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# Financial risk management in the planning of refinery operations

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**Abstract**

Most models for refinery planning are deterministic, that is, they use nominal parameter values without considering the uncertainty. This paper addresses the issue of uncertainty and studies the financial risk aspects. The problem addressed here is that of determining the crude to purchase and decide on the production level of different products given forecasts of demands. The profit is maximized taking into account revenues, crude oil costs, inventory costs, and cost of unsatisfied demand. The model developed in this paper was tested using data from the Refinery owned by the Bangchak Petroleum Public Company Limited, Thailand. The results show that the stochastic model can suggest a solution with higher expected profit and lower risk than the one suggested by the deterministic model.



*Keywords:* Refinery planning; Uncertainty; Financial risk management

## 1. Introduction

In the last 20 years, a number of models have been developed to perform short term scheduling and longer term planning of batch plant production to maximize economic objectives (Shah, 1998). In particular, the application of formal mathematical programming techniques to the problem of scheduling the crude oil supply to a refinery was considered by Shah (1996). The consideration includes the allocation of crude oils to refinery and harbour tanks, the connection of refinery tanks to crude distillation units (CDUs), the sequence and amount of crude pumped from the tanks to the refineries, and the details related to discharging of tankers at the harbour.

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**Nomenclature**

*Indices*

| | |
|---|---|
| $c$ | for the set of commodities |
| $q$ | for the set of properties |
| $s$ | for the set of scenarios |
| $t$ | for the set of time periods |
| $u,u'$ | for the set of production units |

*Sets*

| | |
|---|---|
| $C$ | set of commodities |
| $U$ | set of units |
| $U_c$ | set of units that produce commodity $c$ |
| $T$ | set of time periods |
| $\mathrm{QO}_{u,c}$ | set of properties of commodities $c$ leaving unit $u$ |
| $C_\mathrm{P}$ | set of commercial products |
| $C_\mathrm{O}$ | set of crude oils |
| $C_\mathrm{IA}$ | set of purchased intermediate |
| $\mathrm{UC}_u$ | set of ordered pairs of unit and commodity ($u'$,$c$) that feeds unit $u$ |
| $\mathrm{UO}_{u,c}$ | set of units that are fed by commodity $c$ of unit $u$ |
| $\mathrm{CO}_u$ | set of commodities leaving unit $u$ |
| ctank | set of crude oil storage tanks |
| CDU | set of crude distillation units |
| CRU | set of catalytic reforming units |
| NPU | set of naphtha pretreating units |
| HDS | set of hydrodesulphurization units |
| GSP | set of gasoline pool units |
| INT | set of gasoline intermediate tanks |
| $\mathrm{AV}_q$ | set of properties on volume basis |
| $\mathrm{AW}_q$ | set of properties on weight basis |

*Parameters*

| | |
|---|---|
| $\mathrm{pro}_{u,c,q}$ | property $q$ of commodity $c$ from unit $u$ |
| $\mathrm{px}_{c,q}$ | maximum property $q$ of product $c$ |
| $\mathrm{pn}_{c,q}$ | minimum property $q$ of product $p$ |
| $\mathrm{cyield}_{c',c}$ | percent of component $c$ in crude oil $c'$ (%) |
| $\mathrm{yield}_{u,c}$ | percent yield of commodity $c$ from unit $u$ (%) |
| $\mathrm{dem}_{c,t}$ | demand of product $c$ in time period $t$ ($m^3$) |
| $\mathrm{ux}_u$ | maximum capacity of unit $u$ ($m^3$) |
| $\mathrm{un}_u$ | minimum capacity of unit $u$ ($m^3$) |
| $\mathrm{ox}_c$ | maximum monthly purchase of crude oil $c$ ($m^3$) |
| $\mathrm{on}_c$ | minimum monthly purchase of crude oil $c$ ($m^3$) |
| $\mathrm{stox}_c$ | maximum storage capacity of product $c$ ($m^3$) |
| $\mathrm{cp}_{c,t}$ | unit sale price of product $c$ in time period $t$ (\$/$m^3$) |

$co_{c,t}$ unit purchase price of crude oil $c$ in time period $t$ ($\$/m^3$)
$ci_{c,t}$ unit purchase price of intermediate $c$ in time period $t$ ($\$/m^3$)
$cl_{c,t}$ unit cost of lost demand penalty for product $c$ in time period $t$ ($\$/m^3$)
$\rho_s$ probability of scenario $s$
$\text{density}_u$ density of feed to unit $u$ (ton/$m^3$)
$\text{fuel}_u$ percent energy consumption for unit $u$ based on tFOE (%)
disc percent discount from normal price (%)

*Variables*

$PO_{u,c,q,t}$ property $q$ of commodity $c$ from unit $u$ in time period $t$
$AF_{u,t}$ amount of feed to unit $u$ in time period $t$ ($m^3$)
$AO_{u,c,t}$ amount of outlet commodity $c$ from unit $u$ in time period $t$ ($m^3$)
$A_{u,c,u',t}$ amount of commodity $c$ flow between unit $u$ and unit $u'$ in time period $t$ ($m^3$)
$MANU_{c,t}$ amount of product $c$ produced in time period $t$ ($m^3$)
$AC_{c,t}$ amount of crude oil $c$ refined in time period $t$ ($m^3$)
$AI_{c,t}$ amount of intermediate $c$ added in time period $t$ ($m^3$)
$AS_{c,t}$ amount of product $c$ stored in time period $t$ ($m^3$)
$AL_{c,t}$ amount of lost demand for product $c$ in time period $t$ ($m^3$)
$AD_{c,t}$ amount of discount product sold $c$ in time period $t$ (m3)
$\text{Burned}_{c,t}$ amount of product $c$ burned in time period $t$ ($m^3$)
$\text{Used}_t$ amount of fuel used in time period $t$ (tFOE)
$\text{sales}_{c,t}$ sales of product $c$ in time period $t$ ($m^3$)

On the scheduling of crude oil unloading, Lee et al. (1996) and Jia et al. (2003) addressed the problem of inventory management of a refinery that imports several types of crude oil which are delivered by different vessels. Wenkai et al. (2002) presented a solution algorithm and mathematical formulations for short term scheduling of crude oil unloading, storage, and processing with multiple oil types, multiple berths, and multiple processing units. Göthe-Lundgren et al. (2002) described a production planning and scheduling problem in an oil refinery company focusing on the production cost of changing mode and holding inventory. Moro et al. (1998) developed a non-linear planning model for diesel production. Pinto and Moro (2000), Pinto et al. (2000) and Joly et al. (2002) focused on the refinery production problems. The problems involve the optimal operation of crude oil unloading from pipelines, transfer to storage tanks and the charging schedule for each crude oil distillation unit. Moreover, they discussed the development and solution of optimization models for short term scheduling of a set of operation that includes product receiving from processing units, storage, and inventory management in intermediate tanks, blending in order to attend oil specifications and demands, and transport sequencing in oil pipelines. Moro and Pinto (2004) addressed the problem of crude oil inventory management of a refinery that receives several types of oil delivered through a pipeline. On the blending process, Glismann and Gruhn (2001) developed an integrated approach to coordinate short term scheduling of multi-product blending facilities with nonlinear recipe optimization. Jia and Ierapetritou (2003) introduced a MILP model based on continuous representation of the time domain for gasoline blending and distribution scheduling. Finally, a decomposition technique that is applied to overall refinery optimization was presented by Zhang and Zhu (2000).

### 1.1. Planning of the petroleum supply chain under uncertainty

Bopp et al. (1996) described the problem of managing natural gas purchases under conditions of uncertain demand and frequent price change. Similarly, Guldmann and Wang (1999) presented a large MILP and a much smaller NLP approximation of the MILP, involving simulation and response surface estimation via regression analysis to solve the problem of the optimal selection of natural gas supply contracts by local gas distribution utilities. To effectively deal with uncertainty, Liu and Sahinidis (1996) used a two-stage stochastic programming approach for process planning under uncertainty.

The optimization of a multiperiod supply, transformation, and distribution (STD) has also been studied. Escudero et al. (1999) proposed a modeling framework for STD optimization of an oil company that accounts for uncertainty on the product demand, spot supply cost, and spot selling price. Hsieh and Chiang (2001) developed a manufacturing-to-sale planning system to deal with uncertain manufacturing factors. Neiro and Pinto (2003) extended the single refinery model of Pinto et al. (2000) to a corporate planning model that contains multiple refineries. They also examined for different types of crude oil and product demand scenarios. The optimization model for the supply chain of a petrochemical company operating under uncertain operating and economic conditions was developed by Lababidi et al. (2004). In this work, uncertainties were introduced in demands, market prices, raw material costs, and production yields. Finally, using the fuzzy theory, Liu and Sahinidis (1997) presented an application of fuzzy programming to process planning of petrochemical complex.

### 1.2. Financial risk management

Barbaro and Bagajewicz (2004) presented a methodology to include financial risk management in the framework of two-stage stochastic programming for planning under uncertainty. The definition of risk and the methodology outlined there was used in this article. Based on this definition, several theoretical expressions were developed, providing new insights on the trade-offs between risk and profitability. Thus, the cumulative risk curves were found to be very appropriate to visualize the risk behavior of different alternatives. New measures and procedures to manage financial risk were later introduced by Aseeri and Bagajewicz (2004). They use the concepts of Value at Risk and Upside Potential as means to weigh opportunity loss versus risk reduction as well as an area ratio. In addition, they proposed upper and lower bounds for risk curves corresponding to the optimal stochastic solutions. Finally, they also introduced a new measure to evaluate risk: the risk area ratio (RAR). The method takes advantage of the sampling average algorithm. All these concepts are briefly summarized in the Appendix.

In this paper, a model was developed for the production planning in the Bangchak Petroleum Public Company Limited in Bangkok, Thailand. Uncertainty of product demand and price was considered to build a stochastic model. The model was implemented by general algebraic modelling system (GAMS) and financial risk is discussed. We first present the model. Then we discuss results of a deterministic case (planning using mean values of forecasted demands and prices) followed by discussing the results obtained when uncertainty is considered. We finally present a method to reduce financial risk, especially because there are scenarios where losses can take place.

## 2. Problem statement

This work addresses the planning of crude oil purchasing and its processing schedule to satisfy both specification and demand with the highest profit. The decision variables are: crude oil supply purchase decisions, processing, inventory management, and blending over time periods. The length of time periods needs to be decided based on business cycles. The model represents a scheme of a refinery that includes product paths to each production unit. The product paths are recognized by the composition and some key properties, e.g. sulphur and aromatic content. Capacities and yields of several units are also taken into account.

A unit model consists of blending relations and production yields. Yield expressions are based on averaged values obtained from plant data. Processing of a unit must satisfy bound constraints, which include maximum and minimum unit feed.

Physical and chemical properties are calculated using volume and weight average (linear relations) whereas the properties that cannot be blended linearly are calculated by using blending index numbers.

The optimization model is based on a discretization of the time horizon and is linear.

## 3. Planning model

A set-up of input–output balancing is based on the network structure proposed by Pinto et al. (2000). Fig. 1 shows the general representation of balancing a production unit. The notation for the model can be found in the Nomenclature section.

In Fig. 1, commodity $c_1$ from unit $u_1'$ is sent to unit $u$ at flow rate $A_{u1',c1,u,t}$ in period $t$. The same unit $u_1'$ may send different commodities $c$ $(c_2,c_3,\ldots,c_n)$ to unit $u$. In addition, $u'$ $(u_2',u_3',\ldots,u_n')$ can feed commodities $c$ $(c_1,c_2,\ldots,c_n)$ to unit $u$. The summation of feed for unit $u$ is represented by $\mathrm{AF}_{u,t}$. Parameters $\mathrm{PO}_{u1',c1,q}$ denote properties $q$ of commodity $c_1$ flow from $u_1'$. Variables $\mathrm{AO}_{u,c,t}$ represents the outlet flow rate of

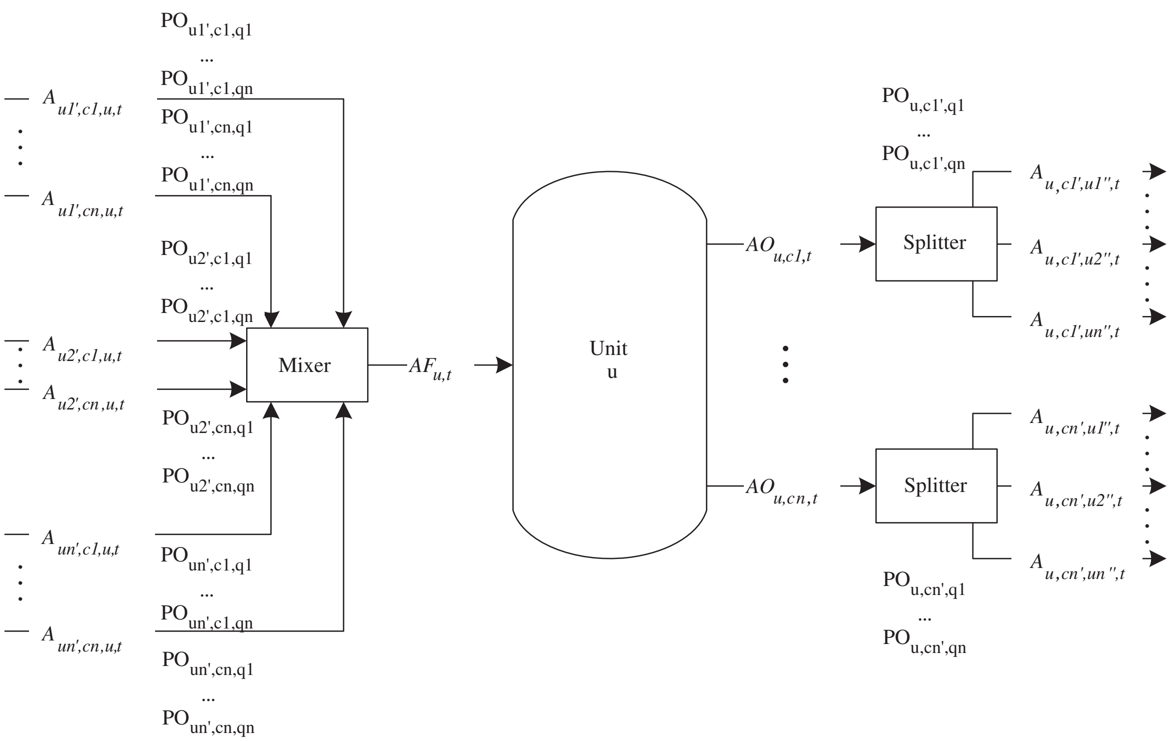


Fig. 1. Balancing of a typical unit.

commodity $c$ from unit $u$ in time period $t$. A splitter is represented at every outlet stream because a product stream can be sent to more than one unit for further processing or storage.

The model of a typical unit $u$ in Fig. 1 is represented by two sets of equations. The first set involves balance equations and the other involves stream property equations. Balance equations include:

1. Balance of feeds to unit $u$ which is represented by

$$\mathrm{AF}_{u,t} = \sum_{(u',c)\in \mathrm{UC}_u} A_{u',c,u,t}, \quad \forall u \in U, t \in T. \tag{1}$$

2. Balance of products from splitter which is represented by

$$\mathrm{AO}_{u,c,t} = \sum_{u'\in \mathrm{UO}_{u,c}} A_{u,c,u',t}, \quad \forall c \in \mathrm{CO}_u, u \in U, t \in T. \tag{2}$$

3. Balance of products from unit $u$ which is represented in two ways: For percent yields that do not depend on the feed properties, the amount of products is equal to the total inlet flow multiply by a constant, the percent yield of that unit.

$$\mathrm{AO}_{u,c,t} = \mathrm{AF}_{u,t} \times \mathrm{yield}_{u,c}, \quad \forall c \in \mathrm{CO}_u, u \in U, t \in T. \tag{3}$$

For percent yields that depend on the feed properties, the amount of products is equal to the sum of each inlet flow times percent yield of each inlet flow.

$$\mathrm{AO}_{u,c,t} = \sum_{u'\in \mathrm{ctank}} \sum_{c'\in \mathrm{C_O}} (A_{u',c',u,t} \times \mathrm{cyield}_{c',c}), \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{CDU}. \tag{4}$$

The stream property equations include the calculation of product properties that can be accomplished in two ways:

1. Product properties leaving unit $u$ calculated by the sum of the flow fraction times the properties of each flow as in the following equation. These are called blending equations.

$$\mathrm{PO}_{u,c,q,t} = \frac{\sum_{u'\in U'} \sum_{c'\in \mathrm{CO}_{u'}} (A_{u',c',u,t} \times \mathrm{pro}_{u',c,q})}{\sum_{u'\in U'} \sum_{c'\in \mathrm{CO}_{u'}} A_{u',c',u,t}}, \quad \forall c \in \mathrm{CO}_u, u \in U. \tag{5}$$

The equation is nonlinear. However, this is not an equation we use in the model. We use bounds on this property. This is further discussed below.

2. Product properties from unit $u$ that can be determined over average values obtained from plant data, e.g. isomerate from isomerization unit and reformate from reformer unit:

$$\mathrm{PO}_{u,c,q,t} = \mathrm{pro}_{u,c,q}, \quad \forall c \in \mathrm{CO}_u, q \in \mathrm{QO}_{u,c}, u \in U, t \in T. \tag{6}$$

The stream flowing to each unit should be within established minimum and maximum values

$$\mathrm{ux}_u \geqslant \mathrm{AF}_{u,t} \geqslant \mathrm{un}_u, \quad \forall u \in U, t \in T. \tag{7}$$

The allowable quantity of crude oil refined in each time period is shown in the following equation:

$$\mathrm{ox}_c \geqslant \mathrm{AC}_{c,t} \geqslant \mathrm{on}_c, \quad \forall c \in C_\mathrm{O}, t \in T. \tag{8}$$

The allowable quantity of finish product stored in each time period is limited:

$$\mathrm{stox}_c \geqslant \mathrm{AS}_{c,t}, \quad \forall c \in C_\mathrm{P}, t \in T. \tag{9}$$

Quality constraint: The product quality must be greater or equal to its minimum specifications and must not be over its maximum specifications. The set of product ($C_\mathrm{p}$) must satisfy the following equation:

$$\mathrm{px}_{c,q} \geqslant \mathrm{PO}_{u,c,q,t} \geqslant \mathrm{pn}_{c,q}, \quad \forall c \in \mathrm{CO}_u, q \in \mathrm{QO}_{u,c}, u \in U, t \in T. \tag{10}$$

Substitution of $\mathrm{PO}_{u,c,q,t}$ given by Eq. (5) in this equation and rearrangement by multiplying the whole inequality by the denominator of $\mathrm{PO}_{u,c,q,t}$ renders a linear expression.

*Objective function:* The objective function in this model is profit that is obtained by the product sales minus crude oil cost, intermediate cost, storage cost, expense from lost demand, and expense from discounted product. This is shown by the following equation:

$$\begin{aligned}\text{Max Profit} = {} & \sum_{t\in T}\sum_{c\in C_\mathrm{P}} \mathrm{MANU}_{c,t} \times \mathrm{cp}_{c,t} - \sum_{t\in T}\sum_{c\in C_\mathrm{O}} \mathrm{AC}_{c,t} \times \mathrm{co}_{c,t} - \sum_{t\in T}\sum_{c\in C_\mathrm{IA}} \mathrm{AI}_{c,t} \times \mathrm{ci}_{c,t} \\ & - \sum_{t\in T}\sum_{c\in C_\mathrm{P}} \left(\frac{\mathrm{AS}_{c,t} + \mathrm{AS}_{c,t-1}}{2}\right) \times \mathrm{cp}_{c,t} \times \mathrm{int} - \sum_{t\in T}\sum_{c\in C_\mathrm{P}} \mathrm{AL}_{c,t} \times \mathrm{cl}_{c,t} \\ & - \sum_{t\in T}\sum_{c\in C_\mathrm{P}} \mathrm{AD}_{c,t} \times \mathrm{cp}_{c,t} \times \mathrm{disc}.\end{aligned} \tag{11}$$

$\mathrm{MANU}_{c,t}$ is equal to the amount of product produced in that time period.

$$\mathrm{MANU}_{c,t} = \sum_{u\in U_c} \mathrm{AO}_{u,c,t}, \quad \forall c \in C_\mathrm{P}, t \in T, \tag{12}$$

where $\mathrm{AO}_{u,c,t}$ is the amount of product flow out from production unit in each time period.

$\mathrm{AC}_{c,t}$ is the amount of crude oil refined in that time period.

$$\mathrm{AC}_{c,t} = \sum_{u\in U_c} \mathrm{AO}_{u,c,t}, \quad \forall c \in C_\mathrm{O}, t \in T, \tag{13}$$

where $\mathrm{AO}_{u,c,t}$ is the amount of crude oil flow out from crude oil storage tank in each time period.

$\mathrm{AI}_{c,t}$ is equal to the amount of purchased intermediate added in that time period.

$$\mathrm{AI}_{c,t} = \sum_{u\in U_c} \mathrm{AO}_{u,c,t}, \quad \forall c \in C_\mathrm{IA}, t \in T, \tag{14}$$

where $\mathrm{AO}_{u,c,t}$ is the amount of MTBE and DCC flow out from their storage tank in each time period.

$\mathrm{AL}_{c,t}$ is the product volume that cannot satisfy its demand. The demand of each product must be equal to the volume of that product sale plus the volume of lost demand of that product:

$$\mathrm{dem}_{c,t} = \mathrm{sales}_{c,t} + \mathrm{AL}_{c,t}, \quad \forall c \in C_\mathrm{P}, t \in T. \tag{15}$$

The volume of the lost demand is taken into account as the opportunity cost if that production cannot satisfy the demand.

$\mathrm{AS}_{c,t}$ represents the closing stock, $\mathrm{AS}_{c,t-1}$ represents the opening stock and int represents the average rate of interest payable in that period. In the equation, the financial cost incurred relates to the average stock level over the period. Unless the stock levels are known, they are assumed that the average stock level is equal to the arithmetic mean of the opening and closing stock (Favennec, 2001). The balance of product storage can be found in the following equation:

$$\mathrm{AS}_{c,t} = \mathrm{AS}_{c,t-1} + \mathrm{MANU}_{c,t} - \mathrm{sales}_{c,t} - \mathrm{AD}_{c,t}, \quad \forall c \in C_\mathrm{P}, t \in T. \tag{16}$$

Finally, sometimes production exceeds demand and therefore, production needs to be sold at a cheaper discounted price. Thus $AD_{c,t}$ is the product volume that exceeds demand which will be sold at a cheaper price.

This completes the model.

### 3.1. Stochastic formulation

The stochastic formulation technique used in this work is the two-stage stochastic linear program with recourse, which is reviewed in the Appendix. Uncertainty is considered only in the demand and product prices. The first-stage decisions are the amount of crude oil purchased, $AC_{c,t}$, for every planning period. The second-stage decisions are the amount of product production, $MANU^{s}_{c,t}$, the amount of product stock, $AS^{s}_{c,t}$, the amount of intermediate purchased, $AI^{s}_{c,t}$, amount of product that cannot satisfy demand, $AL^{s}_{c,t}$, and amount of discount sales, $AD^{s}_{c,t}$. These second-stage scenarios are denoted by the index $s$ and assumed to occur with individual probabilities $\rho_s$.

The stochastic results are obtained by using a special implementation of the average sampling algorithm method (Verweij et al., 2001), which was introduced by Aseeri and Bagajewicz (2004) based on original ideas proposed by Barbaro and Bagajewicz (2004). In this method, a full deterministic model is run for the parameters of each scenario and then the results are used to fix the first stage variables (commitment to buy a certain sets of crudes in our case). Then the same model is run for all the rest of the scenarios, with the first stage variables fixed. Usually a ‘‘design’’ is characterized by the values of the first stage variables, which are also called ‘‘here and now’’ variables. When these are fixed and the model is run for all the rest of the scenarios to obtain the values of the second stage (recourse or ‘‘wait and see’’) variables, one obtains then how that ‘‘design’’ performs when uncertainty unveils. Since each scenario contsins uncertainties spread throughout time, one obtains the net present value of that particular ‘‘design’’ for each scenario. This allows constructing a histogram, obtain the expected profit of that ‘‘design’’ and also the risk profile. Once as many designs as scenarios have been constructed are obtained, the same amount of risk curves can be constructed. After the risk curves (cumulative probabilities) are constructed, dominated curves are disregarded and then that trade off between expected profit and risk is determined and solutions are picked.

## 4. Case study

The model was applied to the production planning of Bangchak Refinery. Fig. 2 shows a simplified scheme illustrating the application of the model. The refinery has two atmospheric distillation units (CDU2 and CDU3), two naphtha pretreating units (NPU2 and NPU3), one light naphtha isomerization unit (ISOU), two catalytic reforming units (CRU2 and CRU3), one kerosene treating unit (KTU), one gas oil hydrodesulphurization (GO-HDS), and one deep gas oil hydrodesulphurization (DGO-HDS). The commercial products from the refinery are liquefied petroleum gas (LPG), gasoline RON 91 (SUPG), gasoline RON 95 (ISOG), jet fuel (JP-1), high speed diesel (HSD), fuel oil 1 (FO1), fuel oil 2 (FO2), and low sulphur fuel oil (FOVS). Fuel gas (FG) and some amount of FOVS produced from the process are used as an energy source for the plant.

There are six crude oil available: Oman (OM), Tapis (TP), Labuan (LB), Seria light (SLEB), Phet (PHET), and Murban (MB).

The properties of FG and LPG are not considered because FG is burned as an energy source in the plant and LPG properties are mostly in the range of its specification. We now describe which properties are considered in the model and how.

The properties of intermediates for gasoline blending are the octane number (RON), the aromatic content (ARO), and the Reid vapor pressure (RVP). The properties of FPI and ARO, used for jet fuel

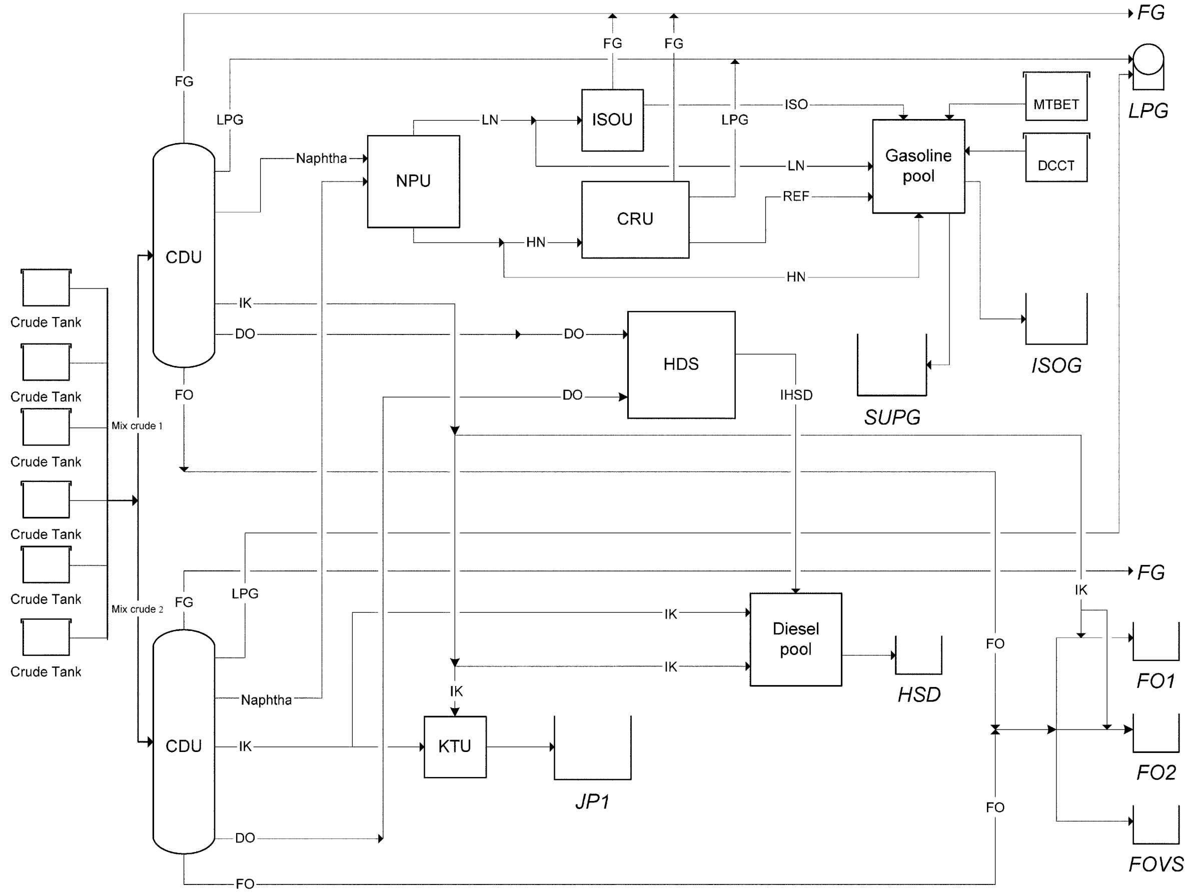


Fig. 2. Simplified scheme of Bangchak Petroleum Public Company Limited.

(JP-1) production, are not very important since most IK product is in the range of the jet fuel specification. Only two properties are used in the DO production that is CI and Sulphur. Since these properties are the specification for HSD products. The properties associated to fuel oil (FO) (S, V50, V100, PPI) are considered as follows: S, V100, and PPI are used for the low sulphur fuel oil (FOVS) production while S, V50, and PPI are required for the low pour point fuel oil (FO1 and FO2) production. These fuel oils, FO1 and FO2, are different in viscosity after being blended with IK. The refinery planning model is described next in detail.

### 4.1. Crude tank model

The crude oil streams are mixed together and fed to each CDU. The process is assumed to have two charging tanks for each CDU in each period and no capacity limit in order to find the exact amount of each crude oil refined to satisfy demand in each month. In this process, each charging tank works as a mixer. The mixing is represented by

$$\mathrm{AO}_{u,c,t} = \sum_{u' \in \mathrm{CDU}} A_{u,c,u',t}, \quad \forall c \in C_{\mathrm{O}}, u \in \mathrm{ctank}, t \in T. \tag{17}$$

In addition, the PHET crude has to be fed to CDU2 only due to the limitation of unit. This operation rule is represented by

$$A_{\mathrm{PHETT,PHET,CDU3},t} = 0, \quad \forall t \in T. \tag{18}$$

### 4.2. Crude distillation unit (CDU) model

Eqs. (1), (4), (5), (7), and (10) are used to model the two CDUs. The total feed flow from crude storage tanks to both CDUs is represented by the following equation:

$$\mathrm{AF}_{u,t} = \sum_{u' \in \mathrm{UC}_u} A_{u',c,u,t}, \quad \forall u \in \mathrm{CDU}, t \in T, \tag{19}$$

where $c$ in above equation is referred to crude oils.

Furthermore, the feed flow must satisfy both CDUs operating capacity:

$$\mathrm{ux}_u \geqslant \mathrm{AF}_{u,t} \geqslant \mathrm{un}_u, \quad \forall u \in \mathrm{CDU}, t \in T. \tag{20}$$

The amount of product yield depends on the feed flow and feed properties:

$$\mathrm{AO}_{u,c,t} = \sum_{u' \in \mathrm{ctank}} \sum_{c' \in C_\mathrm{O}} (A_{u',c',u,t} \times \mathrm{cyield}_{c',c}), \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{CDU}. \tag{21}$$

Since the properties of product streams have to be determined from properties of each fraction from each crude oil, Eq. (5) is applied to account for the component in each crude oil fed to crude distillation unit. This is done by multiplying each component flow by the percent yield of that component for each crude oil. The properties expressed on a volume basis (RON, RVPI, ARO, CI, PPI, and SG) are calculated as follows:

$$\mathrm{PO}_{u,c,q,t} = \frac{\sum_{u' \in \mathrm{ctank}} \sum_{c' \in C_\mathrm{O}} (A_{u',c',u,t} \times \mathrm{cyield}_{c',c} \times \mathrm{pro}_{u',c,q})}{\sum_{u' \in \mathrm{ctank}} \sum_{c' \in C_\mathrm{O}} (A_{u',c',u,t} \times \mathrm{cyield}_{c',c})}, \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{CDU}, q \in \mathrm{AV}_q. \tag{22}$$

The properties expressed on a weight basis (FPI, S, V50, and V100) are calculated as follows:

$$\mathrm{PO}_{u,c,q,t} = \frac{\sum_{u' \in \mathrm{ctank}} \sum_{c' \in C_\mathrm{O}} (A_{u',c',u,t} \times \mathrm{cyield}_{c',c} \times \mathrm{pro}_{u',c,q} \times \mathrm{pro}_{u',c,\mathrm{SG}})}{\sum_{u' \in \mathrm{ctank}} \sum_{c' \in C_\mathrm{O}} (A_{u',c',u,t} \times \mathrm{cyield}_{c',c} \times \mathrm{pro}_{u',c,\mathrm{SG}})}, \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{CDU}, q \in \mathrm{AW}_q. \tag{23}$$

The properties of products leaving from both CDUs shown in the above equation are substituted in the inequalities given by Eq. (10), which, as explained, render a linear model. The bounds are shown in Table 1.

Eqs. (1), (3), and (7) model both naphtha pretreating unit (NPUs). The feed flow from crude distillation unit ($u'$) is determined by

$$\mathrm{AF}_{u,t} = \sum_{u' \in \mathrm{UC}_u} A_{u',c,u,t}, \quad \forall u \in \mathrm{NPU}, t \in T, \tag{24}$$

where $c$ in above equation is referred to naphthas.

Both NPUs operate within the following range:

$$\mathrm{ux}_u \geqslant \mathrm{AF}_{u,t} \geqslant \mathrm{un}_u, \quad \forall u \in \mathrm{NPU}, t \in T. \tag{25}$$

Table 1
Property constraints of products leaving from both CDU

| Product | Property | | CDU | |
|---|---|---|---|---|
| | | | 2 | 3 |
| IK | ARO | lv% | 25 (Max) | 25 (Max) |
| | FPI | index | 11.8 (Max) | 11.8 (Max) |
| DO | CI | index | 47 (Min) | 47 (Min) |
| FO | S | wt% | 0.5 (Max) | 2.0 (Max) |
| | Vis50 | cSt | — | 300 (Max) |
| | Vis100 | cSt | 3–30 | — |
| | PP | °C | 57 (Max) | 24 (Max) |

The amount of product from both NPUs is given by

$$\mathrm{AO}_{u,c,t} = \left( \sum_{u' \in \mathrm{CDU}} A_{u',c,u,t} \right) \times \mathrm{yield}_{u,c}, \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{NPU}, t \in T. \tag{26}$$

The NPU reduce the sulphur content of all naphthas. However, the sulphur content calculation is not necessary in this process because the sulphur in the gasoline is lower than the gasoline specification.

Eqs. (1), (3), (6), and (7) model both catalytic reformer units (CRUs). The feed flow from NPU ($u'$) is given by

$$\mathrm{AF}_{u,t} = \sum_{u' \in \mathrm{UC}_u} A_{u',c,u,t}, \quad \forall u \in \mathrm{CRU}, t \in T, \tag{27}$$

where $c$ in above equation is referred to naphthas.

and the CRUs operate within the following range:

$$\mathrm{ux}_u \geqslant \mathrm{AF}_{u,t} \geqslant \mathrm{un}_u, \quad \forall u \in \mathrm{CRU}, t \in T. \tag{28}$$

The amount of product yield depends on feed flow and feed properties:

$$\mathrm{AO}_{u,c,t} = \mathrm{AF}_{u,t} \times \mathrm{yield}_{u,c}, \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{CRU}, t \in T. \tag{29}$$

The percent yield of LPG and FG from the CRUs is calculated using the following equations:

$$\mathrm{yield}_{u,\mathrm{LPG}} = (100 - \mathrm{yield}_{u,\mathrm{REF}}) \times 0.75, \quad \forall u \in \mathrm{CRU} \tag{30}$$

$$\mathrm{yield}_{u,\mathrm{FG}} = (100 - \mathrm{yield}_{u,\mathrm{REF}}) \times 0.25, \quad \forall u \in \mathrm{CRU} \tag{31}$$

The properties of the reformate (octane number, aromatic content, and RVP) from both CRUs are constant:

$$\mathrm{PO}_{u,\mathrm{REF},q,t} = \mathrm{pro}_{u,\mathrm{REF},q}, \quad \forall u \in \mathrm{CRU}, q \in \mathrm{QO}_{u,\mathrm{REF}}, t \in T \tag{32}$$

Eqs. (1), (3), (6), and (7) model the isomerization unit (ISOU). Since the ISOU is fed only with light naphtha (LN) from NPU, inlet variables are equal to outlet variables of the LN stream:

$$\mathrm{AF}_{\mathrm{ISOU},t} = \sum_{u' \in \mathrm{NPU}} A_{u',\mathrm{LN},\mathrm{ISOU},t}, \quad \forall t \in T. \tag{33}$$

The ISOU has a maximum capacity expressed by

$$\mathrm{ux}_{\mathrm{ISOU}} \geqslant \mathrm{AF}_{\mathrm{ISOU},t}, \quad \forall t \in T. \tag{34}$$

There are two products, FG and ISO, from ISOU. Its production yield can be estimated using the following equations:

$$\mathrm{AO}_{\mathrm{ISOU,FG},t} = \mathrm{AF}_{\mathrm{ISOU},t} \times \mathrm{yield}_{\mathrm{ISOU,FG}}, \quad \forall t \in T, \tag{35}$$

$$\mathrm{AO}_{\mathrm{ISOU,ISO},t} = \mathrm{AF}_{\mathrm{ISOU},t} \times \mathrm{yield}_{\mathrm{ISOU,ISO}}, \quad \forall t \in T. \tag{36}$$

The properties of the products (octane number, aromatic content, and RVP) are constant and are given by

$$\mathrm{PO}_{\mathrm{ISOU,ISO},q,t} = \mathrm{pro}_{\mathrm{ISOU,ISO},q}, \quad \forall q \in \mathrm{QO}_{\mathrm{ISOU,ISO}}, t \in T. \tag{37}$$

Eqs. (1), (2), and (7) model the kerosene treating unit (KTU). The total feed flow and the operating range are shown next:

$$\mathrm{AF}_{\mathrm{KTU},t} = \sum_{u' \in \mathrm{CDU}} A_{u',\mathrm{IK},\mathrm{KTU},t}, \quad \forall t \in T, \tag{38}$$

$$\mathrm{ux}_{\mathrm{KTU}} \geqslant \mathrm{AF}_{\mathrm{KTU},t} \geqslant \mathrm{un}_{\mathrm{KTU}}, \quad \forall t \in T. \tag{39}$$

The product from KTU is equal to the feed:

$$\mathrm{AO}_{\mathrm{KTU,JP\text{-}1},t} = \mathrm{AF}_{\mathrm{KTU},t}, \quad \forall t \in T. \tag{40}$$

KTU converts mercaptan sulphur to sulphur since mercaptan is limited in jet fuel (JP-1). However, the level of mercaptan is very low so it is not taken into account here.

Eqs. (1), (3), and (7) model the gas oil hydrodesulphurization and deep gas oil hydrodesulphurization unit (GO-HDS and DGO-HDS). The feed and the operating range are:

$$\mathrm{AF}_{u,t} = \sum_{u' \in \mathrm{CDU}} A_{u',\mathrm{IK},u,t} + \sum_{u' \in \mathrm{CDU}} A_{u',\mathrm{DO},u,t}, \quad \forall u \in \mathrm{HDS}, t \in T, \tag{41}$$

$$\mathrm{ux}_u \geqslant \mathrm{AF}_{u,t} \geqslant \mathrm{un}_u, \quad \forall u \in \mathrm{HDS}, t \in T. \tag{42}$$

Note that the volumes of DO feed to HDS are 50% and 100% of DO leaving from CDU2 and CDU3, respectively.

Production yield from both HDS units are given by

$$\mathrm{AO}_{u,\mathrm{IHSD},t} = \mathrm{AF}_{u,t} \times \mathrm{yield}_{u,\mathrm{IHDS}}, \quad \forall u \in \mathrm{HDS}, t \in \mathrm{T}. \tag{43}$$

The total production of FG is

$$\mathrm{AF}_{\mathrm{FGT},t} = \sum_{u' \in \mathrm{UC}_{\mathrm{FGT}}} A_{u',\mathrm{FG},\mathrm{FGT},t}, \quad \forall t \in T. \tag{44}$$

The amount of product from FGT is represented by

$$\mathrm{AO}_{\mathrm{FGT,FG},t} = \mathrm{AF}_{\mathrm{FGT},t}, \quad \forall t \in T. \tag{45}$$

The total production of LPG is given by

$$\mathrm{AF}_{\mathrm{LPGT},t} = \sum_{u' \in \mathrm{UC}_{\mathrm{LPGT}}} A_{u',\mathrm{LPG},\mathrm{LPGT},t}, \quad \forall t \in T. \tag{46}$$

The amount of product from LPGT is represented by

$$\mathrm{AO}_{\mathrm{LPGT,LPG},t} = \mathrm{AF}_{\mathrm{LPGT},t}, \quad \forall t \in T. \tag{47}$$

Gasoline is produced by blending six intermediate streams which include ISOT, REFT, LNT, HNT, MTBET, and DCCT. The feed flow to both GSPs is given by

$$\mathrm{AF}_{\mathrm{GSP},t} = A_{\mathrm{ISOT,ISO,GSP},t} + A_{\mathrm{REFT,REF,GSP},t} + A_{\mathrm{LNT,LN,GSP},t} \\ A_{\mathrm{HNT,HN,GSP},t} + A_{\mathrm{MTBET,MTBE,GSP},t} + A_{\mathrm{DCCT,DCC,GSP},t}, \quad \forall u \in \mathrm{GSP}, t \in T. \tag{48}$$

In addition, there is an operating rule in blending gasoline with MTBE. The amount of MTBE in gasoline must be lower than 10%

$$A_{\mathrm{MTBET,MTBE},u,t} \leqslant \mathrm{AF}_{u,t} \times 0.1, \quad \forall u \in \mathrm{GSP}, t \in T. \tag{49}$$

The amount of product from both GSPs are:

$$\text{For GSP91}: \mathrm{AO}_{\mathrm{GSP91,SUPG},t} = \mathrm{AF}_{\mathrm{GSP91},t}, \quad \forall t \in T, \tag{50}$$

$$\text{For GSP95}: \mathrm{AO}_{\mathrm{GSP95,ISOG},t} = \mathrm{AF}_{\mathrm{GSP95},t}, \quad \forall t \in T. \tag{51}$$

The product RON, ARO, and RVPI for both GSPs are given by

$$\mathrm{PO}_{u,c,q,t} = \frac{\sum_{c' \in \mathrm{CO}_{u'}} \sum_{u' \in \mathrm{INT}} (A_{u',c',u,t} \times \mathrm{pro}_{u',c',q})}{\sum_{c' \in \mathrm{CO}_{u'}} \sum_{u' \in \mathrm{INT}} A_{u',c',u,t}}, \quad \forall c \in \mathrm{CO}_u, u \in \mathrm{GSP}, q \in \mathrm{QO}_{u',c'}, t \in T. \tag{52}$$

Moreover, the product properties must satisfy the product specifications:

$$\text{For GSP91}: \mathrm{px}_{\mathrm{SUPG},q} \geqslant \mathrm{PO}_{\mathrm{GSP91,SUPG},q,t} \geqslant \mathrm{pn}_{\mathrm{SUPG},q}, \quad \forall q \in \mathrm{QO}_{\mathrm{GSP91,SUPG}},\ t \in T. \tag{53}$$

$$\text{For GSP95}: \mathrm{px}_{\mathrm{ISOG},q} \geqslant \mathrm{PO}_{\mathrm{GSP95,ISOG},q,t} \geqslant \mathrm{pn}_{\mathrm{ISOG},q}, \quad \forall q \in \mathrm{QO}_{\mathrm{GSP95,ISOG}},\ t \in T. \tag{54}$$

In blending gasoline, four intermediate streams including LN, HN, ISO, and REF are produced from the refinery while MTBE and DCC are purchased from the outside.

JP-1 is a product that is produced by KTU. The total production of JP−1 is given by

$$\mathrm{AF}_{\mathrm{JPT},t} = A_{\mathrm{KTU,JP\text{-}1,JPT},t}, \quad \forall t \in T. \tag{55}$$

The amount of product flow out from JPT is represented by

$$\mathrm{AO}_{\mathrm{JPT,JP\text{-}1},t} = \mathrm{AF}_{\mathrm{JPT},t}, \quad \forall t \in T. \tag{56}$$

High speed diesel (HSD) is produced from six intermediate streams given by

$$\mathrm{AF}_{\mathrm{DSP},t} = \sum_{u \in \mathrm{CDU}} A_{u,\mathrm{IK,DSP},t} + \sum_{u \in \mathrm{CDU}} A_{u,\mathrm{DO,DSP},t} + \sum_{u \in \mathrm{HDS}} A_{u,\mathrm{IHSD,DSP},t}, \quad \forall t \in T \tag{57}$$

The amount of product flow out from DSP is determined by

$$\mathrm{AO}_{\mathrm{DSP,HSD},t} = \mathrm{AF}_{\mathrm{DSP},t}, \quad \forall t \in T. \tag{58}$$

There are three types of fuel oil with different viscosity, pour point and sulphur content: Fuel oil #1 (FO1), Fuel oil #2 (FO2), and Low sulphur fuel oil (FOVS). All fuel oils are blended in FO1P, FO2P, and FOVSP. The following equation represents the feed flow to each fuel oil pool.

$$\text{For FO1P}: \mathrm{AF}_{\mathrm{FO1P},t} = \sum_{u \in \mathrm{CDU}} A_{u,\mathrm{IK,FO1P},t} + \sum_{u \in \mathrm{CDU}} A_{u,\mathrm{FO,FO1P},t}, \quad \forall t \in T, \tag{59}$$

$$\text{For FO2P}: \text{AF}_{\text{FO2P},t} = \sum_{u \in \text{CDU}} A_{u,\text{IK,FO2P},t} + \sum_{u \in \text{CDU}} A_{u,\text{FO,FO2P},t}, \quad \forall t \in T, \tag{60}$$

$$\text{For FOVSP}: \text{AF}_{\text{FOVSP},t} = \sum_{u \in \text{CDU}} A_{u,\text{FO,FOVSP},t}, \quad \forall t \in T. \tag{61}$$

In addition, the recipe used in blending FO1 and FO2 with IK is 7% and 2.5% of the FO1 and FO2 volume, respectively. This is shown in the following equations:

$$\sum_{u \in \text{CDU}} A_{u,\text{IK,FO1P},t} = \text{AF}_{\text{FO1P},t} \times 0.07, \quad \forall t \in T, \tag{62}$$

$$\sum_{u \in \text{CDU}} A_{u,\text{IK,FO2P},t} = \text{AF}_{\text{FO2P},t} \times 0.025, \quad \forall t \in T. \tag{63}$$

The amount of product from all fuel oil pools are given by

$$\text{For FO1P}: \text{AO}_{\text{FO1P,FO1},t} = \text{AF}_{\text{FO1P},t}, \quad \forall t \in T, \tag{64}$$

$$\text{For FO2P}: \text{AO}_{\text{FO2P,FO2},t} = \text{AF}_{\text{FO2P},t}, \quad \forall\, t \in T, \tag{65}$$

$$\text{For FOVSP}: \text{AO}_{\text{FOVSP,FOVS},t} = \text{AF}_{\text{FOVSP},t}, \quad \forall\, t \in T. \tag{66}$$

There are two energy sources burned in this refinery which are FG and FOVS. FG consists of methane and ethane that has been produced in different units. These gases are burned in the refinery to provide the energy required for operation of the different units and to provide utilities (steam, electricity, etc.). There are no purchasing or selling of these gases and there is no fixed demand. Therefore, production of these gases from the process is equal to the burned amount:

$$\text{AO}_{\text{FGT,FG},\,t} = \text{Burned}_{\text{FG},t}, \quad \forall t \in T. \tag{67}$$

On the other hand, FOVS can be sold as a product and burned as an energy source for the plant. The amount of FOVS produced can be calculated from the following equation:

$$\text{AO}_{\text{FOVSP,FOVS},t} - \text{Burned}_{\text{FOVS},t} = \text{MANU}_{\text{FOVS},t}, \quad \forall t \in T, \tag{68}$$

where $\text{AO}_{\text{FOVSP,FOVS},t}$ is equal to the amount of FOVS leaving from the process.

The refinery fuel balance is expressed in fuel oil equivalence and given on a weight basis. The calorific equivalent of 1 ton FG is estimated to be 1.3 ton of FO. The refinery fuel balance equation is

$$\text{Used}_t = (\text{Burned}_{\text{FG},t} \times 0.3 \times 1.3) + (\text{Burned}_{\text{FOVS},t} \times 0.93), \quad \forall t \in T, \tag{69}$$

where 0.3 and 0.93 are specific gravities of FG and FOVS, respectively, $\text{Used}_t$ is the energy consumption for operating the process expressed in ton of fuel oil equivalence (tFOE) which is given by

$$\text{Used}_t = \sum_{u \in U} (\text{AF}_{u,t} \times \text{density}_u \times \text{fuel}_u), \quad \forall t \in T, \tag{70}$$

where $\text{AF}_{u,t}$ is the volume of feed and $\text{density}_u$ is density of feed to each unit. This density is an average value for each unit except CDUs which are different between crude oil types. The energy consumption for each unit is calculated by using $\text{fuel}_u$ which is percent of energy consumption for each unit.

Table 2
Crude oil cost and available quantity

| Crude oil | Cost ($/bbl) | Max volume ($m^3$/month) | Min volume ($m^3$/month) |
|---|---|---|---|
| Oman (OM) | 27.40 | No limit | 0 |
| Tapis (TP) | 30.14 | No limit | 0 |
| Labuan (LB) | 30.14 | 95,392.2 | 0 |
| Seria lt (SLEB) | 30.14 | 95,392.2 | 0 |
| Phet (PHET) | 25.08 | 57,235.32 | 0 |
| Murban (MB) | 28.19 | 95,392.2 | 0 |

Table 3
Product demand, price, and cost of lost demand penalty

| | | LPG | SUPG | ISOG | JP-1 | HSD | FO #1 | FO #2 | FOVS |
|---|---|---|---|---|---|---|---|---|---|
| Demand (period1) | $m^3$ | 14,100 | 42,400 | 20,000 | 46,500 | 145,700 | 15,000 | 67,100 | 33,600 |
| Demand (period 2) | $m^3$ | 14,815 | 55,000 | 25,000 | 60,000 | 170,000 | 10,000 | 80,000 | 30,000 |
| Demand(period 3) | $m^3$ | 14,458 | 48,700 | 22,500 | 53,250 | 157,850 | 12,500 | 73,500 | 31,800 |
| Price (period 1) | US$/bbl | 22.97 | 33.64 | 35.61 | 32.47 | 33.59 | 25.43 | 25.43 | 25.43 |
| Price (period 2) | US$/bbl | 22.46 | 33.91 | 35.92 | 31.65 | 32.75 | 26.64 | 26.64 | 26.64 |
| Price (period 3) | US$/bbl | 22.55 | 34.90 | 36.26 | 33.90 | 34.98 | 26.64 | 26.64 | 26.64 |
| Penalty for demand lost | US$/bbl | 22.97 | 33.64 | 35.61 | 32.47 | 33.59 | 25.43 | 25.43 | 25.43 |

Table 4
Standard deviation of demand and price

| Description | | LPG | SUPG | ISOG | JP-1 | HSD | FO #1 | FO #2 | FOVS |
|---|---|---|---|---|---|---|---|---|---|
| Demand | $m^3$ | 465 | 1,374 | 800 | 6,091 | 7,489 | 896 | 5,272 | 2,280 |
| Price | US$/bbl | 3.75 | 3.10 | 3.12 | 2.88 | 3.21 | 1.92 | 1.92 | 1.92 |

## 5. Results and discussion

The LP planning model was implemented in GAMS using CPLEX 9.0 solver and run on a Pentium IV/ 2.4 GHz PC platform. The time horizon of this problem was divided into three equal time periods.

### 5.1. Input data

Table 2 give the values of crude oil cost and available quantity. It is assumed that the crude oil cost is the same in all periods. Table 3 shows the mean values for demand and price of all products in each time period while Table 4 shows standard deviations of these values. These standard deviations were estimated only from historical data given by the EPPO Thai Energy Data Notebook (EPPO, 2003).

Table 5
Volume and percentage of petroleum purchased for each period from the deterministic model ($m^3$)

| Crude oil | Available quantity | First period | | Second period | | Third period | |
|---|---|---|---|---|---|---|---|
| OM | No limit | 149,822 | 39.65% | 154,311 | 36.22% | 174,909 | 36.30% |
| TP | No limit | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% |
| LB | 95,392 | 0 | 0.00% | 23,739 | 5.57% | 95,392 | 19.80% |
| SLEB | 95,392 | 75,416 | 19.96% | 95,392 | 22.39% | 58,876 | 12.22% |
| PHET | 57,235 | 57,235 | 15.15% | 57,235 | 13.43% | 57,235 | 11.88% |
| MB | 95,392 | 95,392 | 25.25% | 95,392 | 22.39% | 95,392 | 19.80% |
| Total | | 377,865 | 100.00% | 426,070 | 100.00% | 481,805 | 100.00% |
| Total (kbd) | | 79 | | 89 | | 101 | |
| GRM | 7.376 US$M | | | | | | |

Table 6
Percentage of crude fed to each CDU

| Crude oil | Cost ($/bbl) | First period | | Second period | | Third period | |
|---|---|---|---|---|---|---|---|
| | | CDU2 | CDU3 | CDU2 | CDU3 | CDU2 | CDU3 |
| OM | 27.40 | 13.80 | 55.08 | 12.66 | 55.08 | 12.64 | 51.82 |
| TP | 30.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| LB | 30.14 | 0.00 | 0.00 | 12.53 | 0.00 | 31.70 | 12.00 |
| SLEB | 30.14 | 45.67 | 4.61 | 44.60 | 4.61 | 25.67 | 3.41 |
| PHET | 25.08 | 40.53 | 0.00 | 30.21 | 0.00 | 30.00 | 0.00 |
| MB | 28.19 | 0.00 | 40.31 | 0.00 | 40.31 | 0.00 | 32.78 |
| Total | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Total (kbd) | | 29.61 | 49.61 | 39.72 | 49.61 | 40.00 | 61.02 |

### *5.2. Deterministic model results*

Optimization results of the deterministic model using mean values show a Gross Refinery Margin (GRM) of US$M 7.376 with less than a second of execution time on a Pentium IV 2.4 GHz and 1 GB memory (790 variables and 690 constraints). The amount of the crude oil purchased is shown in Table 5 whereas the percentage of the crude oil fed to each CDU is shown in Table 6.

Crudes SLEB, PHET, and MB are purchased at the maximum available quantity. Crude PHET is fed to CDU2 only due to the high pour point in the fuel oil portion. This high pour point property is not suitable for the production of FO1 and FO2 (low pour point fuel oil). In addition, crude PHET has to be fed to CDU2 only due to the limitation of unit. For crude OM, Table 6 shows that OM is the major supply for CDU3. This can be understood since OM is an important crude in low pour point fuel oil (FO1 and FO2) production, which is produced from CDU3. The FO portion of crude OM is the only one with pour point in the range of FO1 and FO2 specification. In the second and third periods, crude LB is used because the demand in HSD product is higher. The DO portion of LB is the highest volume of all crude oils.

### *5.3. Stochastic model results*

The stochastic model takes into account that the demand and price of products are uncertain. The model was solved for 600 scenarios. The demand and price were randomly generated independently for each

Table 7
Volume and percentage of petroleum purchased for each period from the stochastic model ($m^3$)

| Crude oil | Available quantity | First period | | Second period | | Third period | |
|---|---|---|---|---|---|---|---|
| OM | No limit | 153,856 | 36.53% | 154,436 | 36.13% | 220,126 | 38.46% |
| TP | No limit | 0 | 0.00% | 0 | 0.00% | 8,815 | 1.54% |
| LB | 95,392 | 19,315 | 4.59% | 24,962 | 5.84% | 95,392 | 16.67% |
| SLEB | 95,392 | 95,392 | 22.65% | 95,392 | 22.32% | 95,392 | 16.67% |
| PHET | 57,235 | 57,235 | 13.59% | 57,235 | 13.39% | 57,235 | 10.00% |
| MB | 95,392 | 95,392 | 22.65% | 95,392 | 22.32% | 95,392 | 16.67% |
| Total | | 421,191 | 100.00% | 427,418 | 100.00% | 572,353 | 100.00% |
| Total (kbd) | | 88 | | 90 | | 120 | |

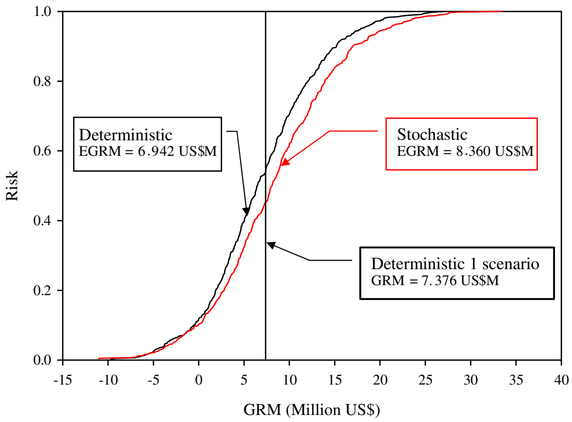


Fig. 3. Risk curves of the deterministic and stochastic model solutions.

variable by sampling from a normal distribution. The rest of the parameters are the same as the one in the base case of the deterministic model.

As stated above the methodology used is based on running the deterministic models using the parameters for each scenario, followed by running the same model for all the scenarios with the first stage variables obtained in the first run fixed. The execution time used to run all scenarios (600 scenarios) with the first stage decisions fixed is about 10 min. The volumes of petroleum purchased corresponding to the solution having the largest expected profit are shown in Table 7.

The type of primary crude oil selected is the same as in the case of the solution obtained using deterministic model, i.e. PHET, MB, and SLEB. This reflects simply that these crudes provide a high margin. The volumes purchased are, however, different.

### 5.4. Risk management

The risk curves of the stochastic solution and deterministic solution are compared in Fig. 3. As stated above, the stochastic solution was obtained by choosing the solution with highest EGRM from all the solutions obtained. We first note that that expected GRM of the deterministic solution is different from the GRM cited in Table 5. In fact, it is lower. The reason is that the expected value is calculated fixing the first

Table 8
Expected profit VaR and opportunity value for selected nondominated solutions (in US$M)

| Generating scenario | EGRM | VaR (5%) | OV (95%) | Area ratio | VaR reduction (from stochastic solution) (%) | EGRM reduction (from stochastic solution) (%) | OV reduction (from stochastic solution) (%) |
|---|---|---|---|---|---|---|---|
| 227 (Stochastic solution) | 8.360 | 11.128 | 12.407 | — | — | — | — |
| 309 (Alternative solutions) | 8.250 | 10.268 | 11.109 | 1.61 | 7.73 | 1.32 | 10.47 |
| 576 | 8.064 | 9.912 | 10.955 | 3.12 | 10.93 | 3.54 | 11.71 |
| 553 | 8.035 | 10.596 | 11.108 | 4.42 | 4.78 | 3.89 | 10.47 |
| 145 | 7.999 | 9.798 | 10.811 | 3.75 | 11.95 | 4.32 | 12.87 |
| 74 | 7.985 | 9.769 | 10.397 | 3.60 | 12.22 | 4.48 | 16.20 |
| 600 | 7.971 | 9.666 | 10.706 | 3.68 | 13.14 | 4.65 | 13.71 |
| 112 | 7.903 | 9.762 | 10.594 | 4.94 | 12.28 | 5.47 | 14.62 |
| 445 | 7.890 | 10.028 | 10.961 | 5.37 | 9.89 | 5.62 | 11.65 |

Table 9
Volume and percentage of petroleum purchased for alternative solution ($m^3$)

| Crude oil | Available quantity | First period | | Second period | | Third period | |
|---|---|---|---|---|---|---|---|
| OM | No limit | 155,884 | 36.13% | 164,416 | 39.72% | 180,136 | 36.29% |
| TP | No limit | 0 | 0.00% | 6,433 | 1.55% | 0 | 0.00% |
| LB | 95,392 | 27,543 | 6.38% | 0 | 0.00% | 95,392 | 19.22% |
| SLEB | 95,392 | 95,392 | 22.11% | 90,415 | 21.85% | 68,198 | 13.74% |
| PHET | 57,235 | 57,235 | 13.27% | 57,235 | 13.83% | 57,235 | 11.53% |
| MB | 95,392 | 95,392 | 22.11% | 95,392 | 23.05% | 95,392 | 19.22% |
| Total | | 431,447 | 100.00% | 413,892 | 100.00% | 496,353 | 100.00% |
| Total (kbd) | | 90 | | 87 | | 104 | |

stage variables to be those of Table 5 and then running the model against all scenarios. More important, this plot shows that the stochastic solution provides a higher expected GRM than deterministic solution with the lower risk. The risk curves of the stochastic solution are fairly stretched around the GRM of the deterministic solution.

After all dominated solutions (solutions whose risk curve lies entirely on the left of the stochastic solution) have been removed, we identified a series of non-dominated solutions (solutions that cross the stochastic solution). The expected GRM, VaR and opportunity value (or upside potential, as well as the area ratio for these solutions is shown in Table 8. The solutions are ordered in descending order of expected GRM.

Notably, in Table 8, the first solution has large VaR reduction (7.73%) and a very small expected profit reduction (1.32%). In addition, one property of all these solutions is that the probability of loosing money, that is the cumulative probability for profit zero, is very much around 10% for all these solutions. Had this been different, this probability, together with VaR would play a role in choosing a solution that would manage risk. This alternative plan for purchasing crude oil which is obtained from scenario 309 can be found in Table 9. The VaR reduces from 11.13 to 10.27 or 7.73% in the result of the second versus first plan

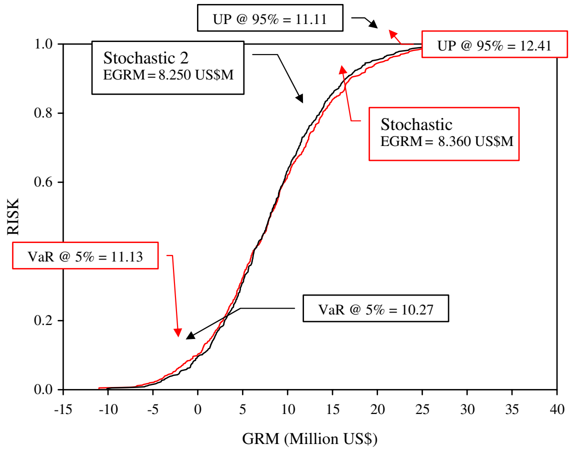


Fig. 4. Risk curves corresponding to the two more profitable stochastic model solutions.

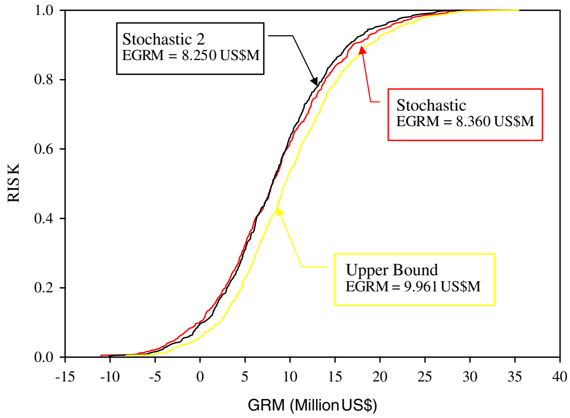


Fig. 5. Upper bound risk curve for the stochastic solution.

and the UP is educed from 12.41 to 11.11 or 10.47%. This result shows that the second plan is more robust than the first plan. In other word, the GRM at 5% and 95% risk of second plan has less deviation from the expected GRM than the first plan.

This alternative plan suggests purchasing TAPIS crude in the second period and lower amount of crude oil purchased in the third period. Fig. 4 shows the risk curve of the stochastic solution and its alternative choice. It is important to note that, decreasing in crude oil purchase resulted in lower risk of loss but also a lower a chance to make a higher profit (10.47%). This second plan may be preferred by a risk-averse decision maker. The Risk Area Ratio (RAR) is equal to 1.6. This means that the loss in opportunity of second plan is more than one half of gain in risk reduction. The closer this number to one, the better the alternative solution behaves in terms of reducing risk on the downside while maintaining the opportunities on the upside.

Finally, Fig. 5 shows the upper bound risk curve together with the two stochastic solutions. The upper bound curve has an expected GRM of 9.96 U$M, which is 19% above the best obtained result. No solution can have a higher value than this. In fact, it is unknown if in this gap between the upper bound and the best solution another solution exists.

## 6. Conclusions

In this work, a two-stage stochastic optimization approach to the refinery planning was used to show how one can manage financial risk. The models were tested on the simplified process of the Bangchak Petroleum Public Company Limited. When uncertainty was considered, the risk curve of the deterministic solution provided a lower expected GRM and a higher risk. It was also shown that the procedure used, which is based on the use of the sampling average algorithm to solve two stage stochastic problems, one can find alternative solutions with smaller risk but also with not so much loss in expected profit or upside potential.

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## Appendix

We review here some of the essential features of Two-stage stochastic programming and some recent measures and procedures to manage financial risk.

### *A.1. Two-stage stochastic programming*

This kind of problems is characterized by two essential features: the uncertainty in the problem data and the sequence of decisions (Barbaro and Bagajewicz, 2004). Some model parameters are accounted as random variables with a certain probability distribution. In turn, some of these decisions must be made with incomplete information about the future (these are called first stage decisions or some time "here and now" decisions). Then, as some of the uncertainties are revealed, the remaining decisions are made (called second-stage or recourse decisions). Among the two-stage stochastic models, the expected value of the cost (or profit) resulting from optimally adapting the plan according to the realizations of uncertain parameters is referred to as the recourse function.

Solving this kind of model involves maximization or minimization of expected profits or expected cost. Expectations are obtained by representing uncertainties through a number of scenarios constructed via sampling.

The general form of a two-stage linear stochastic problem with fixed recourse and a finite number of scenarios can be defined as (Birge and Louveaux, 1997):

$$\text{Max } E[\text{Profit}] = \sum_{s \in S} p_s q_s^{\mathrm{T}} y_s - c^{\mathrm{T}} x \tag{A.1}$$

$$\begin{aligned} \text{s.t.} \quad & Ax = b \\ & T_s x + W y_s = h_s, \quad && s \in S, \\ & x \geq 0, && x \in X, \\ & y_s \geq 0, && \forall s \in S. \end{aligned}$$

In the above model, first-stage decisions are represented by variable $x$ and second-stage decisions are represented by variable $y_s$, which has probability $p_s$. The objective function contains a deterministic term, $c^T x$, and the expectation of the second-stage objective, $q_s{}^T y_s$, taken over all realizations of the random event $s$. For a given realization of the random events, $s \in S$, the second-stage problem data $q_s$, $h_s$, and $T_s$ become known, and then the second-stage decisions, $y_s$(x), must be made. Very often the recourse matrix $W$, is fixed.

### A.2. Financial risk

According to Barbaro and Bagajewicz (2004), financial risk related with a planning project can be defined as the probability of not meeting a certain target profit (maximization) or cost (minimization) level. Several alternative point measures have also been used.

Value at Risk (VaR) is defined as the expected loss for a certain confidence level usually set at 5% (Jorion, 2000). A more general definition of VaR is given by the difference between the mean value of the profit and the profit value corresponding to the $p$-quantile (value at $p$ risk). VaR has been used as a point measure very similar to the variance. VaR measures the deviation of the profit at 5% risk from the expected value. However, VaR can only be used as a measure of robustness, but not risk. To relieve these difficulties, Aseeri and Bagajewicz (2004) proposed that VaR be compared to a similar measure, the Upside Potential (UP) or Opportunity Value (OV), defined in a similar way to VaR but at the other end of the risk curve with a quantile of $(1-p)$ as the difference between the value corresponding to a risk of $(1-p)$ and the expected value. They discussed the need of the Upside Potential for a good evaluation of the project.

VaR and UP are point measures and do not represent the behavior of the entire risk curve, only its values at certain points. Aseeri and Bagajewicz (2004) proposed a method that compares the areas between two curves. The proposed ratio, the Risk Area Ratio (RAR), can be calculated as the ratio of the Opportunity Area (O_Area), enclosed by the two curves above their intersection, to the Risk Area (R_Area), enclosed by the two curves below their intersection (Eq. (A.2) and Fig. A.1).

$$\mathrm{RAR} = \frac{\mathrm{O\_Area}}{\mathrm{R\_Area}} \tag{A.2}$$

Note that this is only true if the second curve is minimizing risk in the downside region. If risk on the upside is to be minimized, then the relation is reversed (i.e. O_Area is below the intersection and R_Area is above it).

In addition, Aseeri and Bagajewicz (2004) have proposed the construction of an upper bound curve. The upper bound risk curve is defined as the curve constructed by plotting the set of net present values (NPV) for the best design under each scenario, that is by using all "wait and see" solutions. Fig. A.2 shows the

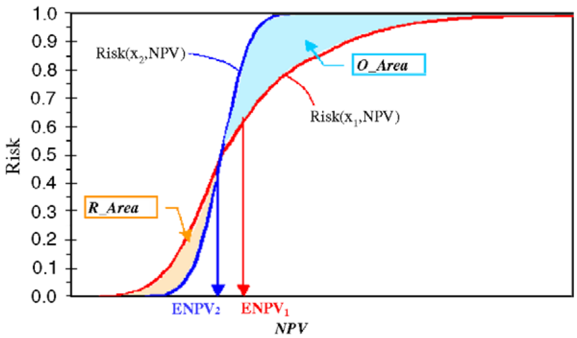


Fig. A.1. Risk Area Ratio (Aseeri and Bagajewicz, 2004).

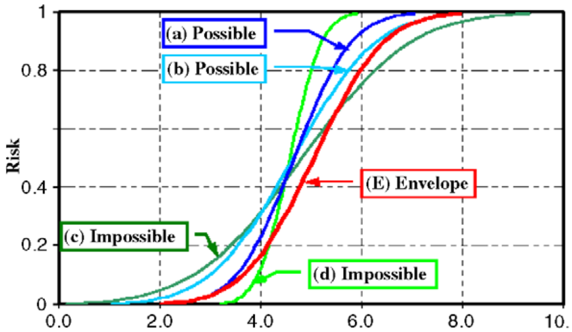


Fig. A.2. Upper bound (Envelope) risk curve (Aseeri and Bagajewicz, 2004).

upper bound risk curve and curves corresponding to possible and impossible solutions. The risk curve for any feasible design is positioned entirely above (to the left of) the upper bound risk curve (Aseeri and Bagajewicz, 2004).

### *A.3. Use of the sampling algorithm (Verweij et al., 2001)*

In this method, a relatively small number of scenarios are generated. Then, the deterministic model is run for each scenario. After these series of solutions are obtained, the first stage variables of each of these solutions are called ''designs'' and are used as fixed numbers to run the deterministic model for all the scenarios again. Sometimes, more scenarios than those used to generate ''designs'' are used in this phase. Thus, each of these set of runs performed with the first stage variables fixed, provide a profit for each scenario from which a risk curve can be constructed. The result tends asymptotically to such optimum which was proven by Aseeri and Bagajewicz (2004). Once all risk curves are generated the curve with the highest EGRM is chosen. The curves which are dominated by this highest EGRM (completely to the left of the highest EGRM curve) are disregarded and the others (nondominated curves) are selected as alternative solutions.

## References

Aseeri, A., Bagajewicz, M.J., 2004. New measures and procedures to manage financial risk with applications to the planning of gas commercialization in Asia. Computers & Chemical Engineering 28 (12), 2791–2821.

Barbaro, A., Bagajewicz, M.J., 2004. Managing financial risk in planning under uncertainty. AIChE Journal 50 (5), 963–989.

Birge, J.R., Louveaux, F., 1997. Introduction to Stochastic Programming. Springer, New York.

Bopp, A.E., Kannan, V.R., Palocsay, S.W., Stevens, S.P., 1996. An optimization model for planning natural gas purchases, transportation, storage and deliverability. Omega 24 (5), 511–522.

EPPO, 2003. Energy Data Notebook Quarterly Report, Energy Policy and Planning Office. Ministry of Energy, Thailand.

Escudero, L.F., Quintana, F.J., Salmerón, J., 1999. CORO, a modeling and an algorithmic framework for oil supply, transformation and distribution optimization under uncertainty. European Journal of Operational Research 114, 638–656.

Favennec, J.P. (Ed.), 2001. Refinery operation and management. Petroleum Refining, Vol. 5. Technip, Paris.

Glismann, K., Gruhn, G., 2001. Short-term scheduling and recipe optimization of blending processes. Computers & Chemical Engineering 25, 627–634.

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

Guldmann, J.M., Wang, F., 1999. Optimizing the natural gas supply mix of local distribution utilities. European Journal of Operational Research 112, 598–612.

Hsieh, S., Chiang, C.C., 2001. Manufacturing-to-sale planning model for fuel oil production. Advanced Manufacturing Technology 18, 303–311.

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

Jia, Z., Ierapetritou, M., Kelly, J.D., 2003. Refinery short-term scheduling using continuous time formulation: crude-oil operations. Industrial & Engineering Chemistry Research 42, 3085–3097.

Jorion, P., 2000. Value at Risk, The New Benchmark for Managing Financial Risk, 2nd ed. McGrawHill, NewYork.

Joly, M., Moro, L.F.L., Pinto, J.M., 2002. Planning and scheduling for petroleum refineries using mathematical programming. Brazilian Journal of Chemical Engineering 19 (2), 207–228.

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

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

Liu, M.L., Sahinidis, N.V., 1996. Optimization in process planning under uncertainty. Industrial & Engineering Chemistry Research 35, 4154–4165.

Liu, M.L., Sahinidis, N.V., 1997. Process planning in a fuzzy environment. European Journal of Operational Research 100, 142–169.

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

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

Neiro, S.M.S., Pinto, J.M., 2003. Supply chain optimization of petroleum refinery complexes. FOCAPO Proceedings, Coral Springs, FL, pp. 59–72.

Pinto, J.M., Joly, M., Moro, L.F.L., 2000. Planning and scheduling models for refinery operations. Computers & Chemical Engineering 24, 2259–2276.

Pinto, J.M., Moro, L.F.L., 2000. A planning model for petroleum refineries. Brazilian Journal of Chemical Engineering 17 (4–7), 575–586.

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

Shah, N., 1998. Single and multisite planning and scheduling: Current status and future challenges. FOCAPO AIChE Symposium Series 94 (320), 91–110.

Verweij, B., Ahmed, S., Kleywegt, A.J., Nemhauser, G., Shapiro, A., 2001. The sample average approximation method applied to stochastic routing problems: A computational study. Computational and Applied Optimization 24, 289–333.

Wenkai, L., Hui, C.W., Hua, B., Tong, Z., 2002. Scheduling crude oil unloading, storage, and processing. Industrial & Engineering Chemistry Research 41, 6723–6734.

Zhang, N., Zhu, X.X., 2000. A novel modeling and decomposition strategy for overall refinery optimization. Computers & Chemical Engineering 24, 1543–1548.