		categorical (2 categories)	binomial test
		categorical	Chi-square goodness-of-fit
	1 IV with 2 levels (independent groups)	interval & normal	2 independent sample t-test
		ordinal or interval	Wilcoxon-Mann Whitney test
		categorical	Chi-square test
			Fisher's exact test
	1 IV with 2 or more levels (independent groups)	interval & normal	one-way ANOVA
		ordinal or interval	Kruskal Wallis
		categorical	Chi-square test
	1 IV with 2 levels (dependent/matched groups)	interval & normal	paired t-test
		ordinal or interval	Wilcoxon signed ranks test
		categorical	McNemar
	1 IV with 2 or more levels (dependent/matched groups)	interval & normal	one-way repeated measures ANOVA
		ordinal or interval	Friedman test
		categorical	repeated measures logistic regression
	2 or more IVs (independent groups)	interval & normal	factorial ANOVA
		ordinal or interval	ordered logistic regression
		categorical	factorial logistic regression
	1 interval IV	interval & normal	correlation
		interval & normal	simple linear regression
		ordinal or interval	non-parametric correlation
		categorical	simple logistic regression
	1 or more interval IVs and/or 1 or more categorical IVs	interval & normal	multiple regression
			analysis of covariance
		categorical	multiple logistic regression
			discriminant analysis
2+	1 IV with 2 or more levels (independent groups)	interval & normal	one-way MANOVA
	2+	interval & normal	multivariate multiple linear regression
	0	interval & normal	factor analysis
2 sets of 2+	0	interval & normal	canonical correlation

Appendix D

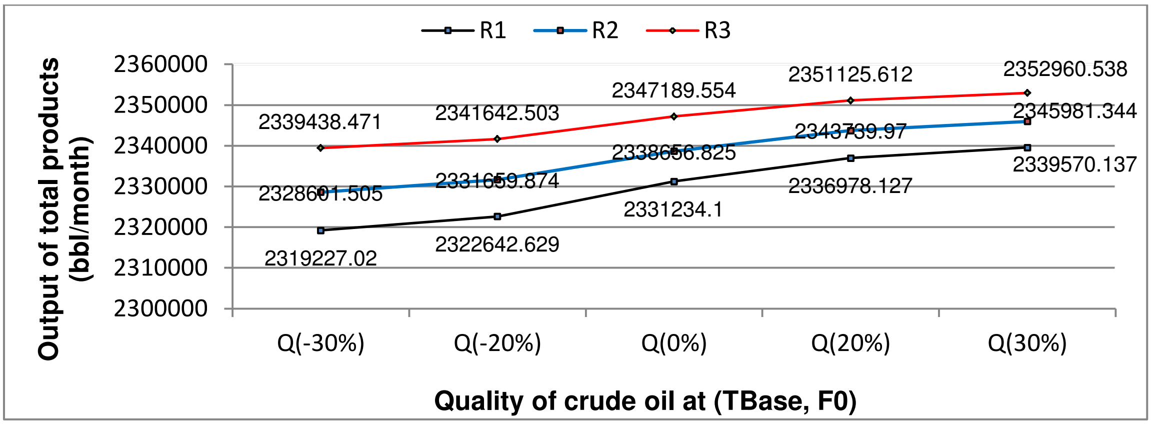


Figure D.1 Output of total products against quality of crude oil with three oil flow rates at (TBase, F0)

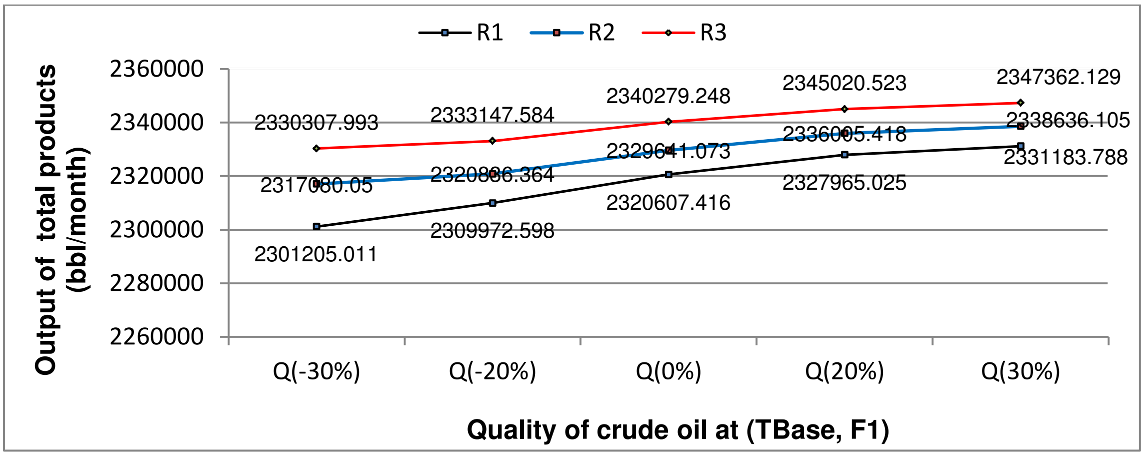


Figure D.2 Output of total products against quality of crude oil with three oil flow rates at (TBase, F1)

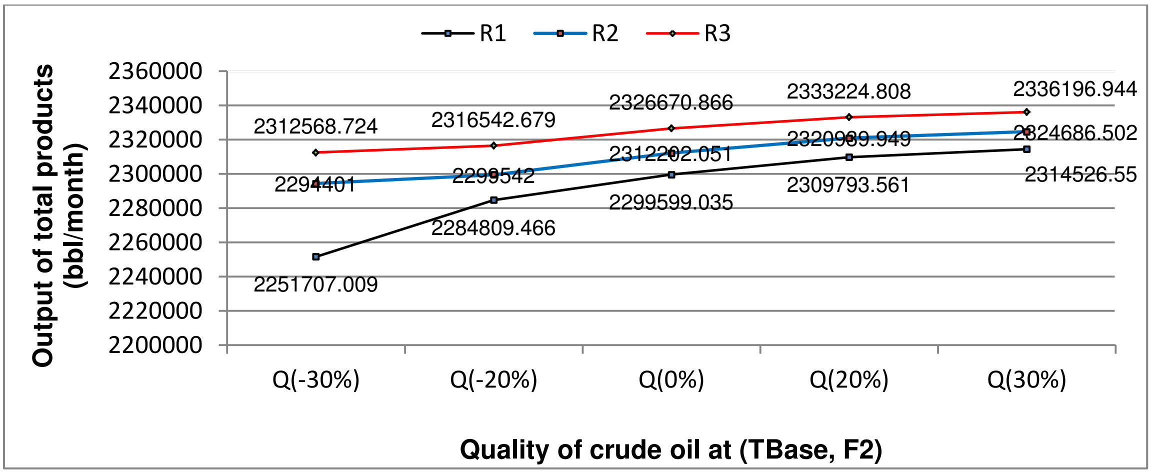


Figure D.3 Output of total products against quality of crude oil with three oil flow rates at (TBase, F2)

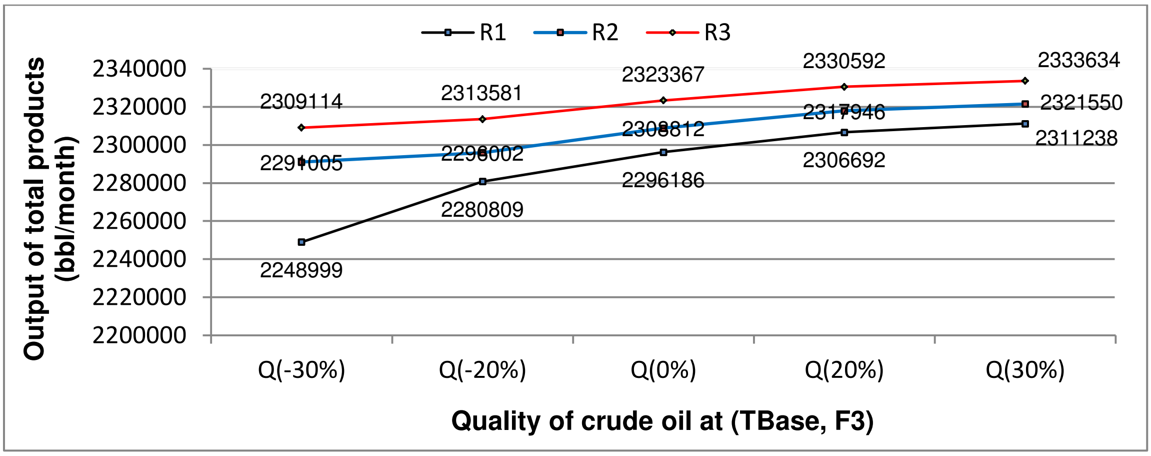


Figure D.4 Output of total products against quality of crude oil with three oil flow rates at (TBase, F3)

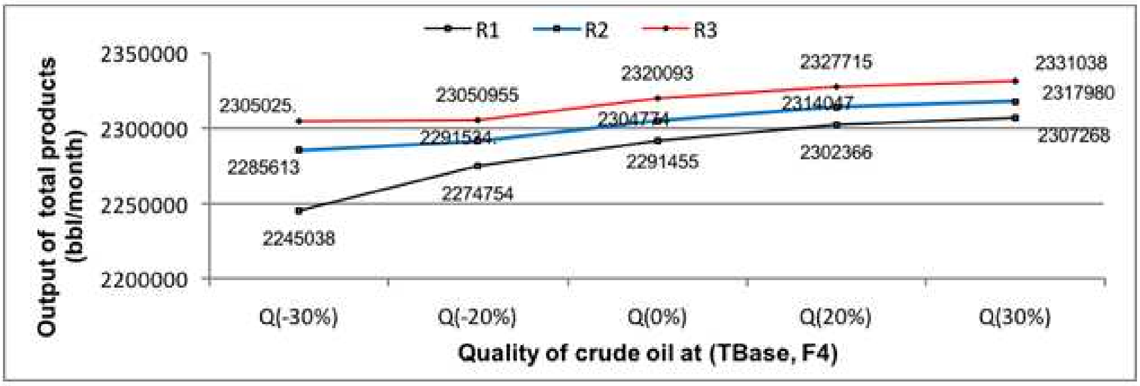


Figure D.5 Output of total products against quality of crude oil with three oil flow rates at (TBase, F4)

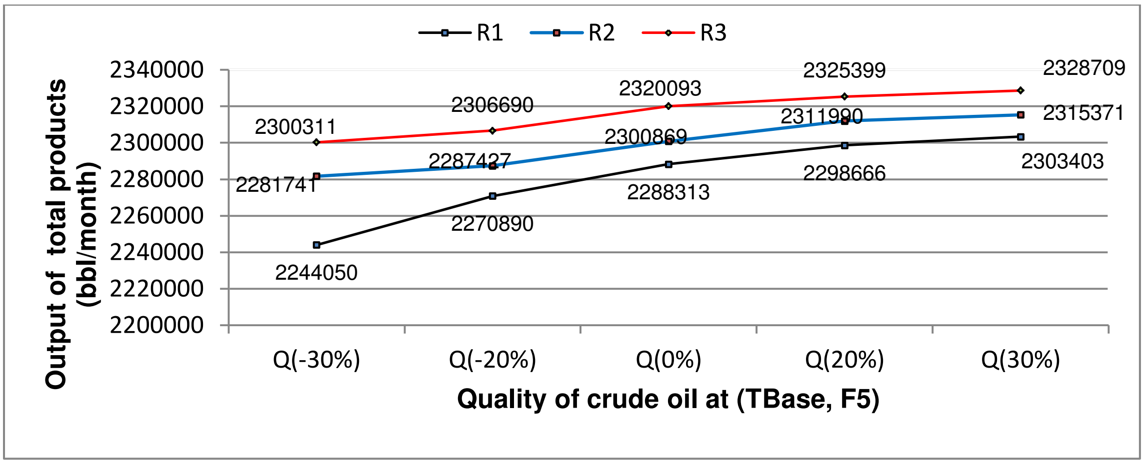


Figure D.6 Output of total products against quality of crude oil with three oil flow rates at (TBase, F5)

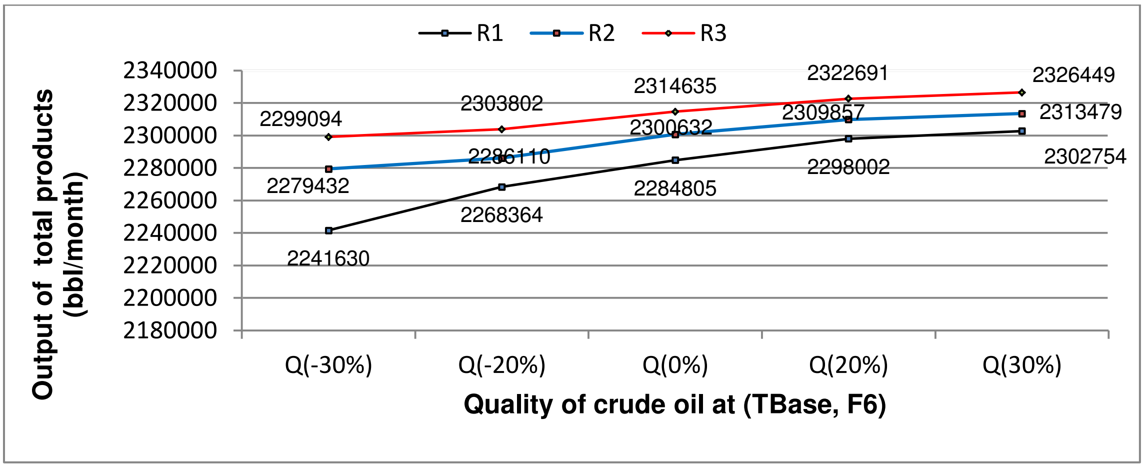


Figure D.7 Output of total products against quality of crude oil with three oil flow rates at (TBase, F6

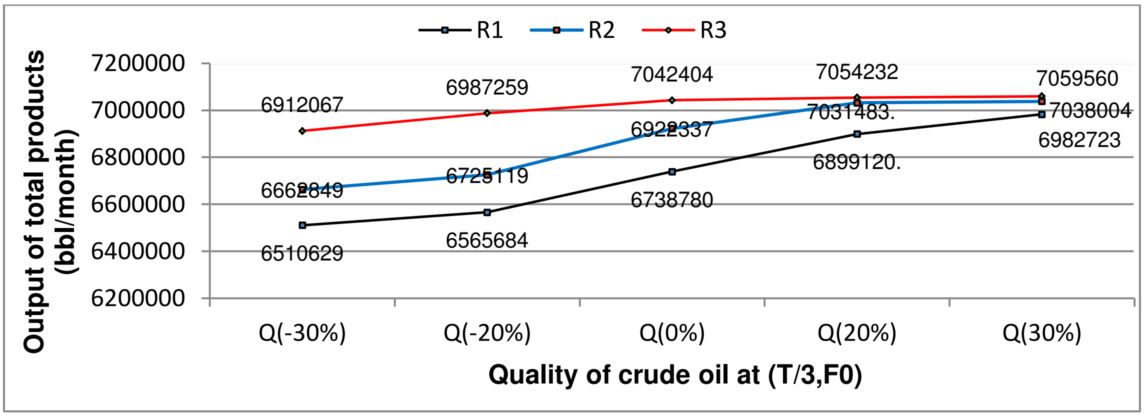


Figure D.8 Output of total products against quality of crude oil with three oil flow rates at (T/3, F0)

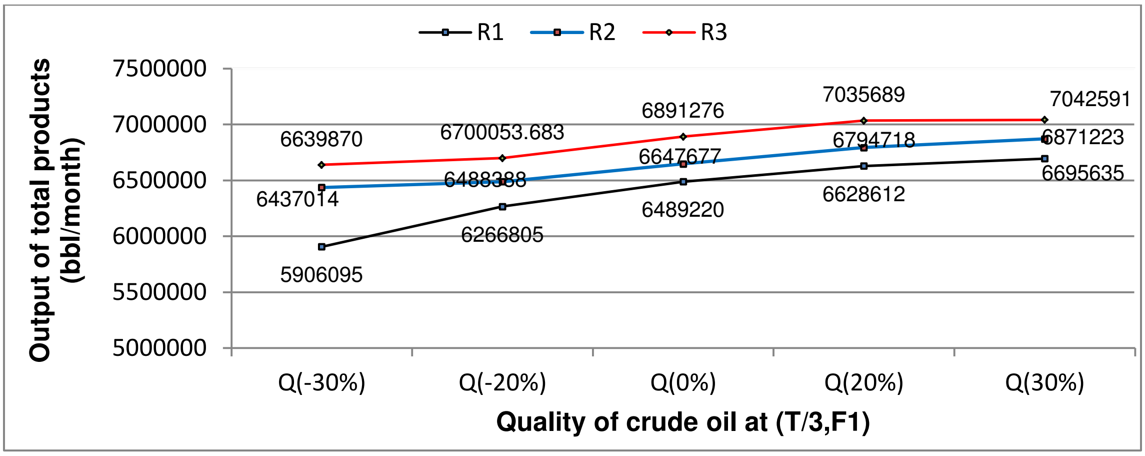


Figure D.9 Output of total products against quality of crude oil with three oil flow rates at (T/3, F1)

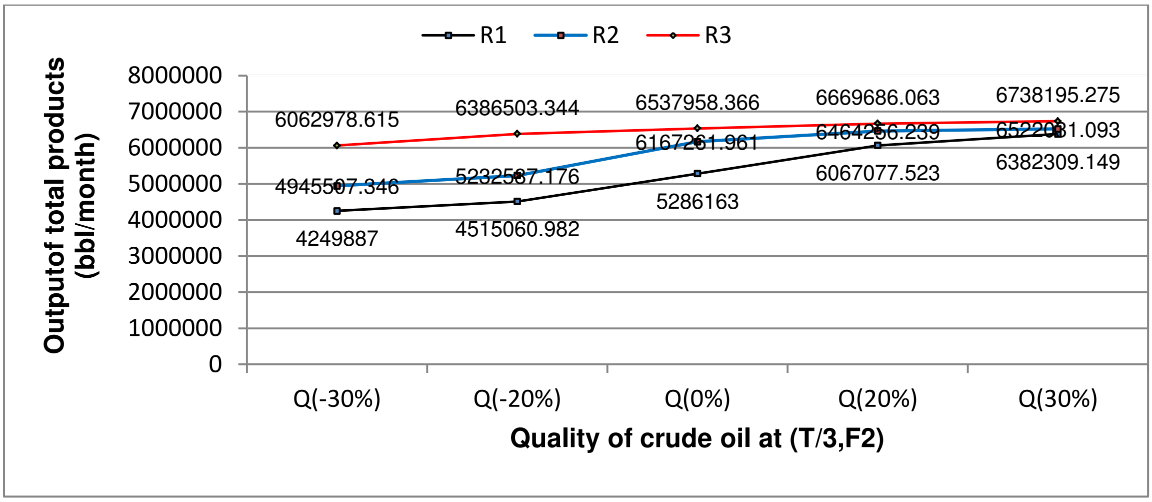


Figure D.10 Output of total products against quality of crude oil with three oil flow rates at (T/3, F2)

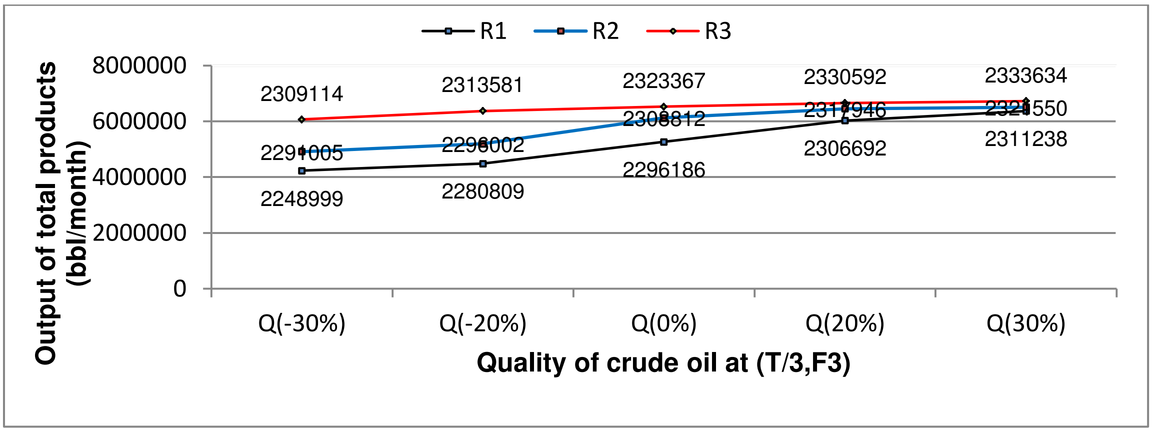


Figure D.11 Output of total products against quality of crude oil with three oil flow rates at (T/3, F3)

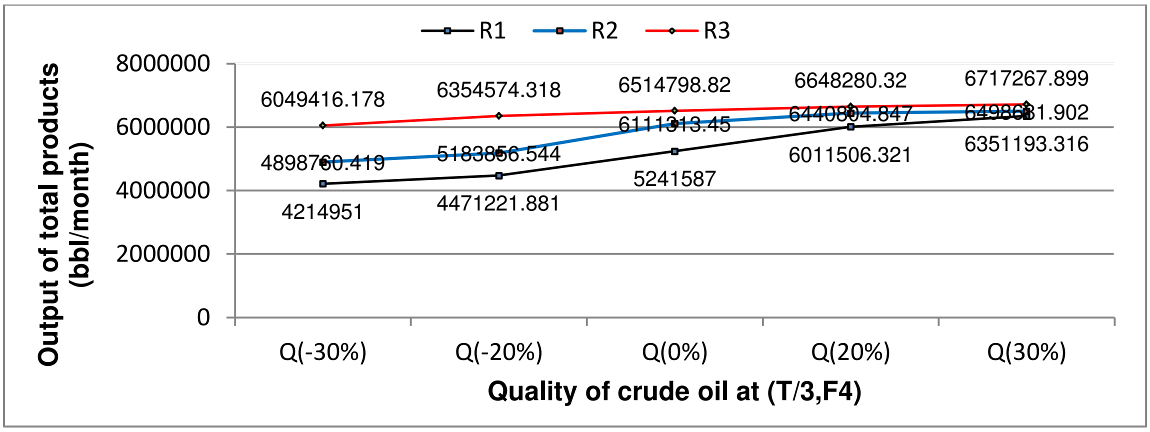


Figure D.12 Output of total products against quality of crude oil with three oil flow rates at (T/3, F4)

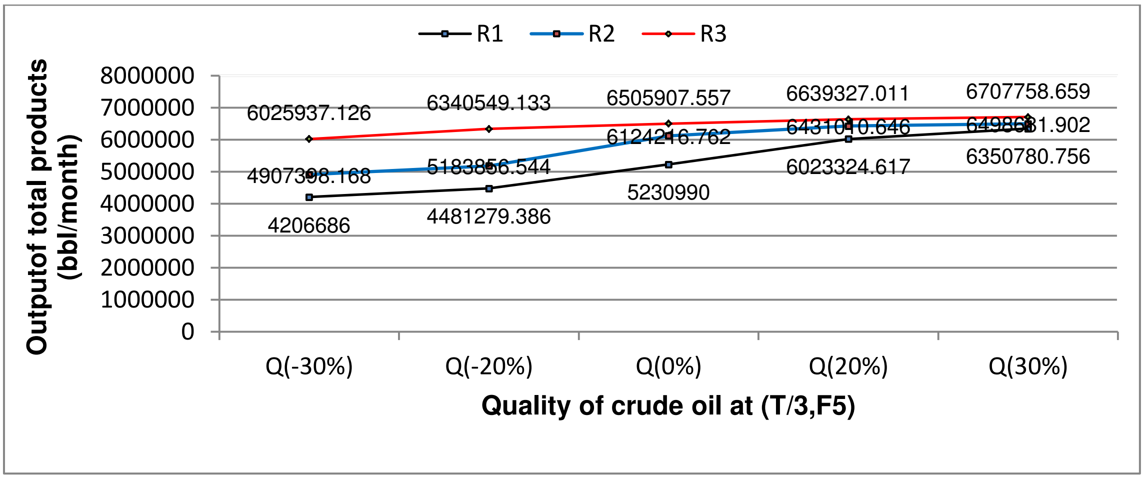


Figure D.13 Output of total products against quality of crude oil with three oil flow rates at (T/3, F5)

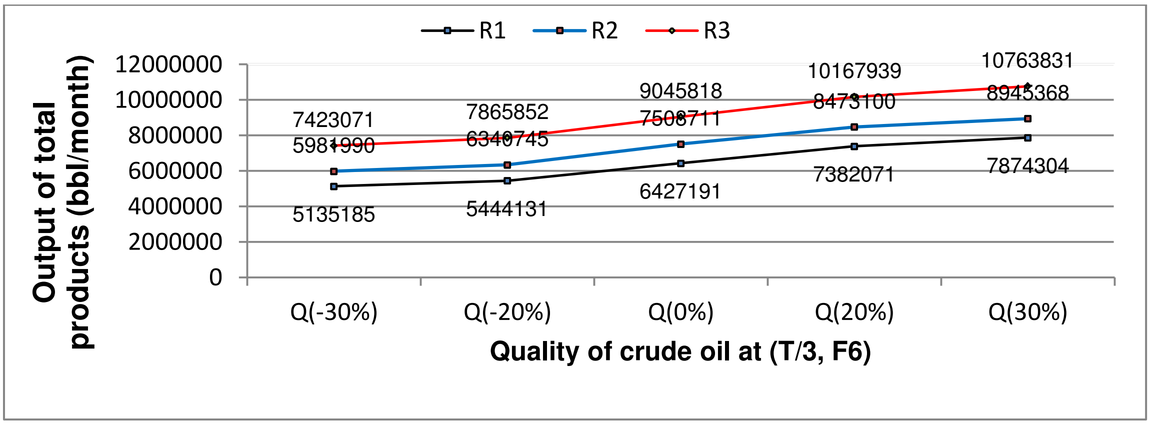


Figure D.14 Output of total products against quality of crude oil with three oil flow rates at (T/3, F6)

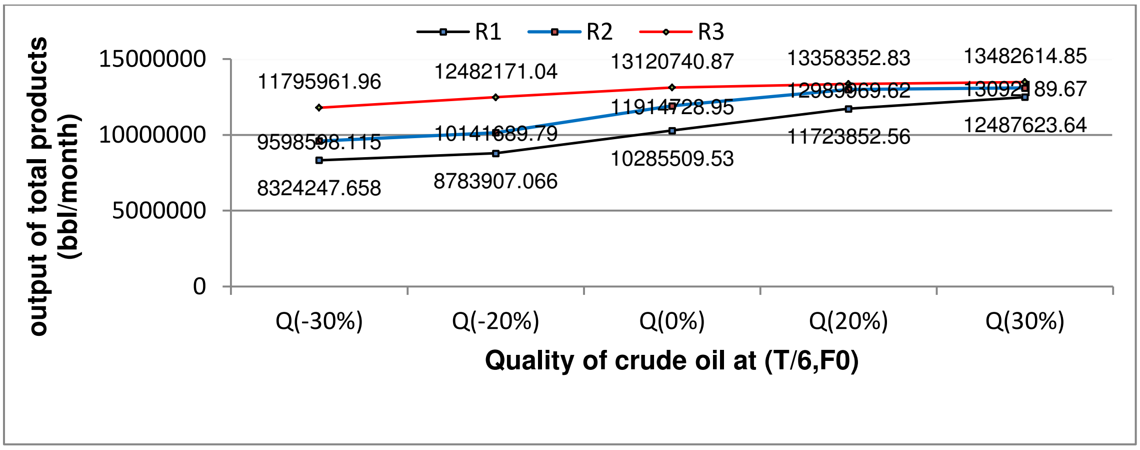


Figure D.15 Output of total products against quality of crude oil with three oil flow rates at (T/6, F0)

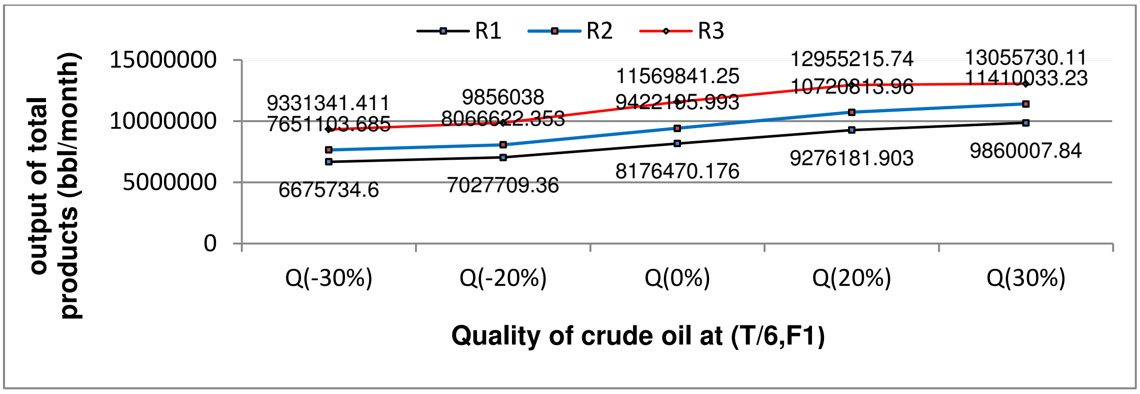


Figure D.16 Output of total products against quality of crude oil with three oil flow rates at (T/6, F1)

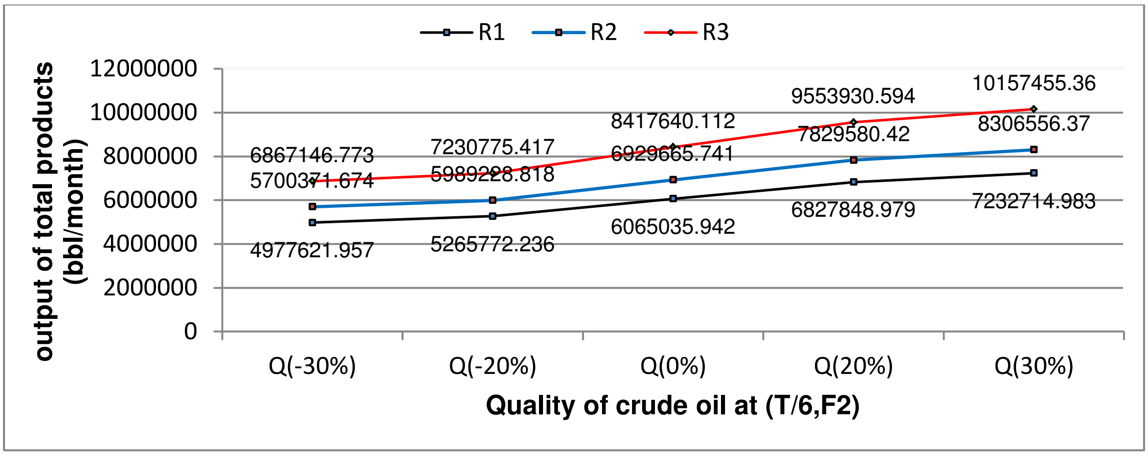


Figure D.17 Output of total products against quality of crude oil with three oil flow rates at (T/6, F2)

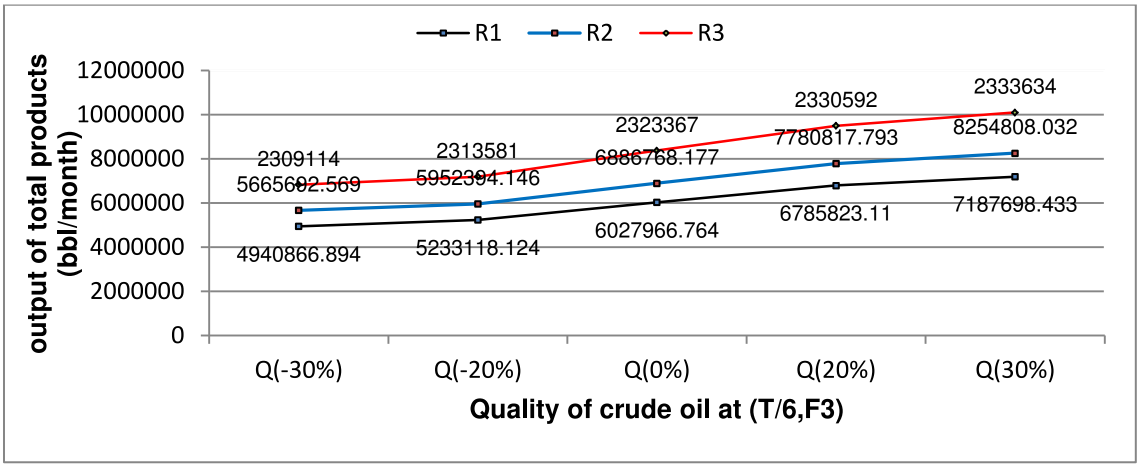


Figure D.18 Output of total products against quality of crude oil with three oil flow rates at (T/6, F3)

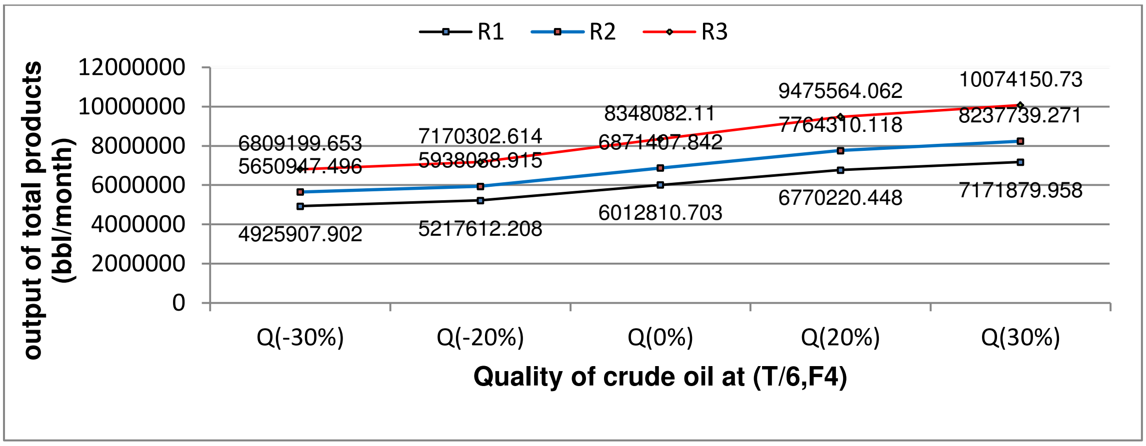


Figure D.19 Output of total products against quality of crude oil with three oil flow rates at (T/6, F4)

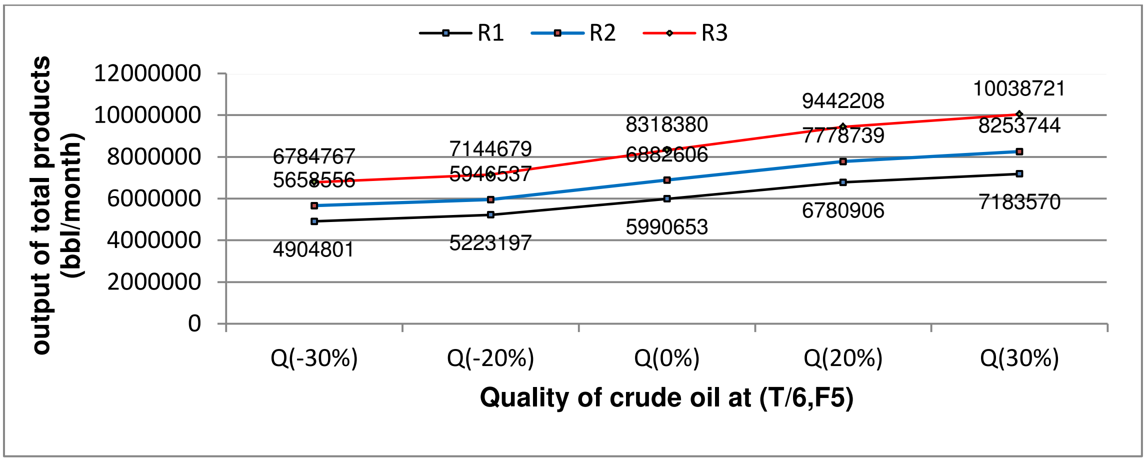


Figure D.20 Output of total products against quality of crude oil with three oil flow rates at (T/6, F5)

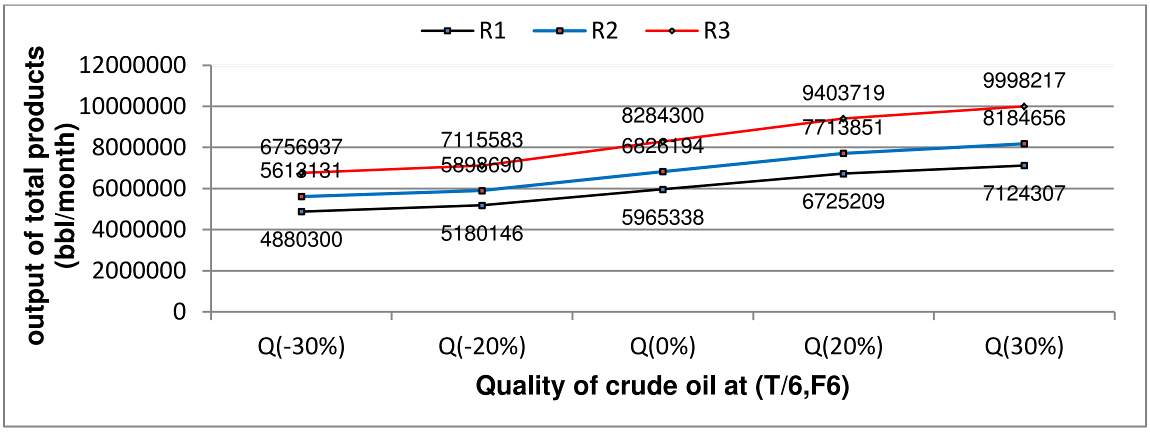


Figure D.21 Output of total products against quality of crude oil with three oil flow rates at (T/6, F6)

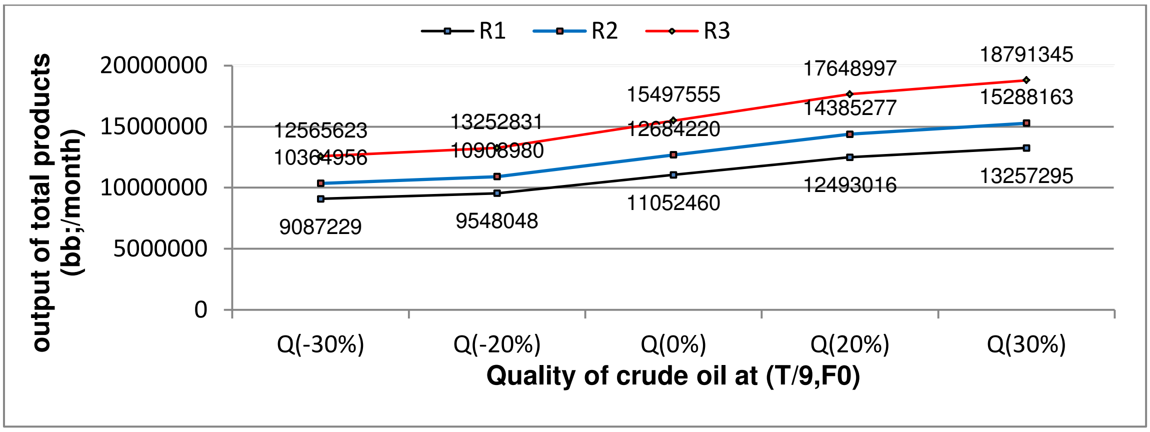


Figure D.22 Output of total products against quality of crude oil with three oil flow rates at (T/9, F0)

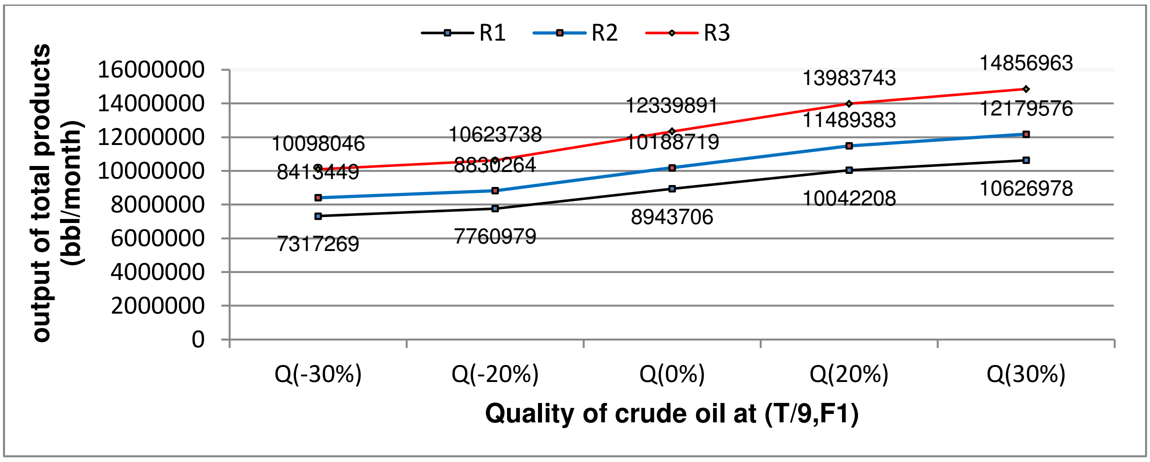


Figure D.23 Output of total products against quality of crude oil with three oil flow rates at (T/9, F1)

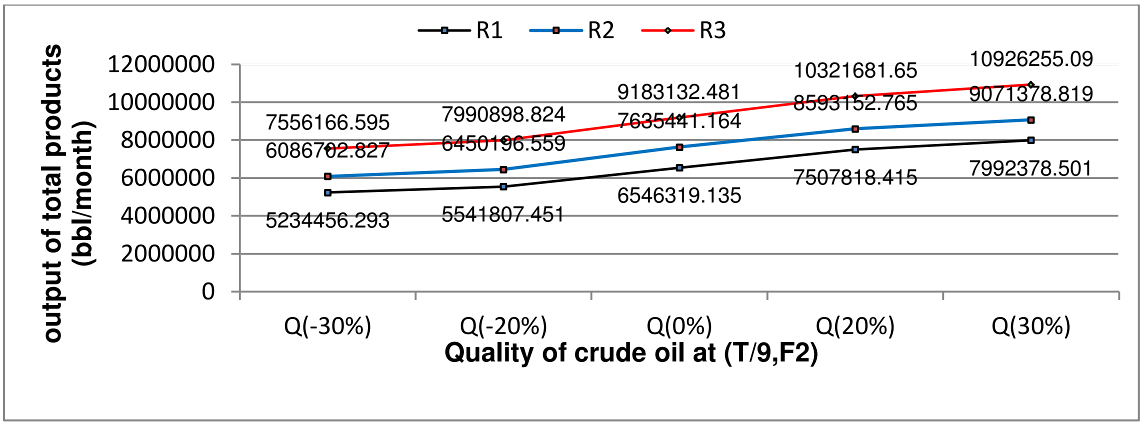


Figure D.24 Output of total products against quality of crude oil with three oil flow rates at (T/9, F2)

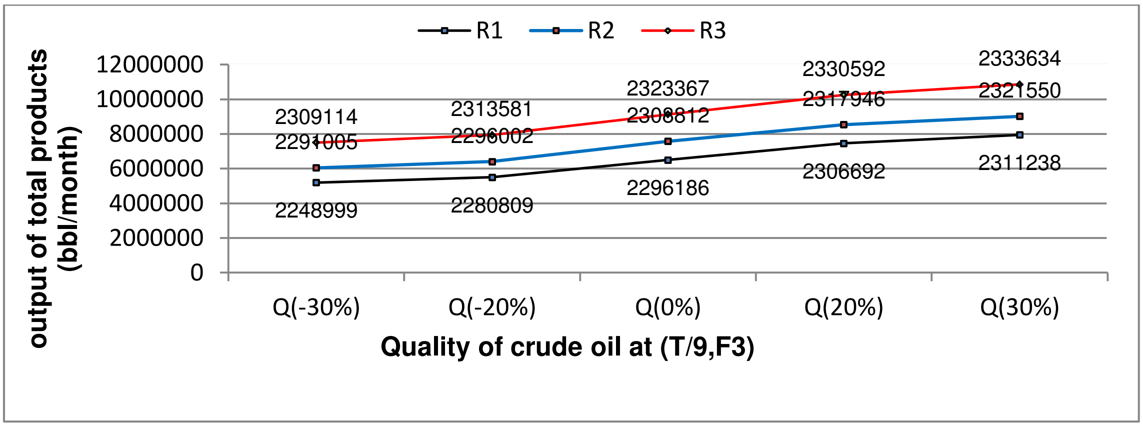


Figure D.25 Output of total products against quality of crude oil with three oil flow rates at (T/9, F3)

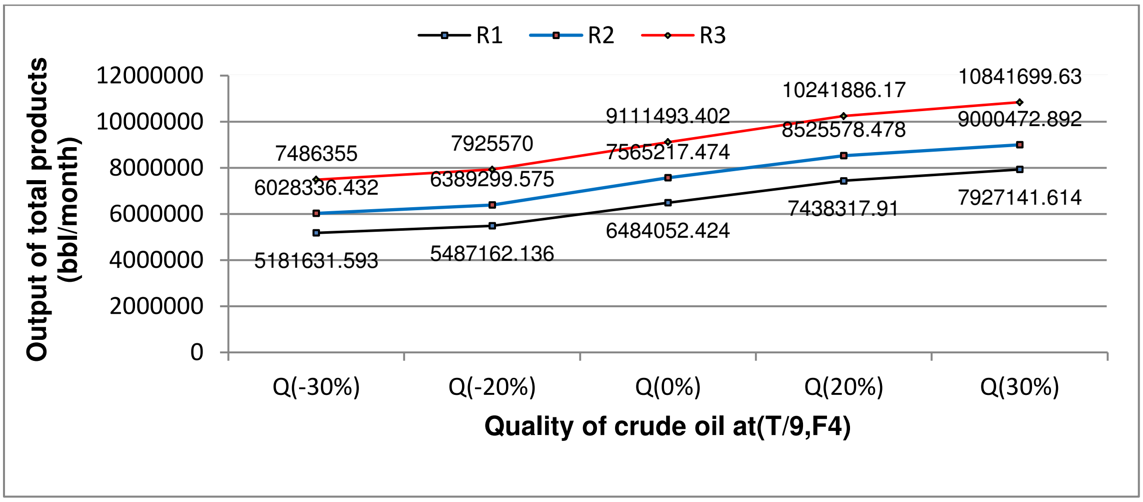


Figure D.26 Output of total products against quality of crude oil with three oil flow rates at (T/9, F4)

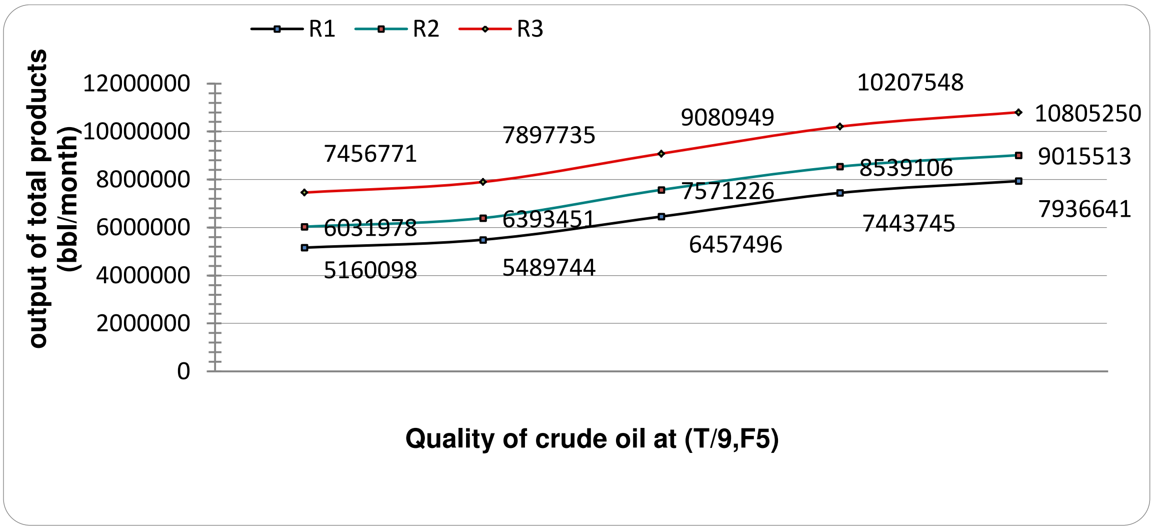


Figure D.27Output of total products against quality of crude oil with three oil flow rates at (T/9, F5)

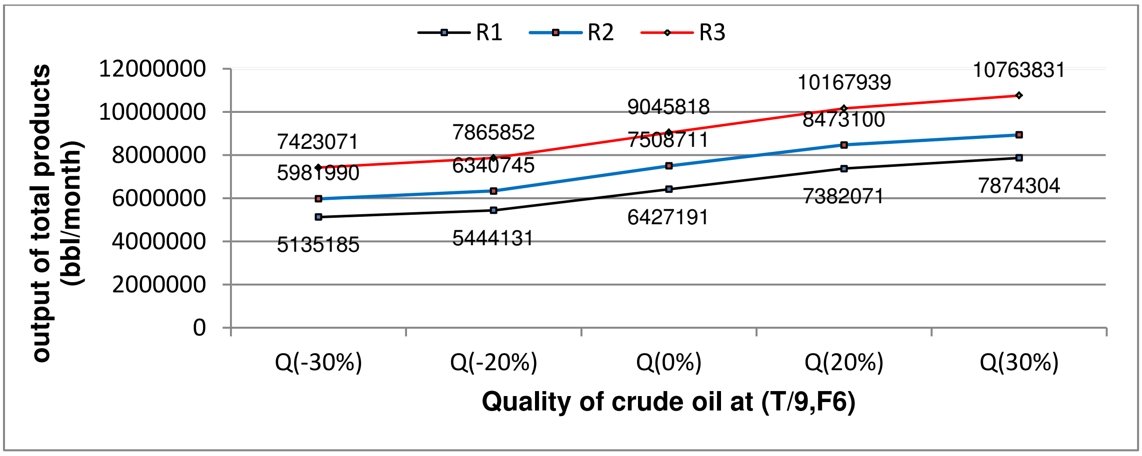


Figure D.28 Output of total products against quality of crude oil with three oil flow rates at (T/9, F6)

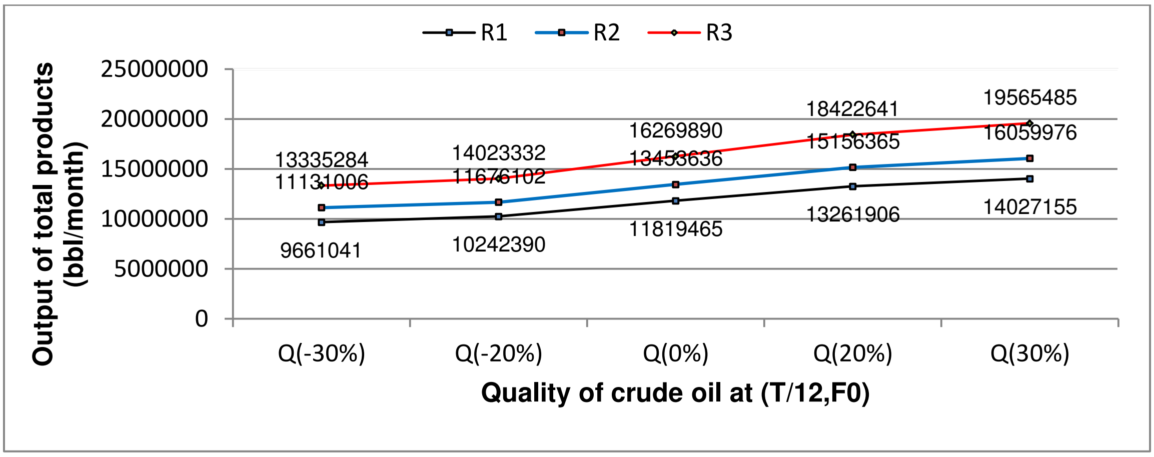


Figure D.29 Output of total products against quality of crude oil with three oil flow rates at (T/12, F0)

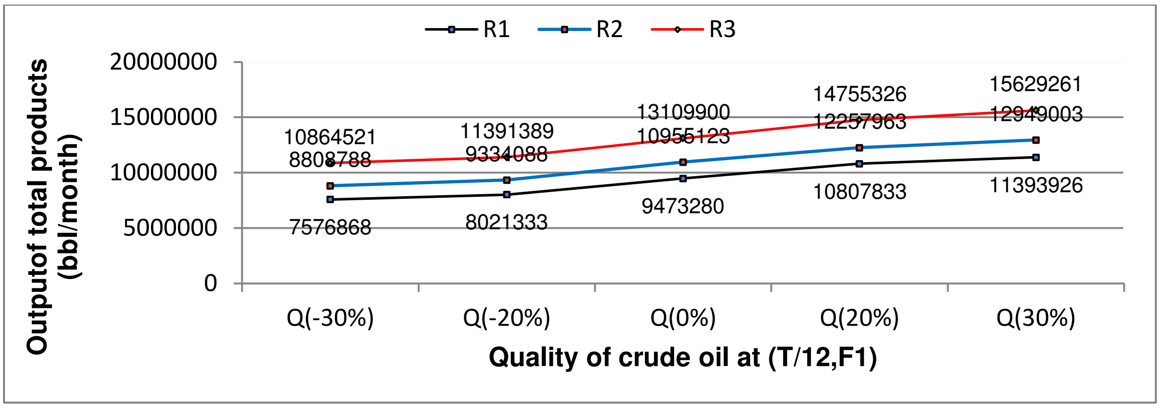


Figure D.30 Output of total products against quality of crude oil with three oil flow rates at (T/12, F1)

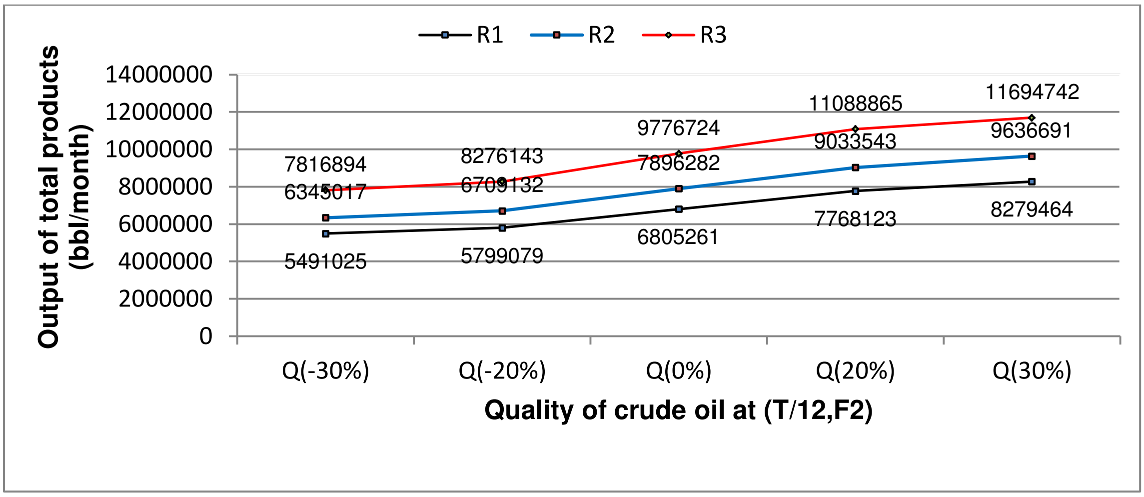


Figure D.31 Output of total products against quality of crude oil with three oil flow rates at (T/12, F2)

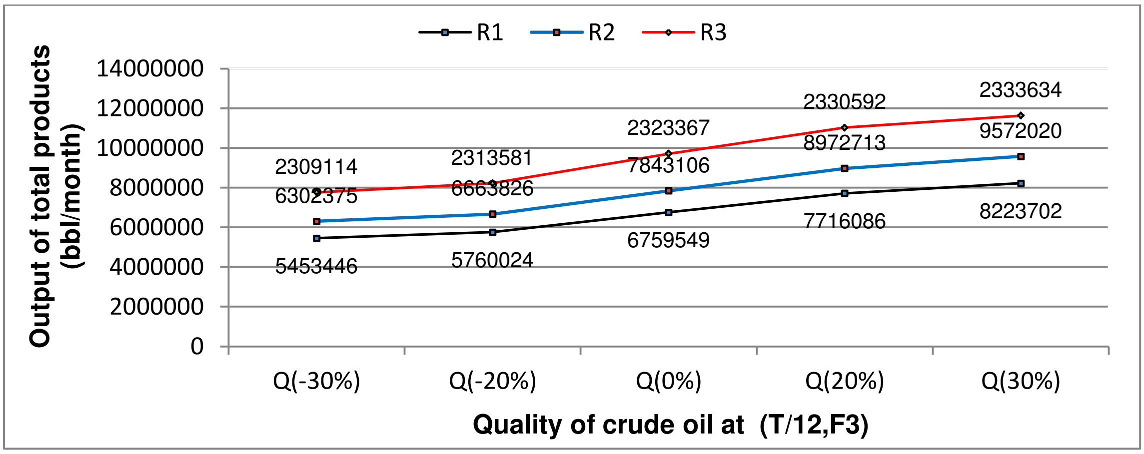


Figure D.32 Output of total products against quality of crude oil with three oil flow rates at (T/12, F3)

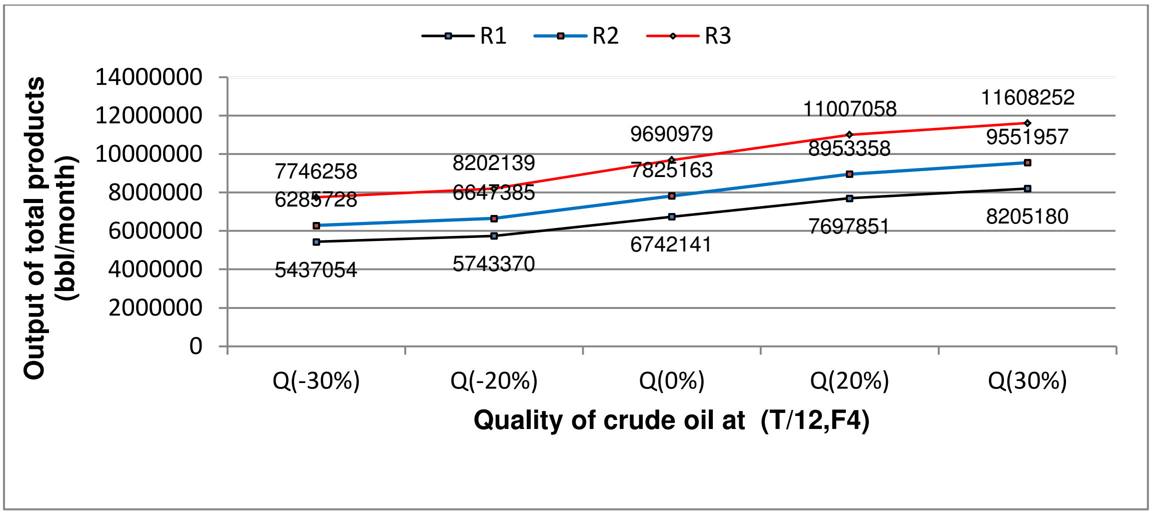


Figure D.33 Output of total products against quality of crude oil with three oil flow rates at (T/12, F4)

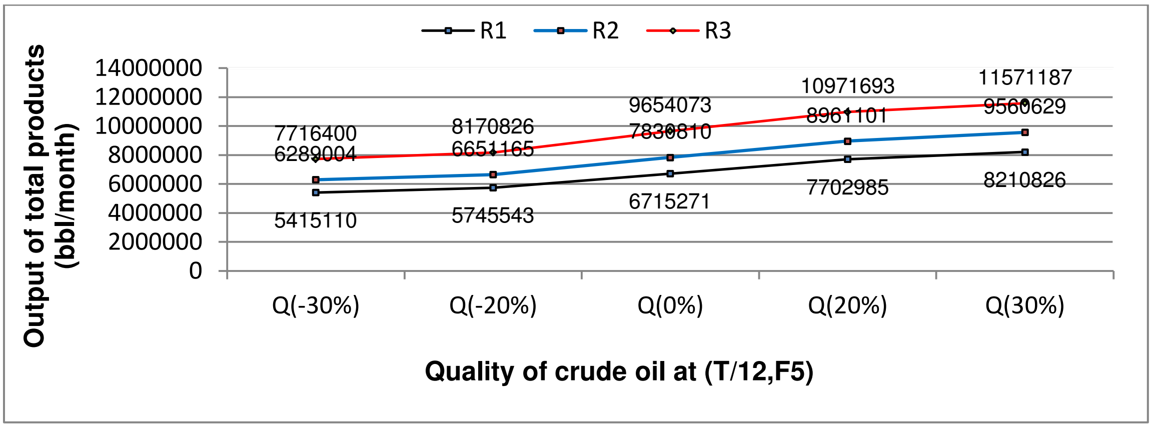


Figure D.34 Output of total products against quality of crude oil with three oil flow rates at (T/12, F5)

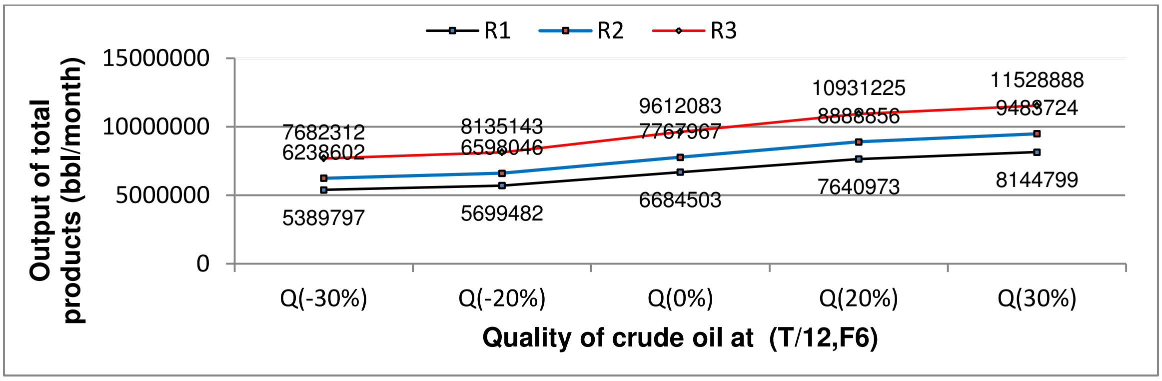


Figure D.35 Output of total products against quality of crude oil with three oil flow rates at (T/12, F6)