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A Model-Based Investment Assessment for Heavy Oil Processing in the Petroleum Refining Industry

Cheng Seong Khor

Abstract

The need for heavy oil processing has increased in recent years worldwide, backed by higher demands for petroleum products in the face of declining light crude oil resources. The situation encourages refineries to focus more on maximizing the production of high-value outputs from this lower-value heavier feedstock. This study purports to assess heavy oil processing potential in the refining industry through model-based economic evaluation. We formulate a refinery model suitable for preliminary investment decision making, which considers various cost elements for a number of conventional commercial heavy oil processing technologies. The formulated model is applied to a case study on the worldwide potential for heavy oil processing. This chapter demonstrates the application of a model-based approach to perform or assist with investment assessment.

Keywords: refinery design, optimization model, linear programming, residue fluid catalytic cracking (RFCC), fluid coking

1. Introduction

Heavy crude oil upgrading has gained the interests of refineries as demand for petroleum products increased in the face of declining lighter crude oil resources. In today's market, there are abundant heavier crude oils in the market as compared to conventional lighter ones. However, multiple competing technologies exist with a wide range of product yields and energy (or utility) requirements to refine these heavy oil resources [1, 2].

Heavy crude oils contain high fractions of residue and are generally classified by the density measure of API gravity of less than 20. The residue requires additional upgrading processes to break the complex molecular structure in obtaining valuable products. Residue upgrading processes include several thermal and catalytic processes, which can be categorized as carbon rejection or hydrogen addition. Examples of carbon rejection processes are delayed coking (DCK), visbreaking (VB), fluid coking (FCK), and solvent deasphalting, while hydrogen addition technologies include fixed bed hydroprocessing (e.g., Hyvahl F) and ebullated bed hydroprocessing (e.g., LC Fining) [3].

Integrating these technologies into refinery systems requires a systems approach-based economic evaluation instead of relying on, for example, monovariable decision making such as solely based on attaining the highest product yields. The increasing demand for high-value petroleum products and declining for that of bottom distillate products encourage refinery to give more focus on maximizing the yields on heavier crudes. In addition to that, the price for heavy crude oils is generally lower than lighter crude oils. Installing and operating heavy oil upgrading technologies enable refineries to buy cheaper feedstock and still produce high-value marketable products [4].

There are available refinery optimization models of various complexities in terms of time and space scales, which give rise to different computational requirements as based on the purpose and activity. For high-level decision making, linear programming (LP) models are suitable when only preliminary results are needed [5–8]. Nonlinear and/or mixed-integer models have been proposed for detailed refinery design [9–12] and for operation management [13–15]. A recent review on refinery optimization advances, which encompass developments in both academic and industrial settings, is available in [16].

The present work attempts to contribute toward assessing heavy oil processing potential in the petroleum refining industry by adopting a model-based economic evaluation approach. Using product demands and crude oil feed properties as base data, a refinery model can be developed to evaluate potentially profitable technologies including those for residue oil upgrading. For this purpose, we formulate an optimization model suitable for a preliminary high-level investment decision making with an appropriate economic objective function and a set of constraints that consider a number of conventional commercial technologies. A case study using available current data on market conditions is illustrated to carry out the intended assessment. A secondary goal of the study is to demonstrate the use of a standard business productivity tool (such as an Excel spreadsheet) to conduct such an assessment.

2. Problem statement

We consider the following investment decision-making problem for heavy oil processing in refineries. Given the (a) fixed market demand for desired refinery products and their prices, (b) available process technologies and their cost structures and capacities, and (c) cost of crude oil (single type or mixtures) and their nominal product yields, we wish to determine the optimal process technologies or units and their indicative processing capacities (flow rates) by minimizing the total operating cost, which mainly consist of utility requirements on energy demand for processing operations.

3. Optimization model formulation

A refinery model suitable for preliminary investment decision making is posed as a linear optimization (LP) model. The model admits process parameters for heavy oil processing including raw material availabilities, nominal product yields of a number of representative commercial technologies, market demands and prices for main product streams, and global processing or product capacities besides various cost-related economic parameters. An optimum solution is determined as a point in the solution space, which minimizes an economic-based objective function that stipulates the total operating cost for all heavy oil processing technologies considered that is feasible in satisfying all the associated constraints encompassing the aforementioned economic parameters.

This model uses the following notations:

Parameters

- $yd_{i,u}$ yield of component i from unit u
- oc_u operating cost of unit u
- nc_i capacity expansion cost of component i
- cp_u capacity of process unit u
- dm_i product demand of component i

Variables

- $F_{i,u}$ inlet flow rate of component i to unit u
- Z_i new capacity flow rate of component i

A compact representation of the optimization model formulation is presented and explained as follows:

$$\text{Minimize } \sum_{i,u} oc_u F_{i,u} + \sum_i nc_i Z_i \quad (1)$$

$$\text{Subject to } \sum_u yd_{i,u} F_{i,u} = 0, \forall i \in I \quad (2)$$

$$\sum_i yd_{i,u} F_{i,u} = 0, \forall u \in U \quad (3)$$

$$\sum_i F_{i,u} \leq cp_u, \forall u \in U \quad (4)$$

$$Z_i + \sum_u F_{i,u} \geq dm_i, \forall i \in I \quad (5)$$

$$F_{i,u}, Z_i \geq 0, \forall i \in I \quad (6)$$

where the minimizing objective function shown in Eq. 1 caters for operating cost oc_u , which consists of raw material cost on crude oils and utility cost of process units as based on their inlet flow rates as well as capacity expansion cost nc_i to meet market demands dm_i . Eq. 2 describes component balances for each material i using fixed yield coefficients $yd_{i,u}$ (on mass basis), which render linear relation between the feed inputs and product outputs of unit u that are implicitly dependent on the unit's operating conditions. On the other hand, Eq. 3 represents the total material balances for each unit u . Eq. 4 ensures that the total inlet flows into unit u does not exceed its maximum capacity cp_u in determining the required processing level. Eq. 5 stipulates that total processing rates for material i meet or exceed its demand dm_i including a provision for new capacity Z_i (or alternatively available product imports) to cover market requirements. Equation 6 enforces nonnegative values for all the decision variables.

4. Case study

We consider a case study of assessing the worldwide potential for heavy oil processing in the downstream petroleum processing sector by applying the foregoing model. Economic model parameters are estimated based on commercial data available in the literature as cited for **Tables 1–4**. The raw material is assumed to be a vacuum residue stream available from a vacuum distillation unit or, alternatively, a vacuum rerun unit with comparable processing capacity.

Product	Price (\$/kg)	Demand (kg/hour)	Reference
Dry gas	0.0078	6000	[17, 18]
Total LPG	0.0020	30,000	[18, 19]
Gasoline	0.0097	150,000	[20, 21]
Diesel	0.0039	121,000	[18, 22]
Gas oil	0.0031	40,000	[18, 22]
Coke	0.0027	60,000	[23]

Table 1.
Model economic parameters for products used in this chapter.

The products of each process technology are categorized according to their cut temperatures. Product yields of process technologies are typically given in volume percentages in the literature. To make use of mass conservation principle, we convert them to weight percentages by assuming fixed densities of the product and feed components. The weight-based yields are then normalized as listed in **Table 2** according to the process technologies for use as input-output constants in the process unit material balances described by Eqs. (2) and (3).

Table 1 gives the product economic parameters in terms of selling prices and market demands. The operating cost data for the heavy oil process technologies are summarized in **Tables 3** and **4**. Annual operating time is taken to be 8150 hours per year corresponding to an onstream factor of about 93% (0.9304).

The technologies considered in this case study (with their associated abbreviations in parentheses as used in **Tables 3** and **4**) are delayed coking (DCK); fluid coking (FCK); fluid catalytic cracking (FCC); visbreaking (VB); ebullated bed hydrocracking technology of LC Fining (LCF); Cherry-P (CP) and fluid thermal cracking (FTC) technologies; residual fluid catalytic cracking (RFCC) technologies of heavy oil treating (HOT), heavy oil cracking (HOC), and R2R (roughly stands for residue cracking with two-step regeneration); solvent deasphalting technology of MDS; and other residue hydrotreating and hydroconversion technologies of asphaltenic bottoms cracking (ABC) and Hyvahl F (HF).

Further, we consider several assumptions in representing operating requirements of these technologies. Solvent deasphalting operation depends on the solvent type. Visbreaking is a relatively inexpensive mild thermal cracking process that is assumed to generate steam on a net basis, which can be sold (i.e., negative steam cost), while its cooling utility uses air instead of water. Delayed coking requires a furnace to heat the feed stream for coke removal; thereby, it uses a large fuel quantity as compared to other technologies. Fluid coking is a catalytic operation which uses steam for heating and air or water for cooling. Heavy oil cracking (HOC) is similar to fluid catalytic cracking (FCC) with the capability to remove heat from the generator, which can be recovered to produce steam, thus contributing as revenue (i.e., negative steam cost). Hydrotreating (HDT) heavy oil consumes hydrogen in the reaction scheme to decrease carbon-to-hydrogen ratio, in which the model considers the worst-case operating requirements for cycle oil feed. Due to limited literature data, cost parameters for certain technologies are approximated to similar ones (e.g., LC fining to FCK).

We use the model to conduct a general assessment of the probable technologies required to meet heavy oil processing capacity globally. The result obtained is graphically summarized in **Figure 1**. The objective value on total annualized cost of heavy oil processing is found to be about 164.2 million US\$ with total utility cost for the selected units determined to make up 80%, while that of raw material cost only

Product	Technology													
	DCK	FCK	FCC	VB (low ^a)	VB (high ^b)	LCF	CP	FTC	HOT	HOC	MDS	ABC	HF	R2R
Dry gas	0.8	1.1	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total LPG	12.5	11.0	15.0	2.0	2.3	2.6	0.0	0.0	0.0	12.4	0.0	0.0	0.0	0.0
Naphtha	16.8	19.2	42.1	5.5	6.2	12.0	6.6	16.5	13.0	53.7	0.0	7.5	0.0	63.0
Middle distillate	14.9	22.9	20.6	10.5	11.8	41.2	30.7	38.2	9.7	14.6	61.2	17.9	4.2	18.1
Gas oil	33.6	13.1	10.1	82.0	79.7	44.2	62.7	24.2	28.7	8.8	38.8	74.5	25.5	4.8
Coke	21.5	32.7	10.4	0.0	0.0	0.0	0.0	21.1	48.6	10.6	0.0	0.0	70.3	14.1

^aLow API feed.

^bHigh API feed.

Table 2.
 Product yields (in normalized weight percentages) for process units used in this work [24–26].

Technology	Electricity (kWh/b)	HPS (lb/b)	LPS (lb/bl)	Fuel (kBtu/b)	CW (gpm/ b/hour)	Cat (lb/b)	H ₂ (ft ³ /b)	Total (\$/(year- (kg/hour))
MDS	0.133	60	—	80	—	—	—	266.4
VB	0.033	-50	—	80	—	—	—	265.8
DCK	0.239	—	40	120	0.6	—	—	403.5
FCK	0.865	200	100	—	30	—	—	273.9
FCC	0.067	—	20	80	400	0.3	—	312.2
HOC	0.017	—	-80	80	—	0.25	—	267.0
HDT	0.093	—	—	24	400	—	900	128.3

Notes: HPS = HP steam, LPS = LP steam, CW = cooling water, Cat = catalyst, H₂ = hydrogen, unit b = barrel (0.136 barrel = 1000 kg), gpm = gallon/minute.

Table 3.
Utility requirements (base data) and cost for heavy oil process technologies [21].

Technology	Parameter							
	Basis	Operating cost (\$·year ⁻¹ (kg/hour) ⁻¹)						
		SDA	VB	DC	FCK	FCC	HOC	HDT
Electricity tariff	0.060 \$/kWh	0.133	0.033	0.239	0.865	0.067	0.017	0.093
HP ¹ steam cost	0.0045 \$/lb	0.299	-0.249	0.200	1.330	0.100	-0.399	0.036
LP ² steam cost	0.003 \$/lb							
Fuel cost	3.000 \$/kBtu	266.0	266.0	399.0	0.0	266.0	266.0	79.8
Cooling water cost	0.10 \$/gal	0.000	0	3.990	3.325	44.336	0.000	44.34
Catalyst cost	5.00 \$/lb	0.000	0.000	0.000	0.000	1.663	1.386	0.000
Hydrogen cost	0.004 \$/ft ³	0.000	0.000	0.000	0.000	0.000	0.000	3.990
Total	—	266.4	265.8	403.5	273.9	312.2	267.0	312.2
Capacity (ton/hour)	—	173.3	141.6	130.8	130.8	288.8	173.3	288.8

¹High pressure.

²Low pressure.

Table 4.
 Operating cost parameters [21].

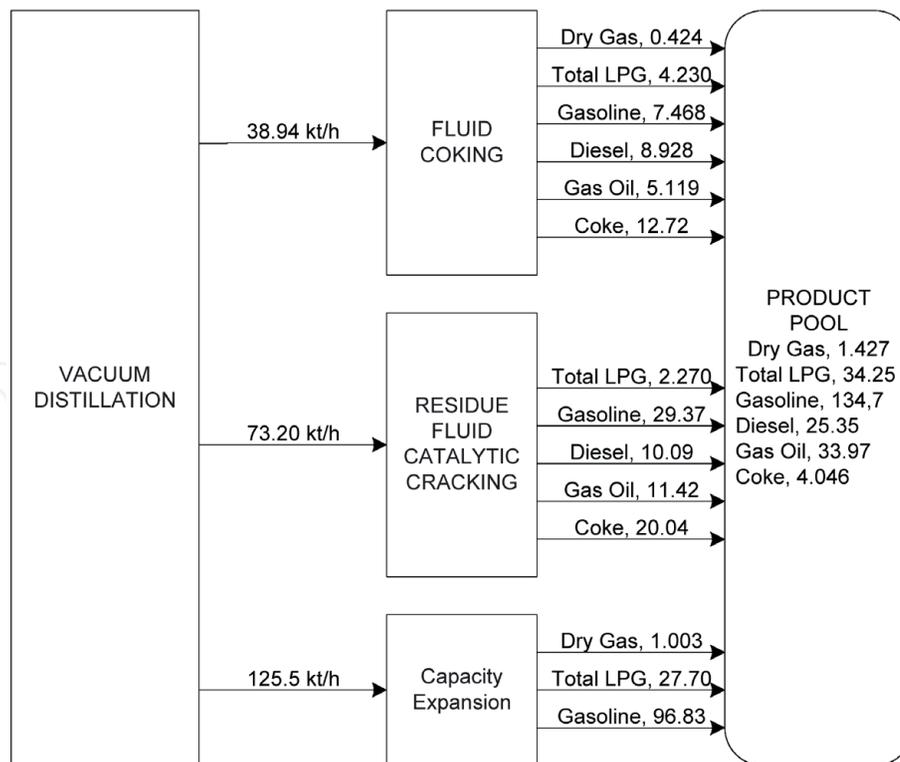


Figure 1. Model solution for the case study (all flow rates in kiloton per hour).

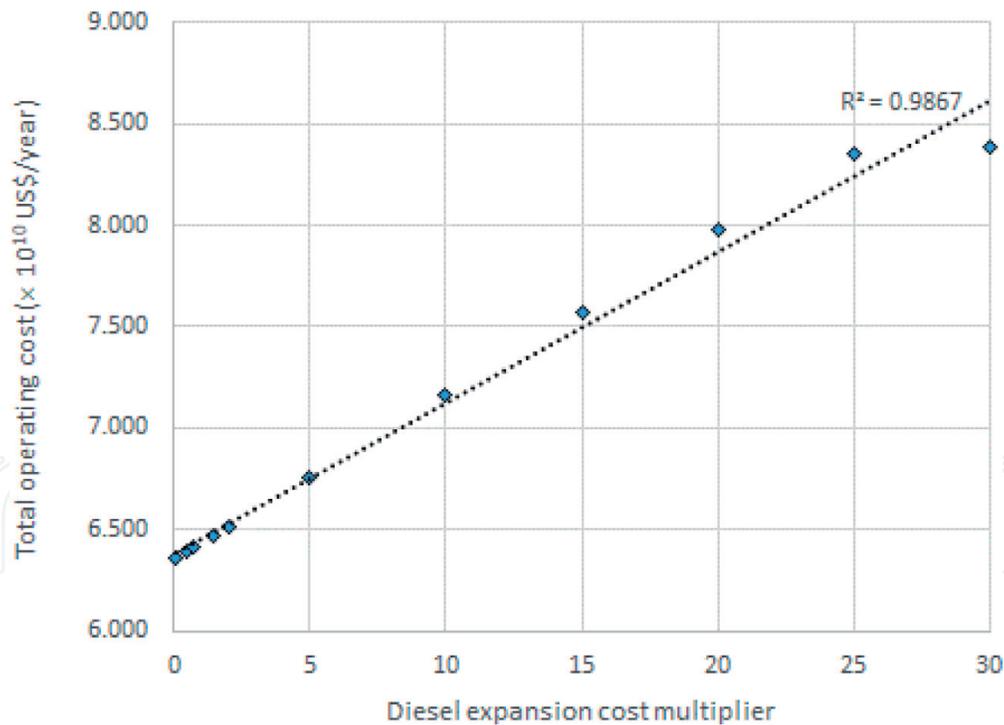


Figure 2. Sensitivity analysis on effect of diesel capacity expansion cost on total operating cost.

17%. RFCC can account for nearly 31% of the available capacity, while the remaining can be met by a fluid coking technology. The potential RFCC technologies identified include HOC, HOT, and R2R [24]. It is also projected that there is demand for 53% of capacity expansion for heavy oil processing.

In general, RFCC can be designed compactly to produce high yields of valuable products with low maintenance cost as similar to the FCC technology that it is based upon. Fluid coker is reported to promote reactor heat transfer, which allows it to be

operated at high temperature for high product yields with increased product separation into valuable products. It also uses burner operated with steam and air as utilities as opposed to an expensive fuel, which is reflected in its low operating cost [26, 27].

We conduct sensitivity analysis to examine how the model parameter values influence the solution. As an example, **Figure 2** shows the linear effect of varying the capacity expansion cost for diesel product output (in terms of a fixed multiplicative factor) on the total operating cost for heavy oil processing as is considered in our case study. Indeed, a trend of continuous high demand for distillate products (including diesel) necessitates correspondingly increased investment in the processing cost.

The model implemented in Excel (version for Microsoft Office 365) is freely available upon request from the author.

5. Concluding remarks

This chapter presents a model-based approach to conduct a preliminary assessment for investment decision making in heavy oil processing for refineries. The economic evaluation can be carried out using an Excel spreadsheet or other similar business productivity tools. The results provide an order of magnitude indication of refining capacity potential for this increasingly important resource in the hydrocarbon industry.

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