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Designing an integrated model for a multi-period, multi-echelon and multi-product petroleum supply chain

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ABSTRACT

A petroleum supply chain is a large complex supply chain composed of several sub-problems. Numerous studies have focused on solving a portion of these problems, which led to a non-optimal solution. This study addresses a new multi-period multi-echelon and multi-transportation integrated petroleum supply chain model to obtain a global optimal solution. The main feature of this paper is to design an integrated supply chain model that considers both installation and capacity expansion of pipeline routes and facilities simultaneously, and optimizes location-allocation facilities and routes, capacity expansion, inventory, production, exportation and importation, as well as routing and transportation modes over a vast geographical area. To achieve this, a deterministic mixed-integer linear problem was developed and applied to a real world problem based on the information derived from Iran's petroleum chain. Numerous scenarios and sensitivity analyses have been presented for different cases to deepen more in the model. They showed that the optimal solution is less sensitive to variations of the cost parameters, but changes in the amount of demands and injected crude oil change the objective value remarkably. In general, the analysis showed that the developed model has the ability to present the best strategy in complex market situations.

1. Introduction

Energy is one of the most important issues among the citizens and governments [1]. Managing a Petroleum Supply Chain (PSC) to maintain its competitiveness in the global market is a sophisticated job. Currently, intense competition forces petroleum companies to focus on reducing costs or increasing profits.

The most comprehensive classifications divide the PSC into three major sectors: upstream, midstream and downstream [2]. The upstream sector includes searching for potential crude oil fields, drilling of exploratory crude oil fields, and operating these fields, which recovers and transfers crude oil to storage tanks. The midstream sector involves transportation (pipelines, railways, barges, oil tankers or trucks), storage and wholesale marketing of crude or refined petroleum products. Pipelines and other systems are used to transport crude oil from storage tanks to refineries and deliver various refined products to downstream distributors. Finally, the downstream sector includes distribution of refined products derived from crude oil to the customers, such as gasoline or petrol, kerosene, jet fuel, diesel oil, heating oil, fuel oil, lubricants, waxes, asphalt, natural gas and Liquefied Petroleum Gas (LPG), as well as hundreds of petrochemicals.

Although the majority of petroleum companies such as Shell and the National Iranian Oil Company (NIOC) undertake all PSC processes from oil exportation and delivery of refined products to customers (i.e. upstream, midstream and downstream), designing a PSC for petroleum companies is still a big challenge. Having a wide variety of decision making aspects such as size of the supply network, refinery production rate, volume of flow, inventory size, transportation modes, making a decision between installation or expansion, and decision levels (tactical and strategic tactical) can be considered as the reasons for this complexity. To achieve a global optimal solution and guarantee the maximum amount of overall profit for an assumed PSC, all these aspects should be considered in a single model. Some studies try to achieve a global maximum profit by centralizing the members of the supply chain [3] and some other papers emphasize on the specific section of the chain independently. We bring numerous papers in the literature which, have studied a part of the mentioned aspects.

Sear [4] proposed qualitative and quantitative models for the downstream sector in PSC including three levels of refineries, terminals and customers. Escudero et al. [5] studied a multi-period

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Supply, Transformation and Distribution (STD) scheduling problem under uncertainty on the product demands, spot supply cost and spot selling price. Because of the undesirable results generated by the deterministic treatment for the problem, they applied a two-stage scenario analysis using a partial recourse approach. Dempster et al. [6] suggested a stochastic programming model for an oil consortium at strategic and tactical decision levels. They considered a multi-period STD scheduling problem (DROP[1]) with uncertainty in the product demands and spot supply costs as a base for implementing the stochastic programming formulation.

Pinto et al. [7] applied the integrated model, which optimizes the planning and scheduling of refineries simultaneously. They studied the crude oil inventory management that includes optimal operation of crude oil unloading from pipeline, transferring to storage tanks and charging the schedule for each crude oil distillation. Pinto et al. proposed a large-scale MILP (Mix integer linear problem) model for integration logistics, planning and scheduling. They applied the model for a real case in which the comparison of the optimal result with the existing non-optimal situation showed increase of several million dollars in annual profitability.

Neiro and Pinto [8] proposed a general framework for modeling an integrated PSC, which incorporates transportation modes and supply planning and scheduling at operational level. The decision variables of this large-scale MINLP (Mix integer nonlinear problem) model are stream flow rates, properties, operational variables, inventory, and facility assignment.

Mendez et al. [9] presented an integrated MILP-based approach to optimize the production logistics and scheduling in refineries simultaneously. They proposed sequence MILP approximation for the developed formulation. The decisions of this model include assignment of blenders to final products, inventory level, pumping rates, and optimal timing decisions for production and storage tanks.

Pongsakdi et al. [10] planned the crude oil purchasing and its processing schedule under uncertainty in the demands and product prices. They considered crude oil supply purchase, processing, inventory management and blending. The results showed that the suggested stochastic model can provide a solution with higher expected value and lower risk.

Al-othman et al. [11] studied stochastic planning model for the PSC network consisting of all activities related to crude oil production, processing and distribution. They proposed an integrated PSC model in four stages: crude oil production, refineries, petrochemical sectors and power stream chemical sectors. The uncertainty of the model relates to the amount of demands in the market and prices. They planned the PSC with respect to material balances, demand balances, production yields, bounds of the crude oil production, and petrochemical and downstream chemical production.

Kou and Chang [12] studied the PSC by considering various planning and scheduling decision variables to optimize the supply chain performance. The production planning and scheduling schemes are hierarchically linked together. On the other hand, the planning stage is the higher level decision with long time horizon (say monthly), and the scheduling is the lower level decision with short time horizon (say weekly). In the reality, this approach does not guarantee obtaining a feasible solution; therefore, they proposed an MILP model in which the PSC planning and scheduling are considered simultaneously.

The various supply chain activities such as crude oil supply and transportation, along with the intra-refinery supply chain activities of procurement planning, scheduling and operation management, were developed by Pitty et al. [13] as a dynamic model of an integrated supply chain. They illustrated the capabilities of the integrated refinery in Silico (IRIS) model implemented in a dynamic simulator for strategic and tactical decision support by using several case studies.

Kim et al. [14] proposed an integrated model of supply network and production planning for collaboration among the refineries that produced multiple fuel products at different locations. Their network model was formulated as a mixed integer problem of network reconfiguration where the locations of new DC and the production capacities of the refineries involved were known. Their simulation and optimization model has indicated that distribution costs can be reduced by relocating DCs as well as reconfiguring their linkages to various markets. Performance of the integrated model was examined by an example that included three refineries and four different fuel products.

Al-Qahtani and Elkamel [15] studied the design and analysis of a multi-site integration and coordination strategy within a network of petroleum refineries. They considered production capacity expansion in refineries, different crude combination alternatives and different operating modes. They presented a mixed integer linear problem (MILP) with the overall objective of minimizing total annualized cost in the midstream sector of PSC. They finally illustrated the economic potentials and tradeoffs involved in the optimization of the network, and tested the performance of the proposed model by several industrial scale examples.

Mirhassani [16] examined possible long-term transportation of oil derivatives by pipeline, truck, railway and ship, and reduced the distribution cost created by the capacitated network. He considered decisions about scheduling a multi-product, multi-depot system and distributed multi-product among several depots and market areas with uncertainty in demand. In this problem, depots typically operated independently and solely within their own territories.

Guyonne et al. [17] proposed a tactical model for PSC, which is the integration of uploading, production and distribution. They compared the results of the integrated model to non-integrated model (sequential use of the three parts) from the optimality viewpoint. The results showed that the profit of the integrated model is significantly high rather than the non-integrated model.

Rocha et al. [18] presented an MILP model that provides the link between strategic and operation decisions by considering petroleum allocation to terminals and refineries. Both of the upstream and midstream segments of PSC including production sites, terminals and refineries were embedded in the model, and eventually, a heuristic method was used to solve it in the large scale.

Al-Qahtani and Elkamel [19] proposed a framework for simultaneous analysis of process network integration in a midstream PSC using robust optimization techniques to minimize the annualized cost over a given time horizon. They studied multi-site integration and coordination strategies within a network of petroleum refineries in which the coefficients were considered to be uncertain. The proposed model was tested on two industrial scales: a single refinery and a network of complex refineries.

Ribas et al. [20] proposed a mathematical model to maximize the profit of the oil chain (both upstream and midstream) at the tactical planning level. The model was formulated as a two-stage stochastic program where uncertainty has been incorporated into demand for refined products, oil prices and product prices (exogenous uncertainty factors) that accounted for economic risk at tactical level. Finally, they evaluated the performance of the proposed model in optimizing large scale problems by using real data from the Brazilian industry.

Gill [21] presented a supply chain network design approach for distribution of petroleum products to minimize the number of selected depot locations and gas stations to improve its distribution network for better area coverage. A heuristic method was used for solving this problem. The author used a two-fold approach. Initially,

[1] Depot and refinery optimization problem.