KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

APPLICATION OF SEPARABLE PROGRAMMING TO OIL REFINERY PROBLEMS: THE CASE STUDY OF TEMA OIL REFINERY

BY:

FRANCIS KWAKU NORMANYO

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DECLARATION

I declare that this study is an original research work that I undertook. However, where quotations and ideas used are those of others, they have been duly acknowledged.

FRANCIS NORMANYO/2012108 ....
STUDENT NAME & PG NO. SIGNATURE DATE

PROF. S. K. AMPONSAH ....
SUPERVISOR SIGNATURE DATE

MR. K. F. DARKWAH ....
HEAD OF DEPT. SIGNATURE DATE

PROF. I.K. DONTWI ....
DEAN, IDL SIGNATURE DATE

ABSTRACT

Oil refineries play a major role in the current world's economy by manufacturing one of the world's treasured commodity; crude oil. Crude oil is processed and refined into petroleum products, such as gasoline, diesel fuel, asphalt base, heating oil, kerosene, and liquefied petroleum gas. These products are household names in every part of the world. The refinery undertakes very complex processes in order to arrive at these outputs. These processes involve the passage of raw materials through three basic operational facilities where Separation, Conversion and Treatment are done. Therefore for a refinery to maximize output it has to deal with the raw material inputs, available facilities or utilities subject to financial constraint. Generally refineries have been using softwares which have an underlining assumption that the process of refinery is linear to arrive at their optimum product mix. However, this study found that, the process of the refinery is not linear, hence the application of Separable programming. Separable programming is a non linear programming method which expresses the objective function and the constraint functions as the sum of single – variable functions. As a result, this method furnishes new insights into the problem of refinery optimization and provides significant benefits to the refining industry in exploiting the true potential of the processes and obtaining truly optimal operation.

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DEDICATION

I dedicate this study to my wife Mrs. Bernice Selassie Normanyo and my children, Dzifa, Dela and Dzidzor for the various supportive roles they played during my pursuit of higher education.

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CHAPTER 1

INTRODUCTION

1.0 BRIEF INTRODUCTION OF CHAPTER 1

Crude oil is one of the world's treasures because of its importance in our lives. It has many uses. which are all valuable. When crude oil has gone through the process of oil refining, it will become a D2 diesel fuel, or in layman's term, diesel gasoline.

There are many reasons why gasoline is one of the needs of people today. A petroleum product like ethane is used as fuel. There are also diesel fuels, fuel oils, gasoline, jet fuel, kerosene, Liquid Petroleum Gas (LPG) and natural gas which are all used to make engines work and functions to make automobiles run, thanks to Hydrocarbons. These are referred to as a consisting of a ""backbone"" composed entirely of carbon and hydrogen and other bonded compounds, and lack a functional group that generally facilitates combustion without adverse effects. Diesel gasoline refinery does the job of purifying the crude oil to make it a diesel and be more of use by the people.

An oil refinery is an industrial process plant where crude oil is processed and refined into more useful petroleum products, such as gasoline, diesel fuel, asphalt base, heating oil, kerosene, and liquefied petroleum gas.

1.1 THE PROFILE OF TEMA OIL REFINERY

Tema Oil Refinery was built in 1963 as a hydro skimming plant. It has since undergone revamping and upgrading to become a conversion refinery. It aims at maximizing refined products imports by utilizing fully the operating capacities of the processing plants. At the same time, the company will minimize exports by providing fully the national requirements of refined products.

Commencement of Operation

Ghana's only crude oil refinery, situated at Tema about twenty-four (24) kilometres from the capital, Accra was originally named the Ghanaian Italian Petroleum (GHAIP) Company. The GHAIP Company commenced business in 1963 as a tolling refinery by processing crude oil for the major oil companies, namely, BP, Shell and Mobil for a fee. In 1977, the Government of Ghana (GOG), acting through the Ghana Supply Commission (GSC), replaced the three multinational oil companies. Subsequently in 1983, the Ghana National Petroleum Corporation (GNPC) replaced GSC with an expanded role.

In 1996, as part of the restructuring of the oil sector, Tema Oil Refinery was given additional responsibility to procure crude oil and refined petroleum products, and to export surplus refined petroleum products, if any. The Bulk Oil Storage and Transportation Company Limited (BOST) was formed in 1998 to manage strategic stocks and undertake bulk distribution of refined petroleum products. In 2000, BOST was restricted to managing strategic reserves, thus paving the way for TOR to operate some of the storage depots and to carry out bulk distribution of refined petroleum products. (ENERGYWORLD / Africa - 2010/11)

Plants Configuration

The refinery covers a total area of four hundred and forty thousand (440,000) square meters. It is linked to an oil jetty at the Port of Tema by pipelines of various diameters for the transportation of crude oil and refined petroleum products.

TOR's refining plant was designed by AGIP Petroli and constructed by Snam Progetti both of Italy. The refinery was commissioned in 1963 as a hydro skimming plant with an initial capacity of twenty-eight thousand (28,000) barrels per stream day. It was to process various light and low sulphur crude oils, such as Bonny Light and Brass River from Nigeria, and Palanca Blend from Angola.

In 1997, as part of the first phase of TOR's expansion and modernization program, the Crude Distillation Unit (CDU) was revamped to forty-five thousand (45,000) barrels per stream day. In 2002, as the second phase of the expansion and modernization program, a Residue Fluid Catalytic Cracking (RFCC) unit of capacity fourteen thousand (14,000) barrels per stream day was commissioned. The RFCC was to convert the low valued residual fuel oil from the CDU into high valued products of LPG and gasoline. The products of the refining processes were liquefied petroleum gas, gasoline, illuminating and cooking kerosene, aviation turbine kerosene, gasoil or diesel and residual fuel oil.

Production

The Tema Oil Refinery has evolved from a simple hydro skimming plant into one with a secondary conversion unit. The hydro skimming plant comprises the Topping unit, Light Naphtha Merox unit, the hydro treatment unit, the catalytic reforming unit and the LPG treatment unit.

The secondary conversion unit is essentially made up of a Residue Fluid Catalytic Cracking facility.

In addition to the processing units, there is also a Utilities unit, a Movement of Products (MOP) unit and a Waste Water Treatment (WWT) unit. (http://www.torghana.com, 2010)

Storage

The Refinery has a total crude oil storage capacity of two hundred and eighty-five thousand (285,000) cubic metres. There are also storage facilities for both finished and semi-finished products that service liquefied petroleum gas, Kerosenes, Gasolines, diesel and residual fuel oil. (http://www.torghana.com, 2010)

The Utilities Unit

The utilities unit provides electrical energy, steam, compressed air and cooling water in optimum quantity and quality to meet processing requirements. The unit also offers support for fire fighting and for the protection of fire prevention installations. The utilities unit further serves as distribution point of fuel oil to the boilers and fired heaters within the refinery.

Currently, three boilers operate to meet the demand of producing steam for both process operations and electrical energy generation. The total nominal steam-generating requirement is between one hundred and twenty-five (125) Tonnes per hour and one hundred and thirty (130) Tonnes per hour but actual production capacity of the existing boilers is about 95 Tonnes per hour. The Flue Gas Steam Generator at the RFCC makes up for the deficit.

There is the need for an additional boiler to support sustained steam demand and electrical energy generation to provide for flexibility and reliability.

The utilities unit is made up of the following sections: steam generation, electric power generation, water demineralization, fuel oil Installation, compressed air installation, cooling water system, fire fighting installation and fresh water system.(http://www.torghana.com, 2010)

The Residue Fluid Catalytic Cracking (RFCC) Unit of the Secondary Conversion Unit

The RFCC unit commissioned in October 2003 is the latest addition to TOR's plants. The RFCC was built to convert low priced residual fuel oil from the crude distillation unit to high priced liquefied petroleum gas and gasoline. It is designed to process 14,000 barrels of low sulphur residual fuel oil every day. (http://www.torghana.com, 2010)

The RFCC complex consists of eight units: Reactor/Regenerator, Main Column, Gas Concentration, Gasoline Sweetening, LPG Extraction, Amine Recovery, Sour Water Treatment and Sulphur Units. (http://www.torghana.com, 2010)

The products obtained from the RFCC are liquefied petroleum gas, gasoline, light cycle oil (LCO), heavy cycle oil (HCO) and clarified oil (CLO). Currently, the CLO, the LCO and the HCO are mixed together and used or sold as cracked residual fuel oil. There is however ongoing studies to chemically convert the LCO into diesel, a development that will substantially add value to and raise the price of the residue. (http://www.torghana.com, 2010)

Catalytic Reforming Unit of the Hydro Skimming Plant

The catalytic reforming unit has the capacity to process six thousand, five hundred (6,500) barrels a day of heavy naphtha. The heavy naphtha from the Topping section is passed through the hydro treatment unit to remove hydrogen sulphide and other impurities that are considered poisonous to the catalyst in the catalytic reforming unit. The treated heavy naphtha then undergoes further processing at the catalytic reforming unit to increase the octane rating. The resulting product referred to as reformate is blended with light naphtha to give gasoline. Components or additives are added to the gasoline to enable it meet market specifications.

1.2 BACKGROUND

The theory of separable program has some interesting properties due to its separability nature, and can be solved by specific methods. Consequently many economic, industrial and other problems are described mathematically by separable programs. Its use in agricultural economics is illustrated by the Blakley and Kloth study of plant location and the Holland and Baritelle study of school location. Thus, separable programming is significant from both the theoretical and practical points of view.

Oil refineries on the other hand are faced with the problem of maximizing output for that matter profit subject to constraints. This problem is not necessary peculiar to oil refineries as other industries encounter this problem too. How to effectively combine input in other to arrive at an optimum production level is a major problem that deserves utmost consideration. The problem is aggravated looking at the fact the inputs and for that matter variables to be maximized are generally non-linear in nature. Further in this paper more light would be thrown on the non-linear nature the main variables to be considered for optimality in the case of an oil refinery.

This study has as its primary aim, to tap into the significance of theory on separability to use separable programming and access how it helps to address this general problem facing industries and oil refineries in particular.

To effectively apply separable programming to solve industrial problems and for that matter the oil refinery problem, an appreciable understanding of the concept of separable programming would be necessary. As a way of bringing the reader to par, the theory of separable programming is captured under the broad umbrella of mathematical programming. Mathematical programming deals with the problem of optimizing that is minimizing or maximizing a function called the objective function subject to equality and or inequality constraints that are defined by functions called the constraint functions.

1.3 OVERVIEW OF OIL REFINERIES

A refinery is basically a factory that takes a raw material that is, crude oil and transform it into petrol and hundreds of other useful products. A typical large refinery costs billions of pounds to build and millions more to run and upgrade. It runs around the clock three hundred and sixty-five (365) days a year, employs hundreds of people and occupies as much land as several hundred football pitches.

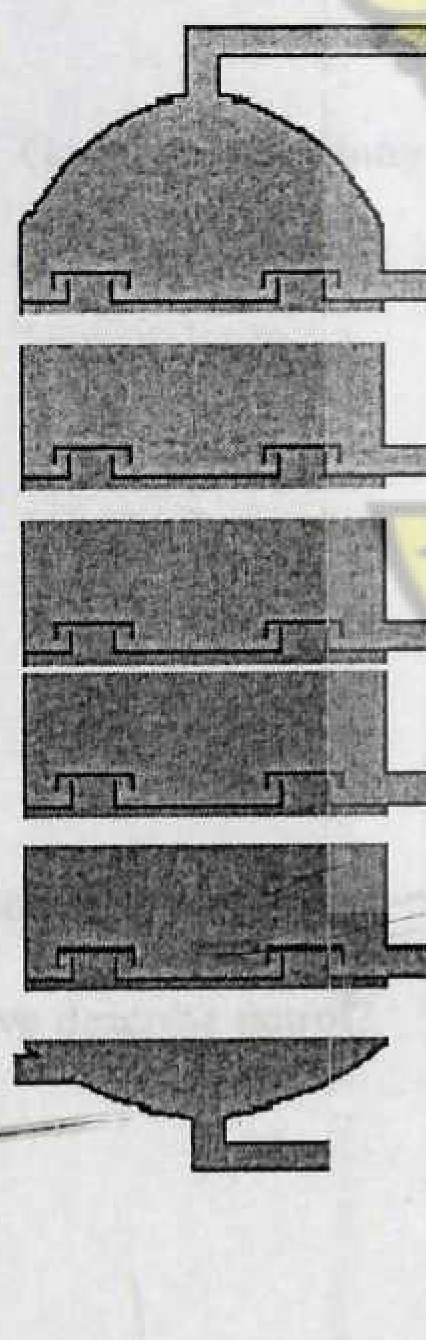
A refinery breaks down crude oil, coal, or natural gases into various components which then are selectively changed into new products including petrol, diesel, paraffin, kerosene. There are various processes involved which include heating and chemical reactions .This process takes place inside a maze of pipes and vessels. The refinery is normally operated from a highly automated control room.

All refineries perform three basic operational steps:

- Separation (fractional distillation)
- Conversion (cracking and rearranging the molecules)
- Treatment

1.3.1 Separation: fractional distillation

Modern separation involves piping crude oil through hot furnaces. The resulting liquids and vapours are passed into distillation towers:-



Hot crude»

FRACTION	Boiling Pt °C	Number of carbons	Uses
»Refinery gas		1-4	Bottled gas, fuels
»Petrol	40	~8	Fuel for cars
»Naptha	110	~10	Raw material for chemicals and plastics.
»Kerosine	180	~15	Fuel for Aeroplanes
»Diesel	250	~20	Fuel for cars and lorries
»Oils	340	~35	Fuel for Power Stations. Lubricants and grease
»Bitumen	400+	40+	Road surfacing.

Key highlights of the process are outlined below.

- It is important to realise that the column is **hot at the bottom** and **cool at the top.**

- The crude oil separates into fractions according to weight and boiling point.
- The lightest fractions, including petrol and liquid petroleum gas (LPG), vapourize and rise to the top of the tower.
- Kerosine (aviation fuel) and diesel oil, stay in the middle of the tower
- Heavier liquids separate lower down.
- The heaviest fractions with the highest boiling points settle at the very bottom.

The following table shows how the behaviour of the hydrocarbon molecules alter:

AT THE TOP OF THE COLUMN	AT THE BOTTOM OF THE COLUMN
• Short carbon chains	• Long carbon chains
• Light molecules	• Heavy molecules
• Low boiling points	• High boiling points
• Gases & very runny liquids	• Thick, viscous liquids
• Very volatile	• Low volatility
• Highly flammable	• Not very flammable
• Light colour	• Dark colour
Petrol comes off near the top of the column. Does the list above describe petrol?	Fuel oil comes off near the bottom of the column. Does the list above describe fuel oil?

The fractions are now ready for piping to the next areas within the refinery. Some fractions require very little additional processing. However, most molecules require much more processing to become high-value products.

1.3.2 Conversion: cracking and rearranging molecules

Some fractions from the distillation towers need to be transformed into new components. This is where a refinery makes money, because the low-value fractions that aren't in great demand can be converted to petrol and other useful chemicals.

The most widely used conversion method is called **cracking** because it uses heat and pressure to "crack" heavy hydrocarbon molecules into lighter ones. A cracking unit consists of one or more tall, thick-walled, reactors and a network of furnaces, heat exchangers and other vessels. Catalytic cracking, or "cat cracking," is the basic petrol-making process.

Using intense heat (about 600°C), low pressure and a powdered catalyst (a substance that speeds up a chemical reaction), the cat cracker can convert most of the heavy fractions into smaller more useful molecules.

Some refineries also have **cokers,** which use heat and moderate pressure to turn the really heavy fractions into lighter products and a hard, coal like substance that is used as an industrial fuel.

Cracking and coking are not the only forms of conversion. Other refinery processes, instead of splitting molecules, rearrange them to add value. **Alkylation** makes petrol components by combining some of the gaseous byproducts of cracking. The process, which essentially is cracking in reverse, takes place in a series of large, horizontal vessels.

Reforming uses heat, moderate pressure and catalysts to turn naphtha into high-octane petrol.

1.3.3 Treatment: The finishing touch

Today, a major portion of refining involves blending, purifying, fine-tuning and improving products to meet specific requirements. To make petrol, refinery workers carefully blend together a variety of hydrocarbons. Technicians also add performance additives and dyes that distinguish the various grades of fuel. By the time the petrol is pumped into a car it contains more than 200 hydrocarbons and additives.

Example: Petrol companies produce different blends of fuels to suit the weather. In winter, they put in more volatile hydrocarbons (with short carbon chains) and in summer they add less volatile hydrocarbons to compensate for the higher temperatures.

1.3.4 REFINERY PROBLEMS

There are two major categories of problems that oil refineries face. The first relates to problems that are external to the refinery. By this, consideration is given to the adverse effects to man and the environment that are as a result of the operations of oil refineries. Top on the list of this category is pollution. The chemical reactions that take place in oil refineries result in the emission of substances, most of which are harmful. Refineries throughout the world have come under pressure to reduce the amount of pollution they emit.

The Atmospheric Pollution Prevention Act, No 45 of 1965, is the main law governing air pollution. In terms of this Act, no one may operate a refinery without having a registration certificate (or permit) from DEAT. The permit sets a limit to the amount of pollution that the refinery is allowed to emit. If the refinery emits more than the permit allows it to, then it is breaking the law and can be punished.

Presently, South Africa refineries for example do not have to actually measure their air emissions but may simply estimate or calculate the amount they are emitting through their stacks according to the article Oil Refineries, your health and the environment; what you need to know. These estimates do not include fugitive emissions and very often pollution from fugitive emissions can by higher than the emissions coming out of the stacks.

However, there are many ways for a refinery to reduce the amount of pollution it causes. But, this usually requires the refinery to install some equipment, which the refinery companies do not want to spend money on reducing pollution unless they are forced to do so.

The second major category of refinery problems is the ones that are internal to the refinery. In other words this category of problems directly affects oil refineries. Top of this list is best described in the article Petroleum Refinery Planning and Optimization Using Linear Programming. According to Sahdev et all, The ultimate challenge a refinery faces is processing the crudes in the best possible manner and maximize the $/bbl (dollars per barrel) for the crude input.

The crudes often land at refinery sites as a mix of various crudes and various options of crude blending are evaluated before it is processed. Determining the "best possible" option is a very difficult task, as modern day refineries are built with complex processing schemes, having a combination of various technologies for heavy ends upgrading, product quality improvement, efficient fuel usage and controlling refinery emissions. The most common configuration includes catalytic cracking, hydro cracking and thermal cracking to maximize the bottom of the barrel. The other process technologies like catalytic reforming, hydro treating and sulfur recovery are a must to comply with stringent environment and product quality regulations.

1.4 HYPOTHESIS

The objective of this research is to examine how the use of separable programming can help address the problem of oil refineries. As the discussions above have shown, a major problem of oil refineries is the problem of coming up with the right mix of materials to be able to operate at optimum levels. It is for this reason the power of separable programming is been explored to bring about optimality.

For example, when we consider the fact that a step in refining crude oil into finished oil products involves a distillation process, and this distillation process further splits the crude into various streams. If the oil refinery is presented with three types of crude: say Blue light, Arabian heavy, and Super. These crudes are distilled into say light naphtha, intermediate naphtha, and heating oil. These are in turn blended into two types of say jet fuel. Jet fuel j_1 is made up of X% intermediate naphtha and Y% heating oil, and jet fuel j_2 is made up of X_1% light naphtha and Y_1% heating oil.

In the example above, the hypothesis would be that, could separable programming be used to effectively determine what amounts of the three crudes maximizes the profit from producing jet fuel (j_1, j_2).

Tema oil refinery would be the hypothetical oil refinery for the purpose of this study. Therefore, the premise for this study in relation to the above example is that separable programming could be used by Tema Oil Refinery to effectively determine the amounts of each input to combine in other to produce outputs that maximize profit subject to prevailing constraints.

The research methodology would throw more light on various inputs as well as the outputs of TOR's operations.

1.5 OBJECTIVE OF THE STUDY

This study generally aims to seek a mathematical model that maximizes the output of components used in the refinery of crude oil at the Tema Oil Refinery.

Specific Objectives

The specific objectives of the thesis are;

i. To assess the efficiency of refinery at the Tema Oil Refinery

ii. To develop a model that optimize production of petroleum products

iii. To make recommendations that will enhance the efficiency of Tema Oil Refinery

1.6 JUSTIFICATION

The emergence of oil refineries dates as far back as 1859 when "Colonel" Edwin L. Drake drilled the world's first working oil well in Titusville, Pennsylvania. Since the 1860s, the refinery processes have advanced beyond the basic distillation processes that had been in use and by 1913 refineries have developed thermal cracking, which was able to produce more gasoline and diesel from a barrel of oil. By 1930 thermal-cracking techniques have been improved and other catalytic processes have been developed to produce high-grade products (Arabe, 2003)

With the advancement in technology in refinery processes the bid to achieve the main objective of profit maximization becomes difficult. According to Gattu et al (2003), the refinery business and process optimization is complex and challenging. This is often characterized by uncertainties, large scope, complex equipment connectivity relationships and a large number of optimization handles. Refinery planning and optimization is mainly addressed through successive linear programming software like RPMS (Honeywell Hi-Spec Solutions), PIMS (Aspen Technology), and GRTMPS (Haverly Systems). (Gattu et al., 2003)

However, due to the non linear nature of refinery processes, there is the need to develop rigorous non linear process planning models which Gattu et al (2003). Alluded to the fact that such non linear model are recently been developed. Hence the essence of this study to examine how Separable Programming could be applied in solving the refinery process planning and optimization problem.

1.7 LIMITATIONS OF THE STUDY

The study covers the optimization problem of oil refinery companies in general. However, the study applied Separable Programming to Tema Oil Refinery (TOR) specifically. This is to examine the Process Planning Optimization of oil refineries with TOR as a case study. Therefore the study sourced information on the theory of Separable Programming as well as relevant information on TOR from books, the internet, periodicals and journals.

The study was however limited in the area of availability of information on the periodic production volumes of TOR as well as cost of books and journals on the subject matter.

1.8 ORGANIZATION OF THE THESIS

Chapter 1 of this thesis deals with the introduction including the objectives of the study. In Chapter 2 we shall put forward a comprehensive review of previous literature in this area of study both in the developed and developing world. This chapter presents the theoretical components of linear programming as well as empirical studies undertaken. Since the study is focusing on separable programming, the literature review concentrates on applicability of this methodology and a brief overview of other methods used in refineries.

Chapter 3 presents the methodology of the study. Chapter 4 presents the data collection and analysis. Chapter 5 which is the final chapter of the thesis then deals with the summary, conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.0 INTRODUCTION

Even though lots of studies have been conducted on how oil refineries can optimize production, much consideration has not been given to the use of separable programming. This can be associated to the fact that the refineries use available softwares to meet their optimization needs and these softwares are also largely based on linear programming. Sankaralingam (1987) confirmed this in his research by saying that Linear Programming is the most widely used Operational Research method for production scheduling problems. Therefore literature available to the study that relates to linear programming where the assumption is made of the linear nature of inputs products and processes of oil refineries are also considered as well.

Box (1965) in his research on "a new method of constrained optimization and a comparison with other methods," described a nonlinear programming problem that arose in his work, for which he described two new computational procedures. The problem was in fact linear except for the presence of four product terms. The interesting thing is that, problems of this nature could be solved by an extension of linear programming known as separable programming, and Box's problem was used by Akeroyd (2010) to illustrate this. The paper outlined the technique of separable programming and the interpolation procedure associated with it in the C-E-I-R mathematical programming code LP/90/94 for the IBM 7094 computer. The application of the technique to Box's problem was then described.

Crowder (1971) used separable programming technique in a production-distribution model designed for a study of closed Oklahoma diary economy. It is this basic model that was also employed by Kloth and Blakey(1971) in their research on the optimum Diary Plant Location with Economies of Size and Market-share restriction. The purpose of their study was to report the development of a fairly realistic model and its application to the diary industry of the United States. In view of this it assessed the effects on total cost and inter regional flow of milk under alternative degrees of market concentration when economies of size of processing plants (not requiring constant marginal processing costs) were permitted.

Kloth and Blakey(1971) specified three levels of market concentration. "Model A" permits only a single firm in each market, and references to this model was in terms of unrestricted plant size. "Model B" involves specific maximum relative sizes of plants for each markets. Generally two or more plants served each market, and references were made in terms of a restricted plant-size environment. "Model C" is an approximation of the existing plant-size environment but is estimated by a less sophisticated model using estimated average processing costs for each area.

The production-distribution model formulated by Martin (1972) was used as the beginning point for Model A and B. Separable programming is one of the technique for extending Martin's model to permit consideration of size economies and this is what was used by Crowder, Kloth and Blakey(1971).

Fresco (2010), reformulated the maximum expected covering location problem (MEXCLP) using a separable programming approach. The resulting formulation—nonlinear maximum expected covering location problem (NMEXCLP)—guaranteed optimality and also solves more quickly than previous heuristic approaches. NMEXCLP allows two important extensions. First, minor formulation changes allow the specification of the minimum number of times each node is to be covered in order to satisfy expected coverage criteria. Second, coverage matrices could be constructed that considered two different types of coverage simultaneously. Both extensions are useful for ambulance location problems and are demonstrated in that setting.

As mentioned earlier, Sankaralingam (1987) in his study of Underground Mining Machine Sequencing admitted that Linear Programming is the most widely used Operational Research method for production scheduling problems. An LP model basically consists of a linear objective function, a set of linear constraints and a set of non-negativity constraints. In production scheduling the objective function is often to optimize total profit, total cost, tonnage, cost/ton or other pertinent operating variables. Most mining operations attempt to maximize the total profits, but other variables such as shift tonnage or longwall tonnage could be maximized. Since the available resources are finite, the constraint expressions mathematically define the resource limitations. The final component, the non-negativity constraints, insures that the variables do not take on negative values. Since the variables normally represent production levels in a scheduling problem, this constraint simply matches the practical limitation that an operation cannot produce negative tonnages.

Wilke and Reimer (1979) proposed a method to optimize the short-term production schedule for an open-pit iron ore mining operation. Short-term production scheduling had to be a well balanced compromise, taking into account a great number of factors that influenced future development. They used an LP algorithm to obtain optimal short term production schedules. The Wilke and Reimer model is oriented toward an actual shift-to-shift production scheduling problem and consequently is a very simple formulation. Production scheduling models which consider long range effects could become quite complicated.

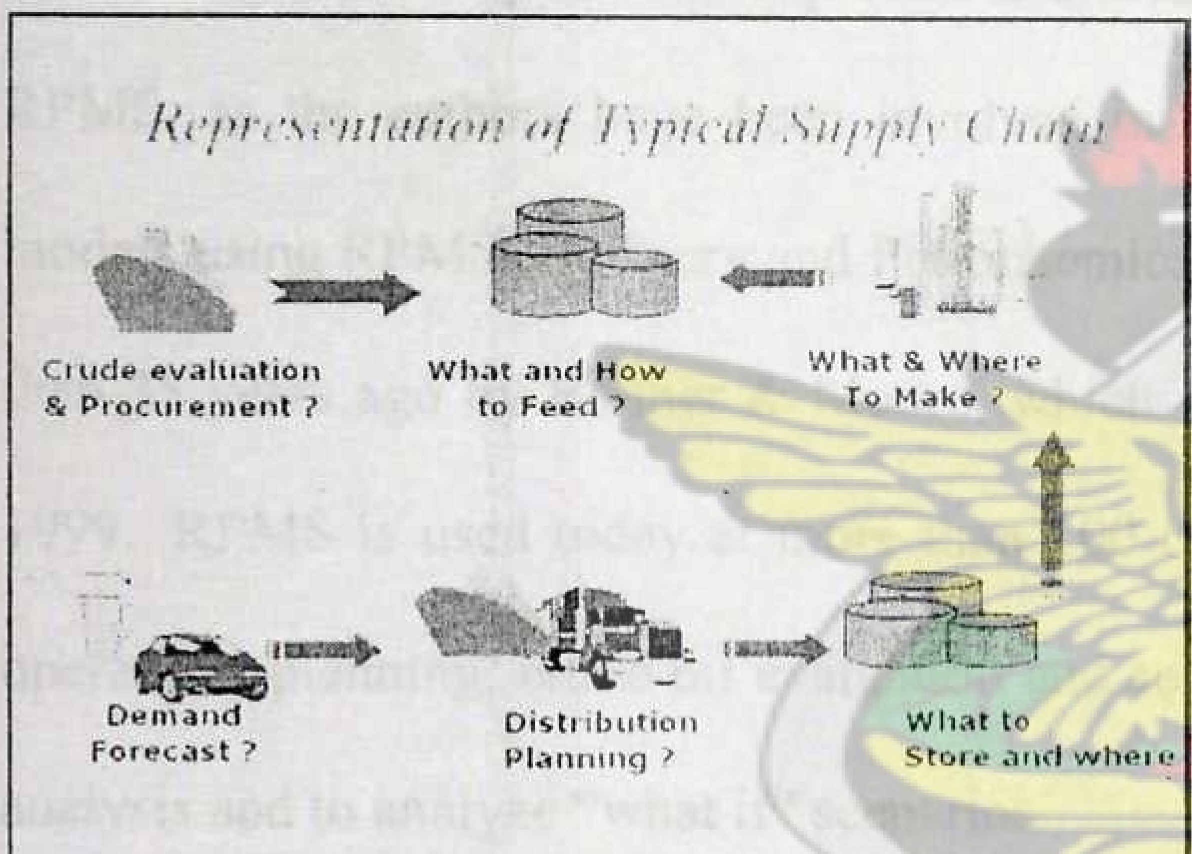
Vinas (1971) illustrated the use of linear programming for scheduling cut and fill, square set, and shrinkage stoping operations. The author used a LP model with an objective function formulation for maximizing profit. His work was purely theoretical and no application appears in the literature. Dessurealt and Galibolis (1973) formulated an interesting LP model for scheduling trucks in an open-pit mine. The objective of their model was to assign all trucks within the pit so that the cost of the operation is minimized Gershon (1982) has described a very general linear programming (LP) formulation for scheduling mining operations.

The assumption of linearity appears to be a serious impediment that limits the use of the LP model. In some cases, if the linearity constraint is relaxed, the problem can still be solved by using one of the several non-linear techniques such as quadratic programming or separable programming Sankaralingam (1987) pointed out.

Optimization techniques have challenged organizations to rethink the way they conduct business both internally and externally, i.e. how efficiently and effectively their entire supply chain is managed. Supply Chain Management (SCM) is one such business function that has benefited substantially from optimization software advances and solutions. The primary goal of SCM is to maximize profit by integrated management of material and transactional flows within a business and to customer and partner companies.

The petroleum refining industry has effectively embraced the software solutions to optimize the business supply chain to maximize the profit margins and create order in the chaos of numerous opportunities and challenges. The supply chain of a typical petroleum refining company involves a wide spectrum of activities, starting from crude purchase and crude transportation to refineries, refining operations, product transportation and finally delivering the product to the end user. The nature of the value chain is such that its economics are extremely complex and heavily linked (Refer to Figure 2.1). For example, the process of selecting the right crude is linked not only to the transportation costs involved in delivering it to the refinery, but it must take into consideration the refinery configuration, capabilities and constraints in converting the crude into products, as well as the product volume and price fluctuations. (http://www.cheresources.com/ Petroleum Refinery Planning and Optmization Using Linear Programming)

Figure 2.1: Typical Supply chain of Petroleum business



Software solutions based on Linear Programming (LP) technique have emerged as leaders among various mathematical optimization techniques available to optimize the entire supply chain from crude evaluation and selection, production planning and product logistic planning.

This review hopes to bring out how far the application of Linear Programming (LP) in refinery planning and optimization as a key component of the business supply chain has come.

The areas included in the review are outlined below.

- Petroleum Refinery: Complexity of operations and the need and scope of optimization
- Implementation of Linear Programming for refinery planning and optimization
- Experiences in implementation and usage of Linear Programming
- The bottom line

Refinery planning and optimization is mainly addressed through successive linear programming software like RPMS (Honeywell Hi-Spec Solutions), PIMS (Aspen Technology), and GRTMPS (Haverly Systems), while more rigorous non-linear planning models for refinery planning have been recently developed. The experiences discussed in the article by Sahdev et al (2010) pertain to RPMS, as the authors have been involved in the development and application of refinery LP models using RPMS (Refinery and Petrochemical Modeling System). RPMS was developed more than 35 years ago by Bonner & Moore, which was acquired by Honeywell Hi-Spec Solutions in 1999. RPMS is used today at more than 100 refineries and petrochemical plants worldwide for operations planning, crude oil evaluation and selection, inventory management, future investment analysis and to analyze "what if" scenarios.

2.1 COMPLEXITY OF REFINERY OPERATIONS

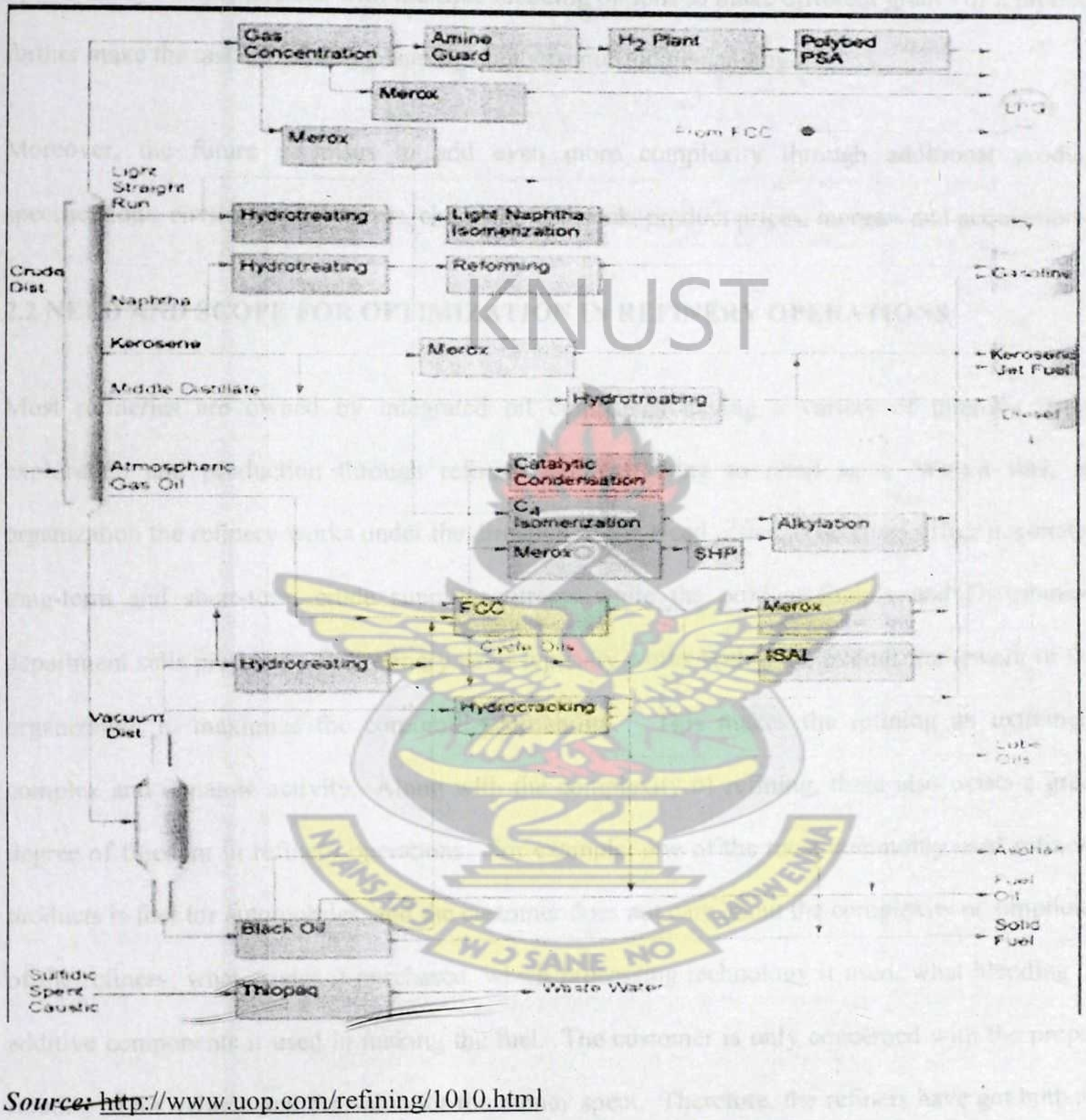
2.1.1 Crude selection

Modern petroleum refineries are designed to process a variety of indigenous and imported crudes. As the crude cost is about 90% of the refinery input cost, the selection of optimum crude mix is extremely important to achieve higher margins. However, the number of options for buying the crudes under a fluctuating price scenario and transporting them to refineries are so enormous that it is very difficult to evaluate all the crudes and decide on the optimum crude mix for the refinery. Refineries buy crudes both on term contracts with leading suppliers and also by spot purchases from the market. The optimum selection of term and spot crudes is extremely difficult when multiple refineries are involved and work in an integrated scenario.

2.1.2 Crude transportation

Once the crudes are selected and purchased, the focus is to optimize the transportation cost from the crude suppliers to refineries. The transportation cost can be minimized by considering the multiple options available for cargo sizes, sea routes, loading and unloading infrastructure facilities, taxes and duties, etc.

Figure 2: Process flow diagram of a modern refinery



Source: http://www.uop.com/refining/1010.html

2.1.3 Product demands

The product demands, quality and prices drive the entire crude processing and secondary unit operations. Multiple streams with multiple blending options to make different grades of a product further make the task of refinery planning cumbersome and demanding.

Moreover, the future promises to add even more complexity through additional product specifications, environmental norms, changing feedstock, product prices, mergers and acquisitions.

2.2 NEED AND SCOPE FOR OPTIMIZATION IN REFINERY OPERATIONS

Most refineries are owned by integrated oil companies having a variety of interests, from exploration and production through refining and marketing to retail sales. Within such an organization the refinery works under the direction of the Head office. The Head office negotiates long-term and short-term crude supply contracts while the product Supply and Distribution department sells products. The refinery itself typically works within the overall framework of the organization to maximize the corporate profitability. This makes the refining an extremely complex and dynamic activity. Along with the complexity of refining, there also exists a great degree of freedom in refinery operations. For example, one of the most commonly used refinery products is fuel for automobiles, and the customer does not care about the complexity or simplicity of the refinery, what crudes it purchased, which processing technology it used, what blending or additive components it used in making the fuel. The customer is only concerned with the proper running of his vehicle and the value for the money spent. Therefore, the refiners have got both an enormous complexity and considerable freedom to satisfy the customer requirement and make profit. This requires the optimization of multiple objectives in the refinery's business supply chain.

The table below provides a glimpse of the multiple objectives of refinery optimization:

Minimize crude landed cost at refinery
Optimize refinery crude mix
Optimize black oil generation and upgradation, optimize overall product mix and dispatch
Minimize quality giveaway
Optimize fuel consumption, minimize losses
Optimize utilization of the assets
Optimize inventory management
Optimize capacity utilization and shutdown planning
Optimize unit operations maintaining highest standards of safety, catalyst life and activity, etc.

All of the objectives mentioned above present a refinery with a challenging problem and an opportunity to maximize the overall profitability.

In a nutshell, the need and scope for optimization is so vast in a refinery that it is essential to use software tools not only to arrive at the best plan, but also to quickly evaluate the new optimum with internal or external changes in the business scenario. However, in today's refinery environment, data acquisition, simulation and optimization tools often reside in "silos" in different groups across the refinery. This results in various local and plant-level optimizations only, not the most profitable refinery-wide optimization. A holistic view via an integrated model of the refinery is required to give refinery planners the ability to evaluate opportunities optimally, accurately and quickly.

2.3 MEANING OF OPTIMIZATION AND LINEAR PROGRAMMING

Optimization means "the action of finding the best solution within the given constraints and flexibilities." Linear Programming (LP) is a mathematical technique for finding the maximum value of some equation subject to stated linear constraints. It is commonly used in refinery planning to identify with confidence the most profitable refinery-wide operating strategy.

LP has been around since the 1940s and has now reached a very high level of advancement with the meteoric rise in computing power. The "linear" in LP stands for the algebraic aspect, i.e. all the constraints and objective functions are linear and satisfy two fundamental properties: proportionality and additivity. The "programming" in LP actually means "planning" only. The implementation of LP involves the development of an integrated LP model representing the refinery operations with all constraints and flexibilities and then solving it to determine the optimum plan.

The refinery-wide optimization using an LP model has been proven to bring economic gains far higher than unit-specific simulation models or advance process control techniques.

In short, the LP model is an excellent economic evaluation tool to drive the entire supply chain toward higher profit.

Some of the key areas for LP applications in the oil industry are:

- Grassroots refinery design/configuration
- Selection and evaluation of crude oils and raw materials
- Long-range and short-term operations planning
- Capital investments evaluation for process equipment

- Analysis of the profitability of merging and acquisition plans and the creation of ad-hoc models for joint venture refineries
- Evaluation of processing agreements and product exchange contracts
- Evaluation of new process technologies
- Control of the refinery performance
- Product blending control
- Down-time planning
- Inventory management

2.4 TRADITIONAL LIMITATIONS AND LATEST ADVANCES IN LP

The LP modeling has changed substantially. The static yield-driven models with fixed stream properties have now been replaced by variable property-driven models using latest non-linear distributive recursion techniques. Swing cuts for cut-point optimization have been semi-automated using implicit pooling techniques. Multi-period and multi-refinery modeling capabilities have been enhanced. The linkage of crude assay data into the LP assay tables has been enhanced and automated. Process unit representations have changed from multiple "mode" type yield structures to base-delta vector yield representations.

In a nutshell, current LP systems offer embedded process simulation and other non-linear representation capabilities to provide even more accuracy and realism for refinery LP representations. The LP technique is far superior when compared to any Excel programs traditionally used for planning. However, it is worthwhile to keep in mind certain limitations of LP in order to appreciate the LP solutions:

1. **Non-linear nature of refinery processes:** The nature of the refining processes is mainly non-linear whereas linear programming - as the name already suggests - assumes that a linear combination of the provided options is valid. RPMS uses a specialized recursion technique called Successive Linear Programming (SLP) for modeling and solving non-linear problems. For most of these, engineers have developed "linear blend indices," which transform the measured qualities into index values, which can be constrained using ordinary linear constraints.

2. **Data overload:** While developing the model, providing all the possible processing options is impossible. Increasing the number of variables and constraints increases the efforts to maintain the database and the difficulty to maintain the required data consistency. It also reduces the system's transparency, therefore increasing the chances of big errors in data and logic. RPMS has a powerful interface with Excel and tools like Fast Data Import, model comparison, etc. to minimize the data errors.

3. **LP does not consider the elements of time and storage:** It assumes that all activities occur simultaneously and that all identified components are separately available for further processing or blending (like there are separate tanks available for all individual components).

A refinery may process HS and LS crudes in a blocked-out fashion, whereas an LP model mixes HS and LS crudes simultaneously. This limitation is addressed by reducing the time bucket while making the plan and using multi-period models. Weekly planning methodology can be used for making plans closer to actual operations and address scheduling issues.

4. **LP exercises no judgment**: One point must always be remembered: "LP Models are just as good as the data put in and the assumptions used to create them. Models should not replace good and sound engineering judgment." The LP requires quality input data in order to provide workable and practical solutions. Yield and property data are based on plant measurements and rule-of-thumb calculations or estimations. Pricing data used is often based on the statistical average of past months or years. Based on the input data only, the LP model solves the problem and it exercises no judgment. A small change in one piece of data may result in a completely different solution, and will ignore all uncertainties and risks to achieve just a minor increase in profits. This problem has been tackled by sensitivity analysis where many cases can be run using Model Modifier (MMOD)-feature of RPMS and arriving at practical and implement-able solutions.

2.5 EXPERIENCES AND BENEFITS

- **Building a refinery LP model is not a trivial exercise**. It needs clear understanding of the entire web of refinery operations and the compilation of good quality data. The model development activity is very time consuming and can take about a year for developing a good and robust model. The following important points need to be kept in mind while building the model:
    - Make sure that the crude cut strategy represents accurately the qualities (and variations) of the cuts that are critical for a site. For example, if there are issues concerning distillate 95% point or CCR values, characterize your crude cuts very thinly around the heavy gas oil/atmospheric residue cut (typically in the 330 - 390C range).
    - Obtain good representation of unit operating modes and parameters from process models. As the LP cannot work with non-linear correlations, there is a need to

linearize the non-linear behavior of process units by introducing several linear "vectors." These vectors can be generated through sound refinery process models (e.g. KBC Profimatics FCC-SIM for the FCC, REF-SIM for a reformer, etc.) for different feeds/crudes, operating conditions (severities, conversion, etc.), etc.

  - Ensure that the model has sufficient flexibility to generate feasible solutions in the first place. It is easier to start with a fairly "loose" model, which can be subsequently tightened.

- **Interpretation of LP Output:** The task of analyzing the LP output is not a simple exercise, mainly due to the limitations of the technique and the complexity of its output. It requires sustained effort in generating and analyzing the various feasible and optimum solutions and rigorous sensitivity analysis.
- **Computation Time:** Today, we solve substantially more complex LP problems in mere seconds on our desktop PCs. The running time limitations have lost much of their relevancy with the availability of desktop PCs with higher computing power. For example, solving four-period models takes only about two to three minutes on a Pentium-IV and 256 MB RAM PC.

2.6 BENEFITS OF LP IN REFINERY PLANNING

LP works on the principles of pure mathematics and Petroleum Refining is more complex than the mathematics that describes it. With all the approximations and uncertainty we should not expect or even desire a "true mathematical optimum." LP should be viewed only as a mathematical optimization technique, or as a convenient method to obtain a feasible and economic plan for the supply, processing and logistic activities of a petroleum complex, together with a description of its driving forces and constraints. In day-to-day working, an LP solution helps in achieving two key practical aspects:

- It facilitates in the decision-making process by keeping the focus on profit under any scenario
- It provides the targets and operating strategies for the actual operation

LP does much more than planning for the future. LP refinery models always challenge the people and their deep-rooted rule-of-thumb approach in the refinery operations. The implementation of LP models often creates awareness among executives and management about the profit factor. LP-based planning can provide potential benefits to the tune of 15-20 cents/bbl. One of the major advantages of LP programming is that it acts as a watch dog for the refinery operations – always asking for more, the LP model helps in identifying the bottlenecks in processing more crude and directs in achieving the benchmark for operation. It clearly tells the inefficiency of operations in terms of money, and that's where it is very close to management's heart.

The LP solution has not only enabled arriving at a better plan, but has also provided many valuable insights for optimizing unit operations, crude mix and product blending. The other most important benefit realized is it quantifies the impact of a change in a variable on overall refinery profitability. As a tool, RPMS provides answers to the typical questions that refinery management asks for faster decision making, including: What is optimum HS-LS crude mix?, How to maximize distillate yield and minimize the fuel & loss?, What products to be maximized?, Which units to be run and what capacity levels?, When to plan unit shutdowns?, etc.

2.7 KEY TO SUCCESSFUL IMPLEMENTATION OF LP IN REFINERY PLANNING

The output from an LP model gives us an optimal plan. In practice, the real benefit comes from implementation of the strategies and guidelines from the model. Implementing all of the LP solutions in a refinery is a difficult task. Product pricing and unit constraints often change weekly, but changing unit operating philosophy and addressing hardware constraints take time to accomplish. Even after the steps for improving optimal performance have been identified and implemented, if the pressure to improve is removed, operation tends to return to the older, more comfortable routine. The LP optimization group must continue to stress the potential savings while improving the operations until the savings are achieved.

The key to the successful implementation of LP in refinery planning is an integrated approach that addresses the following issues:

- **Regular Model updates and maintenance:** There is one human tendency of giving maximum care and attention to the thing which is very valuable or important to him. The same tendency should be kept alive for LP models, as these models provide the decision-making power (involving large amounts of money), money-related policies and future action plans. The models are continuously interacting with inside constraints and outside changes (price and product demands), making them dynamic in nature. All of these factors imply that the maintenance of these models should be carried out as regularly as possible. The type of updates can be a reduction in the yield of unit, change of catalyst, property change of secondary stream, energy consumption reduction due to application of energy conservation suggestion, etc.

1. **Integrated application of different software solutions:** Refineries use a number of stand-alone software solutions like Automation Blenders, Online analyzers and sensors, APC, Scheduling software, Simulation software, RTDBMS for optimization of operations. There is a strong need to integrate the working of such software to create the maximum benefit by bringing the operations and blending close to the LP output.

- **Clear and well documented planning procedures:** There are no two opinions on using LP based software for planning. The real problem of using the LP for economic decision-making is how to interpret the LP results and how to use it for decision-making. The planning tool needs to be backed by clear cut and systematic planning procedures. The entire planning process should be carried out under the overall supervision and guidance of top management group in an integrated way. The procedures for the four key functions of plan preparation, plan implementation, plan monitoring and "what-if" case studies must be in place and working to enable the success of LP optimization.

2.8 SUMMARY

Petroleum refining in the new millennium will continue to be an extremely competitive business. The application of LP methodology has shown potential margin benefits of 15-20 cents/bbl for the refineries.

The bottom line is that experienced people are the key to success: software and computers, no matter how powerful and quick, are not the substitutes for understanding and optimizing the refinery business. However, LP technique has provided an efficient and effective method to quickly evaluate and quantify the impact of internal and external changes on overall refinery profitability

CHAPTER 3

METHODOLOGY

3.0 BRIEF INTRODUCTION TO SEPARABLE PROGRAMMING

Further in the preface to his book, Separable Programming; Theory and Methods, Stefan Stefanov defined separable programming as a branch of mathematical programming where the objective function and the constraint functions can be expressed as the sum of single –variable functions. Such functions are said to be separable.

"Any Non-Linear Program (NLP) in which all the nonlinear terms are just functions of single variables is called a separable program and the method of linear approximation is sometimes called separable programming." Beasley (1998)

There is also one important case of separable programming that needs to be quickly mentioned. This is called convex separable programming. It is where the objective function and the constraint functions are convex. Convex functions have many special properties, for example, any local minimum of a convex function over a convex set is also a global minimum, and optimality criteria for convex programs are both necessary and sufficient conditions.

It is possible to approximate the original separable problem by a linear program where a simplex method with the restricted basis entry rule is used to solve the resulting linear program. However, due to convexity, linear programs that approximate convex separable problems can be solved by a standard simplex method, discarding the restricted basis entry rule.

Because the original separable problem is solved by solving the approximate problem, methods employing this approach are approximate. Therefore error estimations are made with regards to the approximating procedure for the convex separable problems.

3.1 MATHEMATICAL DEFINITION

Below is a demonstration of the mathematical definition of separable programming.

Consider a general *NLP*

$\min f(x)$

$s.t.\ g_i(x) \leq b_i,\ \ i = 1, \dots, m.$

Definition 3.1.0

The *NLP* is a separable program if its objective function and all constraints are

consisted of separable functions, i.e.

$$f(x) = \sum_{j=1}^{n} f_j(x_j), \qquad \text{and} \qquad \sum_{j=1}^{n} g_{ij}(x_j) \leq b_i, \quad i = 1, \dots, m;$$

and all x_j are non-negative variables bounded above, i.e., $0 \leq x_j \leq \mu_j$ for some $\mu_j, j = 1, \dots, n$.

The technique *separable programming* basically replaces all separable functions, in objectives and constraints, by piecewise linear functions. Here we further only consider convex functions f_j and g_{ij}.

Definition 3.1.1

A *convex program* is an *NLP* that minimizes a convex function or maximizes a concave function over a convex set.

From the definitions above the following deduction are made;

(i) Any (continuous) convex function can be approximated to any degree of accuracy by a piecewise linear convex function.

Therefore with reference (i) to above, when f_j and g_{ij} are convex functions, they can be approximated to any degree of accuracy by piecewise linear functions. Eventually, such an NLP of piecewise convex functions can be represented by a linear program (LP). Thus, effectively a separable convex program can be approximated by a sequence of LPs to any degree of accuracy.

It is also noteworthy that when f_j and g_{ij} are convex, a local minimum is in fact a global minimum.

Find an illustration by example with a diagram below;

NLP1 is

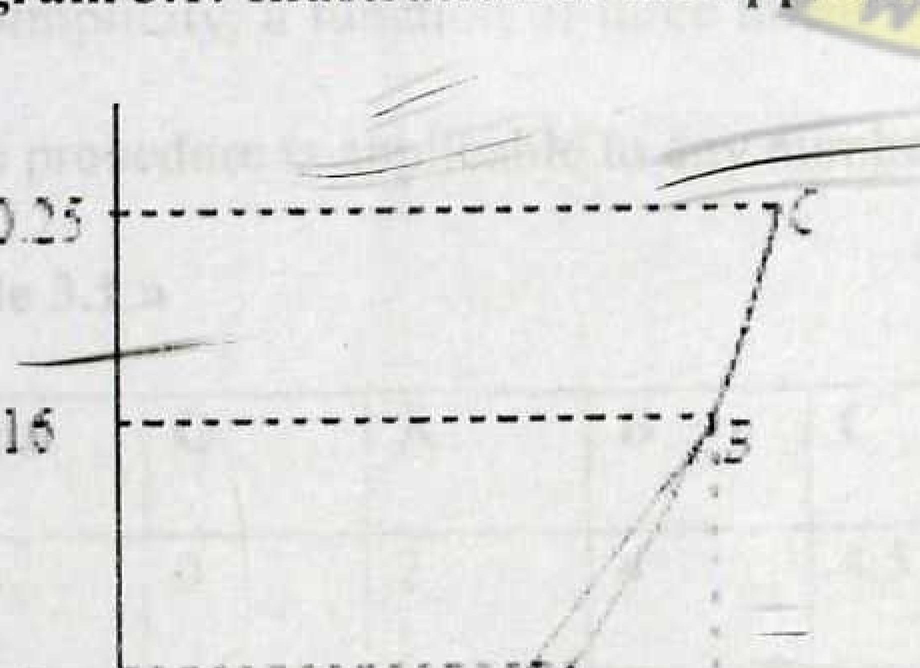
Min $\quad x_1^2 - 2x_1 - x_2$

s.t $\quad x_1 + 2x_2 \leq 5,$

$\quad 2x_1 + x_2 \leq 9,$

$\quad x_1, x_2 \geq 0.$

Diagram 3.1: Illustration of the approximation of a non-linear function



The above is a separable program with

$f_1(x_1) = x_1^2 - 2x_1$

And

$f_2(x_2) = -x_2$. f_2 is linear.

The problem is easy to solve if

f_1, i.e., x_1^2

is approximated by a linear function.

From the constraint, $x_1 \leq 4.5$. The non-linear function $y = x_1^2$ is approximated by a piecewise linear function.

For simplicity, a function of three linear pieces is taken, with break points at 0, 2, 4, and 4.5. The same procedure is applicable to any number of break points at any values.

Table 3.1.a

Points	O	A	B	C
x_1	0	2	4	4.5
y	0	4	16	20.25

There are two ways, the λ- and the δ-forms, to represent the function in piecewise linear form.

λ-form: For any point within a linear segment, its functional value is the convex combination of the values of the two break points of the linear segment. Let $\lambda_i \geq 0$ be the weight of break point i, $i = O, A, B$, and C.

$$\begin{cases} x_1 = 0\lambda_O + 2\lambda_A + 4\lambda_B + 4.5\lambda_C, & (1) \\ y = 0\lambda_O + 4\lambda_A + 16\lambda_B + 20.25\lambda_C, & (2) \\ \lambda_O + \lambda_A + \lambda_B + \lambda_C = 1, & (3) \end{cases}$$

at most two adjacent λ_i take non - zero values. (4)

Now **NLP1** is reformulated into **NLP2**

min $y - 2x_1 - x_2$

s.t. $x_1 + 2x_2 \leq 5$,

$2x_1 + x_2 \leq 9$,

(1), (2), (3), and (4),

$x_1, x_2, \lambda_i, i = O, A, B, C \geq 0$.

Constraints (4) can be omitted if **NLP 1** is a convex program. Check that whenever (4) is violated by a set of λ_i, the value of the corresponding y is above the three-piece linear function, and hence the set of λ_i cannot be a minimum point.

In general, if the NLP is a non-convex program, constraints (4) are needed though they are implemented implicitly through the separable programming extension of the simplex method.

The pivoting step of the separable programming extension simply ensures that at any time at most two adjacent λ_i are in the basis. It can be shown that such a restricted basis rule will lead to the optimum solution.

In general, if the NLP is a non-convex program, constraints (4) are needed, though they are implemented implicitly through the separable programming extension of the simplex method. The pivoting step of the separable programming extension simply ensures that at any time at most two adjacent λ_i are in the basis. It can be shown that such a restricted basis rule will lead to the optimum solution.

The idea of separable program is applicable to non-convex programs. Of course, in those cases, the optimum solution can be a local rather than global optimum.

δ-form: Instead of taking weighted value of break points, we can add up the contribution from each linear segment. Let δ_i be the proportion of the ith segment taken, $i = OA, AB, BC$.

$$\begin{cases} x_1 = 2\delta_{OA} + 2\delta_{AB} + 0.5\delta_{BC}, \\ y = 4\delta_{OA} + 12\delta_{AB} + 4.25\delta_{BC}, \\ 0 \le \delta_{OA}, \delta_{AB}, \delta_{BC} \le 1, \\ there\ exist\ \delta_j > 0\ such\ that\ \delta_i = 1\ for\ i < j\ and\ \delta_i = 0\ for\ i > j. \end{cases}$$

As for the λ-form, the δ-form may also give a local optimum if the original program is non-convex. When the original program is convex, constraint (8) is not necessary.

Below are few remarks about the above discussions;

(1) To get more accurate result, the piecewise linear approximation of f_1 can be refined with more linear segments. There are studies on segment refinement to get the best tradeoff between accuracy and computational effort.

(2) It is possible to approximate constraints by similar procedure.

(3) A product term x_1x_2 can be transformed to separable form by letting

$s_1 = (x_1+x_2)/2$ and $s_2 = (x_1-x_2)/2$. Then $x_1x_2 = s_1^2 - s_2^2$.

3.2 IMPLEMENTATION OF LP FOR REFINERY PLANNING AND OPTIMIZATION

Refinery planning forms the foundation for the business decisions that have the biggest impact on refinery profitability.

A refinery typically prepares the following types of plans:

- **Annual plans** for annual budgeting, term crude contracts and maintenance shutdown planning
- **Monthly rolling plans** for spot crude purchases and conducting refinery operations inline with product demands
- **Weekly plans** for finding operating strategies for units at the weekly level, i.e. the refinery knows precisely which crudes it has and must decide which crude cocktails to run, how long to do so and how it is going to meet any particularly large or difficult product demands
- **Strategic plans** for future years and expansion projects

- **Profitability improvement plans** for plant -level modifications and revamp projects

The preparation of any of the above types of plans requires a set of standard procedures and an LP model customized for the refinery configuration.

3.2.1 Development of a refinery LP model

Development of a refinery planning LP model primarily involves customization of commercially available LP modeling software to refinery configuration. The table below provides a list of major suppliers and the LP software.

Supplier	LP Software
Honeywell Hi-Spec Solutions	RPMS – Refinery & Petrochemical Modeling System
Aspentech	PIMS – Process Industry Modeling System
Haverly	GRMPTS

Development of a refinery LP model is an arduous task that demands sound, accurate and complete understanding of the refining process and planning functions. It requires compilation of enormous plant data and meticulous documentation of the same.

Major steps in the development of a refinery LP model

Some of the major steps involved in the development of a refinery LP model include:

- Mapping of the existing planning process and data collection

- Development of a future planning process inline with best practices
- Finalization of Functional and Design Specifications (FDS) for the refinery LP model building, software and hardware configuration
- Refinery model building as per FDS
- Factory acceptance test of refinery model
- Tuning of model at site and trial usage for planning and case studies
- Site acceptance test of the refinery LP model

The list of steps mentioned is not exhaustive and requires micro-level activity planning. The role of an LP consultant is very important as he has to balance the needs of the refinery planner and the intricacies involved in modeling each constraint and options. Initially, it is better to keep the model simple and understand its behavior. The complexities must be added gradually, keeping in mind what economic impact they have on refinery profitability.

3.2.2 Description of a refinery LP model

A good LP model is one that closely represents the operational reality of a refinery. A typical refinery LP model contains the end-to-end configuration of the refinery with a detailed representation of primary and secondary processing units, blending facilities, power and utilities. A model contains structural data, or fixed data, which represents the physical reality concerned, and variable data, which expresses the contingency of the particular problem. The addition of variable data like costs, prices, raw materials availabilities and products requests, process unit's capacities and product quality specifications enables the model to set up a problem, from which infinite variant cases can be created and run to arrive at the optimal plan.

Mathematically, an LP model consists of a matrix, while for the users it can be better thought of as a set of data tables necessary and sufficient for the automatic matrix generation. A typical refinery model represents an LP matrix with 1,500 rows, 3,500 columns, 1,500 equations, 1,500 constraints and 5,000 variables. The LP software uses different optimizers like MOPS, XPRESS, OSL, etc. to solve the matrix. RPMS uses the state-of-the-art XPRESS optimizer software licensed from Dash Associates.

The model can have different time period variants to meet different planning objectives associated with Annual Planning (1X4 quarter), Quarterly Planning (1X3 months) and Monthly Planning (1X4 weeks).

Some of the key features of a refinery LP model include:

Objective function in an LP model

A refinery LP model is generally configured with a single objective function of maximizing the profit as explained below:

- To maximize {∑ (Product value) - ∑ (Raw Material cost) - ∑ (Refinery Variable Costs), subject to the various constraints defined in the model including the inventory value and carrying cost parameters.

Modeling techniques and optimization features

A refinery LP model contains modeling capabilities like Successive Linear Programming (SLP), Mixed integer programming (MIP), Implicit and Explicit Pooling, Multi-period modeling, Distributive property recursion, attribute error tracking, rigorous sulfur distribution, etc.

Compared to an approach based on average values, these techniques provide very accurate estimates of yields and qualities of finished goods, all the while keeping short computation times.

Additional information can be obtained by referring to standard books on LP to understand the meaning of the LP terms used above. A good reference book is Operations Research, 7th Edition by Hamdy A. Taha, Univ. of Arkansas, and Fayetteville.

The refinery LP models use latest unit modeling techniques like swing cut modeling, delta vector modeling and mode wise modeling.

The crude and vacuum unit is modeled based on the stream TBP (True Boiling Point) cut point scheme. The crude assay manager software like ASSAY2, PASSMAN uses TBP cuts and the TBP curve of the crude oils from the various crude assay database for generating the crude wise yields and properties. It is possible to model the single physical crude unit into several logical units depending refinery specific requirement. For example, a refinery processing high sulfur (HS) and low sulfur (LS) crudes in blocked out operation can be modeled with two logical unit one for HS and another for LS crude operation.

The secondary units are modeled using delta-yield vector or mode wise yield vectors. For example, the catalytic cracker is generally modeled by setting up base yield vectors with yield controlling delta vectors for Feed UOP K, MeABP and Severity/Conversion. The static input data for determination of delta vectors can be generated from kinetic models, test runs and standard correlations. Relevant capacity and quality constraints on the feed and product side are configured. All possible blending options for unit feed and products are configured. Unit wise steam, power, fuel consumption and catalyst consumption are also built in. The rigorous recursion structure for feed and product stream properties is set up. For example, sulfur in cat cracker streams is recalculated on the basis of feed sulfur changes.

Model Input

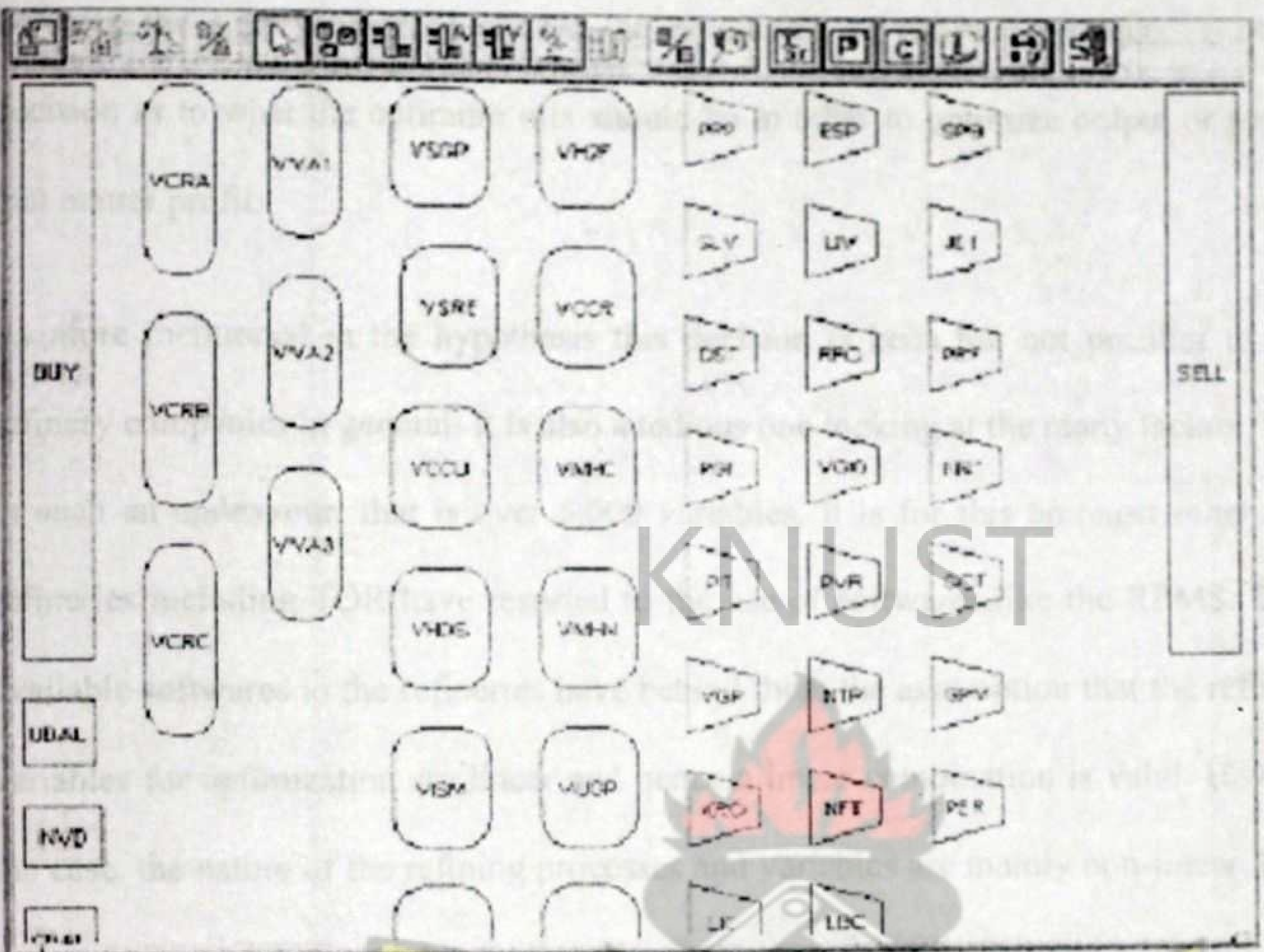
Once all the static data is configured, the model is updated with the variable data in model for solving a particular problem. The common variable data required includes:

- Crude oil or any other raw material prices and minimum and maximum availability
- Selling prices and minimum and maximum demands for the different finished goods
- Available process unit capacities
- Available Inventory stocks and minimum and maximum storage limits
- Quality specifications, etc.

User Interface

LP software commercially available today is highly advanced with features to provide a maximum user-friendly experience. RPMS has a powerful Graphical User Interface (GUI), which provides a highly effective and intuitive interface for working with the model. It contains a model navigation window with graphical objects. The graphical objects contain information on Charge Yields, Feeds, Products, Results, etc. Data and Report factory is an integrated application of RPMS for input of static and variable data and generating standard reports in Excel (Fig. 3.0 provides a glimpse of a GUI for a refinery LP model).

Figure 3: RPMS GUI



Model Output

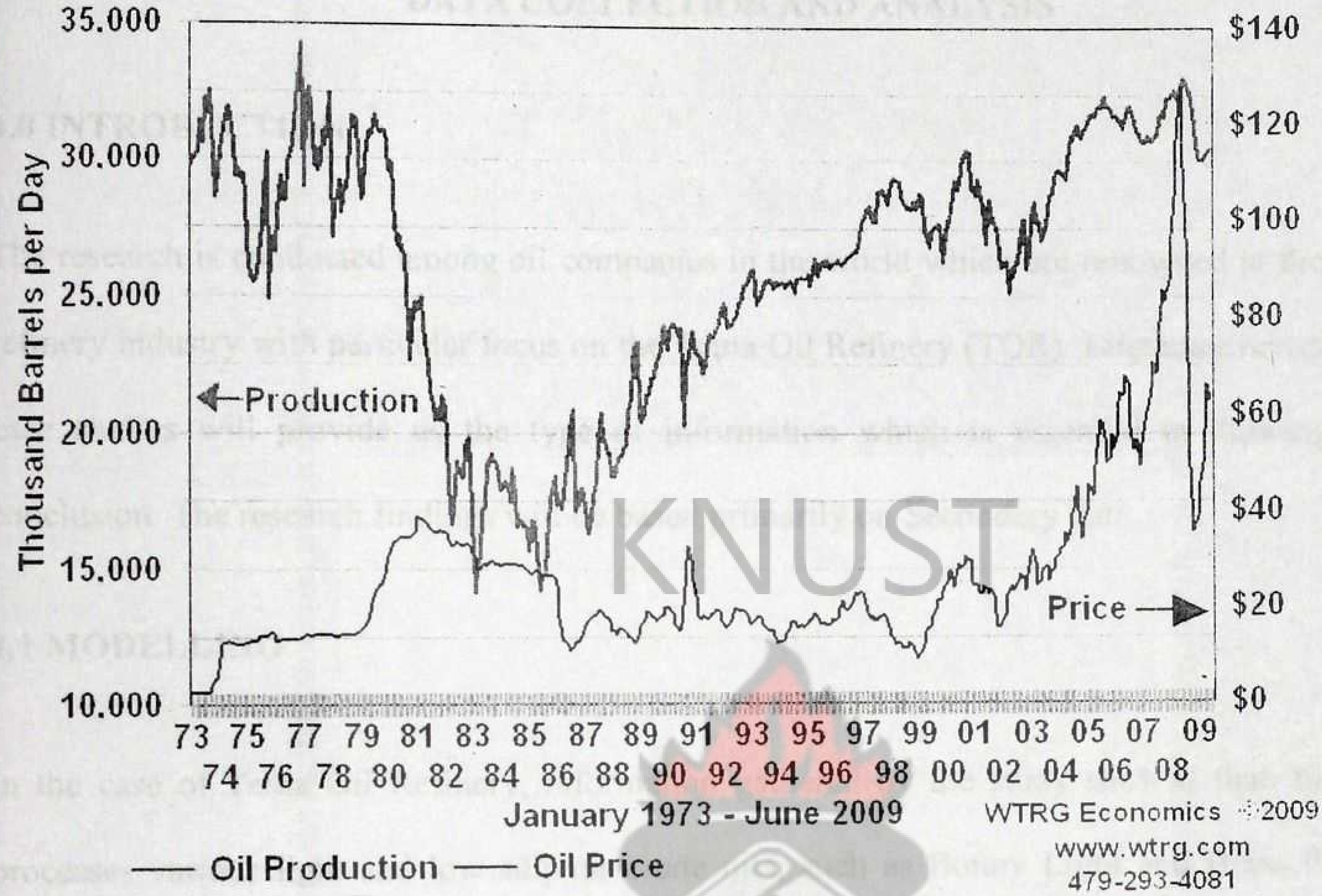
The LP matrix generator transforms the input data into a great number of equations and variables. The LP optimization algorithm solves the matrix and calculates which combination of supply, processing, blending and selling activities gives the highest margin. The LP reporting system reports this optimal combination of activities, together with the financial results. The output is generated in the form of different types of text and Excel files. RPMS has a powerful report factory utility for generating various customized Excel reports. The reports contain detail output with respect to crudes quantities, product numbers, capacity utilization, power, utilities and chemical consumption levels. The outputs also provide valuable information like reduced cost, pi values, DJ values, etc.

3.3 SEPARABLE PROGRAMMING APPLIED TO TOR

Between the supply of crude oil and the production of finished products, TOR has to make a decision as to what the optimum mix should be in other to optimize output or production and for that matter profit.

As afore mentioned in the hypothesis this decision is keen but not peculiar to TOR, rather oil refinery companies in general. It is also a tedious one looking at the many factors that come to play in such an endeavour, that is over 5,000 variables. It is for this amongst other reasons why oil refineries including TOR have resorted to the use of softwares like the RPMS. These commonly available softwares to the refineries have behind them the assumption that the refinery process and variables for optimization are linear and hence a linear combination is valid. However, this is not the case, the nature of the refining processes and variables are mainly non-linear. For example, the main raw material or variable in the oil refining process which is the crude oil has a non-linear distribution. Crude oil prices behave much as any other commodity with wide price swings in times of shortage or oversupply, (WTRG Economics' Energy Economist Newsletter). Figure 4.a below confirms the assertion of the nature of crude oil. Therefore, the need to use separable programming as modeling tool for oil refineries cannot be over emphasized, TOR not being an exception.

Figure 3.3: Crude oil production (Mbbl/d) and prices for OPEC Countries



CHAPTER 4

DATA COLLECTION AND ANALYSIS

4.0 INTRODUCTION

The research is conducted among oil companies in the world which are renowned in the crude oil refinery industry with particular focus on the Tema Oil Refinery (TOR). Literature review and real case studies will provide us the type of information which is essential in drawing realistic conclusion. The research findings will be based primarily on Secondary data.

4.1 MODELLING

In the case of Tema Oil Refinery, information gathered by the study showed that, the refinery processes various light and low sulphur crude oils, such as Bonny Light and Brass River from Nigeria, and Palanca Blend from Angola. However, for the purpose of this study, we would consider Bonny Light (B_L) and Brass River (B_R) crude oil as the two main crudes to be fed to refineries plant. These crudes are then passed through a distillation process in the Crude Distillation Unit (CDU) that spits them into various streams. In the distillation process, electrical energy, steam, sulphur and water among other utilities are applied.

Low valued residual fuel oil from the CDU is then converted into high valued products of LPG and gasoline in the Residual Fluid Catalytic Cracking unit. The resulting products of the refining processes are liquefied petroleum gas, gasoline, illuminating and cooking kerosene, aviation turbine kerosene, gasoil or diesel and residual fuel oil.

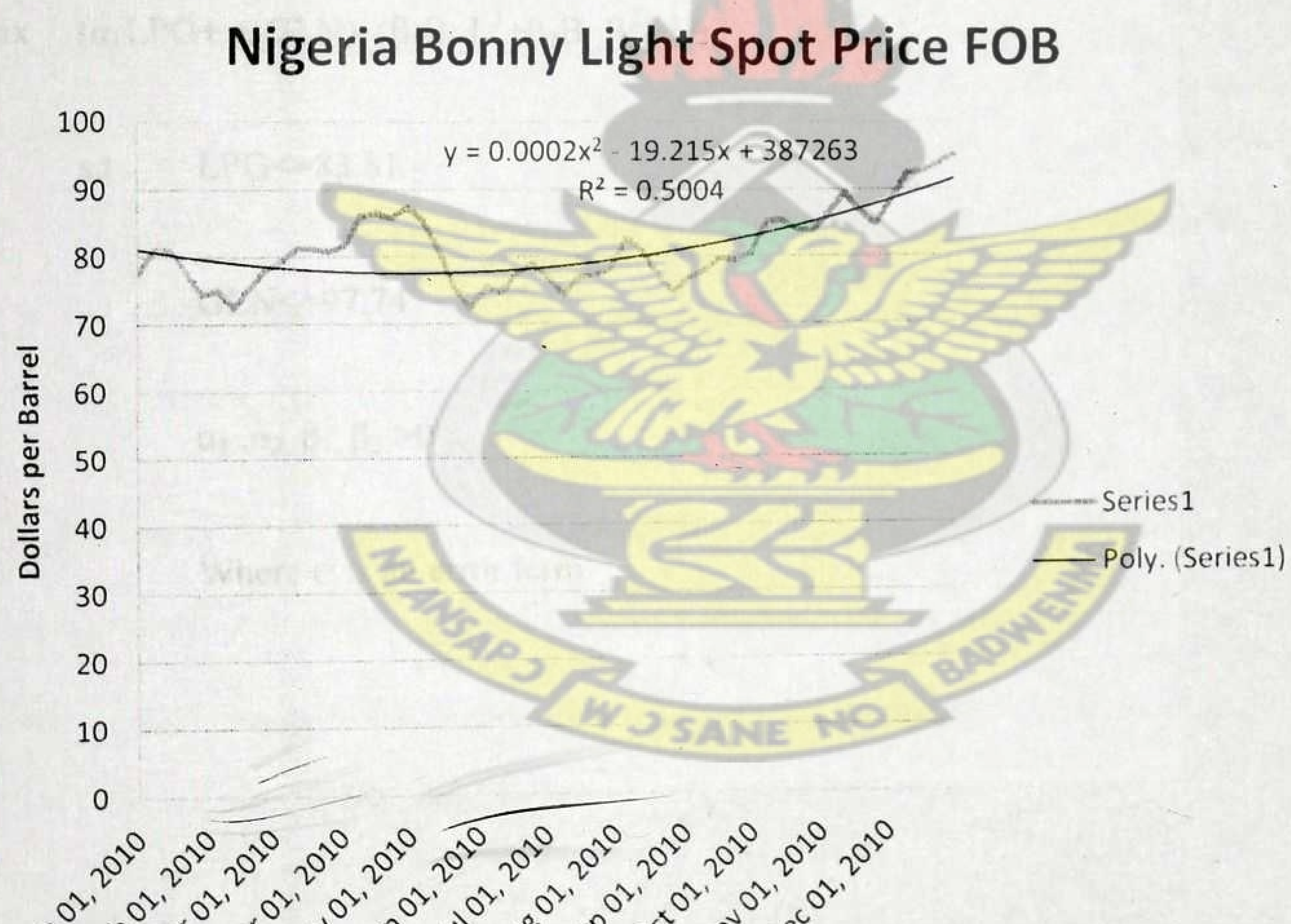
From the foregoing the study would be skewed on providing a suitable model to determine what amounts of the two crudes maximizes the profit from producing liquefied petroleum gas (LPG) and gasoline(GLN) since this is where a refinery makes money. because low-value fractions of residual fuel oil from distillation that aren't in demand is converted to useful products.

This problem can be solve by applying separable programming to a simple oil refinery model maximizing profit with a objective function that has the form below;

Maximise $\sum(Product\_Value) - \sum(Raw\_Material) - \sum(Variable\_Cost)$

s.t various constraints.

Figure 4.1



From the diagram above the nature of crude prices used by the Tema Oil Refinery is non-linear. In addition the non-linear term is just a function of a single variable and this makes the application of separable programming appropriate.

According to Beasley, any NLP in which all the nonlinear terms are just functions of single variables is called a *separable program* and the below method of linear approximation is sometimes called *separable programming*.

Replacing data from TOR, the equation above becomes

$$\text{Max} \quad (\alpha_1 LPG + \alpha_2 GLN) - (\beta_1 B\_L^2 + \beta_2 B\_R^2) + e$$

$$\text{s.t} \quad LPG <= 83.81$$

$$GLN <= 97.74$$

$$\alpha_1, \alpha_2, \beta_1, \beta_2 > 0$$

Where e is an error term

4.2 FINDINGS

The research found out that the Government of Ghana has a crude oil allocation contract, renewable annually, with the Nigerian National Petroleum Corporation (NNPC) for the supply of 30,000 barrels of crude oil a day. Tema Oil Refinery Company Limited manages the contract on behalf of the Government of Ghana.

Ghana does not produce significant quantities of crude oil internally and therefore imports all its requirements. Tema Oil Refinery prefers feeding the plants on a diet of low sulphur crude oils, typically of quality between 30 Degrees API gravity and 45 Degrees API gravity.

Also the proximity of Ghana to Nigeria and the preference of Tema Oil Refinery for light and sweet crude oils, which form a bulk of Nigerian production, make TOR and NNPC ideal trading partners.

Since the capacity of the Topping unit is 45,000 barrels of crude oil a day, the balance of 15,000 barrels of crude oil a day is purchased through a competitive tender organized by the National Petroleum Authority (NPA).

TOR transports its crude oil liftings from Nigeria loading-ports to Tema by a time-chartered Panamax tanker (60,000 to 80,000 Metric Tonnes Deadweight). The time-charter arrangement enables TOR to have the vessel continuously available for use and also to lock in favorable freight rates for the duration of the contract

In addition, an oil jetty located at the Port of Tema is available to TOR for the loading and discharging of cargoes. The oil jetty, which was built in 1963, has a draft of 9.6 metres and therefore limits the sizes of vessel that call. There are five pipelines for transporting refined petroleum products. They are the 24-inch pipeline for transporting crude oil, the 18-inch pipeline for diesel or residual fuel oil, the 14-inch pipeline for gasoline or diesel, the 10-inch pipeline for Jet A1 and naphtha (heavy gasoline) and the 6-inch pipeline for liquefied petroleum gas.

Nevertheless, under the government deregulation policy of the downstream sector of the petroleum industry, TOR no longer imports the shortfall of refined products arising out of its crude oil processing operations. The responsibility of importation of refined products has shifted to the Bulk Oil Storage and Transportation (BOST) Company Limited and the Oil Marketing Companies.

Therefore, TOR would normally advise the National petroleum Authority (NPA) of its refined products requirements and the delivery date ranges. The NPA would in turn organize a competitive tender to meet TOR's supply requirements.

4.3 PRODUCTS OF TOR

A step in refining crude oil into finished oil products involves a distillation process that splits crude into various streams. The research showed that, among other things, Tema Oil refinery produces 7 finished products from their supply of crude. Table 5.3.a shows the details of TOR's products.

Table 4.3.a

PRODUCT	DESCRIPTION
Liquefied Petroleum Gas (LPG)	The main constituents of LPG produced by the Tema Oil Refinery are Propylene and butane. LPG is environmentally friendly and finds use as domestic, commercial and industrial fuel. TOR produces LPG in excess of national requirement and therefore exports the surplus to countries in the West Africa sub region, Europe and the USA.
Motor Gasoline (Mogas)	This product is mainly produced for motor vehicles with internal combustion engines. TOR currently supplies single grade gasoline using anti-knock additives (Methyl Cyclopentadienyle Manganese Tricarbonyl or MMT) as octane enhancer. Unleaded gasoline mainly from Europe is imported to supplement production at TOR.
Kerosene	This is petroleum distillate used mainly for illumination in wick-fed lamps. for cooking in stoves and pressure burners. It is a very useful fuel for the rural communities.
Aviation Turbine Kerosene (Jet A1)	It is a special grade of kerosene with stringent specifications and is suitable for use in aircraft engines

Gas Oil (Diesel)	This is also petroleum distillate. It is commonly referred to as diesel oil and is suitable for high-speed diesel engines. Gas oil produced at the Tema Oil Refinery normally contains about 0.18% sulphur and has a viscosity range of 2.5 centistokes to 6.5 centistokes. Imports mainly from Europe supplement local production from TOR.
Premix	The refinery produces a purpose-made fuel known as premix for fisher folks who use outboard motors. It is a blend of Marine Mix lubricants and gasoline .Premix is suitable for two-stroke engines.
Cracked Fuels	Cracked fuels are a blend of Light Cycle Oil, Heavy Cycle Oil and Clarified Oil produced from the Residue Fluid Catalytic Cracking unit. These are blended in varying ratios to produce inland diesel oil and inland fuel oil. The inland fuel oil is used mainly for low and medium speed diesel engines

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

LP works on the principles of pure mathematics and Petroleum Refining is more complex than the mathematics that describes it. With all the approximations and uncertainty we should not expect or even desire a "true mathematical optimum." LP should be viewed only as a mathematical optimization technique, or as a convenient method to obtain a feasible and economic plan for the supply, processing and logistic activities of a petroleum complex, together with a description of its driving forces and constraints. In day-to-day working, an LP solution helps in achieving two key practical aspects:

- It facilitates in the decision-making process by keeping the focus on profit under any scenario
- It provides the targets and operating strategies for the actual operation

LP does much more than planning for the future. LP refinery models always challenge the people and their deep-rooted rule-of-thumb approach in the refinery operations. The implementation of LP models often creates awareness among executives and management about the profit factor. LP-based planning can provide potential benefits to the tune of 15-20 cents/bbl. One of the major advantages of LP programming is that it acts as a watch dog for the refinery operations – always asking for more, the LP model helps in identifying the bottlenecks in processing more crude and directs in achieving the benchmark for operation. It clearly tells the inefficiency of operations in terms of money, and that's where it is very close to management's heart.

The LP solution has not only enabled arriving at a better plan, but has also provided many valuable insights for optimizing unit operations, crude mix and product blending. The other most important benefit realized is it quantifies the impact of a change in a variable on overall refinery profitability. As a tool, RPMS provides answers to the typical questions that refinery management asks for faster decision making, including: What is optimum HS-LS crude mix?, How to maximize distillate yield and minimize the fuel & loss?, What products to be maximized?, Which units to be run and what capacity levels?, When to plan unit shutdowns?, etc.

5.2 RECOMMENDATIONS

The Tema Oil Refinery has over the years implored Linear Programming techniques in the determination of blends to maximize profit.

Given the non-linear nature of its operating variables it is recommended that the Tema Oil Refinery implore the use of separable programming method in determining the right blend of its crude oil mix to maximize profit.

Also Tema Oil Refinery should source for external funds to restore and upgrade its boilers and possibly build additional boilers to support sustained steam demand and electrical energy generation. This would help provide for flexibility and reliability in the day-to-day operations of the refinery.

Finally, policies that would help tighten controls on emissions from the refinery operations needs to be implemented in-country to ensure the refinery and any other that would come into operations in the future conforms to minimum emission standards.

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APPENDIX

Date	Weekly Nigeria Bonny Light Spot Price FOB (Dollars per Barrel)
Jan 01, 2010	77.69
Jan 08, 2010	81.27
Jan 15, 2010	80.99
Jan 22, 2010	77.75
Jan 29, 2010	74.41
Feb 05, 2010	74.99
Feb 12, 2010	72.47
Feb 19, 2010	75.48
Feb 26, 2010	78.07
Mar 05, 2010	79.35
Mar 12, 2010	81.29
Mar 19, 2010	81.26
Mar 26, 2010	80.83
Apr 02, 2010	81.68
Apr 09, 2010	86.13
Apr 16, 2010	86.53
Apr 23, 2010	85.82
Apr 30, 2010	87.52
May 07, 2010	85.35
May 14, 2010	80.93
May 21, 2010	75.46
May 28, 2010	72.33
Jun 04, 2010	75.61
Jun 11, 2010	74.56

Jun 18, 2010	77.56
Jun 25, 2010	79.03
Jul 02, 2010	76.84
Jul 09, 2010	74.34
Jul 16, 2010	77.04
Jul 23, 2010	77.29
Jul 30, 2010	78.2
Aug 06, 2010	82.73
Aug 13, 2010	80.87
Aug 20, 2010	77.13
Aug 27, 2010	74.62
Sep 03, 2010	76.81
Sep 10, 2010	77.91
Sep 17, 2010	79.79
Sep 24, 2010	79.28
Oct 01, 2010	80.51
Oct 08, 2010	85.33
Oct 15, 2010	85.42
Oct 22, 2010	83.87
Oct 29, 2010	83.88
Nov 05, 2010	86.55
Nov 12, 2010	89.46
Nov 19, 2010	86.66
Nov 26, 2010	84.82
Dec 03, 2010	88.3
Dec 10, 2010	92.34
Dec 17, 2010	92.64
Dec 24, 2010	93.85
Dec 31, 2010	95.16