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Planning and optimising petroleum supply chain

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Abstract

The purpose of this paper is to develop and implement an integrated framework for planning and optimising petroleum supply chain (SC). The framework consists of two stages; first-stage is to address mathematically the strategic planning and the optimisation of the extracted oil which is needed within the petroleum supply chain. While the second stage focuses on the operational planning of the refinery area using a combined discrete and continues simulation modelling techniques. The simulation model considered 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 statistically using SPSS Program.

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Keywords: Petroleum supply chain, logistics, simulation, mathematics, optimisation

1. Introduction

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 globalized 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 [1]. 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

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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 organisations 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 such as [2-5], 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 supply chain 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.

This paper focuses on the planning and optimisation of petroleum industry logistics and the supply chain, from the recovery of the raw materials to production and distribution, using integrated mathematical and simulation modelling techniques. It consider a range of parameters including crude oil production, transportation plans, production levels, operating conditions, products distribution plans, the prices of raw materials and products under significant sources of uncertainty (reflecting current market conditions).

Figure 1 displays the proposed framework for planning and optimising petroleum supply chain. The framework 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. The objective function of the proposed mathematical model is to optimise the petroleum supply chain by minimising total production and logistics costs, as well as lost demand and backlog penalties, and maximising sales revenues.

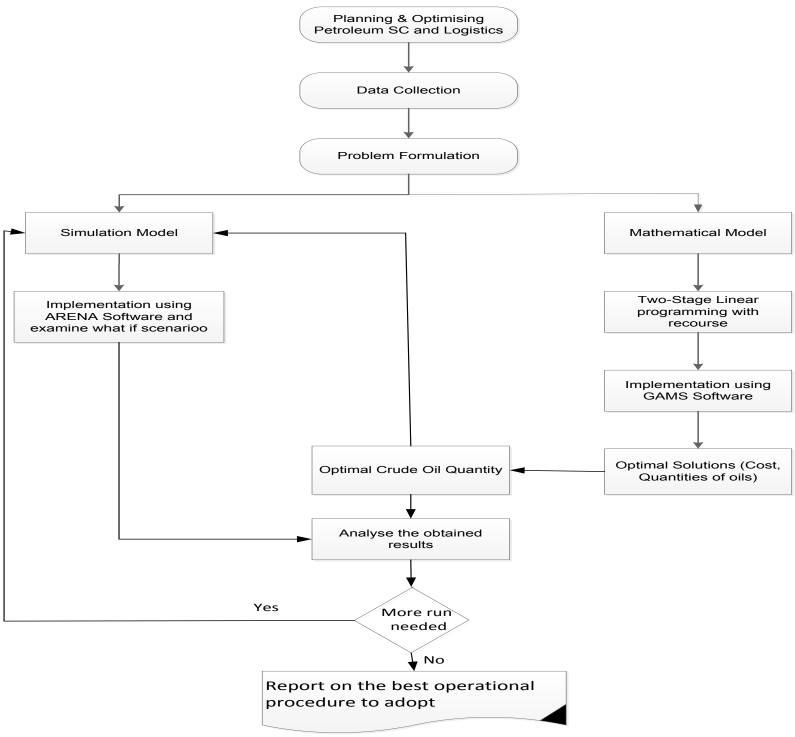

Fig. 1. The proposed framework for planning and optimising petroleum SC

As can be seen from Figure 1 the proposed mathematical model arrives to 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.

2. Framework of the proposed petroleum supply chain

The petroleum supply chain proposed in this paper is illustrated in Figure 2. It includes majority of the activities related to raw materials supply to final product passing through a complex logistics network including oil production, refinery area, transportation, storage of the refinery products which can be considered as distribution centres, and several conversion processes that take place in refinery plant.

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.

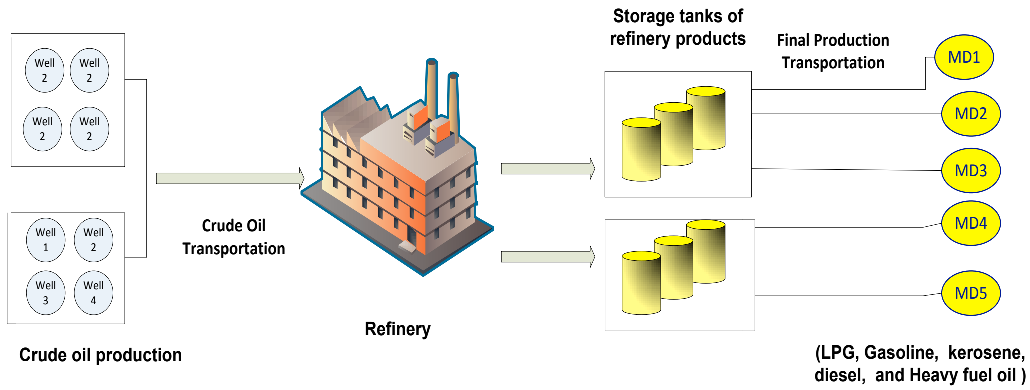

Fig. 2. Petroleum supply chain network proposed

3. 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.

3.1 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 in equation (1) as follows:

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

$$Z = min\left\{\left[\sum_{i\epsilon I}\sum_{t\epsilon T} CO_i . Q_{i,t}\right] + \left[\sum_{j\epsilon J}\sum_{t\epsilon T} C_j . V_{j,t}\right] + \left[\sum_{i\epsilon I}\sum_{t\epsilon T} TC_i . TV_{i,t}\right] + \left[\sum_{j\epsilon J}\sum_{t\epsilon T} CS_j . SV_{j,t}\right] + \left[\sum_{j\epsilon J}\sum_{md\epsilon MD}\sum_{t\epsilon T} CT_j . F_{j,md,t}\right] + \left[\sum_{j\epsilon J}\sum_{md\epsilon MD}\sum_{t\epsilon T} \beta_{j,md} . DS_{j,md,t}\right] + \left[\sum_{j\epsilon J}\sum_{md\epsilon MD}\sum_{t\epsilon T} CB_{j,md} . VB_{j,md,t}\right] - \left[\sum_{j\epsilon J}\sum_{md\epsilon MD}\sum_{t\epsilon T} PS_{j,md}\, F_{j,md,t}\right]\right\} \quad (1)$$

where:

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).
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).

3.2. Constraints

There are five main constraints considered for this mathematical model including material balance, demand balance, storage constraints, transportation constraints and production yield. Due to space limitation, the mathematical presentation and details of these constraints will be presented in the conference.

4. Simulation model

The main objectives of simulation modelling 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, oil 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.

4.1. System Description

The process flowchart shown in Figure 3 illustrates the processing stages of the proposed simulation model. The crude oil flows from its source through two production lines, each line consists of three separation machines for separating the oil from water and gas. The pure oil extracted from third stage separator passes through two delivery tanks which are connected to a storage tank that feeds the distillation unit to produce the final products. All of these operations change with the time and therefore, it is considered as a continuous system, although some discrete event occurs.

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 1.

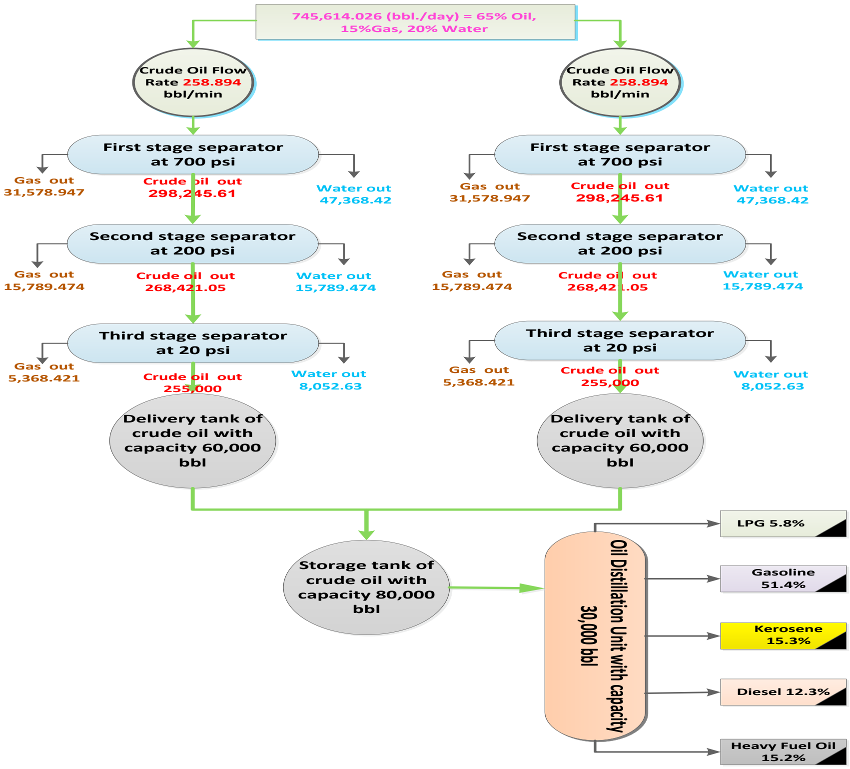

Fig. 3. Process Flow Chart of the proposed model

Table 1. 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

4.2. Model building

Arena Simulation Software [6] was used to develop the proposed simulation model due its modelling capabilities of both discrete and continuous type of processes. The model representing activities from the crude oil source which flow through separation processes to distillation unit processes passing through delivery tanks and storage tanks 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 3.

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 4 illustrates a brief process description of the 1st stage of separation using a flow chart. The three separation stages were controlled by Equations containing variables used in the model.

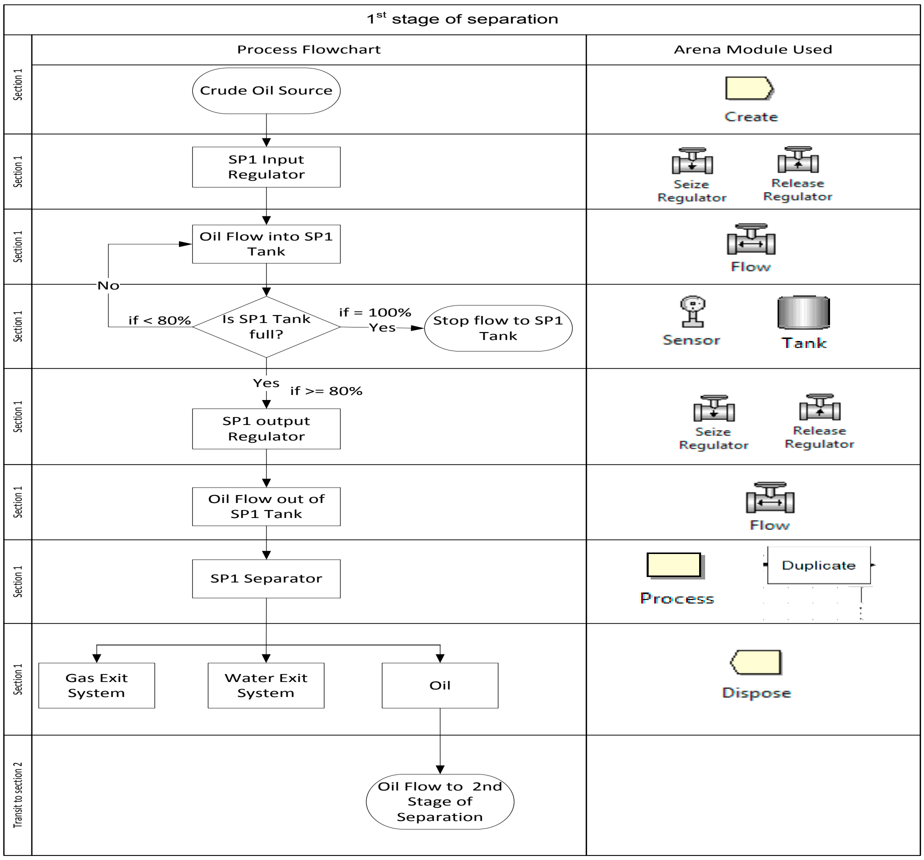

Fig. 4. The 1st Stage of Separation Illustrated by a Process Flow Chart and Respective Arena Modules Used

5 Results and discussion

5.1 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.

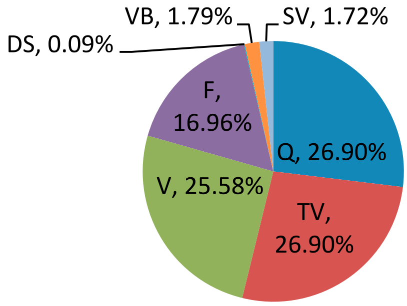

Fig. 5 Optimal quantities of supply chain parameters (Case 0)

- The optimal quantity of crude oil production is accomplished for all time periods during the planning horizon that are shown in Table 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 used in the simulated model for calculating other key performance measures of petroleum supply chain.

Table 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

5.2. Simulation model results

The experimental design of the model had 945 runs (3 X 5 X 9 X 7 levels). Three input rates of oil at level R1, R2 and R3, five quality of crude oil at levels Q1, Q2, Q3, Q4 and Q5, nine levels of distillation capacity and 7 levels of separators failure. To analyse the outputs, the distillates were summed up as one value called total product and Equipment Utilisation was averaged. This helped reduce the complexity for analysing the outputs of the experiment using SPSS. The results obtained from MANOVA analysis will be presented in the conference, which is a set of plots showing the effect of the four input factors on the performance-measure (total products output). It was clear that the number of barrel of total product increases whenever input rate and quality of crude oil increases. Obviously, distillation processing time had big impact on the output. The number of failed separator had effect on the performance measure (total products) by dropping sharply from F0 to F2 and then stayed stable at low level of the output from F3 to F6. It is clear that, the distillation processing time had a significant impact on the performance measure equipment utilisation as a drop in the percentage of equipment utilisation from 100% at processing time of 69.9 minutes to about 25% at processing time of 0.73 minute was experienced. Otherwise, the output increases with an increase in both input rate of crude oil and quality of crude oil. The effect of number of failed separators showed a sharp fall in the percentage of equipment utilisation from F0 at 69% to F2 at 57% and steady from F3 to F6 at about 50%.

6. Conclusions

The integrated mathematical and simulation framework were developed and implemented for planning and optimising petroleum supply chain. The first part of this framework, was the mathematical model of deterministic linear programming 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. The optimal quantity of crude oil presented into deterministic model which was (5.10E+05 bbl./d) used in the simulation model for calculating the performance measurement of the petroleum supply chain. The second part of the optimisation framework was the 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 supply chain system characteristics (continuous, discrete, dynamic, static, deterministic, stochastic and non-terminating) into one model, which should be considered as a major contribution, 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 to use and monitor. The model allows users to check the estimated input factors and their effect on output, showing how productivity and profitability can be improved and helping decision makers in production planning.

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.

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