Application of a Mathematic Programming Model for Integrated Planning and Scheduling of Petroleum Supply Networks

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The scope of this study is concerned with the petroleum supply network operated by a typical oil company, in which the crude oil is consumed to produce ethylene, propylene, liquefied petroleum gas, butadiene, benzene, toluene, xylene, gasoline, kerosene, diesel, and other byproducts. These petrochemical products are usually manufactured with a cluster of strategically located *conversion refineries*.[1] A complete petroleum supply chain consists of at least 13 different types of production units, that is, the atmospheric distillation units, the vacuum distillation units, the cokers, the fluid catalystic cracking units, the naphtha crackers, the butadiene extraction units, the hydrotreaters, the aromatics extraction units, the reforming units, the xylene fractionation units, the parex units, the xylene isomar units, and the tatory units. Traditionally, the production plan of an industrial supply chain is 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, a single mixed-integer linear program (MILP) has been formulated in this study to coordinate various planning and scheduling decisions for optimizing the supply chain performance. Solving this MILP model yields 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. In particular, the optimal production schedule of olefins, aromatics, and other petrochemical products over the specified planning horizon is configured by selecting throughput, operating conditions, and technology options for each unit in the chain, by maintaining the desired inventory level for each process material, by securing enough feedstock, and by delivering appropriate amounts of products to the customers.

1. Introduction

The general goal of supply chain management is to create an efficient coordination framework to facilitate the suppliers, manufacturers, distributors, and retailers in the supply network to work closely together to acquire raw materials, to convert them into specified final products, and to deliver these final products to retailers.[2,3,4] A petroleum supply chain can be roughly divided into four segments: (1) exploration, (2) transportation, (3) refining, and (4) distribution. Notice that the first segment of this chain may not exist in regions lacking oil resources. Crude oils are shipped directly from oversea sources by tankers to the oil terminals, which are then connected to refineries through a pipeline network. Logistic decisions at this level include supply planning, scheduling, and selection of the appropriate transportation modes. Crude oil is converted to various products at refineries. These refineries are often interconnected so as to achieve a high degree of flexibility for meeting fluctuating market demands. Products produced at the refineries are sent to the distribution centers, and then transported via pipelines, trucks, or rail cars to the customers. It should be noted that some of the aforementioned refining products are actually raw materials of a variety of other processes. For example, benzene can be alkylated to ethylbenzene and cumene, which are then used as the raw materials for the production of styrene and phenol. In other words, the petroleum supply chain may be further extended downstream. To keep the problem scope to a manageable size, the petrochemical processes discussed in this article are limited to those in a typical *conversion refinery*.

The aim of the present study is to develop a systematic approach to create the production planning and scheduling schemes for the refinery segment of a petroleum supply chain. These two activities are in fact hierarchically linked. Both involve the allocation of resources over time to manufacture the required products. In the planning stage, the goal is to settle the higher-level decisions, such as the procurement amounts of crude oils and the inventory and production levels of various products, according to the given forecasts of market demands over a relatively long time horizon (say, months). The lower-level scheduling tasks, on the other hand, should be performed on the basis of shorter time intervals (say, weeks) to determine the specific timing in which every unit must be operated to meet the production goals set in the planning stage. However, if a sequential approach is taken to carry out the needed computation procedures, the detailed scheduling constraints are often ignored in the planning stage. As a result, there is really no guarantee that a feasible schedule can be obtained. It is thus desirable to address the planning and scheduling issues simultaneously.

This viewpoint has actually been adopted in several recent studies for different types of supply chains. Jackson and Grossmann[5] adopted the Lagrangean decomposition (spatial and temporal) techniques for the solution of a nonlinear programming problem that models multisite production planning in a chemical company. Tang et al.[6] proposed an integrated system to achieve the same goal for steel production planning and scheduling. Ho and Chang[7] presented a computation framework to address related issues in the multistage manufacturing system by incorporating the concepts of material requirements planning and just-in-time production. Dogan and Grossmann[8] constructed

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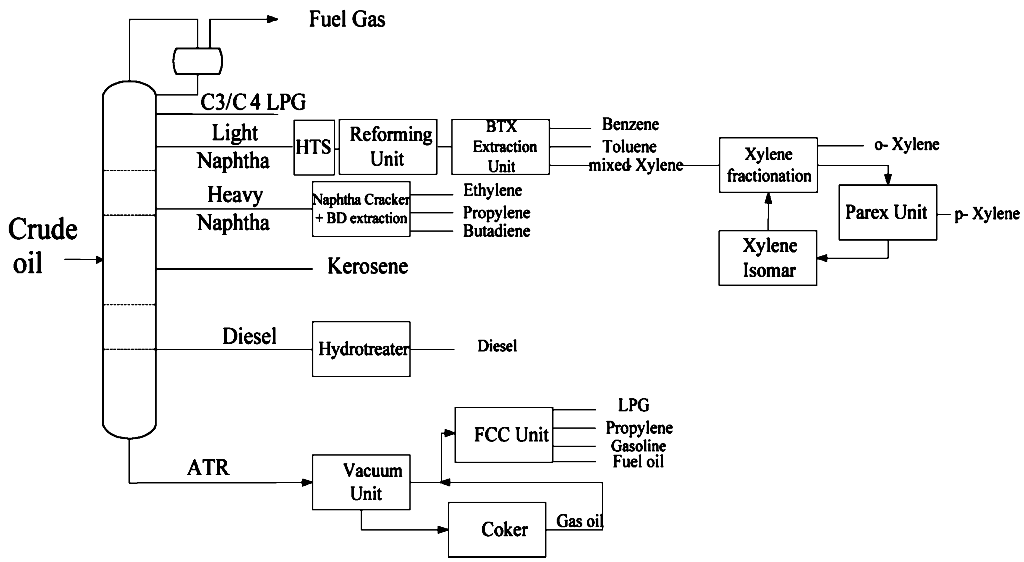

Figure 1. Simplified flow diagram of a typical conversion refinery.

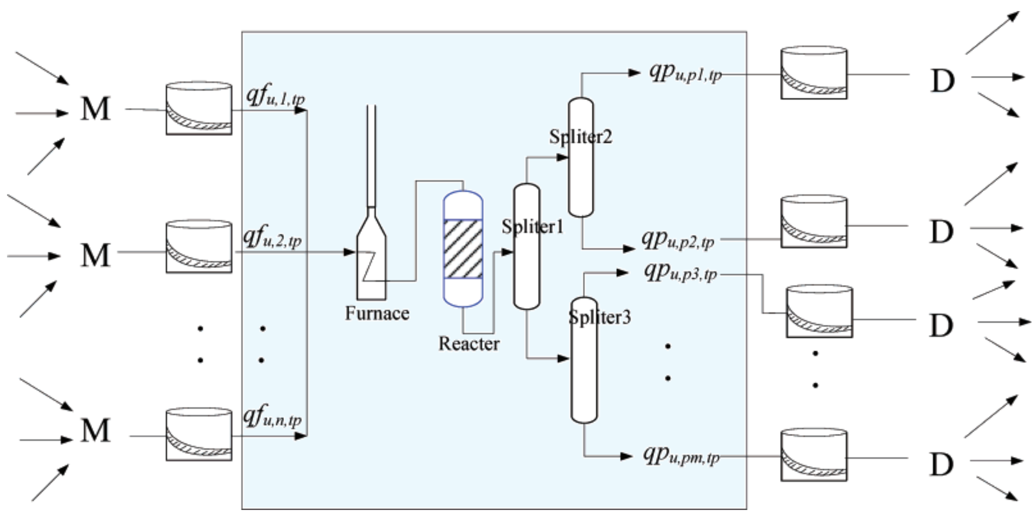

Figure 2. Flow structure around a reaction process.

a multiperiod MILP model to integrate planning and scheduling decisions for continuous multiproduct plants that consist of a single processing unit. It should be pointed out that, although interesting results have been reported in the above articles, none of them were concerned specifically with the operation of conversion refineries.

The available planning and scheduling strategies have traditionally been developed *separately* for the petrochemical processes. A number of LP-based commercial software packages are available for generating production plans in the refineries, for example, RPMS[9] (refinery and petrochemical modeling system) and PIMS[10] (process industry modeling system). There are, however, relatively few generic scheduling tools on the market, and the existing ones do not allow rigorous representation of the plant particularities. Notice also that the issues concerning optimal planning and scheduling of the *continuous* multiproduct petrochemical plants have not been studied extensively, as opposed to the large amount of work devoted to batch manufacturing processes.[11] A brief review of the related literature is given in the sequel: Pinto et al.[12] and Pinto and Moro[13] have studied the refinery operations in detail. The former work focused primarily on production scheduling for several specific areas in a refinery, whereas the latter developed a nonlinear production planning model for the same purpose. Li et al.[14] integrated the CDU, FCC, and product blending models into a refinery planning model. Carvalho and Pinto[15] presented an optimization model for planning the production infrastructure of offshore oilfields. Persson and Gothe-Lundgren[16] proposed a mathematical programming model and the corresponding solution method for a shipment planning problem. Gothe-Lundgren et al.[17] studied the production planning and scheduling problem in an oil refinery company. Their scope concerns a production process with one distillation unit and two hydrotreatment units. The study of Jia and Ierapetritou[18] focused on the short-term scheduling issues associated with refinery operations. Más and Pinto[19] and Magalhães and Shah[20] proposed a detailed MILP formulation for the optimal scheduling of an oil supply chain, which includes tankers, piers, storage tanks, substations, and refineries. Méndez et al.[21] addressed the simultaneous optimization issues associated with off-line blending and scheduling problems in oil-refinery applications. Finally, Neiro and Pinto[22] presented a comprehensive planning/scheduling framework for the front end of a petroleum supply chain.

It should be pointed out that the scopes adopted in the aforementioned works are *not* comprehensive enough for realistic applications. This is due to the fact that a wide spectrum of important petrochemical products, for example, liquefied petroleum gas (LPG), gasoline, kerosens, ethylene, propylene, butadiene, benzene, toluene, and xylenes, etc., are produced in a conversion refinery, and these previous studies only address

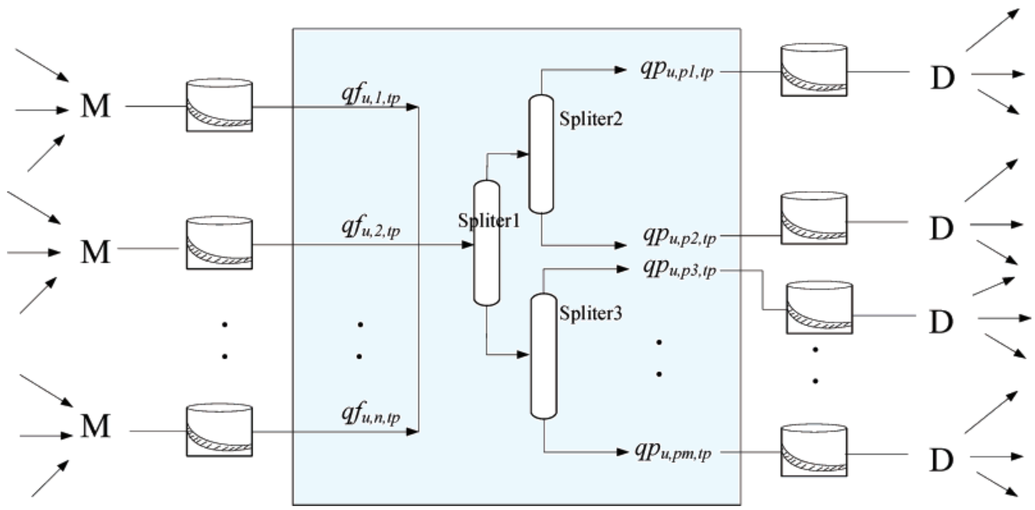

Figure 3. Flow structure around a separation process.

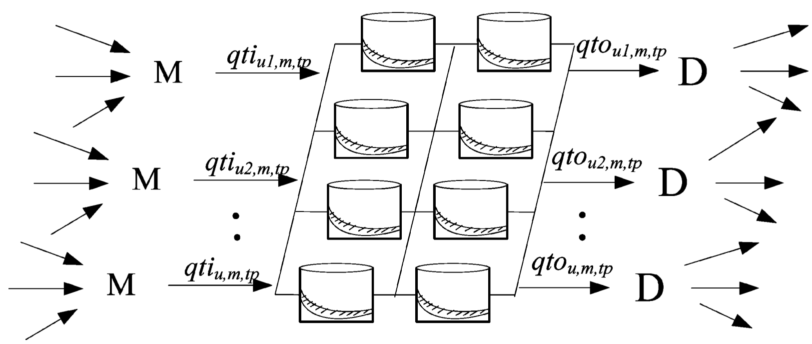

Figure 4. Flow structure around a storage and transportation terminal.

the planning and/or scheduling issues concerned with a subset of these materials. To circumvent the drawbacks of aforementioned studies, a single integrated MILP model has been built in the present study to coordinate various planning and scheduling tasks for optimizing the supply chain performance of a complete refining process. All of the critical decisions can be obtained from the optimal solution of the proposed model. On the corporate level, this model can be used to determine which crude to purchase and its quantity, which products to produce and their amounts, and which processing route to follow during each planning period over a given time horizon. On the plant level, the detailed operating conditions of each processing unit, for example, temperatures, pressures, and throughputs, can be computed according to the higher-level decisions and the inherent process constraints and, in addition, the product transportation policies can be developed by considering the available storage spaces. More specifically, the appropriate production levels and distribution schedules for fuels, for example, LPG, gasoline, kerosene, diesel, and jet fuel, and other intermediate petrochemical products, for example, ethylene, propylene, butadiene, benzene, toluene, *p*-xylene, and *o*-xylene, can be determined at shorter scheduling intervals.

2. Basic Production Units of a Conversion Refinery

The petroleum refining process can be regarded as a series of manufacturing steps by which the crude oil is converted into saleable products with desired qualities and in quantities dictated by the market. A refinery is essentially a group of processing and storage facilities interconnected for the purpose of realizing this process. The refining units and their connection structure are selected to accommodate a wide variety of product distributions. The most versatile configuration is known as the *conversion refinery*.[1] A simplified flow diagram is shown in Figure 1. It should be noted that approximately two-thirds of the outputs generated from a modern conversion refinery are in the forms of unleaded gasoline, high jet fuel, LPG, low-sulfur diesel fuel, lubricants, and petrochemical intermediates, that is, ethylene, propylene, butadiene, benzene, toluene, and xylenes. The basic production units considered in this study are the atmospheric distillation units, the vacuum distillation units, the butadiene extraction units, the aromatics extraction units, the xylene fractionation units, the parex units, naphtha crackers, cokers, fluidized catalytic cracking units, hydrotreaters, reforming units, the isomar units, the tatory units, the import and export facilities, and storage and transportation facilities.[23−27]

3. Basic Unit Models

The various processing units in the conversion refinery can be classified into three general types. They are referred to in this article as the reaction processes, the separation processes, and the storage processes. The naphtha crackers, the fluidized catalytic cracking units, the hydrotreaters, the cokers, the reforming units, the isomar units, and the tatory units are considered as the reaction processes in this work. The separation processes in this study are those in which only separation operations are present, that is, the atmospheric distillation units, the vacuum distillation units, the butadiene extraction units, the aromatics extraction units, the xylene fractionation units, and the parex units. Detailed descriptions of these three general models for planning purpose can be found in an article published by Kuo and Chang.[28] In the present study, because it is necessary to address both planning and scheduling issues

Table 1. Connections of Processing Units in a Petroleum Supply Chain

processing unit	feedstock	source unit	product	sink unit
atmospheric distillation (AD)	crude oil	IEF	C_3/C_4 LPG	PDT
			light naphtha	HT
			heavy naphtha	NC
			kerosene	PDT
			diesel	HTD
vacuum distillation (VD)	residual oil	AD	residual oil	VD
			vacuum gas oil	FCC
			lube oil	PDT
			asphalt	PDT
			crude oil residua	CK
coking (CK)	crude oil residua	VD	C_3/C_4 LPG	PDT
			heavy naphtha	NC
			fuel oil	PDT
			gas oil	PDT
			coke	PDT
fluidized catalystic cracking (FCC)	vacuum gas oil	VD,CK	C_3/C_4 LPG	PDT
			propylene	IEF, PDT
			gasoline	PDT
			light cycle oil	PDT
			C_3/C_4 LPG	PDT
naphtha cracking (NC)	heavy naphtha	IEF, AD, CK	ethylene	IEF, PDT
			propylene	IEF, PDT
			crude C_4	BD
			pyrolysis gasoline	AET
butadiene extraction (BD)	crude C_4	NC	BBR	PDT
			butadiene	IEF, PDT
hydrotreating (HT)	light naphtha	IEF,AD	light naphtha	RF
hydrotreating (HTD)	diesel	AD	diesel	PDT
			C_3/C_4 LPG	PDT
reforming (RF)	light naphtha	IEF, HT	C_5 gasoline	PDT
			reformate	AET
			C_9-aromatic	TT
			C_6-gasoline	PDT
aromatic extraction (AET)	reformate pyrolysis gasoline	RF naphtha cracker	benzene	PDT, IEF
			toluene	TT, PDT, IEF
			mixed xylenes	XF, PDT, IEF
xylene fractionation (XF)	mixed xylenes	AET, TT, IM, IEF	*o*-xylene	PDT, IEF
			C_{9+}gasoline	PDT
			parexf	PR

processing unit	feedstock	source unit	product	sink unit
tatory (TT)	toluene C_9	AET, PDT RF	benzene	PDT, IEF
			mixed xylenes	XF, PDT, IEF
			C_{10}-gasoline	PDT
parex (PR)	parexf	XF	*p*-xylene	PDT, IEF
			isomarf	IM
xylene isomar (IM)	isomarf	PR	mixed xylenes	XF, PDT, IEF
import and export facility (IEF)	benzene	ET, TT,OS	benzene	OC, PDT
	butadiene	BD,OS	butadiene	OC, PDT
	crude oil	OS	crude oil	AD
	ethylene	NC,OS	ethylene	OC, PDT
	gasoline	FCC	gasoline	OC
	heavy naphtha	OS	heavy naphtha	NC
	light naphtha	OS	light naphtha	RF
	mixed xylenes	OS, ET, TT, IM,OS	mixed xylenes	OC, XF, PDT
	o-xylene	XF,OS	*o*-xylene	OC, PDT
	propylene	NC,FCC,OS	propylene	OC, PDT
	p-xylene	PR,OS	*p*-xylene	OC, PDT
	toluene	ET,OS	toluene	OC, PDT
	asphalt	VD	asphalt	DC
product distribution terminal (PDT)	benzene	ET, TT,IEF	benzene	DC
	BBR	BD	BBR	DC
	butadiene	BD,IEF	butadiene	DC
	C_3/C_4 LPG	AD,CK,FCC	C_3/C_4 LPG	DC
	coke	CK	coke	DC
	diesel	HT	diesel	DC
	ethylene	NC,IEF	ethylene	DC
	fuel oil	CK	fuel oil	DC
	gas oil	CK	gas oil	DC
	gasoline	AET,FCC, RF, TT,XF	gasoline	DC
	kerosene	AD	kerosene	DC
	light cycle oil	FCC	light cycle oil	DC
	lube oil	VD	lube oil	DC
	mixed xylenes	ET, TT, IM,IEF	mixed xylene	DC
	o-xylene	XF,IEF	*o*-xylene	DC
	p-xylene	PR,IEF	*p*-xylene	DC
	propylene	NC,FCC,IEF	propylene	DC
	toluene	ET,IEF	toluene	DC, TT

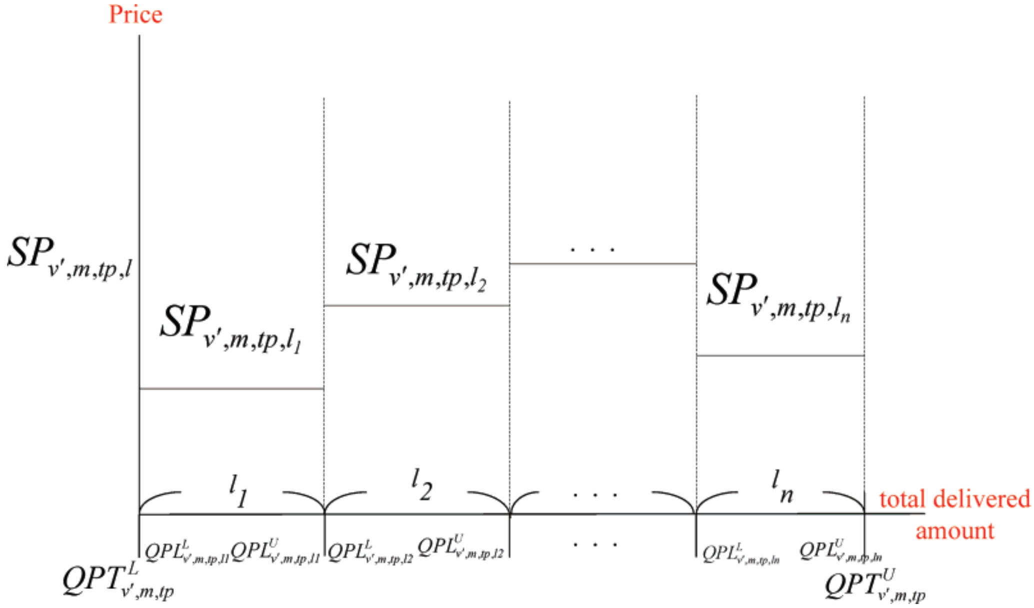

Figure 5. General relationship between the amount of delivered product and its selling price.

simultaneously in an integrated mathematical program, two different time scales must be defined for these two tasks respectively. Specifically, let us introduce two distinct sets of time intervals, that is,

$$\mathbf{TP} = \{tp|tp \text{ is the label of the } tp\text{th planning period}\} \quad (1)$$

$$\mathbf{TS}_{tp} = \{ts|ts \text{ is the label of the } ts\text{th scheduling interval in the } tp\text{th planning period}\} \quad (2)$$

The aforementioned unit models can be modified accordingly for use in the integrated program. The specific mathematical formulations are presented in the Appendix for the sake of completeness.

4. Supply Chain Structure

To facilitate construction of a comprehensive system structure, let us assume that one buffer-tank system is available for every feedstock and one for every product in each processing unit of the generalized supply chain. More specifically, the storage facilities are installed in the reaction and separation processes according to the frameworks presented in Figures 2 and 3, respectively. It should be emphasized that this assumption is by no means restrictive. If a particular buffer system is not present in a practical application, it is only necessary to set both the upper and lower bounds of the corresponding inventory in the mathematical model to be zeros. On the other hand, there are certainly various storage tanks in the product distribution terminals and also in the import/export terminals for raw materials, intermediates, and final products. Usually, their capacities are larger than those in the reaction and separation processes. The general framework of the corresponding storage and transportation processes can be found in Figure 4.

Notice that the symbols M and D in all three general structures mentioned above represent *mixers* and *distributors*, respectively. The inputs of mixers in a production unit are originated from the distributors in the upstream source units of its feeds, and, similarly, the distributors in this unit are linked to the mixers in downstream sink units of its products. It should be realized that the mixers and distributors may or may not be present physically in the supply chain. They are included conceptually to facilitate an accurate formulation of the mathematical programming model. The detailed connections in the general configuration of a petroleum supply chain are listed in Table 1. For the sake of conciseness, every unit is represented with a two- or three-letter code, and these codes are defined in the first column of this table. In addition, a blank indicates that the corresponding sink unit is not modeled in the present study. Finally, the feeds of parex and isomar units are denoted as *parexf* and *isomarf*. The former is mainly a mixture of *o*-xylene, *p*-xylene, ethylbenzene, and *m*-xylene, and the latter consists of *o*-xylene, ethylbenzene, and *m*-xylene.

To construct an integrated planning and scheduling model, the unit models presented in the Appendix must be augmented with a complete mathematical description of the aforementioned supply chain structure. These formulations are outlined below.

4.1. Mixer and Distributor Connections. The material balance around a mixer can be written as

$$qti_{u,s,ts} = \sum_{u' \in \mathbf{UI}_{u,s}} q_{u',u,s,ts} \; \forall\, u \in \mathbf{U}, \quad \forall s \in \mathbf{F}_u,\ \forall ts \in \mathbf{TS}_{tp},\ \forall tp \in \mathbf{TP} \quad (3)$$

where $\mathbf{UI}_{u,s}$ denotes the set of all of the source units (or suppliers) of feedstock s received by unit u; $qti_{u,s,ts}$ denotes the accumulated amount of feedstock s sent to the buffer tank in unit u during interval ts; and $q_{u',u,s,ts}$ represents the accumulated amount of feedstock s transported from unit u' to unit u during interval ts. The material balance around a distributor can be formulated with a similar equation, that is,

$$qto_{u,p,ts} = \sum_{u' \in \mathbf{UO}_{u,p}} q_{u,u',p,ts} \; \forall u \in \mathbf{U}, \quad \forall p \in \mathbf{P}_u,\ \forall ts \in \mathbf{TS}_{tp},\ \forall tp \in \mathbf{TP} \quad (4)$$

where $\mathbf{UO}_{u,p}$ denotes the set of all sink units (or customers) of the product p generated in unit u; $qto_{u,p,ts}$ denotes the accumulated amount of product p withdrawn from the buffer tank in unit u during interval ts; and $q_{u,u',p,ts}$ represents the accumulated amount of product p transported from unit u to unit u' during interval ts.

Notice that the mixers and distributors may be present in all processes of the supply chain. In the import/export facility or product distribution terminal, every storage tank is equipped

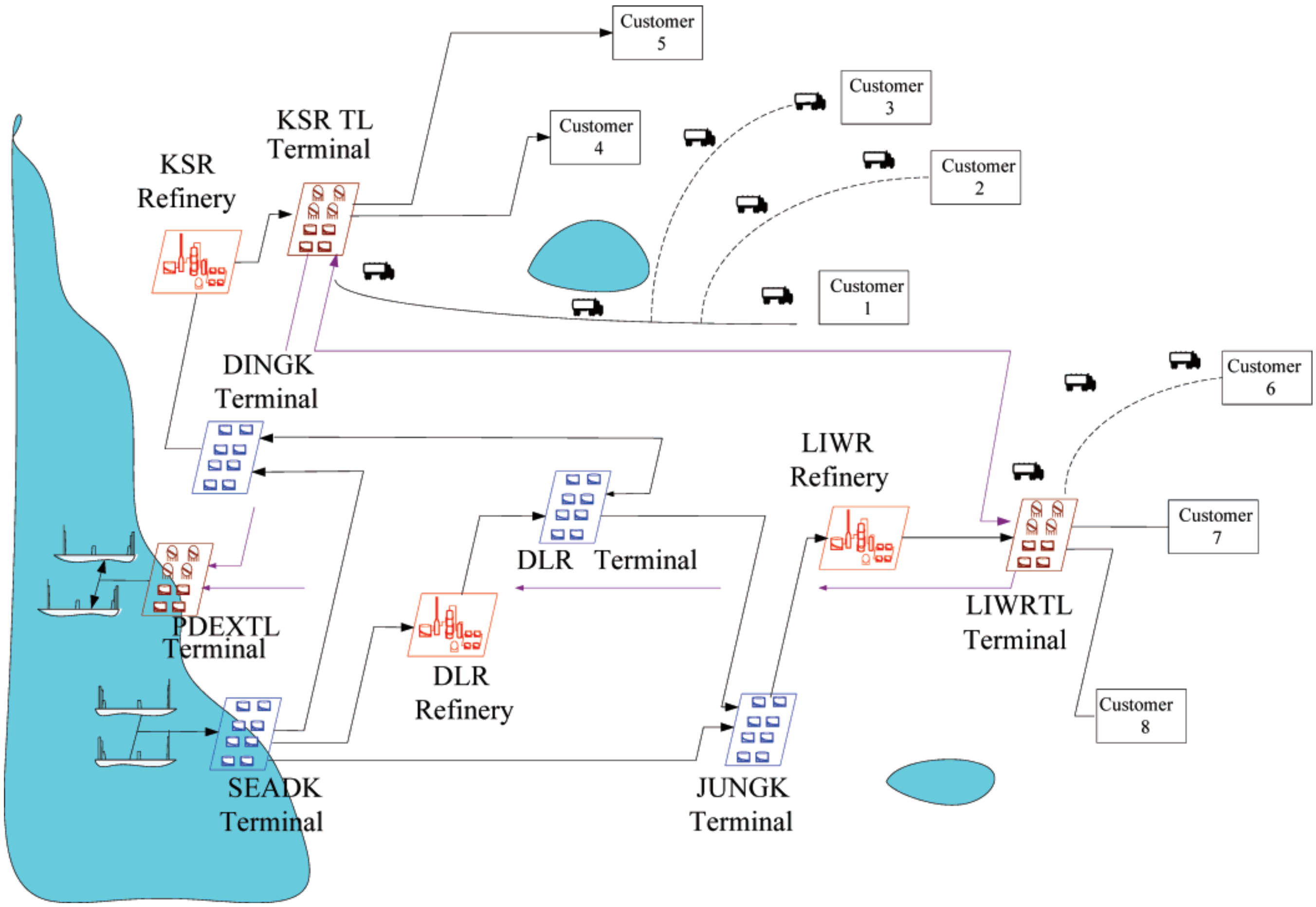

Figure 6. Petroleum supply network in case studies.

with both mixers and distributors (Figure 4). However, in the cases of reaction and separation processes, the mixers are attached to the feedstock buffer tanks, whereas the distributors are dedicated to the product buffer tanks (Figures 3 and 4). In other words, the outputs of the former tanks can be regarded as the inputs of reaction and separation processes, that is,

$$qto_{u,s,ts} = \sum_{k \in \mathbf{K}_{u,s}} qfi_{u,s,k,ts} \forall u \in \mathbf{UA}, \quad \forall s \in \mathbf{F}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (5)$$

$$qto_{u,s,ts} = qf_{u,s,ts} \forall u \in \mathbf{UB}, \forall s \in \mathbf{F}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (6)$$

Similarly, the inputs of the product tanks should be considered as the outputs of these processes, that is,

$$qti_{u,p,ts} = qp_{u,p,ts} \forall u \in \mathbf{U}', \forall p \in \mathbf{P}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (7)$$

where, $\mathbf{U}' = \mathbf{UA} \cup \mathbf{UB}$.

4.2. Transportation Capacity. It is obvious that the process materials must be transported from one unit to another with pumps and pipelines. The transportation methods for importing the raw materials and intermediates should be tankers. The products and byproducts could be delivered to domestic customers either via pipelines or by trucks. Because the corresponding transportation capacities should always be limited in practice, the following inequalities are included in our model,

$$Q^L_{v,v',m} \le q_{v,v',m,ts} \le Q^U_{v,v',m} \quad \forall v,v' \in \mathbf{USC}, \forall m \in \mathbf{M}, ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (8)$$

and

$$\mathbf{USC} = \mathbf{U} \cup \mathbf{S} \cup \mathbf{C}$$
$$\mathbf{M} = \cup_{u \in \mathrm{U}} \mathrm{M}_u \quad (9)$$

where **S** is the set of all suppliers of the raw materials and/or intermediates, **C** is the set of all customers of the final products and/or byproducts, $Q^U_{v,v',m}$ and $Q^L_{v,v',m}$ denote respectively the upper and lower limits of the transportation capacity for material m from unit v to unit v', and $q_{v,v',m,ts}$ represents the accumulated amount of delivered material m from unit v to unit v' during scheduling interval ts.

4.3. Input Constraints. It is assumed in this study that the crude oil is purchased from the international market, and its quality, quantity, and shipment dates can be reasonably predicted over a relatively small number of planning periods. These forecasts are characterized with the following equality constraints in this study,

$$\sum_{v' \in \mathbf{UT}} q_{v,v',m,ts} = QCS_{v,m,ts} i^{Cr}_{v,m,ts} + QCC_{v,m,ts} \quad v \in \mathbf{S}_{crude}, m \in \mathbf{P}_v, ts \in \mathbf{TS}^{v,m}_{tp}, tp \in \mathbf{TP} \quad (10)$$

where $\mathbf{S}_{crude}$ denotes the set of overseas suppliers of crude oils, $\mathbf{P}_v$ represents the set of different types of crudes provided by supplier v, $\mathbf{TS}^{v,m}_{tp}$ denotes the set of scheduling intervals (within the planning period tp) in which shipment of crude m from supplier v can be scheduled (i.e., $\mathbf{TS}^{v,m}_{tp} \subset \mathbf{TS}_{tp}$), $QCS_{v,m,ts}$ represents the amount of crude m that can be obtained from supplier v during the scheduling interval ts. $QCC_{v,m,ts}$ denotes

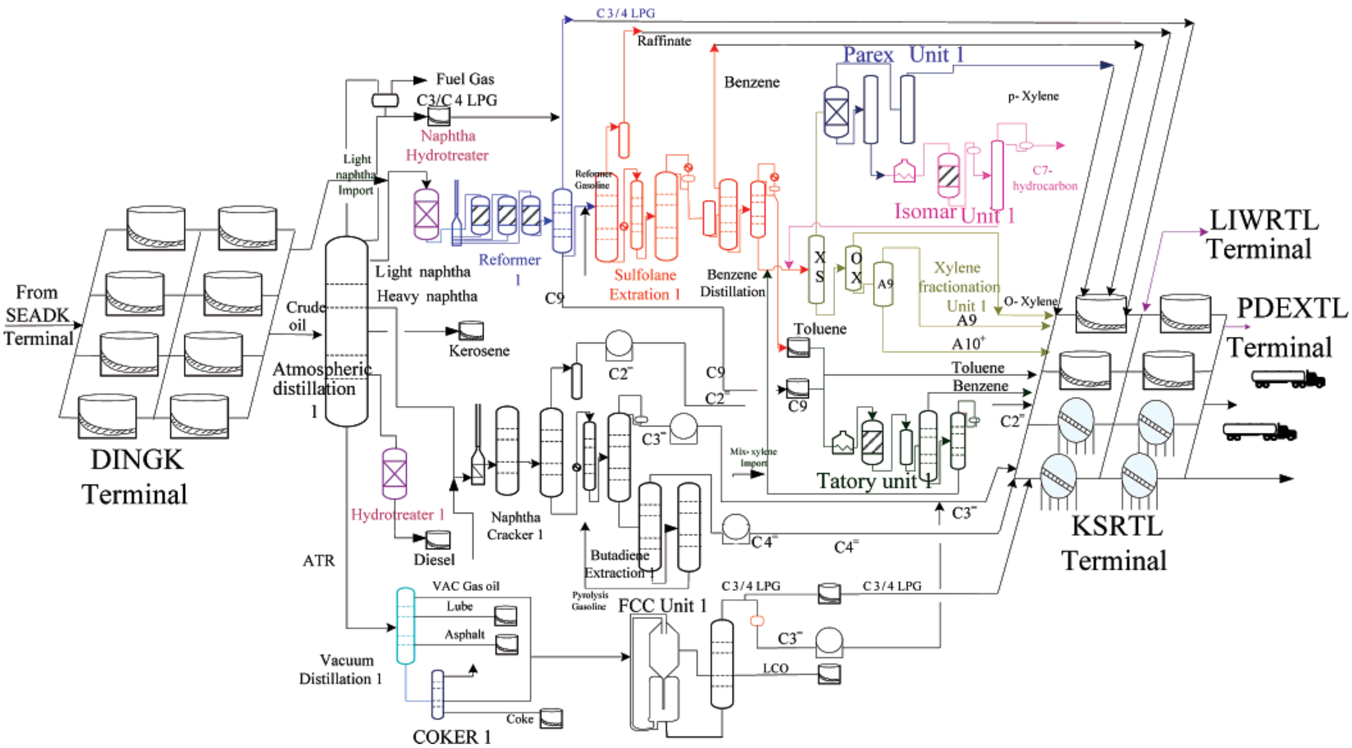

Figure 7. KSR Refinery.

a fixed amount of crude m guaranteed in a long-term contract by supplier v during the scheduling interval ts. If $ts \in \mathbf{TS}_{tp}^{v,m}$, the binary variable $i_{v,m,ts}^{Cr} \in \{0,1\}$ denotes whether or not the crude is selected. However, the constraint $i_{v,m,ts}^{Cr} = 0$ should be imposed if $ts \notin \mathbf{TS}_{tp}^{v,m}$.

Let us further assume that three intermediates of the petroleum supply chain, that is, heavy naphtha, light naphtha, and mixed xylenes, can be imported for use in the naphtha crackers, reforming units, and xylene fractionation units, respectively. Therefore, additional equality constraints are imposed upon the total imported quantity of each of these intermediates,

$$\sum_{v' \in \mathbf{UT}} q_{v,v',m,ts} = QHN_{v,m,ts} i_{v,m,ts}^{Hn} + QHNC_{v,m,s} \quad v \in \mathbf{S}_{hvynap},$$
$$m \in \mathbf{P}_v,\ ts \in \mathbf{TS}_{tp}^{v,m},\ tp \in \mathbf{TP} \quad (11)$$

$$\sum_{v' \in \mathbf{UT}} q_{v,v',m,ts} = QLN_{v,m,ts} i_{v,m,ts}^{Ln} + QLNC_{v,m,s} \quad v \in \mathbf{S}_{litnap},$$
$$m \in \mathbf{P}_v,\ ts \in \mathbf{TS}_{tp}^{v,m},\ tp \in \mathbf{TP} \quad (12)$$

$$\sum_{v' \in \mathbf{UT}} q_{v,v',m,ts} = QXI_{v,m,ts} i_{v,m,ts}^{Mx} + QXIC_{v,m,ts} \quad v \in \mathbf{S}_{mxyl},$$
$$m \in \mathbf{P}_v,\ ts \in \mathbf{TS}_{tp}^{v,m},\ tp \in \mathbf{TP} \quad (13)$$

where $\mathbf{S}_{hvynap}$, $\mathbf{S}_{litnap}$, and $\mathbf{S}_{mxyl}$ denote the sets of overseas suppliers of heavy naphtha, light naphtha and mixed xylene respectively; $\mathbf{P}_v$ represents the set of different types of heavy naphtha, light naphtha, or mixed xylene provided by supplier v; $\mathbf{TS}_{tp}^{v,m}$ denotes the set of scheduling intervals (within the planning period tp) in which the shipment of process material m from supplier v can be scheduled (i.e., $\mathbf{TS}_{tp}^{v,m} \subset \mathbf{TS}_{tp}$); $QHN_{v,m,ts}$, $QLN_{v,m,ts}$, and $QXI_{v,m,ts}$ represent respectively the amounts of heavy naphtha, light naphtha, and mixed xylene m that can be purchased from supplier v during the scheduling interval ts. $QHNC_{v,m,ts}$, $QLNC_{v,m,ts}$, and $QXIC_{v,m,ts}$ denote respectively the fixed amounts of heavy naphtha, light naphtha, and mixed xylene (m) guaranteed in a long-term contract by supplier v during the scheduling interval ts. If $ts \in \mathbf{TS}_{tp}^{v,m}$, the binary variable $i_{v,m,ts}^{Hn}$, $i_{v,m,ts}^{Ln}$, or $i_{v,m,ts}^{Mx}$ denotes whether or not intermediate m is chosen. If, on the other hand, $ts \in \mathbf{TS}_{tp}^{v,m}$, then the constraints $i_{v,m,ts}^{Hn} = 0$, $i_{v,m,ts}^{Ln} = 0$, and $i_{v,m,ts}^{Mx} = 0$ should be imposed.

It is assumed that the major petrochemical products of the supply chain, that is, ethylene, propylene, butadiene, benzene, toluene, and xylene, can also be purchased from oversea suppliers to fulfill contract obligations to customers. A set of equality constraints are thus included in the model, that is,

$$\sum_{v' \in \mathbf{UT}} q_{v,v',m,ts} = QPET_{v,m,ts} i_{v,m,ts}^{Pet} + QPETC_{v,m,ts} \quad v \in \mathbf{S}_{\mathrm{Pet}},$$
$$m \in \mathbf{P}_v,\ ts \in \mathbf{TS}_{tp}^{v,m},\ tp \in \mathbf{TP} \quad (14)$$

where $\mathbf{S}_{\mathrm{Pet}}$ denotes the set of overseas suppliers of the above-mentioned petrochemical products, $\mathbf{P}_v$ represents the set of these products provided by supplier v, $\mathbf{TS}_{tp}^{v,m}$ denotes the set of scheduling intervals within the planning period tp in which shipment of product m from supplier v can be scheduled (i.e., $\mathbf{TS}_{tp}^{v,m} \subset \mathbf{TS}_{tp}$), $QPET_{v,m,ts}$ represents the amount of product m that can be purchased from supplier v during the scheduling interval ts. $QPETC_{v,m,ts}$ represents a fixed amount of product m guaranteed in a long-term contract by supplier v during the scheduling interval ts. If $ts \in \mathbf{TS}_{tp}^{v,m}$, the binary variable $i_{v,m,ts}^{Pet}$ denotes whether or not the petrochemical product m is actually purchased. Again, the constraint $i_{v,m,ts}^{Pet} = 0$ should be imposed if $ts \in \mathbf{TS}_{tp}^{v,m}$. Notice finally that the set of all possible inputs of the petroleum supply chain can be expressed as: $\mathbf{S} = \mathbf{S}_{crude} \cup \mathbf{S}_{hvynap} \cup \mathbf{S}_{litnap} \cup \mathbf{S}_{mxyl} \cup \mathbf{S}_{pet}$.

4.4. Output Constraints. In this study, the customer demands for the petrochemical products (i.e., ethylene, propylene, butadiene, benzene, toluene, and xylenes) are assumed to be predictable at least in the short term. This is due to the fact that these products are consumed mainly in the downstream production processes. It is also assumed that the total amounts actually

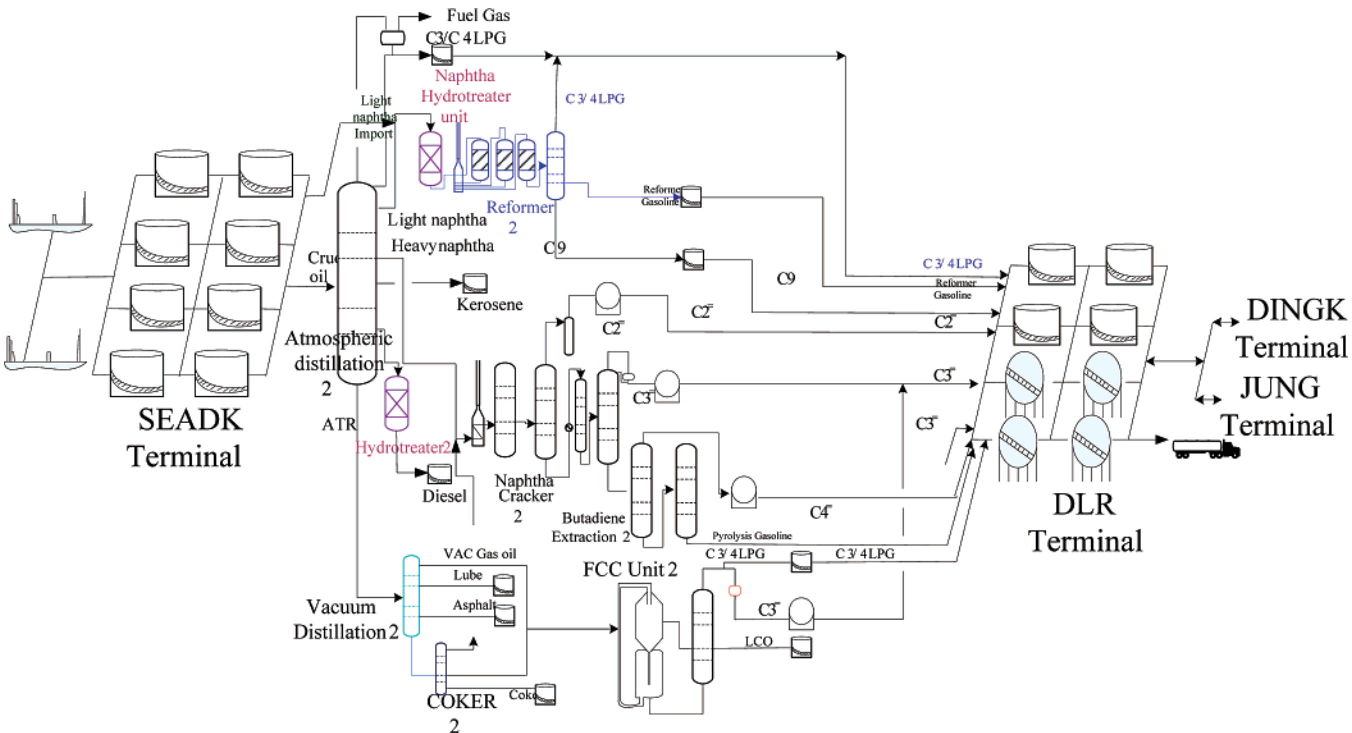

Figure 8. DLR Refinery.

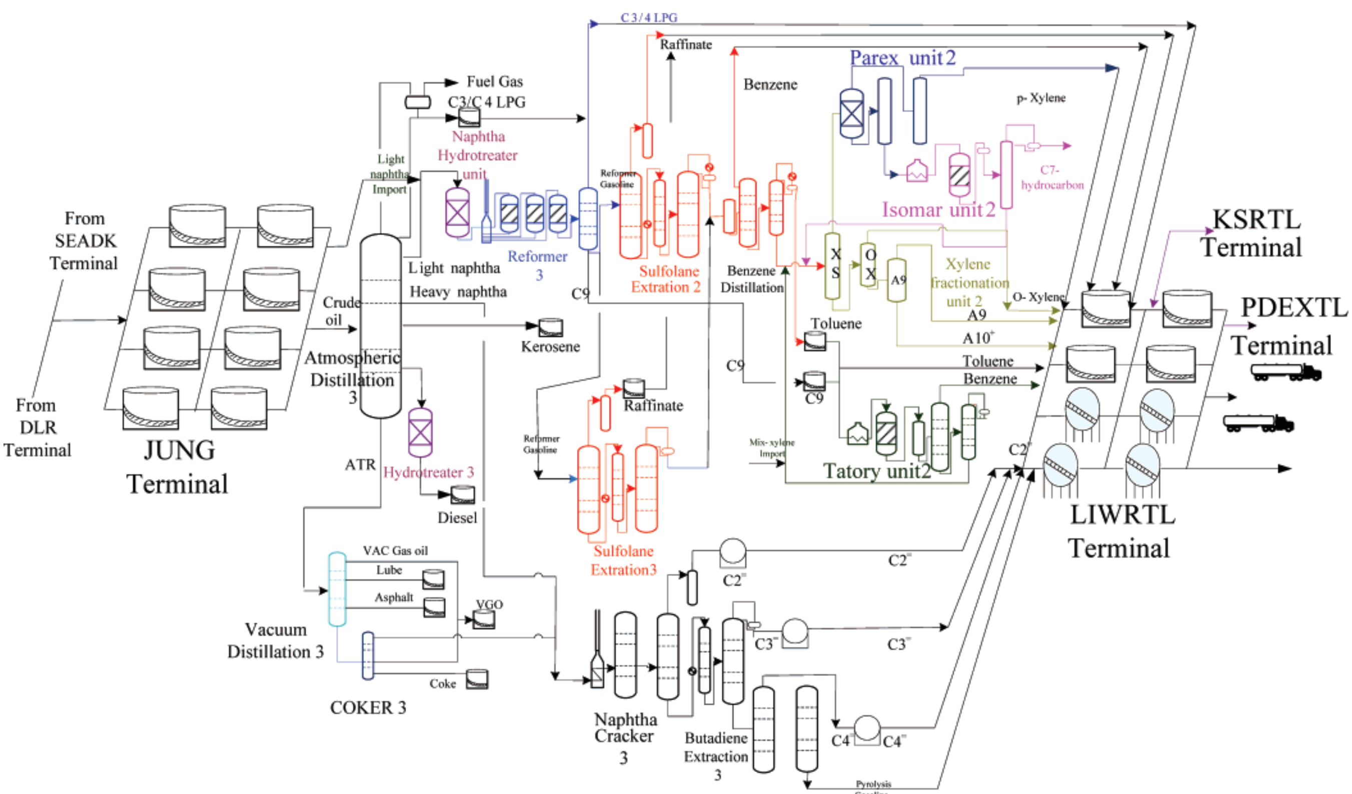

Figure 9. LIWR Refinery.

shipped to these customers during a particular planning period are allowed to vary in several given ranges, that is,

$$\sum_{l\in \mathbf{L}_{v',m,tp}} QPL^{L}_{v',m,tp,l} j_{v',m,tp,l} \le \tilde{q}_{v',m,tp} \le \sum_{l\in \mathbf{L}_{v',m,tp}} QPL^{U}_{v',m,tp,l} j_{v',m,tp,l} \quad v' \in \mathbf{C}_{pet},\ m \in \mathbf{F}_{v'},\ tp \in \mathbf{TP} \quad (15)$$

$$\sum_{l\in \mathbf{L}_{v',m,tp}} j_{v',m,tp,l} = 1 \quad v' \in \mathbf{C}_{pet},\ m \in \mathbf{F}_{v'},\ tp \in \mathbf{TP} \quad (16)$$

where $\tilde{q}_{v',m,tp} = \sum_{ts\in \mathbf{TS}_{tp}} \sum_{v\in \mathbf{UD}} q_{v,v',m,ts}$, $QPL^{U}_{v',m,tp,l}$ and $QPL^{L}_{v',m,tp,l}$ represent respectively the upper and lower bounds of the lth range of the amount of material m delivered to customer v' during planning period tp. The binary variable $j_{v',m,tp,l}$ is used to reflect if the amount of material m sent to customer v' during period tp is in range l ($j_{v',m,tp,l} = 1$) or not ($j_{v',m,tp,l} = 0$).

The aforementioned petrochemical products should also be allowed to be sold on the overseas market so that the overall

Table 2. Allowable Delivery Ranges of the Main Products Per Month

			tp1			tp2			tp3		
product (unit)	customer	bounds	range 1	range 2	range 3	range 1	range 2	range 3	range 1	range 2	range 3
ethylene (en) (kg)	Kuco2	lower	17 425	19 475	21 525	17 000	19 000	21 000	12 325	13 775	15 225
		upper	19 475	21 525	23 575	19 000	21 000	23 000	13 775	15 225	16 675
	LIWRco3	lower	172 040	192 280	212 520	333 285	372 495	411 705	245 650	274 550	303 450
		upper	192 280	212 520	232 760	372 495	411 705	450 915	274 550	303 450	332 350
propylene (pn)(m^3)	Kuco3	lower	481 100	537 700	594 300	129 200	144 400	159 600	21 250	23 750	26 250
		upper	537 700	594 300	650 900	144 400	159 600	174 800	23 750	26 250	28 750
	Kuco5	lower	144 500	161 500	178 500	17 000	19 000	21 000	773 840	864 880	955 920
		upper	161 500	178 500	195 500	19 000	21 000	23 000	864 880	955 920	1 046 960
	LIWRco2	lower	8330	9310	10 290	34 000	38 000	42 000	51 170	57 190	63 210
		upper	9310	10 290	11 270	38 000	42 000	46 000	57 190	63 210	69 230
butadiene (bd) (m^3)	Kuco3	lower	850	950	1050	1275	1425	1575	3230	3610	3990
		upper	950	1050	1150	1425	1575	1725	3610	3990	4370
benzene(bz) (m^3)	Kuco2	lower	17 850	19 950	22 050	17 850	19 950	22 050	18 700	20 900	23 100
		upper	19 950	22 050	24 150	19 950	22 050	24 150	20 900	23 100	25 300
	Kuco5	lower	53 380	59 660	65 940	17 000	19 000	21 000	57 715	64 505	71 295
		upper	59 660	65 940	72 220	19 000	21 000	23 000	64 505	71 295	78 085
toluene(tl) (m^3)	Kuco1	lower	2550	2850	3150	2550	2850	3150	9690	10 830	11 970
		upper	2850	3150	3450	2850	3150	3450	10 830	11 970	13 110
	LIWRco2	lower	5100	5700	6300	5100	5700	6300	5270	5890	6510
		upper	5700	6300	6900	5700	6300	6900	5890	6510	7130
mixed xylenes (mx) (m^3)	Kuco1	lower	11 900	13 300	14 700	17 000	19 000	21 000	15 300	17 100	18 900
		upper	13 300	14 700	16 100	19 000	21 000	23 000	17 100	18 900	20 700
	Kuco5	lower	25 500	28 500	31 500	28 560	31 920	35 280	35 955	40 185	44 415
		upper	28 500	31 500	34 500	31 920	35 280	38 640	40 185	44 415	48 645
	LIWRco2	lower	2754	3078	3402	2040	2280	2520	64 260	71 820	79 380
		upper	3078	3402	3726	2280	2520	2760	71 820	79 380	86 940
p-xylene (px) (m^3)	Kuco1	lower	3400	3800	4200	3400	3800	4200	3400	3800	4200
		upper	3800	4200	4600	3800	4200	4600	3800	4200	4600
	Kuco3	lower	37 400	41 800	46 200	34 000	38 000	42 000	68 000	76 000	84 000
		upper	41 800	46 200	50 600	38 000	42 000	46 000	76 000	84 000	92 000
o-xylene (ox) (m^3)	Kuco1	lower	10 710	11 970	13 230	8500	9500	10 500	17 850	19 950	22 050
		upper	11 970	13 230	14 490	9500	10 500	11 500	19 950	22 050	24 150
	Kuco3	lower	21 760	24 320	26 880	5100	5700	6300	21 250	23 750	26 250
		upper	24 320	26 880	29 440	5700	6300	6900	23 750	26 250	28 750
		lower	18 530	20 710	22 890	9350	10 450	11 550	47 175	52 725	58 275
	LIWRco1	upper	20 710	22 890	25 070	10 450	11 550	12 650	52 725	58 275	63 825

performance of the supply chain may be further enhanced. This practice is justifiable if the selling prices and/or demands for some of the products are high enough to compensate for the losses due to the needs to cut down inventories of the other products and to sell them at lower prices and/or higher transportation costs. The quantities delivered to overseas customers should be subject to simple inequality constraints, that is,

$$QOS^L_{\upsilon',m,tp} \leq \sum_{\upsilon\in\mathbf{UD}} \sum_{ts\in\mathbf{TS}_{tp}} q_{\upsilon,\upsilon',m,ts} \leq QOS^U_{\upsilon',m,tp} \quad \upsilon' \in \mathbf{C}_{o\upsilon s}, \quad m \in \mathbf{F}_{\upsilon'}, tp \in \mathbf{TP} \tag{17}$$

where $\mathbf{C}_{o\upsilon s}$ denotes the sets of overseas customers for the petrochemical products, and $QOS^U_{\upsilon',m,tp}$ and $QOS^L_{\upsilon',m,tp}$ represent respectively the acceptable maximum and minimum amounts of product m transported to customer υ' in period tp.

Finally, it is assumed in this work that the remaining products and byproducts of the supply chain, LPG, mixed xylenes, gasoline, kerosene, and diesel, can always be sold to the domestic consumers. The corresponding constraints are

$$QXO^L_{\upsilon',m,tp} \leq \sum_{\upsilon\in\mathbf{UD}} \sum_{ts\in\mathbf{TS}_{tp}} q_{\upsilon,\upsilon',m,ts} \leq QXO^U_{\upsilon',m,tp} \quad \upsilon' \in \mathbf{C}_{dt}, \quad m \in \mathbf{F}_{\upsilon'}, tp \in \mathbf{TP} \tag{18}$$

where $\mathbf{C}_{dt}$ denotes the sets of these domestic customers, and $QXO^U_{\upsilon',m,tp}$ and $QXO^L_{\upsilon',m,tp}$ represent respectively the acceptable maximum and minimum amounts of product m delivered to customer υ' in period tp. Notice finally that the set of all possible outputs of the petroleum supply chain can be expressed as $\mathbf{C} = \mathbf{C}_{pet} \cup \mathbf{C}_{dt} \cup \mathbf{C}_{o\upsilon s}$ in the present model.

5. Objective Function

The objective function of the proposed optimization problem is chosen to be the total profit realized over a specified planning horizon, that is,

$$\text{Total Profit} = \sum_{tp\in\mathbf{TP}} pf_{tp} \tag{19}$$

and

$$pf_{tp} = rs_{tp} - cr_{tp} - co_{tp} - ct_{tp} - ci_{tp} \tag{20}$$

where, pf_{tp}, rs_{tp}, cr_{tp}, co_{tp}, ct_{tp}, and ci_{tp} denote respectively the net profit, the total revenue secured from various product sales, the total cost of raw materials, the total operation cost, the total transportation cost, and the total inventory cost in planning period tp. The total sale revenue can be expressed as

$$rs_{tp} = \sum_{\upsilon'\in\mathbf{C}_{pet}} \sum_{m\in\mathbf{F}_{\upsilon'}} \left(\sum_{l\in\mathbf{L}_{\upsilon',m,tp}} SP_{\upsilon',m,tp,l}\, qj_{\upsilon',m,tp,l} \right) + \sum_{\upsilon'\in\mathbf{C}_{o\upsilon s}} \sum_{m\in\mathbf{F}_{\upsilon'}} \left(\sum_{\upsilon\in\mathbf{UD}} \sum_{ts\in\mathbf{TS}_{tp}} q_{\upsilon,\upsilon',m,ts} \right) SPO_{\upsilon',m,tp} + \sum_{\upsilon'\in\mathbf{C}_{dt}} \sum_{m\in\mathbf{F}_{\upsilon'}} \left(\sum_{\upsilon\in\mathbf{UD}} \sum_{ts\in\mathbf{TS}_{tp}} q_{\upsilon,\upsilon',m,ts} \right) SPD_{\upsilon',m,tp} \tag{21}$$

Table 3. Optimal Amounts of Crude Oils to be Purchased in the Base Case ($10^3 \cdot m^3$ /wk)

material	month / week / supplier	ts1 (tp1)	ts2 (tp1)	ts3 (tp1)	ts4 (tp1)	ts5 (tp2)	ts6 (tp2)	ts7 (tp2)	ts8 (tp2)	ts9 (tp3)	ts10 (tp3)	ts11 (tp3)	ts12 (tp3)
cro 2	Sup1		500	650		400							
	Sup3	800	200			250							
	Sup4			300	600								
cro 3	Sup1	900			500					100	250		400
	Sup2							700	700	450			
	Sup3						300						
	Sup4		900										
	Sup5					750	500			750		1600	400
cro 4	Sup1	400		850						500		100	150
	Sup2	400		400				550	400	750	700		200
	Sup3		900		600	350				350			600
	Sup4		800			400							300
	Sup5	750			300			500			550	800	400
cro 5	Sup1		250	350						300	750	350	400
	Sup2	400	400	400		550		500	400	750			200
	Sup3					450			400				
	Sup4	500			300								
	Sup5						700			650	1650	600	600
cro 7	Sup1	100	250										
	Sup2					450							
	Sup3					650			600				
	Sup4	500										500	
	Sup5							500		650			
cro 8	Sup1	200	250	350							350	350	400
	Sup2	700		200		650	500	200	1600		550	300	200
	Sup3						500	400					
	Sup4	400	1800	400	300								
	Sup5						600	500	400	550	350	800	700
cro 9	Sup1	200	250	350								350	
	Sup2	400	700										
	Sup3							400					
	Sup4	500		600									
	Sup5					550			300				
cro 10	Sup1	500	250	350								350	
	Sup2	600	400	400								500	
	Sup3								300				
	Sup4	600	700	200	1800								
total (month)			28 750				16 800				22 500		
sum							68 050						

Table 4. Optimal Amounts of Intermediate Oils and Final Products to be Purchased in the Base Case

material	month / week / supplier	ts4 (tp1)	ts5 (tp2)	ts6 (tp2)	ts7 (tp2)	ts8 (tp2)	ts9 (tp3)	ts10 (tp3)	ts11 (tp3)	ts12 (tp3)
en ($10^3 \cdot$kg)	sup2	21								
	sup4		42							
	sup5	6								
	total (month)	27		42						
ln1 ($10^3 \cdot m^3$)	sup1						6.5	6.5		15.5
	total (month)							18.5		
ln2 ($10^3 \cdot m^3$)	sup1		6			0.5		5.5		
	sup2		11			0.5		6.5	5.5	
	sup3				16					
	sup4		1					1.5	6	
	sup5							1.5		
	total (month)			35				26.5		
hn3 ($10^3 \cdot m^3$)	sup1	1					1.5	1.5		
	sup2						1.5	1.5		
	sup4						1.5	1.5		
	sup5							1.5		
	total (month)	1						10.5		

It should be noted that a new variable $qj_{\upsilon',m,tp,l}$ is introduced here to covert the revenue model into linear form. Specifically, the total amount of product m sent to customer υ' in planning period tp, that is $\tilde{q}_{\upsilon',m,tp}$, can be related to this variable with the following two constraints,

$$\tilde{q}_{\upsilon',m,tp} = \sum_{l \in \mathbf{L}_{\upsilon',m,tp}} qj_{\upsilon',m,tp,l}$$
$$0 \le qj_{\upsilon',m,tp,l} \le j_{\upsilon',m,tp,l} U$$
$$\upsilon' \in \mathbf{C}_{pet}, m \in \mathbf{F}_{\upsilon'}, tp \in \mathbf{TP}, l \in \mathbf{L}_{\upsilon',m,tp} \quad (22)$$

where U is a sufficiently large constant, $SP_{\upsilon',m,tp,l}$ represents the selling price of product m sold to customer υ' during period tp in level range l, $SPO_{\upsilon',m,tp}$ denote the selling price of intermediate or final product m sold to overseas customer υ' during period tp, and $SPD_{\upsilon',m,tp}$ denote the selling price of intermediate or final product m sold to domestic customer υ' during period tp. The general relationship between the delivered amount of a product and its selling price is sketched in Figure 5.

The second term on the right-hand side of eq 20 is the sum of the purchasing costs of the crudes, the imported intermediates (i.e., heavy naphtha, light naphtha, and mixed xylenes), and

Table 5. Optimal Throughputs of all Production Units in Base Case

	first month				second month				third month			
week unit	1	2	3	4	5	6	7	8	9	10	11	12
AD1												
AD2	5 858 900	5 517 500	4 676 230	3 512 006	5 585 090	2 462 527	1 727 159	4 688 248	2 877 576	2 029 846	4 458 590	3 033 280
AD3	2 040 410	2 713 190	1 958 563			502 382	2 626 181	282 479	3 039 260	2 973 517	2 248 038	2 860 440
VD1	1 700 000	1 700 000	1 692 549	1 416 827	1 700 000	1 563 805	1 700 000	1 677 900	1 700 000	1 700 000	1 700 000	1 700 000
VD2	1 800 000	1 800 000	1 676 694					450 000	450 000	450 000	450 000	450 000
VD3	524 777	702 180		432 000	1 188 007		523 632	432 000	951 679	467 491	1 305 928	956 823
CK1	375 000	375 000	375 000	375 000	375 000	375 000	375 000	375 000	375 000	375 000	375 000	375 000
CK2	322 142	316 445	125 000			143 099		125 000	125 000		125 000	125 000
CK3	450 000	450 000	450 000	192 671	383 642		274 815	144 710	450 000	414 186	450 000	440 823
FCC1	1 650 000	1 650 000	1 650 000	1 643 506	1 650 000	1 580 645	1 650 000	1 650 000	1 650 000	1 650 000	1 650 000	1 650 000
FCC2	565 276	1 625 000	225 000				225 000		828 845	292 654	793 051	631 263
NC1	359 112	375 794	350 000	350 000	413 696		325 000	350 929	350 000		350 000	350 000
NC2												
NC3			354 773						300 000	300 000		351 566
BD1	11 904							23 266				
BD2	11 904							30 000	14 010			28 471
BD3		11 904	11 822	23 205	27 428		25 468	32 000	32 000	32 000	32 000	32 000
HTD1				350 000					350 000			
HTD2	113 3427	1 076 661	927 546	274 136	1 109 124	273 697	360 627	573 889	275 323	416 286	878 531	596 876
HTD3	424 786	558 329	364 359			350 000	492 114	350 000	623 179	584 383	455 284	563 152
RF1	857 483	406 333	305 000	411 515	387 878	355 555	315 255	376 835	364 664	348 205	363 958	387 878
RF2		802 224	682 249		457 208		405 578	310 000	479 862	310 000	633 935	421 627
RF3	295 000											
AET1	240 000	241 255	264 642	381 048	240 000	240 000	206 460	240 000	361 963	255 407	264 173	329 573
AET2	220 000	212 357	220 000	220 000	220 000	220 000	220 000	220 000	220 000	220 000	220000	220 000
AET3	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
XF1	110 000	110 000	110 000	110 000	110 000	110 000	110 000	110 000	110 000	110 000	110 000	110 000
XF2	100 000	100 000	100 000	100 000	100 000	100 000	100 000	100 000	100 000	100 000	100 000	100 000
TT1	60 534	108 000	87 740	41 151	88 038	60 029	79 455	108 000	108 000	108 000	108 000	86 582
TT2	54 000	93 450	79 209		65 117	35 000	51 600	52 157	52 157	52 157	52 157	51 739
PR1	70 682	72 739	63 131	68 473	74 249	75 605	63 010	71 604	79 604	71 604	71 604	71 158
PR2	55 639	55 815	48 710	53 781	62 160	59 170	55 674	45 735	65 735	55 735	55 735	55 689
IM1	68 392	67 242	55 684	81 423	62 161	74 279	68 165	67 764	67 764	67 764	67 764	68 065
IM2												

also possibly the final products provided by domestic suppliers. In particular, this term can be written as

$$cr_{tp} = \sum_{v\in \mathbf{S}_{cr}} \sum_{m\in \mathbf{P}_v} \left(\left[\sum_{ts\in \mathbf{TS}_{tp}} QCS_{v,m,ts} i^{Cr}_{v,m,ts} \right] CRO_{v,m,tp} + \left[\sum_{ts\in \mathbf{TS}_{tp}} QCC_{v,m,ts} \right] CROC_{v,m,tp} \right) + \sum_{v\in \mathbf{S}_{hvynap}} \sum_{m\in \mathbf{P}_v} \left(\left[\sum_{ts\in \mathbf{TS}_{tp}} QHN_{v,m,ts} i^{Hn}_{v,m,ts} \right] CHN_{v,m,tp} + \left[\sum_{ts\in \mathbf{TS}_{tp}} QHNC_{v,m,ts} \right] CHNC_{v,m,tp} \right) + \sum_{v\in \mathbf{S}_{litnap}} \sum_{m\in \mathbf{P}_v} \left(\left[\sum_{ts\in \mathbf{TS}_{tp}} QLN_{v,m,ts} i^{Ln}_{v,m,ts} \right] CLN_{v,m,tp} + \left[\sum_{ts\in \mathbf{TS}_{tp}} QLNC_{v,m,ts} \right] CLNC_{v,m,tp} \right) + \sum_{v\in \mathbf{S}_{mxyl}} \sum_{m\in \mathbf{P}_v} \left(\left[\sum_{ts\in \mathbf{TS}_{tp}} QXI_{v,m,ts} i^{Mx}_{v,m,ts} \right] CMX_{v,m,tp} + \left[\sum_{ts\in \mathbf{TS}_{tp}} QXIC_{v,m,ts} \right] CMXC_{v,m,tp} \right) + \sum_{v\in \mathbf{S}_{pet}} \sum_{m\in \mathbf{P}_v} \left(\left[\sum_{ts\in \mathbf{TS}_{tp}} QPET_{v,m,ts} i^{Pet}_{v,m,ts} \right] CPET_{v,m,tp} + \left[\sum_{ts\in \mathbf{TS}_{tp}} QPETC_{v,m,ts} \right] CPETC_{v,m,tp} \right) \quad (23)$$

where $CRO_{v,m,tp}$, $CHN_{v,m,tp}$, $CLN_{v,m,tp}$, $CMX_{v,m,tp}$, and $CPET_{v,m,tp}$ denote respectively the unit costs for purchasing crude oils, heavy naphtha, light naphtha, mixed xylenes, and final products, respectively; and $CROC_{v,m,tp}$, $CHNC_{v,m,tp}$, $CLNC_{v,m,tp}$, $CMXC_{v,m,tp}$, and $CPETC_{v,m,tp}$ represent the unit costs specified in long-term contracts for crude oils, heavy naphtha, light naphtha, mixed xylenes, and final products, respectively. The total operating cost can be considered as the sum of the operating costs for running all of the reaction and separation processes, that is,

$$co_{tp} = \sum_{ts\in \mathbf{TS}_{tp}} \sum_{u\in \mathbf{UA}} \left(l_{u,ts} CXA_{u,ts} + \sum_{s\in \mathbf{F}_u} \sum_{k\in \mathbf{K}_{u,s}} qfi_{u,s,k,ts} CVA_{u,s,k,ts} \right) + \sum_{ts\in \mathbf{TS}_{tp}} \sum_{u\in \mathbf{UB}} \left(l_{u,ts} CXB_{u,ts} + \sum_{s\in \mathbf{F}_u} qf_{u,s,ts} CVB_{u,s,ts} \right) \quad (24)$$

where $CXA_{u,ts}$ and $CXB_{u,ts}$ denote the fixed operating costs for unit u in **UA** and **UB** during scheduling interval ts respectively, $CVA_{u,k,s,ts}$ represents the variable operating cost of reaction unit u for processing feedstock $s$under operation mode k during scheduling interval ts, and $CVB_{u,ts}$ is the variable operating cost of separation unit u during scheduling interval ts.

The overall transportation cost can be expressed as

$$ct_{tp} = \sum_{v\in \mathbf{USC}} \sum_{v'\in \mathbf{USC}} \sum_{m\in \mathbf{M}} \sum_{ts\in \mathbf{TS}_{tp}} q_{v,v',m,ts} CTP_{v,v',m,ts} \quad (25)$$

where $CTP_{v,v'm,ts}$ represents the unit transportation cost for moving material m from unit v to unit v' during scheduling interval ts. Finally, the unprocessed inventories remaining in the supply chain at the end of each scheduling interval can be penalized by incorporating additional costs, that is,

$$ci_{tp} = \sum_{u\in \mathbf{U}} \sum_{m\in \mathbf{M}_u} \sum_{ts\in \mathbf{TS}_{tp}} vin_{u,m,ts} CIN_{u,m,ts} \quad (26)$$

Table 6. Suggested Amounts of Products and by Products to be Delivered to the Customers In Each Planning Period in the Base Case

	month	tp1		tp2		tp3	
product (unit)	customer	amount	level	amount	level	amount	level
ethylene (en) (kg)	Kuco2	21 525	2	21 000	2	15 225	2
	LIWRco3	212 520	2	411 705	2	303 450	2
propylene (pn) (m^3)	Kuco3	650 900	3	174 800	3	28 750	3
	Kuco5	195 500	3	23 000	3	1 046 960	3
	LIWRco2	11 270	3	46 000	3	69 230	3
butadiene (bd) (m^3)	Kuco3	1050	2	1575	2	3990	2
benzene (bz) (m^3)	Kuco2	22 050	2	22 050	2	23 100	2
	Kuco5	65 940	2	21 000	2	71 295	2
toluene (tl) (m^3)	Kuco1	3150	2	3150	2	11 970	2
	LIWRco2	6300	2	6300	2	6510	2
mixed xylenes (mx) (m^3)	Kuco1	14 700	2	21 000	2	18 900	2
	Kuco5	31 500	2	35 280	2	44 415	2
	LIWRco2	3402	2	2520	2	79 380	2
p-xylene (px)(m^3)	Kuco1	4200	2	4200	2	4200	2
	Kuco3	46 200	2	42 000	2	84 000	2
o-xylene (ox) (m^3)	Kuco1	13 230	2	10 500	2	22 050	2
	Kuco3	26 880	2	6300	2	26 250	2
	LIWRco1	22 890	2	11 550	2	58 275	2

where $CIN_{u,m,ts}$ represents the inventory cost per unit of process material *m* in unit *u* during scheduling interval *ts*.

6. Case Studies

The petroleum supply network considered in our case studies is sketched in Figure 6. It is assumed that the crude oils and intermediates, i.e., heavy naphtha, light naphtha, and mixed xylenes, are shipped from foreign suppliers by oil tankers via terminal SEADK, whereas the products and byproducts of the supply chain, i.e., ethylene, propylene, liquefied petroleum gas, butadiene, benzene, toluene, xylene, gasoline, kerosene, and diesel, are transported via terminal PDEXTL to and from the overseas customers and suppliers, respectively. This terminal is equipped with refrigerated and pressurized tanks as well as vaporization facilities for storing and transporting ethylene and LPG. There are three refineries (KSR, DLK, and LIWR) in this example. The crude oils are transferred from terminal SEADK to refinery DLR directly but sent to refineries KSR and LIWR through terminals DINGK and JUNGK, respectively (Figure 6).

It is assumed that the network configuration of this supply chain is *fixed* and it consists of three atmospheric distillation units, three diesel hydrotreaters, three vacuum distillation units, three naphtha crackers, three butadiene extraction units, three naphtha hydrotreaters and reforming units, three cokers, three aromatic extraction units, two fluidized catalytic cracking units, two xylene fractionation units, two tatory units, two parex units, and two xylene isomar units. The actual locations of these units are given in the detailed process flow diagrams shown in Figures 7, 8, and 9. The first complete set of production units, that is, an atmospheric distillation unit, a naphtha cracker, a butadiene extraction unit, a fluidized catalytic cracking unit, a vacuum distillation unit, a diesel hydrotreater, a coker, a naphtha hydrotreater, a reforming unit, an aromatic extraction unit, a xylene fractionation unit, a tatory unit, a parex unit, and a xylene isomar unit, are situated in the KSR refinery (Figure 7). The second atmospheric distillation unit, diesel hydrotreater, naphtha hydrotreater, reforming unit, naphtha cracker, butadiene extraction unit, fluidized catalytic cracking unit, vacuum distillation unit, and coker are located in the DLR refinery (Figure 8),

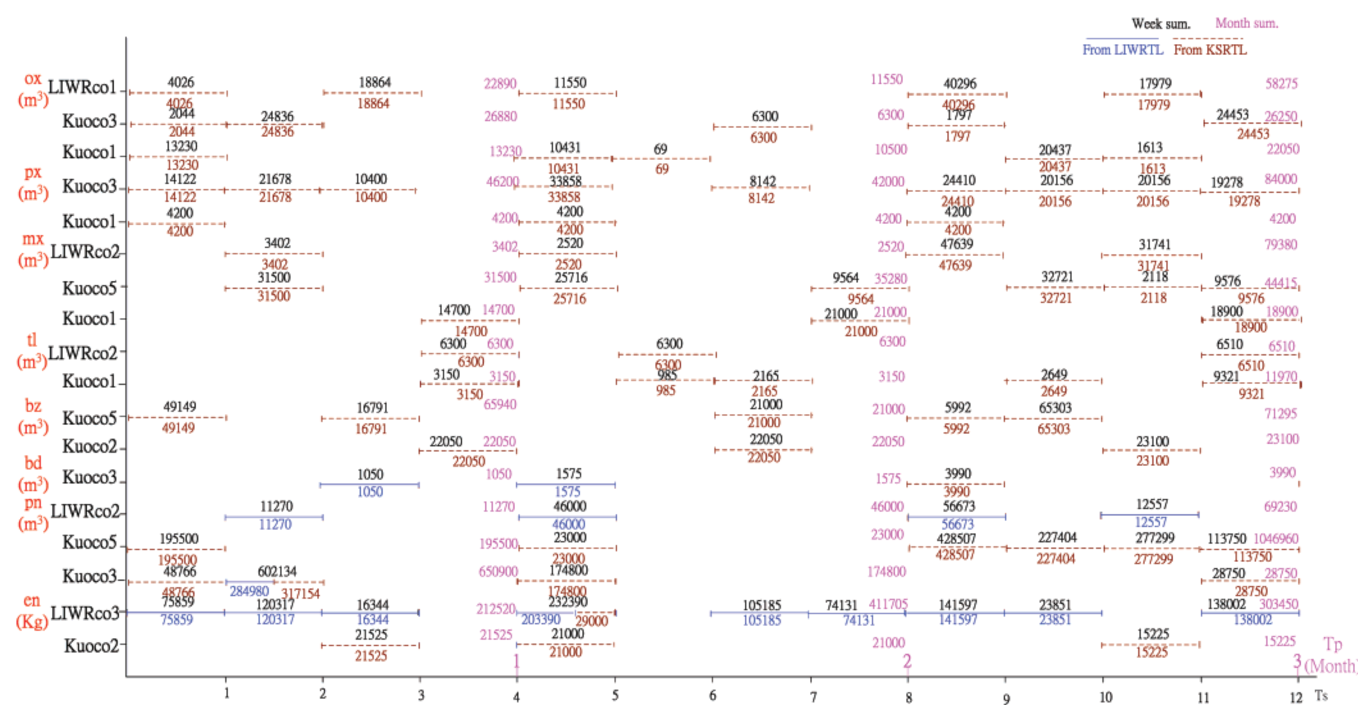

Figure 10. Suggested amounts of products and byproducts to be delivered in base case.

Table 7. Optimal Throughputs of all Production Units in Scenario 1

	first month				second month				third month			
week unit	1	2	3	4	5	6	7	8	9	10	11	12
AD1					394820	1582110		2427666		255000	255000	
AD2	5864200	6483812	5994170	4795230	scheduled maintenance				3033280	3033280	3033280	2162327
AD3	2049170	322817	1281024		2887088	3455750	3109809	3496130	1826742	1977902	3012106	2098571
VD1	1700000	1700000	1700000	1654321	1700000	1700000	1656785	1700000	1700000	1700000	1700000	1700000
VD2	1800000	1800000	1576855	450000				518804				
VD3	552133		432000	432000		914114		854339	880043	1067148	1600000	580479
CK1	375000	375000	375000	375000	375000	375000	375000	375000	375000	375000	375000	375000
CK2	255095	233035	150773		125000		125000	125000			125000	
CK3	450000	450000	450000	410370		366449		284071	441335	416486	450000	287645
FCC1	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000
FCC2	399321	1546306	225000	239938		225000			803922	567257	562341	225000
NC1	429617	468967	430535	350000	325000		325000				363069	
NC2								340000			350000	
NC3						300000		300000		333177		
BD1	4674	7230						30000				
BD2	11904						24645	30000			8621	
BD3	11904			13613	25469	31800	32000	32000		19991	32000	13969
HTD1				350000		357903		438980		350000		
HTD2	1134307	1250000	1099640	521058					631877	336192	596877	432222
HTD3	426416		350000		686283	660679	606355	654629	410256	402405	646904	411421
RF1	Scheduled maintenance				399324	305000	376131	323333				
RF2	826394	984615	884519	663441		483210		487390	421627	315000	398586	315000
RF3	308542		295000						295000	401627	411627	305000
AET1	240000	240000	246903		367100	255408	257100	308003	Scheduled maintenance			
AET2	220000	220000	220000		220000	220000	220000	220000				
AET3	220000	220000	220000		220000	220000	220000	220000				
XF1	110000	110000	110000	25000	98572	110000	110000	110000	75180			
XF2	100000	100000	100000	20023	100000	100000	100000	100000	38834			
TT1	52826	99800	108000		40558	108000	25181	108000				
TT2	61708	68763	120000		35000	93758	35000	114561				
PR1	69526	69968	60896		70576	63792	76145	66017	58088			
PR2	56786	57561	52874	30000	60286	48676	62786	49596	30000			
IM1	68392	67649	42239	14551	67202	54947	81386	42314	42546			
IM2			12000	12000				12000	12000			

whereas all of the other production units are in the LIWR refinery (Figure 9). In our case studies, these units are identified according to the codes given in Table 1. Because each reaction or separation process can be carried out in an alternative unit, these units are numbered according to their locations. Finally, it is assumed that the first aromatic extraction unit contains two processing trains designed for two distinct feedstock types, that is, reformer gasoline and pyrolysis gasoline, and the remaining aromatic extraction units are only capable of processing the reformer gasoline.

The selling prices of the petrochemical products in set $\mathbf{C}_{pet}$ are given in three different demand ranges. The price in the target range of each product is the highest, whereas those in the lower and higher delivery ranges are set at 80 and 90% of the target level respectively. All of these products are shipped to the local customers from the product distribution terminals KSRTL and LIWRTL via pipelines and/or trucks. The allowed delivery ranges in every planning period are presented in Table 2. In addition, it is assumed that 10 different crude oils are available on the international market, and there are 5 providers for each species in every scheduling interval (i.e., 1 week). It is further assumed that no long-term supply contracts of crude oils or intermedia oils are in effect with any of these providers. In addition, the initial inventories of crude oils, the intermediates, and final products are assumed to be zero, and all of the transportation capacities are assumed to be limitless in order to simplify the model formulation. For the sake of conciseness, the remaining model parameters are presented with a GAMS input file in the Supporting Information. These parameters include: the upper and lower throughput limits of all of the production units, the purchasing costs and supply rates of crude oils in each scheduling period, the purchasing costs of final products if obtained from domestic suppliers, the purchasing costs and supply amounts of light naphtha, heavy naphtha, and mixed xylenes if bought from overseas suppliers, the selling prices of the products and byproducts, the largest available quantities of the raw materials, intermediates, and final products that can be purchased from international and domestic markets, the maximum amounts of exportable products and byproducts, the performance indices of the reaction and separation processes, that is, the product yields of the former processes and the recovery efficiencies of the latter, the feed compositions of separation units, the upper limits of all of the inventories and their costs, and all transportation costs.

There are 22 449 variables (3518 binary variables and 18 931 real variables) and 20 335 constraints in the corresponding MILP model. The base case was solved with module CPLEX of the commercial software *GAMS* in 0.438 s (CPU time) on a personal computer with a Pentium IV 3.0 CPU and 1024 kB RAM. The most appropriate types and quantities of crude oils, intermediates, and products to be purchased each week are presented in Tables 3 and 4. It can be seen that the total amounts of purchased enthylene, light naphthas, and heavy naphthas in 3 months are 69 000 kg, 80 000 m^3, and 11 000 m^3, respectively. The optimal throughputs of all of the production units in 12 scheduling intervals can be identified from the solution of the MILP model and these data are summarized in Table 5. Let us use the production schedule of unit FCC1 as an example to illustrate these results. Notice that this FCC unit is located in refinery KSR (Figure 7). It can be observed from Table 5 that FCC1 has been chosen to operate in all 12 scheduling intervals, and the total throughputs in the three planning periods are found to be 6 593 506 m^3, 6 530 645 m^3, and 6 600 000 m^3, respectively. Notice also that all of the aromatic extraction units (i.e., AET1, AET2, and AET3) and all of the xylene fractionation units (i.e., XF1 and XF2) are required to be operated at full capacities in

Table 8. Optimal Amounts of Crude Oils, Intermedtaes and Final Products to be Purchased for Different Cases ($10^3 \cdot m^3$ or10^3 kg)

	period material		tp1	tp2	tp3	Total
base case	crude oil		28750	16800	22500	68050
	en		27	42		69
	ln1				18.5	18.5
	ln2			35	26.5	61.5
	hn3		1		10.5	11.5
case1	crude oil		28050	27550	19700	75300
	en		21	18.5	1	40.5
	ln1		1	33.5		34.5
	ln3		51	19.5	48	118.5
	hn1			10		10
	hn3		2	11		13
	bz			11.5		11.5
	mx		3	25	74	102
	ox				9	9
case2	crude oil		27800	31850	21700	81350
	ln2			27.5	24.5	52
	ln3		18		20	38
	hn2		3	10.5		13.5
case3	crude oil		26950	18000	22000	66950
	ln1		13	50		63
	ln2			16.5	5.5	22
	ln3		35.5		45.5	81
	hn2				27.5	27.5
	hn3			4	18	22
case4	crude oil		24850	20100	21500	66450
	ln2			25	3	28
	ln3			4		4
	hn2		24	10	39.5	73.5
	hn3		11	22		33
	mx				34	34
case5	crude oil	purchased	21450	13200	15000	49650
		contract	5000	5000	5000	15000
		month sum	26450	18200	20000	64650
	ln1	purchased		15.5		15.5
		contract	20	20	20	60
		month sum	20	35.5	20	75.5
	en		27	81		108
	ln2			25.5		25.5
	ln3		18.5	18.5		37
	hn2		13.5			13.5
	hn3			27.5		27.5

all 12 weeks. Thus, it is clear that these two groups of units are the bottlenecks of the supply chain. It should be noted that the units (and also the network configurations of the supply chain) chosen during the three planning periods are *not* the same. The best delivery schedules for the products and byproducts can be found in Table 6. In particular, the qualities and quantities of products sent to every customer and the corresponding delivery times and terminals are shown in Figure 10, for example, the amounts of propylene sent to customer Kuoco3 in week 2 via terminals LIWR and KSR are 284 980 and 317 154 m^3, respectively. It is interesting to note that the suggested delivery amounts almost always fall within the second range (with the highest selling price) so as to maximize profit. The total profit over the planning horizon in this base case is predicted to be 15 525 720 311 U.S. dollars.

Several scenarios have been studied with the proposed model, and the results of five of them are presented below. In the first case, we assumed that the first reforming unit (RF-1) in the first planning period, the second atmospheric distillation unit (AD-2) in the second period, and the first aromatic extraction unit (AET-1) in the third period are not operable due to scheduled maintenance. The resulting optimal throughputs of all of the production units in the 12 scheduling intervals are shown in Table 7. Notice that, as a result of the availabilities of other units (i.e., the second reforming unit RF-2 and the first atmospheric distillation unit AD-1), the required schedules can be maintained in the first two planning periods. However, as a result of the AET-1 outage, the production capacities of the supply chain have to be reduced in the third period and, consequently, it becomes necessary to import final products, for example, benzene and xylenes, to satisfy customer demands. The optimal levels of purchased crude oils, intermediate oils and final products in this scenario are presented in Table 8. It was found that the total profit is about 2.49 thousand million U.S. dollars less than that achieved with the complete set of production units in the base case.

In the second scenario, it was assumed that no suitable petrochemical products (i.e., ethylene, propylene, butadiene, benzene, toluene, and xylenes) could be purchased in all of the planning periods. Thus, the quantities of raw materials consumed in this situation must be larger than those used in the base case. The optimal supply rates of the purchased materials can be identified from the MILP solution (Table 8). It can be observed that the total amounts of purchased crude oils and naphtha (intermediates) are more than those required in the base case by 13 300 000 and 12 000 m^3, respectively. The optimal throughputs of all of the production units in this case are shown in Table 9. When compared with Table 5, it can be observed that the throughputs of the production units here are almost all larger than those in the base case. Profit in this case is reduced to 15 520 219 285 U.S. dollars.

The impacts of demand variations are examined in the third case study. Let us assume that all of the ethylene orders from customer LIWRco3 are cancelled unexpectedly just before the first week due to equipment problems. As a result, the total demand for ethylene drops to 94% of the original level. This reduction in product demand in turn forces some production units in the supply chain to lower their processing rates, and, consequently, the total amounts of purchased crude oils and ethylene must be decreased accordingly. Because the production rates of other intermedia oils, such as light naphtha, are also reduced as a result, it becomes necessary to make up for this by increasing their purchase levels (Table 8). Notice that the total amount of purchased crude oils is indeed less than that in the base case by 1 100 000 m^3 (1.6%) and no ethylene needs to be purchased. In addition, about 86 000 m^3 extra light naphtha (about 107.5% more) must be bought from the suppliers. The corresponding total profit is about 444.99 million U.S. dollars less than that of the base case.

The fourth scenario is concerned with export reductions. Let us assume that the maximum exportable amounts of benzene and toluene are both less than their original predictions in the base case by 800 000 m^3 (i.e., 80% lower) in every planning period. As a result of these changes, it is not beneficial to operate the supply chain at a high throughput level. In this case, the total amount of purchased crude oils was found to be less than that in the base case by 1 600 000 m^3 (2.35%). Consequently, the total amounts of purchased naphthas and mixed xylenes must be increased to 47 000 and 34 000 m^3 respectively during the 3 month period (Table 8). The profit in this case is lowered to 13 855 925 468 U.S. dollars.

To secure enough raw materials to meet the demand targets, it is a common practice for a refinery to sign long-term contacts with its upstream suppliers. In this last case study, it is assumed that the suppliers of crude oils and light naphthas are required to ship fixed amounts of their products according to predetermined schedules (Table 10). Under this condition, the amounts of raw materials purchased from other sources must be reducd. It can be found in the optimization results that the total amount of purchased crude oils over 3 months in this case is 64 650 000

Table 9. Optimal Throughputs of all Production Units in Scenario 2

	first month				second month				third month			
week unit	1	2	3	4	5	6	7	8	9	10	11	12
AD1					343040							
AD2	44846190	5026326	1996173	5264200	4150480	3129724	4476410	2068954	2947872	2029846	33702866	3937016
AD3	1916810	2442633	4764147			279800	329541	2390846	2026251	2266230	2963887	2266230
VD1	1700000	1700000	1700000	1700000	1700000	1700000	1700000	1700000	1700000	1700000	1700000	1700000
VD2	450000	511381	450000	450000				590988	899050		450000	450000
VD3	1312106	1600000	1307571	588253	612642	931222	776899			552635	1338791	1085224
CK1	375000	375000	375000	375000	375000	375000	375000	375000	375000	375000	375000	375000
CK2	163402	266722	134255					241193			162429	125000
CK3	450000	450000	450000	450000	267384	339205	296834		448680	279118	450000	450000
FCC1	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000	1650000
FCC2	247863	1625000	535172			225000			613916	388745	857056	682605
NC1	350000	359681		379217	350000	350000	350000		357723		357439	350000
NC2												
NC3		300000	300000					338809		304238		304238
BD1	11300							30000				
BD2	11904							30000	14010			28471
BD3		11904	13543	25142	23205	23205	29119	32000	23717	32000	23948	32000
HTD1				350000		431811			350000			
HTD2	951505	991057	412084	624707	931668	593023	913718	381277	301586	416286	723284	778289
HTD3	424786	558329	364359					439986	450221	459857	584017	459557
RF1	305000	344755	704465	377222	333889	377222	364242	348205	387879	343210	400105	365484
RF2	686228	688633	324661	346157	310000	306848	330960	310949	315000	315000	517595	556616
RF3												
AET1	240000	240000	241888	390038	264642	264642	254642	272575	266069	256190	266016	320833
AET2	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
AET3	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
XF1	110000	110000	110000	110000	110000	110000	110000	110000	110000	110000	110000	110000
XF2	110000	110000	110000	110000	110000	110000	110000	110000	110000	110000	110000	110000
TT1	63250	63250	62863	78720	58146	10800	43674	46952	108000	107362	108000	86582
TT2	51283	51283	51276	84412	57368	118132	35000	52157	52158	52145	52158	52158
PR1	70673	70673	65665	65315	78566	64353	70296	69476	79605	71592	71605	71605
PR2	55639	55639	54109	50489	66414	48202	63362	46683	65735	55735	55735	55735
IM1	68393	68393	68398	67804	70699		83280	68487	67764	67764	67764	67764
IM2						51830						

Table 10. The Shipment Schedules of Crude Oil and Light Naphtha in the Last Case Study

		tp1				tp2				tp3			
material	month week supplier	ts1	ts2	ts3	ts4	ts5	ts6	ts7	ts8	ts9	ts10	ts11	ts12
cro 1 (10^3·m^3)	sup1	2500		2500		2500		2500		2500		2500	
	total (month)		5000				5000				5000		
ln1 (10^3·m^3)	sup1		20				20				20		
	total (month)	20				20				20			

m^3 (in which 15 000 000 m^3 is obtained via the long-term contracts). Because this quantity is at approximately 95% of the base-case level, the amounts of purchased intermediate oils must be increased. For examples, the extra amounts of purchased ethylene, light naphtha (including the long-term supplies), and heavy naththa were found to be higher than their original levels by 39 000 kg (56.5%), 58 000 m^3 (72.5%), and 29 500 m^3 (256.5%) (Table 8). In other words, the flexibility in selecting raw materials during the planning/scheduling stage is to some degree lost due to the need to maintain supply stability. The total profit in this case is 15 188 162 035 U.S. dollars, which is lower than that in the base case by 337 million U.S. dollars.

7. Conclusions

An integrated mixed-integer linear program has been built in this study to coordinate various planning and scheduling decisions for optimizing the performance of a comprehensive petroleum supply network in typical conversion refineries. Realistic scenarios can be efficiently examined accordingly. From the results we obtained so far, it is clear that the proposed approach can be used not only to generate the proper procurement and delivery plans on the basis of given supply and demand rates, but also to simultaneously select the optimal schedules for producing various petrochemical products over the specified planning horizon. This capability is believed to be superior to that achieved by the sequential procedures.

Appendix: Mathematical Formulations of Unit Models

1. Reaction Processes. The naphtha crackers, cokers, fluidized catalytic cracking units, hydrotreaters, reforming units, the isomar units, and the tatory units are considered as the reaction processes in this work. A sketch of the generalized process flow diagram is provided in Figure A1. It should be noted that a separation system is always included in the reaction process for the purpose of removing products and byproducts from the unreacted raw materials. It is assumed that, after the catalytic reaction(s), the reactants can always be recovered and then recycled *completely* with this system. To simplify the mathematical program, only the overall mass balances of the entire reaction process are considered in this study. The reaction yields of products and byproducts are assumed to be dependent upon the feedstock compositions and operation modes. However, all

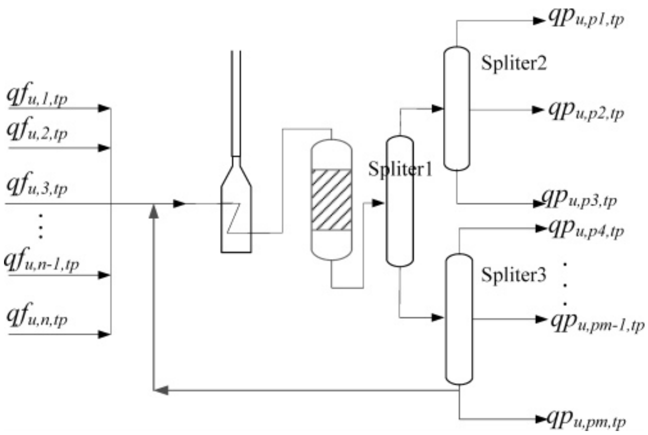

Figure 11. Generalized reaction process.

of them are regarded as available model parameters. The generalized material-balance equation of the reaction processes can be written as,

$$qp_{u,p,ts} = \sum_{s\in \mathbf{F}_u} qf_{u,s,ts}\left(\sum_{k\in \mathbf{K}_{u,s}} fi_{u,s,k,ts} YD_{u,s,k,p}\right) \quad \forall u \in \mathbf{UA}, \forall p \in \mathbf{P}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A1)$$

where **UA** is the union of all reaction sets, that is, $\mathbf{UA} = \mathbf{U}_{nc} \cup \mathbf{U}_{cok} \cup \mathbf{U}_{fcc} \cup \mathbf{U}_{ht} \cup \mathbf{U}_{ref} \cup \mathbf{U}_{isomar} \cup \mathbf{U}_{tatory}$; $\mathbf{F}_u$ is the set of all allowable feeds of unit u; $\mathbf{P}_u$ is the set of all products (and byproducts) of unit u; **TP** is the set of all planning periods; $\mathbf{K}_{u,s}$ is the set of all operation modes of unit u for processing feedstock s; $qf_{u,s,ts}$ and $qp_{u,p,ts}$ denote the process variables representing respectively the total amounts of consumed feedstock s and produced product p of unit u in scheduling interval ts; $fi_{u,s,k,ts}$ is the binary variable reflecting whether or not operation mode k of unit u is chosen to process feedstock s during scheduling interval ts; $YD_{u,s,k,p}$ is a given parameter representing the reaction yield of product p from feedstock s with operation mode k of unit u. To simplify the model formulation, let us next introduce a new variable

$$qfi_{u,s,k,ts} = fi_{u,s,k,ts} qf_{u,s,ts} \quad (A2)$$

Thus, the generalized material balance in eq A1 can be written in a *linear* form as

$$qp_{u,p,ts} = \sum_{s\in \mathbf{F}_u} \sum_{k\in \mathbf{K}_{u,s}} qfi_{u,s,k,ts} YD_{u,s,k,p} \quad \forall u \in \mathbf{UA}, \forall p \in \mathbf{P}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A3)$$

It is also assumed in this study that, other than the tatory unit, only one input is allowed to be processed and only one operation mode can be adopted in every reaction unit during any scheduling interval. This feature is stipulated with the following constraints,

$$\sum_{s\in \mathbf{F}_u} \sum_{k\in \mathbf{K}_{u,s}} fi_{u,k,s,ts} = l_{u,ts} \forall u \in \mathbf{UA}', \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A4)$$

where $\mathbf{UA}' = \mathbf{U}_{nc} \cup \mathbf{U}_{cok} \cup \mathbf{U}_{fcc} \cup \mathbf{U}_{ht} \cup \mathbf{U}_{ref} \cup \mathbf{U}_{isomar}$; $l_{u,ts} \in \{0,1\}$. Because the capacities of these processing units are finite, the upper and lower bounds of the throughputs in each scheduling interval must also be imposed, that is,

$$QFA^{L}_{u,s,k} fi_{u,s,k,ts} \le qfi_{u,s,k,ts} \le QFA^{U}_{u,s,k} fi_{u,s,k,ts} \forall u \in \mathbf{UA}', \forall s \in \mathbf{F}_u, k \in \mathbf{K}_{u,s}, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A5)$$

where $QFA^{U}_{u,s,k}$ and $QFA^{L}_{u,s,k}$ denote respectively the maximum and minimum allowable throughputs of reaction unit u for feedstock s under operation mode k in every scheduling interval.

On the other hand, the decision to use one or more tatory units in a petroleum supply chain must be made on the basis of the market prices of its products (i.e., benzene and xylenes) and costs of its feeds (i.e., toluene and C_9-aromatics). It should also be noted that more than one feedstock is allowed to be processed in this unit. Consequently,

$$\sum_{k\in \mathbf{K}_{u,s}} fi_{u,s,k,ts} \le l_{u,ts}$$
$$\sum_{s\in \mathbf{F}_u} \sum_{k\in \mathbf{K}_{u,s}} fi_{u,s,k,ts} \ge l_{u,ts} \quad \forall u \in \mathbf{U}_{tatory}, \forall s \in \mathbf{F}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A6)$$

Because every operation mode of any given unit can be used to process all of its feeds, one can consider that all of the corresponding sets of operation modes are the same, that is,

$$\mathbf{KT}_u = \mathbf{K}_{u,s} \forall u \in \mathbf{U}_{tatory}, \forall s \in \mathbf{F}_u \quad (A7)$$

Also, because only one of the operation modes in $\mathbf{KT}_u$ can be activated, the following constraints must be incorporated in the mathematical model,

$$fi_{u,s,k,ts} = fi_{u,s',k,ts} \forall u \in \mathbf{U}_{tatory}, \forall s,s' \in \mathbf{F}_u, k \in \mathbf{KT}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A8)$$

where $s \neq s'$. Furthermore, the flow ratio between any two feeds of a tatory unit is usually fixed under a selected operation mode, that is,

$$RT_{u,s,k} qfi_{u,s,k,ts} = RT_{u,s',k} qfi_{u,s',k,ts} \forall u \in \mathbf{U}_{tatory}, \forall s,s' \in \mathbf{F}_u, k \in \mathbf{KT}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A9)$$

where $RT_{u,s,k}$ and $RT_{u,s',k}$ are two constants. The throughput limits in this case should be characterized as

$$QFT^{L}_{u} l_{u,ts} \le \sum_{s\in \mathbf{F}_u} \sum_{k\in \mathbf{K}_{u,s}} qfi_{u,s,k,ts} \le QFT^{U}_{u} l_{u,ts} \forall u \in \mathbf{U}_{totary}, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A10)$$

where QFT^{U}_{u} and QFT^{L}_{u} denote respectively the maximum and minimum allowable throughputs of tatory unit u. Finally, during any given planning period $tp \in \mathbf{TP}$, the following constraint is imposed to prohibit any alteration in the supply chain configuration,

$$l_{u,ts} = l_{u,ts'} \forall u \in \mathbf{UA}, \forall ts, ts' \in \mathbf{TS}_{tp} \quad (A11)$$

where, $ts \neq ts'$.

2. Separation Processes. The separation processes in this study are those in which only separation operations are present, that is, the atmospheric distillation units, the vacuum distillation units, the butadiene extraction units, the aromatics extraction units, the xylene fractionation units, and the parex units. On the basis of the flow diagram presented in Figure A2, the generalized material balances of the separation processes can be written as,

$$qp_{u,p,ts} = \sum_{s\in \mathbf{F}_u} qf_{u,s,ts} X_{u,s,p} FC_{u,s,p} = \sum_{s\in \mathbf{F}_u} qf_{u,s,ts} RF_{u,s,p} \forall u \in \mathbf{UB}, \forall p \in \mathbf{P}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad (A12)$$

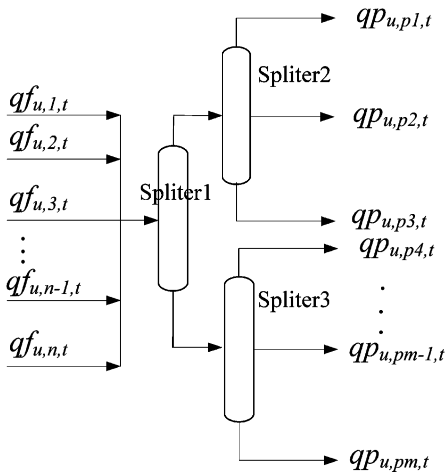

Figure 12. Generalized separation process.

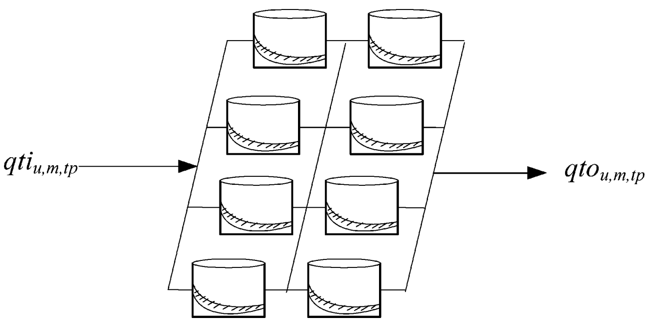

Figure 13. Generalized storage process.

where $\mathbf{UB} = \mathbf{U}_{atm} \cup \mathbf{U}_{vgo} \cup \mathbf{U}_{bd} \cup \mathbf{U}_{ext} \cup \mathbf{U}_{xylene} \cup \mathbf{U}_{parex}$; $X_{u,s,p}$ and $FC_{u,s,p}$ are the design parameters denoting respectively the volume fraction and recovery ratio of product p in feedstock s of unit u; and $RF_{u,s,p}(= X_{u,s,p}FC_{u,s,p})$ is referred to in this article as the *recovery efficiency* of product p in feedstock s of unit u. Notice that the definitions of $qf_{u,s,ts}$ and $qp_{u,p,ts}$ are the same as before.

Because only a single operation mode is implemented in each separation process and mixed feeds are allowed, the throughput limits can be expressed as,

$$QFB_u^L l_{u,ts} \leq \sum_{s \in \mathbf{F}_u} qf_{u,s,ts} \leq QFB_u^U l_{u,ts} \ \forall u \in \mathbf{UB}, \quad \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad \text{(A13)}$$

where, $l_{u,ts} \in \{0,1\}$; and QFB_u^U and QFB_u^L denote respectively the maximum and minimum allowable throughputs of separation unit u in a scheduling interval. Finally, because it is also desirable to maintain a fixed process configuration *within a planning period*, the following logic constraints are also imposed,

$$l_{u,ts} = l_{u,ts'} \ \forall u \in \mathbf{UB}, \forall ts, ts' \in \mathbf{TS}_{tp} \quad \text{(A14)}$$

where $ts \neq ts'$.

3. Storage Processes. As mentioned before, the planning and scheduling tasks are usually carried out over a fixed time horizon on two different time scales according to the forecasts of feedstock supplies and market demands. The material-balance model of a generalized storage process (Figure A3) is formulated in this work on the basis of the finer scheduling intervals, that is,

$$vin_{u,m,ts} = vin_{u,m,ts-1} + qti_{u,m,ts} - qto_{u,m,ts} \ \forall u \in \mathbf{U}, \quad \forall m \in \mathbf{M}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad \text{(A15)}$$

In the above equation, $\mathbf{U}$ is the set of all processing units in which storage tanks may be present, that is,

$$\mathbf{U} = \mathbf{UA} \cup \mathbf{UB} \cup \mathbf{UT} \cup \mathbf{UD} \quad \text{(A16)}$$

where **UT** and **UD** denote respectively the sets of all import/export facilities and product distribution terminals. In addition, $\mathbf{M}_u$ is the set of all process materials in unit u, that is, $\mathbf{M}_u = \mathbf{F}_u \cup \mathbf{P}_u$; $vin_{u,m,ts}$ represents the inventory of material m in unit u at the end of scheduling interval ts; and $qti_{u,m,ts}$ and $qto_{u,m,ts}$ denote respectively the *total* amounts of material m delivered to and withdrawn from unit u during interval ts. Notice that $vin_{u,m,0}$ is the same as the inventory level at the end of the previous planning period, that is,

$$vin_{u,m,0} = vin_{u,m,ts'_f} \quad \text{(A17)}$$

where $ts'_f = \max_{ts' \in \mathbf{TS}_{tp-1}} ts'$. Because in practice the storage capability cannot be unlimited, it is also necessary to impose the following inequality constraints,

$$INV_{u,m}^L \leq vin_{u,m,ts} \leq INV_{u,m}^U \ \forall u \in \mathbf{U}, \quad \forall m \in \mathbf{M}_u, \forall ts \in \mathbf{TS}_{tp}, \forall tp \in \mathbf{TP} \quad \text{(A18)}$$

where $INV_{u,m}^U$ and $INV_{u,m}^L$ represent respectively the upper and lower bounds of the inventory of material m in unit u

Supporting Information Available: Tables of data from programming models used in this study. This material is available free of charge via the Internet at http://pubs.acs.org.

Nomenclature

Indices

s, s' = feedstock
u = unit
k = operation mode
m = material
p = product
tp = time period
ts = scheduling interval

Sets

C = the set of all customers of the final products and/or intermediates
$\mathbf{C}_{dt}$ = the sets of domestic customers for liquefied petroleum gas, mixed xylenes, gasoline, kerosene, and diesel
$\mathbf{C}_{ovs}$ = the sets of overseas customers for the intermediate and final products of petroleum supply chains
$\mathbf{C}_{pet}$ = the sets of domestic customers for the final products of supply chain
$\mathbf{F}_u$ = the set of all allowable feeds of unit u
$\mathbf{F}_{v'}$ = the set of materials consumed by customer v'
$\mathbf{K}_{u,s}$ = the set of all operation modes of unit u for processing feedstock s
$\mathbf{KT}_u$ = the set of all operation modes of unit u
M = the set of all process materials
$\mathbf{M}_u$ = the set of all process materials in unit u
$\mathbf{P}_u$ = the set of all products (and byproducts) of unit u
$\mathbf{P}_v$ = the set of different types of raw materials, intermediate, and products provided by supplier v

TP = the set of all planning periods

$\mathbf{TS}_{tp}$ = the *ts*th scheduling interval in the *tp*th planning period

$\mathbf{TS}_{tp}^{v,m}$ = the set of time intervals within the planning period *tp* in which shipment of crude *m* from supplier *v* can be scheduled

U = the set of all processing units

U′ = the set of all naphtha crackers, cokers, fluidized catalytic cracking units, hydrotreaters, reforming units, xylene isomar units, tatory units, atmospheric distillation units, vacuum distillation units, butadiene extraction units, aromatics extraction units, xylene fractionation units, and parex units

$\mathbf{U}_{atm}$ = the set of all atmospheric distillation units

$\mathbf{U}_{bd}$ = the set of all butadiene extraction units

$\mathbf{U}_{cok}$ = the set of all cokers

$\mathbf{U}_{ext}$ = the set of all aromatics extraction units

$\mathbf{U}_{fcc}$ = the set of fluidized catalytic cracking units

$\mathbf{U}_{ht}$ = the set of hydrotreaters

$\mathbf{U}_{isomar}$ = the set of xylene isomar units

$\mathbf{U}_{parex}$ = the set of all parex units

$\mathbf{U}_{nc}$ = the set of naphtha crackers

$\mathbf{U}_{vgo}$ = the set of all vacuum distillation units

$\mathbf{U}_{ref}$ = the set of reformers

$\mathbf{U}_{tatory}$ = the set of tatory units

$\mathbf{U}_{xylene}$ = the set of all xylene fractionation units

UA = the set of all naphtha crackers, cokers, fluidized catalytic cracking units, hydrotreaters, reforming units, xylene isomar units, and tatory units

UA′ = the set of all naphtha crackers, cokers, fluidized catalytic cracking units, hydrotreaters, reforming units, and isomar units

UB = the set of all atmospheric distillation units, vacuum distillation units, butadiene extraction units, aromatics extraction units, xylene fractionation units, and parex units

UD = the set of all export facilities and product distribution terminals

$\mathbf{UI}_{u,s}$ = the set of all source units (or suppliers) of feedstock *s* received by unit *u*

$\mathbf{UO}_{u,p}$ = the set of all sink units (or customers) of the product *p* generated in unit *u*

USC = the set of all processing units, suppliers of the raw materials and/or intermediates and customers of the final products and/or intermediates

UT = the set of all import facilities and product distribution terminals

S = the set of all suppliers of the raw materials and/or intermediates

$\mathbf{S}_{crude}$ = the set of overseas suppliers of crude oils

$\mathbf{S}_{pet}$ = the set of domestic suppliers of the final products of supply chain

$\mathbf{S}_{hvynap}$ = the set of overseas suppliers of heavy naphtha

$\mathbf{S}_{litnap}$ = the set of overseas suppliers of light naphtha

$\mathbf{S}_{mxyl}$ = the set of overseas suppliers of mixed xylenes

Continuous Variables

ci_{tp} = the total inventory cost in planning period *tp*

co_{tp} = the total operation cost in planning period *tp*

cr_{tp} the total cost of raw materials in planning period *tp*

ct_{tp} = the total transportation cost in planning period *tp*

pf_{tp} = the net profit in planning period *tp*

$qf_{u,s,ts}$ = the total amount of consumed feedstock *s* of unit *u* during interval *ts*

$qfi_{u,s,k,ts}$ = the total amount of consumed feedstock *s* by processing operation mode *k* during interval *ts*

$qp_{u,p,ts}$ = the total amount of produced product *p* of unit *u* during interval *ts*

$q_{u,u',p,ts}$ = the accumulated amount of product *p* transported from unit *u* to *u′* during interval *ts*

$q_{u',u,s,ts}$ = the accumulated amount of feedstock *s* transported from unit *u′* to *u* during interval *ts*

$\tilde{q}_{v',m,tp}$ = the total delivering amount of material *m* to unit *v′* in planning period *tp*

$q_{v,v',m,ts}$ = the accumulated delivering amount of material *m* from unit *v* to unit *v′* during interval *ts*

$qti_{u,p,ts}$ = the accumulated amount of product *p* delivered to the buffer tank in unit *u* during interval *ts*

$qti_{u,s,ts}$ = the accumulated amount of feedstock *s* delivered to the buffer tank in unit *u* during interval *ts*

$qto_{u,p,ts}$ = the accumulated amount of product *p* withdrawn from the buffer tank in unit *u* during interval *ts*

$qto_{u,s,ts}$ = the accumulated amount of feedstock *s* withdrawn from the buffer tank in unit *u* during interval *ts*

rs_{tp} = the total revenue secured from various product sales in planning period *tp*

$vin_{u,m,ts}$ = the inventory of material *m* in unit *u* at the end of planning interval *ts*

Binary Variables

$fi_{u,s,k,ts}$ = the binary indicator used to denote if operation mode *k* of unit *u* is chosen during interval *ts* to process feedstock *s*

$i_{v,m,ts}$ = the binary indicator refelcts if the raw material *m* from supplier *v* is delivered during interval *ts*

$i_{v,m,ts}^{Cr}$ = the binary indicator denotes whether or not the crude *m* from supplier *v* is selected during interval *ts*

$i_{v,m,ts}^{Hn}$ = the binary indicator denotes whether or not the heavy naphtha *m* from supplier *v* is selected during interval *ts*

$i_{v,m,ts}^{Ln}$ = the binary indicator denotes whether or not the light naphtha *m* from supplier *v* is selected during interval *ts*

$i_{v,m,ts}^{Mx}$ = the binary indicator denotes whether or not the mixed xylene *m* from supplier *v* is selected during interval *ts*

$i_{v,m,ts}^{Pet}$ = the binary indicator denotes whether or not the petroleum product *m* from supplier *v* is purchased during interval *ts*

$j_{v',m,tp,l}$ = the binary indicator denotes if the delivered amount of material *m* to customer *v′* during period *tp* is in range *l* or not

$l_{u,ts}$ = the binary indicator used to denote if unit *u* is activated during interval *ts*

Parameters

$CIN_{u,m,ts}$ = the inventory cost per unit of process material *m* in unit *u* during interval *ts*

$CHN_{v,m,tp}$ = the unit cost for purchasing heavy naphtha *m* from supplier *v* during period *tp*

$CHNC_{v,m,tp}$ = the unit purchasing costs of long-term contract for heavy naphtha *m* from supplier *v* during period *tp*

$CLN_{v,m,tp}$ = the unit cost for purchasing light naphtha *m* from supplier *v* during period *tp*

$CLNC_{v,m,tp}$ = the unit costs specified in long-term contracts for light naphtha *m* from supplier *v* during period *tp*

$CMX_{v,m,tp}$ = the unit cost for purchasing mixed xylene *m* from supplier *v* during period *tp*

$CMXC_{v,m,tp}$ = the unit purchasing costs of long-term contract for mixed xylene *m* from supplier *v* during period *tp*

$CPET_{v,m,tp}$ = the unit cost for purchasing final product *m* from supplier *v* during time period *tp*

$CPETC_{v,m,tp}$ = the unit purchasing cost specified in long-term contract for final product m from supplier v during period tp

$CRO_{v,m,tp}$ = the unit cost for purchasing crude oil m from supplier v during period tp

$CROC_{v,m,tp}$ = the unit purchasing costs of long-term contract for crude oil m from supplier v during period tp

$CTP_{v,v',m,ts}$ = the unit transportation cost for moving material m from unit v to unit v' during interval ts

$CVA_{u,k,s,ts}$ = the variable operating cost of reaction unit u for processing feedstock $s$under operation mode k during interval ts

$CVB_{u,ts}$ = the variable operating cost of separation unit u during interval ts

$CXA_{u,ts}$ = the fixed operating cost of unit u in **UA** during interval ts

$CXB_{u,ts}$ = the fixed operating cost of unit u in **UB** during interval ts

$FC_{u,s,p}$ = the recovery ratio of product p in feedstock s of unit u

$INV^U_{u,m}$ = the upper bound of the inventory of material m in unit u

$INV^L_{u,m}$ = the lower bound of the inventory of material m in unit u

$Q^U_{v,v',m}$ = the upper limit of the transportation capacity for delivering material m from unit v to unit v'

$Q^L_{v,v',m}$ = the lower limit of the transportation capacity for delivering material m from unit v to unit v'

$QCC_{v,m,ts}$ = the fixed amount of crude m guaranteed in a long-term contract by supplier v during the scheduling interval ts

$QCS_{v,m,ts}$ = the available amount of type m crude from supplier v during interval ts

$QFA^U_{u,s,k}$ = the maximum allowable throughput of reaction unit u for feedstock s under operation mode k

$QFA^L_{u,s,k}$ = the minimum allowable throughput of reaction unit u for feedstock s under operation mode k

QFB^U_u = the maximum allowable throughput of separation unit u

QFB^L_u = the minimum allowable throughput of separation unit u

QFT^U_u = the maximum allowable throughput of tatory unit u

QFT^L_u = the minimum allowable throughput of tatory unit u

$QHN_{v,m,ts}$ = the amounts of heavy naphtha m that can be purchased from supplier v during the scheduling interval ts

$QHNC_{v,m,ts}$ = the fixed amounts of heavy naphtha m guaranteed in a long-term contract by supplier v during the scheduling interval ts

$QLN_{v,m,ts}$ = the amounts of light naphtha m that can be purchased from supplier v during the scheduling interval ts

$QLNC_{v,m,ts}$ = the fixed amounts of light naphtha m guaranteed in a long-term contract by supplier v during the scheduling interval ts

$QOS^U_{v',m,tp}$ = the acceptable maximum amounts of intermediate or final product m delivered to customer v' in period tp

$QOS^L_{v',m,tp}$ = the acceptable minimum amount of intermediate or final product m delivered to customer v' in period tp

$QPET_{v,m,ts}$ = the amount of product m that can be purchased from supplier v during the scheduling interval ts

$QPETC_{v,m,ts}$ = the fixed amounts of product m guaranteed in a long-term contract by supplier v during the scheduling interval ts

$QPL^U_{v',m,tp,l}$ = the upper bound of the lth range of the amount of material m delivered to customer v' during planning period tp

$QPL^L_{v',m,tp,l}$ = the lower bound of the lth range of the amount of material m delivered to customer v' during planning period tp

$QXI_{v,m,ts}$ = the amounts of mixed xylene m that can be purchased from supplier v during the scheduling interval ts

$QXIC_{v,m,ts}$ = the fixed amounts of mixed xylene m guaranteed in a long-term contract by supplier v during the scheduling interval ts

$QXO^U_{v',m,tp}$ = the acceptable maximum amount of material m delivered to customer v' in period tp

$QXO^L_{v',m,tp}$ = the acceptable minimum amount of material m delivered to customer v' in period tp

$RF_{u,s,p}$ = the recovery efficiency of product p in feedstock s of unit u

$RT_{u,s,k}$ = the flow ratio between feedstock s and a reference feed of tatory unit u under operation mode k

$SP_{v',m,tp,l}$ = the selling price of product m sold to customer v' during period tp in level range l

$SPD_{v',m,tp}$ = the selling price of intermediate or final product m sold to domestic customer v' during period tp

$SPO_{v',m,tp}$ = the selling price of intermediate or final product m sold to overseas customer v' during period tp

U = a sufficiently large constant

$X_{u,s,p}$ = the volume fraction of product p in feedstock s of unit u

$YD_{u,s,k,p}$ = the reaction yield of product p from feedstock s under operation mode k of unit u

Abbreviations

AD = atmospheric distillation unit
AET = aromatic extraction unit
BD = butadiene extraction unit
CK = coker
D = distributor
DS = domestic supplier
DC = domestic customer
FCC = fluidized catalystic cracking unit
HTD = diesel hydrotreater
IEF = import and export facility
IM = xylene isomar unit
M = mixer
NC = naphtha cracker
OC = overseas customer
OS = overseas supplier
PDT = product distribution terminal
PR = parex unit
RF = reforming unit
TT = tatory unit
VD = vacuum distillation unit
XF = xylene fractionation unit
cr = crude oil
bz = benzene isomarf feed of isomar unit
mx = mixed xylenes
ox = *ortho*-xylene
parexf = feed of parex unit
px = *para*-xylene
tl = toluene

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