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Petroleum Refining Operations: Key Issues, Advances, and Opportunities

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Enterprise-wide optimization for the petroleum refining industry involves optimization of the supply chain involving manufacturing and distribution with emphasis on integration of the different decision making levels. The key manufacturing operations include crude oil loading and unloading, mixing of crude oil, production unit operations of conversion and separation, operations of blending, and distribution of products. Other components of the petroleum supply chain network include oil explorations, crude oil procurement, and sales and distribution of products. The main issues present in the petroleum industry across various decision levels (strategic, tactical, and operational) and within oil refinery operations are discussed. This paper presents an extensive literature review of methodologies for addressing scheduling, planning, and supply chain management of oil refinery operations. An attempt is also made to identify the future challenges in efficiently solving these problems.

1. Introduction

The petroleum refining industry is the largest source of energy products in the world and is supplying about 39% of total U.S. energy demand and 97% of transportation fuels. Oil refinery transforms crude oil into gasoline, diesel, jet fuel, and other hydrocarbon products that can be used as either feedstocks or energy source in chemical process industry. Petroleum refining has grown increasingly complex in the last 20 years as a result of tighter competition, stricter environmental regulations, and lower-margin profits. Furthermore, in the modern global economy, most oil industries involve multipurpose, multisite facilities operating in different regions and countries and servicing international clientele. For such a global industry to remain competitive in a dynamic global marketplace, it is essential to achieve enterprise-wide optimization. Enterprise-wide optimization involves optimizing the operations of supply, manufacturing, and distribution in a enterprise, and integration of these different decisions levels leads to creating substantial value to the process.[1,2] The key operational activities in supply chain management are (1) supply-chain design, (2) supply-chain planning and scheduling, and (3) supply-chain control (real-time management).[3] Supply-chain design is a long-term strategic level decision to determine the optimal infrastructure (assets and network), planning is a tactical level decision, and scheduling is an operational level decision in a supply chain. Typically, much of the decision-making in a supply chain is focused across solving subproblems as an entity, but from the enterprise-wide performance viewpoint, local improvements at any sublevel do not necessary lead to an overall improvement. Therefore, a comprehensive integrated approach to enterprise-wide optimization is desired. However, an integrated decision-making problem is significantly challenging and computationally intensive, and literature on the solution approach for integrated optimization of different levels is very sparse. Hence, decomposition, simulation, and heuristic techniques are necessary tools to address the challenges posed by supply chain management problems in the petroleum industry.

A typical petroleum industry supply chain is composed of an exploration phase at the wellhead, crude procurement and storage logistics, transportation to the refineries, refinery operations, and distribution and delivery of its products (Figure 1). Oil refinery production operation is one of the most complex chemical industries, which involves many different and complicated processes with various connections. Instead of tackling a comprehensive large-scale refinery operations optimization problem, decomposition approaches are generally exploited. Oil refinery manufacturing operations can be decomposed into three problems: (1) crude-oil unloading, mixing, and inventory control, (2) scheduling of production units, and (3) finish products blending and distribution.[4]

Substantial work in the literature has been devoted to the oil refinery planning and scheduling problem. However, in the past few years, focus is shifting to an integrated approach to address the problem of enterprise-wide optimization.[5−11] The objective of this paper is to provide an analysis of the complexity present in the oil refinery supply chain and present a literature review on existing approaches that address the problem of enterprise-wide optimization in the petroleum industry. The paper concludes with the challenges that still need to be addressed.

2. Issues in Petroleum Industry Supply-Chain Management

Key issues in petroleum enterprise-wide optimization span a large spectrum in a supply chain, from the strategic through the tactical to the operational level and over various functions in the supply-chain network, from purchasing of the raw materials through the manufacturing to the distribution and sales. Since the emphasis of enterprise-wide optimization is on manufacturing control, scheduling, and planning, the models required for optimization are usually nonlinear models. In this section we organize the issues that are present in the refinery supply chain by first presenting the different components of oil refinery supply chain and providing a detailed description of front end of the supply chain, from crude oil procurement to oil refinery operations.

Integrated and coordinated decision making across various geographically distributed refinery manufacturing and storage sites offers an additional challenge to refinery operations optimization. While manufacturing facilities management is an integral part of enterprise-wide optimization, transportation

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Figure 1. Supply chain in the petroleum industry.

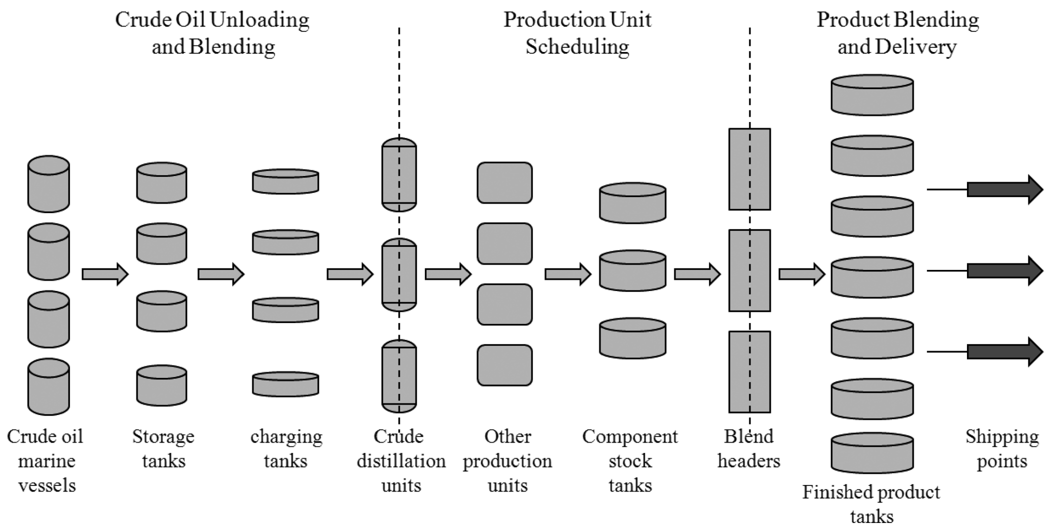

Figure 2. Graphic overview of a standard refinery system.

logistics and finished product distribution management remain important parts of the refinery supply chain.

2.1. Petroleum Industry Supply-Chain Components. As shown in Figure 1, a typical petroleum supply chain involves the exploration phase, crude procurement, storage logistics, transportation to the oil refineries, refinery operations, distribution, and transportation of the final products. The problem of investment and operations in offshore oil field development is characterized by a long planning horizon (typically 10 years) where a large number of choices in platforms, wells, field locations, and pipeline infrastructure is present.[12] The exploration phase involves significant investment costs; thus economical drive exists to maximize the return on investment. Rights for extracted crude oil are then purchased for the production of finished products to satisfy market demand, while respecting product quality specifications. The nature of the petroleum supply chain is such that its economics are extremely complex and heavily linked. For example, the quality and quantity of the finished products are impacted by different crude-oil mixes and by oil refinery configuration, capacity, and yield constraints. As mentioned before, oil refinery production operations are the most complex components of an oil refinery supply chain, and, to effectively tackle scheduling and planning of single site or multisite optimization, it is necessary to decompose the refinery production operations into smaller manageable subproblems.

Generally, oil refinery operations are decomposed into three subproblems based on the structure of the refinery configuration as shown in Figure 2. These problems are (1) crude-oil unloading, mixing, and inventory control, (2) scheduling of production units, and (3) finish products blending and distribution.[4] The crude oil procurement problem and oil refinery operations subproblems are described in detail next. Although the upstream operations including the safety issues associated with wellhead operation should not be underestimated,[13] it is not the focus of this review.

2.1.1. Crude Oil Procurement. A typical crude oil procurement process in a refinery involves three phases: crude selection and purchase, crude transportation and storage, and crude processing, and these phases are explained in detail by Julka et al.[5] The crude selection is an extremely important step in refinery supply chain since it has direct impact on finished product quality, quantity, and it accounts for about 90% of the refinery input cost. Crude oil selection and purchase is done periodically at fixed or variable intervals and is purchased for production over procurement cycle (of few days to a month) in advance. After the crudes are selected and purchased, the focus shifts to optimizing delivery costs from the suppliers to the refinery jetties. The crude oil is carried to the port by tankers, where it is unloaded into tanks when the jetty becomes available for docking. This crude oil unloading problem is limited by tank capacity, pumping rate, setup costs, and demurrage. Care should be taken when transporting high-fusion-point crude oil to avoid large residency time in pipelines.[14] The crude oil loading and unloading problem is further described next.

2.1.2. Crude Oil Operations. Crude oil scheduling problem is one of the most challenging problems in an oil refinery plant. An optimal crude oil scheduling is predetermined based on crude arrival data, production targets, and operational constraints. Once crude oil is loaded into the storage tanks, crude oil mixtures are prepared to charge crude distillation units (CDU) for production. Generally, there are two different types of mixture preparation: (a) in charging tanks and (b) using pipelines in a place called manifold just before the CDU. The complexity in the scheduling problem arises from a bilinear term (flow and inventory) present in mass balance constraints where the intensive properties of the crude oil mixtures charging the CDU must be regulated to meet the downstream product quality specifications. Saharidis and Ierapetritou[15] solved the crude oil scheduling problem using discrete time presentation where they address both types of crude mixture preparation configurations. The economic and operability benefits of the crude oil blend scheduling problem in a refinery is discussed in detail by Kelly and Mann.[16,17]

2.1.3. Production Unit Operations. Once the crude prepared mixture is prepared, it is charged to CDUs for distillation. The distillation cuts from CDU are then sent to other production units for fractionation and reaction to produce blend components for finished products. The most common refinery process includes catalytic, hydro, and thermal cracking units to convert heavy hydrocarbons into light hydrocarbons. They also include other process units like continuous catalytic reforming, hydrotreating, and hydrodesulfurization units. This problem is characterized by continuous processes, intermediate component storage, and a recycle stream. The production units scheduling problem is addressed by Jia and Ierapetritou[4] and Shah et al.[18] where they applied spatial decomposition to solve the scheduling problem. Gary, Handwerk et al.[19] give a comprehensive reference for refinery production unit operations.

2.1.4. Blending and Distribution Operations. Product blending is a crucial step in refinery operations, for example, gasoline can yield 60−70% of a refinery's profit. The finished product blending process is a mixing of various intermediate products, along with some additives, to produce blends with certain qualities in order to minimize cost and maximize performance while satisfying product quality and demand requirements. The finished blend products are stored in storage tanks, and then the products are lifted during a specific time period to satisfy demand orders. While blending is a critical step in refinery operations, it is also the most complex of the subproblems. The blend scheduling problem gives rise to a nonlinear mixed integer model due to bilinear terms. The problem is further complicated by including some important logistics details. These logistics details are sequence dependent switchovers, multipurpose product tanks and blender units, minimum run-length requirements, fill-draw-delay, constant blend rate, one-flow out of blender, maximum heel quantity, and downgrading of product to lower quality. The variables associated with logistics details are combinatorial variables and have an exactly one-to-one correspondence with quantity sizing variables. This combinatorial characteristic of the logistics problem makes the optimization problem NP hard. Kelly[20] emphasized the importance of logic details in the blending and distribution problem and proposed a decomposition technique to deal with complexity present in the model due to logistics and bilinear terms. They decompose the problem into two subproblems: quality and logistic. A simultaneous production and blending and distribution scheduling problem for large scale refinery with logistics details is addressed by Shah and Ierapetritou,[21] in which they assume linear blend property relations to avoid any nonlinearity. They propose valid inequalities to reduce the computational effort of a large scale mixed integer programming model.

Overall, the problem of refinery operations is very complicated and if simultaneous optimization of all the components of a refinery supply chain is attempted, the resulting scheduling and planning models will be highly intractable. Thus, in practice each of the subproblems is addressed individually, and techniques are proposed to integrate the solutions of the subproblems. An overview of the existing work in the area of enterprise-wide optimization for refinery operations is given in next section after a brief discussion of different decision levels in an oil-refinery supply chain.

2.2. Integration of Different Decision-Making Levels in the Supply Chain. Management of the petroleum supply chain is a complex task due to the large size of the physical supply network dispersed over vast geography, complex refinery production operations, and inherent uncertainty involved. There are three main decision levels in a traditional supply chain: (1) strategic, (2) tactical, and (3) operational. Strategic level decisions are made for a few years, tactical level decisions range from several months to a few days, and control level decisions range from a few minutes to seconds. Different decision levels in a traditional supply chain and their complexity are described in detail by Simchi-Levi, Kaminsky et al.[22] The main issues in decision making at different levels are related to temporal integration, where they involve coordination across different time scales.

The goal of supply-chain design is to determine optimal infrastructure (location, number, and capacity of wellheads and refineries, and flow of material through logistics network). The strategic level decisions are made for several years in a highly uncertain environment. In many instances, the supply-chain network design can have extensive impact on the profitability and risk uncertainty of the global supply chain. In the oil refinery industry, the supply-chain network is composed of shipping via vessel, oil tankers, and pipelines that may run across multiple countries. This network is used to transport crude from wellhead to refinery for processing, to transport intermediates between multisite refining facilities, and to transport finished products from product storage tanks to distribution centers and finally to the customers. Any disruptions arising in the global supply chain can have tremendous adverse effects in achieving operational efficiency, maintaining quality, profitability, and customer satisfaction. The adverse events may happen due to uncertainty in supply of crude, demand, transportation, market volatility, and political climate. To effectively model a supply-chain design problem, the dynamics of the supply chain ought to be considered and data aggregation techniques for the extensive data set should be employed.

As in the other chemical industries, production planning in the petroleum refining industry relies on the following sources of information: process topology, plant capacity, operating constraints, market demand, and costs involved in the processes. Planning level decisions are made based on the strategic level decisions. The objective of planning the production is to efficiently take advantage of the company infrastructure so that its products may be competitively offered to customers. Specifically, the refining industry is under immense pressure to produce cleaner products but faces low economic margins because of stricter environmental regulations and depressed market demand. In this situation, refinery planning becomes very important as it can exploit all potential opportunities to push the economic margin to the maximum limit. A planning problem determines how to best allocate the production, distribution, and storage resources in the chain to respond to market demand orders and forecasts in an economically efficient manner, and a scheduling problem determines the detailed schedule for shorter period (typically 10 days) by taking into consideration the operational constraints of the system. Scheduling models use small bucket time-periods which means that only one activity, task, job, or operation can be performed at any given time on a piece of equipment. Scheduling models are in general order-driven, which means that scheduling problems are driven by real product demand and typically accompanied by a customer purchase order. Owing to the complexity of refinery operations, commercial tools for production scheduling are few and these do not allow a rigorous representation of plant particularities. Uncertainty also persists at the planning and scheduling level due to machine breakdown, rush orders, and price fluctuation. A real time optimization model deals with process level optimization to determine the product yields, temperatures, and pressures at each process units. These real times level decisions are made for very short times (seconds), and the process operational complexities give rise to nonlinear dynamic process models.

An integrated optimization of strategic, tactical, operational, and inventory planning and scheduling level decisions under uncertainty gives an intractable computationally intensive large-scale nonlinear model. A further complexity in implementing a globally optimal enterprise solution is the conflicting objectives employed by different components of the supply chain. The best way to address decisions at different levels in an integrated manner is through decomposition techniques, heuristics, and simulation-based optimization methods.

3. Literature Review

3.1. Petroleum Supply-Chain Design and Planning. The petroleum industry can be characterized as a typical supply chain. All levels of decisions (strategic, tactical, and operational) arise in such a supply chain. In the literature, optimization models deal with planning and scheduling of several subsystems of the petroleum supply chain such as oil field infrastructure, crude oil supply, refinery operations, and product transportation. In what follows, developments on the petroleum supply-chain design and planning are reviewed on the basis of the following two classifications: oil field infrastructure investments and operations and petroleum supply-chain planning including crude oil worldwide transportation and multisite distribution planning.

3.1.1. Oil Field Infrastructure Design and Operations. Oil field development represents a complex and expensive undertaking in the oil industry. The problem is characterized by long planning horizons and a large number of choices of platforms, wells, and fields, and their interconnecting pipeline infrastructure. The main challenges in resolving this problem is the complexity of the models usually characterized by uncertainty and the large dimensionality of the problem due to large time horizon and spatial domain.

Van den Heever and Grossmann[23] presented a multiperiod mixed-integer nonlinear programming model for offshore oil field infrastructure planning, where nonlinear reservoir behavior is incorporated directly into the formulation. Goel and Grossmann[24] considered the optimal investment and an operational planning of gas field developments under uncertainty in gas reserves, where the shape of the scenario tree associated with the problem depends on the investment decisions. They presented a stochastic programming model that incorporates the decision-dependence of the scenario tree and proposed a decomposition-based approximation algorithm for the solution of this model. Carvalho and Pinto[25] proposed an optimization model for the planning of an infrastructure in offshore oil fields. The proposed model determines the existence of a given set of platforms and their potential connection with wells, as well as the timing of extraction and production rates. Tarhan et al.[26] proposed a multistage stochastic programming model that captures the economic objectives and nonlinear reservoir behavior and simultaneously optimizes the investment and operating decisions over the entire planning horizon. The uncertainties considered are in the initial maximum oil or gas flow rate, the recoverable oil or gas volume, and the water breakthrough time of the reservoir, and those uncertainties are assumed to be gradually revealed as a function of design and operation decisions.

3.1.2. Multisite Supply-Chain Planning. In a typical petroleum supply chain, a set of crude oil suppliers and refineries are interconnected by intermediate and final product streams and a set of distribution centers. Thus multisite supply and distribution planning is an essential part of an oil-refinery supply-chain design and has also received lots of attention. Considering the details of operations at different sites and integrating the interconnectivity between sites and the appropriate logistics are the main issues on addressing this problem.

Julka et al.[5,27] proposed an agent-based framework for supply-chain decision support systems (DSSs) and demonstrated its application through a prototype system for crude procurement. The system serves as a central DSS through which all processes of a refinery can be studied and enables integrated decisions with respect to the overall refinery business. Rejowski and Pinto[28] proposed a general framework for modeling petroleum supply chains. Nodes of the chain are considered as grouped elementary entities that are interconnected by intermediate streams. The supply-chain topology is then built by connecting the nodes representing refineries, terminals, and pipeline networks. Decision variables include streamflow rates, properties, operational variables, and inventory and facilities assignment. Persson and Gothe-Lundgren[29] suggested an optimization model which integrates the shipment planning and the process scheduling at the refineries. This problem concerns the simultaneous planning of how to route a fleet of ships and the planning of which products to transport in these ships. Nishi et al.[30] proposed a framework for distributed optimization of supply-chain planning using an augmented Lagrangian decomposition and coordination approach. The proposed method is applied to supply-chain planning problems for a petroleum complex and a midterm planning problem for multiple companies, and a near-optimal solution was derived. MirHassani[31] showed how the capacitated network may be used to analyze possible long-term transportation of oil derivatives by pipeline, truck, railway, and ship and reduce the distribution cost. The capacitated network can deal with the scheduling of a multiproduct, multidepot system receiving a number of petroleum products from different refineries and distributes them among several depots and market areas while the demand is an uncertain parameter. Pitty et al.[32] presented a dynamic model of an integrated refinery supply chain. The model explicitly considers the various supply-chain activities such as crude oil supply and transportation along with intrarefinery supply-chain activities such as procurement planning, scheduling, and operations management. Stochastic variations in transportation, yields, prices, and operational problems are also considered in the proposed model.

Al-Qahtani and Elkamel[33] addressed the design and analysis of multisite integration and coordination strategies within a network of petroleum refineries using different crude combination alternatives. Recently, they extended the work to address the design of optimal integration and coordination within a multisite refinery and petrochemical system.[34] The refinery and petrochemical systems were modeled as a mixed-integer problem with the objective of minimizing the annualized cost over a given time horizon among the refineries and maximizing the added value of the petrochemical network. Carneiro et al.[35] analyzed the strategic planning of an oil supply chain. To optimize this chain, a two-stage stochastic model with fixed recourse and incorporation of risk management was developed. The model took a scenario-based approach and addressed three sources of uncertainty.

Although significant progress has been made in the supply-chain design and planning for petroleum refining industry, the production plan of an industrial supply chain is in general created first and a compatible schedule is then identified accordingly. Because the detailed scheduling constraints are often ignored in the planning model, there is no guarantee that an operable schedule can be obtained with this hierarchical approach. To address this issue, it is necessary to propose an efficient formulation to coordinate various planning and scheduling decisions for optimizing the supply-chain performance.[36] Solving this kind of model can yield the proper procurement scheme for crude oils, the schedules for producing various petrochemical products, and the corresponding logistics. The appropriate sources (suppliers) of raw materials, the economic order quantities, the best purchasing intervals, and also the transportation schedules can be identified accordingly.

Finally, it is worth mentioning that most of the oil industry companies still operate their planning, central engineering, upstream operations, refining, and supply and transportation groups as complete separate entities. Therefore, systematic methods for efficiently managing the petroleum supply chain as one entity must be exploited. In the next sections the work that has appeared in the literature to cover these separate problems are reviewed.

3.1.3. Pipeline and Transportation Scheduling. The pipeline network plays a key role in the petroleum business. These operational systems provide connections between ports and/or oil fields and refineries (upstream), as well as between these and consumer markets (downstream). Transportation is among the basic challenges in a refinery supply chain with the dimensionality of the problem and the specificities of each individual implementation to be the main issues.

The system discussed by Rejowski and Pinto[37] is composed of a petroleum refinery, a multiproduct pipeline connected to several depots, and the corresponding consumer markets that receive large amounts of gasoline, diesel, LPG, and aviation fuel. An MILP optimization model that is based on a convex-hull formulation is proposed for the scheduling system. In their later work, Rejowski and Pinto[38] divided the pipeline into segments that connect two consecutive depots and packs that contain one product and that compose the segments. Recently, Rejowski and Pinto[39] proposed a MINLP formulation based on a continuous time representation for the scheduling of multiproduct pipeline systems that must supply multiple consumer markets. The proposed continuous time representation is compared with the previously developed discrete time representation of Rejowski and Pinto[28] in terms of solution quality and computational performance.

Cafaro and Cerda[40] studied the scheduling of a multiproduct pipeline system receiving a number of liquid products from a single refinery source to distribute them among several depots. The problem of scheduling a transmission pipeline carrying several petroleum products from a single oil refinery to a unique distribution center over a monthly horizon is studied in their later work.[41] Recently, they further introduced a continuous formulation for the scheduling of multiple-source pipelines operating on the fungible or segregated mode.[42]

MirHassani and Ghobanalizadeh[43] presented an integer programming approach to oil derivative transportation scheduling. The system reported is composed of an oil refinery, one multibranch multiproduct pipeline connected to several depots and also local consumer markets which receive large amounts of refinery products. Herran et al.[44] also proposed a discrete mathematical approach to solve short-term operational planning of multipipeline systems for refined products. Jetlund an Karimi[45] developed an optimization model to obtain the maximum-profit scheduling of a fleet of multiparcel tankers engaged in shipping bulk liquid chemicals.

Comillier et al.[46,47] studied the petrol station replenishment problem with time windows (PSRPTW) which aims to optimize the delivery of several petroleum products to a set of petrol stations using a limited heterogeneous fleet of tank-trucks. They described two heuristics based on arc preselection and on route preselection. Extensive computational tests on randomly generated instances confirm the efficiency of the proposed heuristics. Abraham and Rao[48] made a study on the existing practices of production planning, scheduling and prevailing constraints in the six plants of a lube oil section in a petroleum refinery. On the basis of the data collected from these plants, some generative and evaluative models were developed. The generative models developed were flow network optimization model and binary integer linear programming model. The evaluative model developed was simulation.

3.2. Refinery Planning. Planning models, or more generally time incremented microeconomic models, are in general multiperiod and traditionally use what are known as big-bucket time-period models compared to small-bucket time-period models for scheduling operations. Planning models are forecast-driven, which means that the quantity and quality specifications of the demanded products are only forecasted or estimates for the time-periods into the future.

3.2.1. Production Planning Model. The availability of LP-based commercial software for refinery production planning, such as RPMS[49] and PIMS,[50] has allowed the development of general production plans of the whole refinery, which can be interpreted as general trends. However, inaccuracy caused by nonrigorous linear models may reduce the overall profitability or sacrifice product quality. Major advances in this area will be on model refinement, notably through the use of nonlinear programming.

As pointed out by Kelly,[51] there are four major driving-forces pressing us to formulate planning models with nonlinearities: complex government regulations, increasingly expensive raw materials of poorer quality, new and more sophisticated production processes, and higher energy, chemical, and utility costs.The refinery planning model uses the nlp process models and blend relations. Pinto and Moro[52] developed a nonlinear planning model for refinery production. The model allows the implementation of nonlinear process models as well as blending relations. Joly et al.[53] presented a nonlinear planning model that represents a general refinery topology and allows implementation of nonlinear process models as well as blending relations. The optimization model is able to define new operating points, thus increasing the production of the more valuable products and simultaneously satisfying all specification constraints. Neiro and Pinto[54] proposed a nonlinear petroleum production planning model, which incorporates multiple planning periods and the selection of different crude oil types. Uncertainties related to petroleum and product prices as well as demand are also included as a set of discrete probabilities. Li et al.[55] presented a refinery planning model that utilizes simplified empirical nonlinear process models with considerations for crude characteristics, product yields, and qualities, etc.

Refinery production planning is usually associated with the crude oil unloading and product distribution problems. These problems have traditionally been solved separately because an overall optimization of the problems together could render the solution of the planning problem intractable. However, with the development of computation algorithm and hardware, the integrated solution received lots of attention in the recent past. Gao et al.[56] addressed a production planning optimization problem of overall refinery using a mixed integer linear programming model, which considers the main factors for optimizing the production plan of overall refinery related to the use of run-modes of processing units. The aim of this planning is to decide which run-mode to use in each processing unit in each period of a given horizon, to satisfy the demand, while the total cost of production and inventory is minimized. Guyonnet et al.[57] explored benefits of the integration of production planning with these two models. Alabi and Castro[58] presented a mathematical model of the refinery operations characterized by complete horizontal integration of subsystems from crude oil purchase through product distribution. To avoid complexity of the overall planning problem, after the identification of the nonzero structure of the constraints matrix, structure-exploiting techniques such as the Dantzig−Wolfe technique and block coordinate-descent decomposition were applied.

Generally, a refinery complex consists of a process system and a utility system. The process system not only produces liquefied petroleum gas, gasoline, diesel, and so on, but also some byproducts, such as fuel gas and residual fuel oil, which supply the utility system as fuel. The utility system converts fuel gas and fuel oil to high pressure or medium pressure steam and electricity to meet the energy demand of the process system. The integrated process system and utility system optimization has also received attention recently. Zhang and Hua[59] presented an approach to address the integration of the process system and utility system for better energy utilization. A plant-wide multiperiod planning mathematical model is proposed with the process unit energy-consumed model embedded in the plant-wide model to gain the overall optimization and for better energy efficiency. Zhang et al.[60] presented a method for overall refinery optimization through integration of the hydrogen network and the utility system with the material processing system. To make the problem of overall optimization solvable, they adopted a decomposition approach, in which material processing is optimized first using linear programming (LP) techniques to maximize the overall profit, and supporting systems, including the hydrogen network and the utility system, are optimized next to reduce operating costs for the fixed process conditions determined from the LP optimization.

The capacity of the world petroleum refining industry has increased rapidly during the past decades. On the one hand, it plays a very important role in international economics and in our daily life, and on the other hand environmental regulations and risks of climate change are pressuring the refinery industry to minimize its greenhouse gas emissions. Elkamel et al.[61] proposed a mixed-integer nonlinear programming (MINLP) model for the production planning of refinery processes to achieve maximum operational profit while reducing CO_2 emissions to a given target through the use of different CO_2 mitigation options. The objective of the MINLP model is to determine suitable CO_2 mitigation options for a given reduction target while meeting the demand of each final product and its quality specifications and simultaneously maximizing profit. Zhang et al.[62] proposed a model-centered approach with an eight-step procedure for the early planning and design of an eco-industrial park around an oil refinery, considering technical and environmental factors.

3.2.2. Uncertainty in Refinery Planning. Uncertainty arises in realistic decision making processes and has huge impact on the refinery planning activities. Three major uncertainties that should be considered in refinery production planning include (1) market demand for products; (2) prices of crude oil and the saleable products; and (3) product (or production) yields of crude oil from chemical reactions in the primary crude distillation unit.

Dempster et al.[63] applied stochastic programming modeling and solution techniques to planning problems for a consortium of oil companies. A multiperiod supply, transformation, and distribution scheduling problem is formulated for strategic or tactical level planning of the consortium's activities. This deterministic model is used as a basis for implementing a stochastic programming formulation with uncertainty in the product demands and spot supply costs. Li et al.[64] presented an approach to address refinery planning under uncertainty. They proposed "loss function" to calculate the expectation of plant revenues. The decision maker's service objectives: confidence level and fill rate are applied to handle possible unmet customer demands. Neiro and Pinto[65] presented a stochastic multiperiod model for representing a petroleum refinery. Uncertainty is taken into account in parameters such as demands, product sale prices, and crude oil prices. Lagrangean decomposition was applied to exploit the block-diagonal structure of the problem and to reduce solution time by decomposing the model on a temporal basis. Khor et al.[66] proposed a two-stage stochastic programming model with fixed recourse via scenario analysis with incorporation of risk management for an optimal midterm refinery planning that addresses three factors of uncertainty: prices of crude oil and saleable products, product demands, and product yields. Li et al.[67] developed a stochastic programming model for refinery production planning under demand uncertainty with uniform distribution assumption, and then a hybrid programming model incorporating the linear programming model with the stochastic programming model by a weight factor is proposed. Subsequently, piecewise linear approximation functions are derived and applied to solve the hybrid programming model under a uniform distribution assumption.

In the literature, several studies also addressed the issue of uncertainty and studied the financial risk aspects in refinery operations planning. Pongsakdi et al.[68] studied the problem of determining what crude to purchase and to 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. Lakkhanawat and Bagajewicz[69] addressed the similar problem. Park et al.[70] developed an integrated model based on two-stage stochastic programming for operational planning and financial risk management of a refinery. Downside risk, which rationally quantifies financial risk, is selected as the objective function to be minimized. Subsequently, the contract sizes and the operational plan are optimized on the basis of the developed model and the price scenarios.

In summary, with the development in mathematical programming and computation facility, the refinery planning operations tend to consider more accurate and complex nonlinear process models, implementing overall optimization among different subsystems in the whole plant, and also tend to systematically address the various uncertainties, with financial risk and finally environmental aspect considerations.

Furthermore, in the past work, uncertainty is in general considered as a set of discrete scenarios, each representing a possible shifting of market expectations. Every environment is weighted through an expected probability of occurrence. Previous work revealed that the computational effort of uncertain multiperiod refinery production planning models grows exponentially with the number of time periods and scenarios. Therefore, in order to reduce the computational effort over uncertain long-planning horizons, special techniques must be employed.

3.3. Refinery Scheduling. The literature generally addressed the refinery scheduling in the form of smaller subproblems: crude oil operations from unloading to the charging into a crude distillation unit; blending of intermediate products from the CDU into finished products; lifting or delivery of the finished products, etc. In what follows, we review literature in the above scheduling applications.

3.3.1. Crude Oil Scheduling. The scheduling of crude oil operations is crucial to petroleum refining, which includes determining the times and sequences of crude oil unloading, blending, and CDU feeding. The infrastructure that serves to facilitate crude oil loading and unloading operations usually comprises (a) one or more jetties, (b) crude storage tanks at port and refinery, (c) intermediate tanks between port and refinery, and (d) pipeline infrastructure connecting port tanks to refinery. In the past decade, many approaches have been proposed for solving this problem.

Shah[71] presented one of the earliest mathematical formulations for the crude oil scheduling problem. Their model is based on a discrete time presentation. Not in their earlier studies,[72−74] but in a recent work of Pinto et al.[75] were the scheduling problems in oil refineries that are formulated as mixed integer optimization models and rely on both continuous and discrete time representations discussed. Chryssolouris et al.[76] addressed primarily the scheduling of a refinery importing various types of crude oil. Karuppiah et al.[77] presented an outer-approximation algorithm to obtain the global optimum of a nonconvex mixed-integer nonlinear programming (MINLP) model for the crude oil scheduling problem. The model relies on a continuous time representation making use of transfer events. The proposed algorithm focuses on effectively solving a MILP relaxation of the nonconvex MINLP to obtain a rigorous lower bound (LB) of the global optimum. The solution of this relaxation is used as a heuristic to obtain a feasible solution to the MINLP which serves as an upper bound (UB). The lower and upper bounds are made to converge to within a specified tolerance in the proposed outer-approximation algorithm. Pan et al.[78] considered the coastal and marine-access refineries with simplified workflow and proposed a mixed integer nonlinear programming formulation for crude oil scheduling. Finally, well scheduling in petroleum fields is a very important activity related to crude oil production, where decisions include the operational status of wells (open or closed), the allocation of wells to manifolds or separators, and the allocation of flow lines to separators. However, the work in that area is not reviewed in this paper, but it can be referred to in Kosmidis et al.[79]

3.3.2. Refinery Production and Blend Scheduling. The production unit scheduling problem is addressed by Jia and Ierapetritou.[4] Shah et al.[80] presented a decomposition strategy for solving a large scale refinery scheduling problem. They proposed a spatial decomposition scheme that generates smaller subsystems that can be solved to global optimality instead of formulating a huge one for the centralized problem. Gothe-Lundgren et al.[81] describe a production planning and scheduling problem in an oil refinery company. The aim of the scheduling is to decide which mode of operation to use in each processing unit at each point in time in order to satisfy the demand while minimizing the production cost and taking storage capacities into account.

The product blending process involves mixing various stocks, which are the intermediate products from the refinery, along with some additives, such as antioxidants and corrosion inhibitors, to produce blends with certain properties. A variety of support systems have been also developed to address the refinery blending operations. Jia and Ierapetritou[82] studied the problem of gasoline blending and distribution. The problem involves the optimal operation of gasoline blending, the transfer to product stock tanks, and the delivering schedule to satisfy all of the orders. An efficient mixed-integer linear programming formulation is developed based on continuous representation of the time domain and on the assumption of a fixed recipe. Joly and Pinto[83] developed mixed-integer programming (MIP) models for a real-world fuel oil and asphalt production scheduling problem. Mendez et al.[84] presents a MILP-based method that addresses the simultaneous optimization of the off-line blending and the short-term scheduling problem in oil-refinery applications. Depending on the problem characteristics as well as the required flexibility in the solution, the model can be based on either a discrete or a continuous time domain representation. To preserve the model's linearity, an iterative procedure is proposed to effectively deal with nonlinear gasoline properties and variable recipes for different product grades. Lee et al.[85] addressed a naphtha feeding problem for the Naphtha Cracking Center (NCC). The naphtha feeding problem involves two key operations: delivering naphtha from refineries to NCC and blending naphtha in storage tanks before feeding it to NCC. This paper considers both issues simultaneously by transforming them into a single mixed linear integer programming problem of minimizing the cost function of naphtha prices, shipping expenses, and unloading costs, etc. In a recent publication Li et al.[86] developed a slot-based MILP formulation for an integrated treatment of recipe, specifications, blending, and storage, considering real-life features such as multipurpose product tanks, parallel nonidentical blenders, minimum run lengths, changeovers, piecewise constant profiles for blend component qualities, and feed rates, etc.

In most of the existing refinery scheduling studies, the problem data are assumed to be deterministic. However, under the current situations of unsteady supply of crude oil, variations of feedstock qualities and yield levels, pressure of intense time, low inventory flexibility, etc., it is very important for refinery companies to assess the extra cost of these changes during making their short-term crude oil scheduling operations. Cao et al.[87] proposed chance constrained mixed-integer nonlinear stochastic and fuzzy programming models for refinery short-term crude oil scheduling problems under demand uncertainties of distillation units. The scheduling problem studied has the characteristics of discrete event and continuous event coexistence, multistage, multiproduct, nonlinear, uncertainty, and large scale.

In summary, a refinery scheduling problem is more complex than a planning problem since in general more operational constraints should be considered and many combinatorial decisions need to be optimized; thus it has been hard to implement an overall scheduling for the whole refinery operations. An efficient decomposition-based solution strategy is still necessary to implement overall refinery scheduling optimization. Finally, efficient reactive scheduling, rescheduling methodologies are also imperative for refinery scheduling operations.[8,88]

4. Future Challenges

This article has shown that a very large amount of work was undertaken to address the problems in refinery supply-chain management, especially in the areas of the scheduling and planning of refinery operations, crude oil procurement, and petroleum supply-chain design and planning. However, a large number of issues still exist which provides challenges for ongoing research.

4.1. Improved Models for Refinery Operations. The crude oil scheduling and planning problem has been traditionally addressed using linear relations for CDU yield prediction as a function of the crude feed. Improvements in the swing cut model for CDU yield in recent years provide an opportunity to develop nonlinear planning models that capture the nonlinearity of the process. Implementing nonlinear process model equations for planning problems using the latest NLP algorithms provides true optimal and accurate solutions to the planning problem.

Efficient models and solution algorithms for the blending and distribution problem are needed to simultaneously address the optimization of blend recipe and blend logistics. The bilinear terms in the quality problem are a result of nonlinear property relations, while the bilinear term in the logistics problem is a result of a constant blending rate where blend duration and amount can vary. Some research has been done to address the simultaneous optimization of quality, quantity, and logistics.[20,86]

4.2. Integrated Models for Supply-Chain Management. There is a great economic potential in enterprise-wide optimization; however, a lack of comprehensive optimization models and computational tools are one of the major issues that must addressed.

(1) Simultaneous refinery operation scheduling (production unit, blend, and distribution scheduling) models are very sparse,[89,21] and they do not incorporate accurate process models (e.g., assumptions of linear blending rules). Moreover the consideration of detailed dynamics and feedback loops will provide a better representation of the realistic problem.

(2) Integrated scheduling planning models with nonlinear scheduling process operations complexity and coordinated control/real time and scheduling decisions making models are still not adequately explored. Efficient decomposition algorithms and computational models that integrate the decision making at different time scales are required.

(3) Coordinated decision making between multisite production facilities and the design of the supply chain is vital for improving profit margin while maintaining customer satisfaction. The challenge in this area is to develop optimization models and computational tools that capture inherent complexities and uncertainties present across modern supply chains.

New comprehensive models and algorithms can significantly improve the economic performance of refinery operations by reducing costs and increasing profits while providing solutions for real world applications. Moving away from simulation-based approaches to optimization models will likely occur in the next years. However there are still many issues, including issues of interfaces and communication barriers among different refinery units.

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