Multirefinery and Petrochemical Networks Design and Integration

K. Al-Qahtani*, A. Elkamel**
E. Alper***

** Saudi Aramco, Dhahran, Saudi Arabia 31311*
(Tel.: (966)-875-4828. e-mail: Khalid.qahtani.7@aramco.com)
*** Department of Chemical Engineering, University of Waterloo, Ontario, Canada N2L 3G1*
(Tel.: (519)-888-4567 ext. 37157. e-mail: aelkamel@uwaterloo.ca)
**** Department of Chemical Engineering, Hacettepe University, Beytepe, Turkey 06800*
((Tel.: (312)-297-7400. e-mail: ealper@hacettepe.edu.tr)

Abstract: In this paper we propose a model for the design of an optimal network integration of multisite refinery and petrochemical systems under uncertainty. The proposed model was formulated as a two-stage stochastic mixed-integer problem with the objective of minimizing the refining cost over a given time horizon and maximizing the added value by the petrochemical network. Uncertainties considered in this study were in terms of imported crude oil price, refinery product price, petrochemical product price, refinery market demand, and petrochemical lower level product demand. The proposed method adopts the sample average approximation (SAA) method for scenario generation and optimal gap statistical bounding. The model performance was tested on an industrial case study of multiple refineries and a polyvinyl chloride (PVC) complex.

Keywords: Integration, petrochemical planning, multirefinery optimization, planning under uncertainty

1. INTRODUCTION

Process integration in the refining and petrochemical industry includes many intuitively recognized benefits of processing higher quality feedstocks, improving value of byproducts, and achieving better efficiencies through sharing of resources. This is evidently seen from the current projects around the world for building integrated refineries and the development of complex petrochemical industries that are aligned through advanced integration platforms.

Despite the fact that petroleum refining and petrochemical companies have recently engaged in more integration projects, relatively little research in the open literature have been reported mostly due to confidentiality reasons. Such concerns render the development of a systematic framework of network integration and coordination difficult. Pervious research in the field assumed either no limitations on refinery feedstock availability for the petrochemical planning problem or fixed the refinery production levels assuming an optimal operation. In this paper, we present a mathematical model for the determination of the optimal integration and coordination strategy for a refinery network and synthesize the optimal petrochemical network required to satisfy a given demand from any set of available technologies. Therefore, achieving a global optimal production strategy by allowing appropriate trade offs between the refinery and the downstream petrochemical markets. The refinery and petrochemical systems were modeled as MILP problems that will also lead to an overall refinery and petrochemical process production levels and detailed blending levels at each refinery site. Furthermore, we apply the sample average approximation (SAA) method within an iterative scheme to generate the required scenarios. The solution quality is then statistically evaluated by measuring the optimality gap of the final solution.

2. MODEL FORMULATION

The proposed formulation addresses the problem of the simultaneous design of an integrated network of refineries and petrochemical processes. The proposed model is based on the formulations proposed by Al-Qahtani and Elkamel (2008) and Al-Qahtani et al. (2008). All material balances are carried out on a mass basis with the exception of refinery quality constraints of properties that only blend by volume where volumetric flowrates are used instead. Uncertainty was accounted for using two-stage stochastic programming with recourse approach. Parameters uncertainties considered in this study included uncertainties in the imported crude oil price $CrCost_{cr}$, refinery product price Pr_{cfr}^{Ref}, petrochemical product price Pr_{cp}^{Pet}, refinery market demand $D_{Ref_{cfr}}$, and petrochemical lower level product demand $D_{Pet_{cp}^{L}}$. Uncertainty is modeled through the use of mutually exclusive scenarios of the model parameters with a finite number N of outcomes. For each $\xi_k = (CrCost_{cr,k}$, $Pr_{cfr,k}^{Ref}$, $Pr_{cp,k}^{Pet}$, $D_{Ref_{cfr,k}}$, $D_{Pet_{cp,k}^{L}})$ where $k = 1,2,...,N$, there corresponds a probability p_k. The generation of the scenarios will be briefly explained in a later section. The proposed stochastic model is as follows:

$$\begin{aligned} Min & \sum_{cr\in CR}\sum_{i\in I}\sum_{k\in N} p_k\, CrCost_{cr,k}\, S^{Ref}_{cr,i} + \sum_{p\in P}\sum_{cr\in CR}\sum_{i\in I} z_{cr,p,i}\, OpCost_p \\ & + \sum_{cir\in CIR}\sum_{i\in I}\sum_{i'\in I} InCost_{i,i'}\, ypipe^{Ref}_{cir,i,i'} + \sum_{i\in I}\sum_{m\in M_{Ref}}\sum_{s\in S} InCost_{m,s}\, yexp^{Ref}_{m,i,s} \\ & - \sum_{cfr\in PEX}\sum_{i\in I}\sum_{k\in N} p_k\, Pr^{Ref}_{cfr,k}\, e^{Ref}_{cfr,i} - \sum_{cp\in CP}\sum_{m\in M_{Pet}}\sum_{k\in N} p_k\, Pr^{Pet}_{cp,k}\, \delta_{cp,m}\, x^{Pet}_{m} \\ & + \sum_{cfr\in CFR}\sum_{k\in N} p_k\, C^{Ref+}_{cfr}\, V^{Ref+}_{cfr,k} + \sum_{cfr\in CFR}\sum_{k\in N} p_k\, C^{Ref-}_{cfr}\, V^{Ref-}_{cfr,k} \\ & + \sum_{cp\in CFP}\sum_{k\in N} p_k\, C^{Pet+}_{cp}\, V^{Pet+}_{cp,k} + \sum_{cp\in CFP}\sum_{k\in N} p_k\, C^{Pet-}_{cp}\, V^{Pet-}_{cp,k} \end{aligned} \tag{1}$$

Subject to

$$z_{cr,p,i} = S^{Ref}_{cr,i} \qquad \forall\ cr\in CR,\ i\in I \text{ and } p\in P' = \{\text{Set of CDU processes } \forall \text{ plant } i\} \tag{2}$$

$$\begin{aligned} & \sum_{p\in P}\alpha_{cr,cir,i,p}\, z_{cr,p,i} + \sum_{i'\in I}\sum_{p\in P}\xi_{cr,cir,i',p,i}\, xi^{Ref}_{cr,cir,i',p,i} \\ & - Fi^{Pet}_{cr,cir\in RPI,i} - \sum_{i'\in I}\sum_{p\in P}\xi_{cr,cir,i,p,i'}\, xi^{Ref}_{cr,cir,i,p,i'} \\ & - \sum_{cfr\in CFR} w_{cr,cir,cfr,i} - \sum_{rf\in FUEL} w_{cr,cir,rf,i} = 0 \end{aligned} \qquad \forall\ cr\in CR,\ cir\in CIR,\ i'\,\&\, i\in I \text{ where } i\neq i' \tag{3}$$

$$\sum_{cr\in CR}\sum_{cir\in CB} w_{cr,cir,cfr,i} - \sum_{cr\in CR}\sum_{rf\in FUEL} w_{cr,cfr,rf,i} - \sum_{cr\in CR} Ff^{Pet}_{cr,cfr\in RPF,i} = x^{Ref}_{cfr,i} \qquad \forall\ cfr\in CFR,\ i\in I \tag{4}$$

$$\sum_{cr\in CR}\sum_{cir\in CB}\frac{w_{cr,cir,cfr,i}}{sg_{cr,cir}} = xv^{Ref}_{cfr,i} \qquad \forall\ cfr\in CFR,\ i\in I \tag{5}$$

$$\sum_{cir\in FUEL} cv_{rf,cir,i}\, w_{cr,cir,rf,i} + \sum_{cfr\in FUEL} w_{cr,cfr,rf,i} - \sum_{p\in P}\beta_{cr,rf,i,p}\, z_{cr,p,i} = 0 \qquad \forall\ cr\in CR,\ rf\in FUEL,\ i\in I \tag{6}$$

$$\begin{aligned} & \sum_{cr\in CR}\sum_{cir\in CB}\left(att_{cr,cir,q\in Qv}\frac{w_{cr,cir,cfr,i}}{sg_{cr,cir}} + att_{cr,cir,q\in Qw} \left[w_{cr,cir,cfr,i} - \sum_{rf\in FUEL} w_{cr,cfr,rf,i} - \sum_{cr\in CR} Ff^{Pet}_{cr,cfr\in RPF,i}\right]\right) \\ & \geq q^{L}_{cfr,q\in Qv}\, xv^{Ref}_{cfr,i} + q^{L}_{cfr,q\in Qw}\, x^{Ref}_{cfr,i} \end{aligned} \qquad \forall\ cfr\in CFR,\ q=\{Qw,Qv\},\ i\in I \tag{7}$$

$$\begin{aligned} & \sum_{cr\in CR}\sum_{cir\in CB}\left(att_{cr,cir,q\in Qv}\frac{w_{cr,cir,cfr,i}}{sg_{cr,cir}} + att_{cr,cir,q\in Qw} \left[w_{cr,cir,cfr,i} - \sum_{rf\in FUEL} w_{cr,cfr,rf,i} - \sum_{cr\in CR} Ff^{Pet}_{cr,cfr\in RPF,i}\right]\right) \\ & \leq q^{U}_{cfr,q\in Qv}\, xv^{Ref}_{cfr,i} + q^{U}_{cfr,q\in Qw}\, x^{Ref}_{cfr,i} \end{aligned} \qquad \forall\ cfr\in CFR,\ q=\{Qw,Qv\},\ i\in I \tag{8}$$

$$MinC_{m,i} \leq \sum_{p\in P}\gamma_{m,p}\sum_{cr\in CR} z_{cr,p,i} \leq MaxC_{m,i} + \sum_{s\in S} AddC_{m,i,s}\, yexp^{Ref}_{m,i,s} \qquad \forall\ m\in M_{Ref},\ i\in I \tag{9}$$

$$\sum_{cr\in CR}\sum_{p\in P}\xi_{cr,cir,i,p,i'}\, xi^{Ref}_{cr,cir,i,p,i'} \leq F^{U}_{cir,i,i'}\, ypipe^{Ref}_{cir,i,i'} \qquad \forall\ cir\in CIR,\ i'\,\&\, i\in I \text{ where } i\neq i' \tag{10}$$

$$\sum_{i\in I}\left(x^{Ref}_{cfr,i} - e^{Ref}_{cfr',i}\right) + V^{Ref+}_{cfr,k} - V^{Ref-}_{cfr,k} = D_{Ref_{cfr,k}} \qquad \forall\ cfr\in CFR,\ cfr'\in PEX,\ k\in N \tag{11}$$

$$IM^{L}_{cr} \leq \sum_{i\in I} S^{Ref}_{cr,i} \leq IM^{U}_{cr} \qquad \forall\ cr\in CR \tag{12}$$

$$\begin{aligned} & Fn^{Pet}_{cp\in NRF} + \sum_{i\in I}\sum_{cr\in CR} Fi^{Pet}_{cr,cp\in RPI,i} + \sum_{i\in I}\sum_{cr\in CR} Ff^{Pet}_{cr,cp\in RPF,i} + \sum_{m\in M_{Pet}}\delta_{cp,m,k}\, x^{Pet}_{m} \\ & + V^{Pet+}_{cp\in CFP,k} - V^{Pet-}_{cp\in CFP,k} = D_{Pet}{}^{L}_{cp\in CFP,k} + xi^{Pet}_{cp\in CIP} \end{aligned} \qquad \forall\ cp\in CP,\ k\in N \tag{13}$$

$$Fn^{Pet}_{cp\in NRF} + \sum_{i\in I}\sum_{cr\in CR} Fi^{Pet}_{cr,cp\in RPI,i} + \sum_{i\in I}\sum_{cr\in CR} Ff^{Pet}_{cr,cp\in RPF,i} + \sum_{m\in M_{Pet}}\delta_{cp,m}\, x^{Pet}_{m} \leq D_{Pet}{}^{U}_{cp\in CFP} \qquad \forall\ cp\in CP \tag{14}$$

$$B^{L}_{m}\, yproc^{Pet}_{m} \leq x^{Pet}_{m} \leq K^{U}\, yproc^{Pet}_{m} \qquad \forall\, m\in M_{Pet} \tag{15}$$

$$\sum_{cp\in CIP} yproc^{Pet}_{m} \leq 1 \qquad \forall\, m\in M_{Pet} \text{ that produces } cp\in CIP \tag{16}$$

$$\sum_{cp\in CFP} yproc^{Pet}_{m} \leq 1 \qquad \forall\, m\in M_{Pet} \text{ that produces } cp\in CFP \tag{17}$$

$$Fn^{Pet}_{cp} \leq S^{Pet}_{cp} \qquad \forall\ cp\in NRF \tag{18}$$

The above formulation is a two-stage stochastic mixed-integer linear programming (MILP) model. Objective function (1) represents a minimization of the annualized cost which consists of crude oil cost, refineries operating cost, refineries intermediate exchange piping cost, refinery production system expansion cost, less the refinery export revenue, added value by the petrochemical processes, plus the recourse variables of refinery and petrochemical networks; respectively. Inequality (2) corresponds to each refinery raw materials balance where throughput to each distillation unit $p\in P'$ at plant $i\in I$ from each crude type $cr\in CR$ is equal to the available supply $S_{cr,i}$. Constraint (3) represents the intermediate material balances within and across the refineries where the coefficient $\alpha_{cr,cir,i,p}$ can assume either a positive sign if it is an input to a unit or a negative sign if it is an output from a unit. The multirefinery integration matrix $\xi_{cr,cir,i,p,i'}$ accounts for all possible alternatives of connecting intermediate streams $cir \in CIR$ of crude $cr \in CR$ from refinery $i \in I$ to process $p \in P$ in plant $i' \in I'$. The variable $xi^{Ref}_{cr,cir,i,p,i'}$ represents the transshipment flowrate of crude $cr \in CR$, of intermediate $cir \in CIR$ from plant $i \in I$ to process $p \in P$ at plant $i' \in I$. Constraint (3) also considers the petrochemical network feedstock from the refinery intermediate streams $Fi^{Pet}_{cr,cir,i}$ of each intermediate product $cir \in RPI$. The material balance of final products in each refinery is expressed as the difference between flowrates from intermediate steams $w_{cr,cir,cfr,i}$ for each $cir \in CIR$ that contribute to the final product pool and intermediate streams that contribute to the fuel system $w_{cr,cfr,rf,i}$ for each $rf \in FUEL$ less the refinery final products $Ff^{Pet}_{cr,cfr,i}$ for each $cfr \in RPF$ that are fed to the petrochemical network as shown in constraint (4). In constraint (5) we convert the mass flowrate to volumetric flowrate by dividing it by the specific gravity $sg_{cr,cir}$ of each crude type $cr \in CR$ and intermediate stream $cir \in CB$. This is needed in order to express the quality attributes that blend by volume in blending pools. Constraint (6) is the fuel system material balance where the term $cv_{rf,cir,i}$ represents the caloric value equivalent for each intermediate $cir \in CB$ used in the fuel system at plant $i \in I$. The fuel production system can either consist of a single or combination of intermediates $w_{cr,cir,rf,i}$ and products $w_{cr,cfr,rf,i}$. The matrix $\beta_{cr,rf,i,p}$ corresponds to the consumption of each processing unit $p \in P$ at plant $i \in I$ as a percentage of unit throughput. Constraints (7) and (8), respectively, represent a lower and an upper bounds on refinery quality constraints for all refinery products that either blend by mass $q \in Q_w$ or by volume $q \in Q_v$. Constraint (9) represents the maximum and minimum allowable flowrate to each processing unit. The coefficient $\gamma_{m,p}$ is a zero-one matrix for the assignment of production unit $m \in M_{Ref}$ to process operating mode $p \in P$. The term $AddC_{m,i,s}$ accounts for the additional refinery expansion capacity of each production unit $m \in M_{Ref}$ at refinery $i \in I$ for a specific expansion size $s \in S$. The integer variable $yexp^{Ref}_{m,i,s}$ represents the decision of expanding a production unit and it can take a value of one if the unit expansion is required or zero otherwise. Constraint (10) sets an upper bound on intermediate streams flowrates between the different refineries. The integer variable $ypipe^{Ref}_{cir,i,i'}$ represents the decision of exchanging intermediate products between the refineries and takes on the value of one if the commodity is transferred from plant $i \in I$ to plant $i' \in I$ or zero otherwise, where $i \neq i'$. When an intermediate stream is selected to be exchanged between two refineries, its flowrate must be below the transferring pipeline capacity $F^{U}_{cir,i,i'}$. Constraint (11) stipulates that the final products from each refinery $x^{Ref}_{cfr,i}$ less the amount exported $e^{Ref}_{cfr',i}$ for each exportable product $cfr' \in PEX$ from each plant $i \in I$ must satisfy the domestic demand $D_{Ref_{cfr}}$. The recourse variables $V^{Ref+}_{cfr,k}$, $V^{Ref-}_{cfr,k}$, $V^{Pet+}_{cp,k}$ and $V^{Pet-}_{cp,k}$ in equations (11) and (13) represent the refinery production shortfall and surplus as well as the petrochemical production shortfall and surplus, respectively, for each random realization $k \in N$. These variables will compensate for the violations in equations (11) and (13) and will be penalized in the objective function using appropriate shortfall and surplus costs C^{Ref+}_{cfr} and C^{Ref-}_{cfr} for the refinery products, and C^{Pet+}_{cp} and C^{Pet-}_{cp} for the petrochemical products, respectively. Resources are limited by constraint (12)

Constraints (13) and (14) represent the material balance that governs the operation of the petrochemical system. The petrochemical network receives its feed from potentially three main sources. These are, 1) refinery intermediate streams $Fi^{Pet}_{cr,cir,i}$ of an intermediate product $cir \in RPI$, 2) refinery final products $Ff^{Pet}_{cr,cfr,i}$ of a final product $cfr \in RPF$, and 3) non-refinery streams Fn^{Pet}_{cp} of a chemical $cp \in NRF$. For a given subset of chemicals $cp \in CP$, the proposed model selects the feed types, quantity and network configuration based on the final chemical and petrochemical lower and upper product demand $D_{Pet^{L}_{cp}}$ and $D_{Pet^{U}_{cp}}$ for each $cp \in CFP$, respectively. Furthermore, in equation (13) an additional term xi^{Pet}_{cp} was added to the left hand side representing the flow of intermediate petrochemical stream of $cp \in CIP$. In constraint (15), defining a binary variables $yproc^{Pet}_{m}$ for each process $m \in M_{pet}$ is required for the process selection requirement as $yproc^{Pet}_{m}$ will equal 1 only if process m is selected or zero otherwise. Furthermore, if only process m is selected, its production level must be at least equal to the process minimum economic capacity B^{L}_{m} for each $m \in M_{pet}$, where K^{U} is a valid upper bound. Finally, we can specify limitations on the supply of feedstock Fn^{Pet}_{cp} for each chemical type $cp \in NRF$ through constraint (18).

3. SCENARIO GENERATION

The solution of stochastic problems is generally very challenging as it involves numerical integration over the random continuous probability space of the second stage variables (Goyal & Ierapetritou, 2007). An alternative approach is the discretization of the random space using a finite number of scenarios. In our study, the Sample Average

Approximation (SAA) method, also known as stochastic counterpart, is employed. The SAA problem can be written as (Verweij et al., 2003):

$$\nu_N = \min_{x \in X} c^T x + \frac{1}{N} \sum_{k \in N} Q(x, \xi^k) \quad (19)$$

It approximates the expectation of the stochastic formulation (usually called the “true” problem) and can be solved using deterministic algorithms. Problem (19) can be solved iteratively in order to provide statistical bounds on the optimality gap of the objective function value. The validation procedure was originally suggested by Norkin et al. (1998) and further developed by Mark et al. (1999).

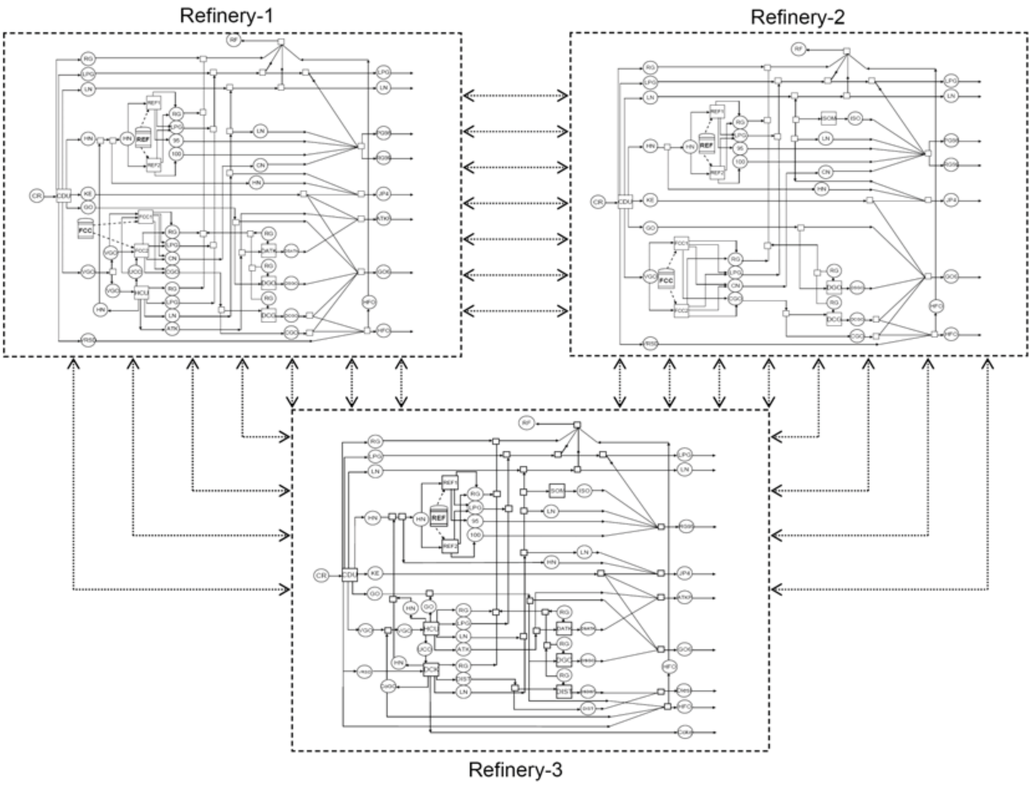

Fig. 1. Refinery Integration Network

originally suggested by Norkin et al. (1998) and further developed by Mark et al. (1999).

Table 1. Major refinery network capacity constraints

Production Capacity	Higher limit (10^3 ton/yr)		
	R1	R2	R3
Distillation	45000.	12000.0	9900.0
Reforming	700.0	2000.0	1800.0
Isomerization	200.0	-	450.0
Fluid catalytic cracker	800.0	1400.0	-
Hydrocracker	-	1800.0	2400.0
Delayed coker	-	-	1800
Des gas oil	1300.0	3000.0	2400.0
Des cycle gas oil	200.0	750.0	-
Des ATK	-	1200.0	1680.0
Des Distillates	-	-	450.0
Crude availability			
Arabian Light		31200.0	
Local Demand			
LPG		$\mathcal{N}(432,20)$	
LN		-	
PG98		$\mathcal{N}(400,20)$	
PG95		$\mathcal{N}(4390,50)$	
JP4		$\mathcal{N}(2240,50)$	
GO6		$\mathcal{N}(4920,50)$	
ATK		$\mathcal{N}(1700,50)$	
HFO		$\mathcal{N}(200,20)$	
Diesel		$\mathcal{N}(400,20)$	
Coke		$\mathcal{N}(300,20)$	

4. ILLUSTRATIVE CASE STUDY

This section presents the computational results of the proposed model and sampling scheme. The case study considers a subsystem of the petrochemical industry for the integration problem with the refinery network as apposed to considering the full scale petrochemical industry, which might have limited applications. The case study will examine the integration between a multirefinery network with a polyvinyl chloride (PVC) petrochemical complex. PVC is a major ethylene derivative with many important applications and uses (e.g. pipe fittings, automobile bumpers, toys, bottles, etc.).

In this paper, we consider the planning for three refineries in one industrial location, which is a common situation in many areas around the world. The state equipment network (SEN) representation of the three refineries is shown in Fig. 1. The final products of the three refineries network consists of liquefied petroleum gas (LPG), light naphtha (LT), two grades of gasoline (PG98 and PG95), No. 4 jet fuel (JP4), military jet fuel (ATKP), No.6 gas oil (GO6), diesel fuel (Diesel), heating fuel oil (HFO), and petroleum coke (coke). The major capacity constraints for the refinery network are given in Table 1. The petrochemical complex, on the other hand, starts with the production of ethylene from the refineries feedstocks by steam cracking. The main feedstocks

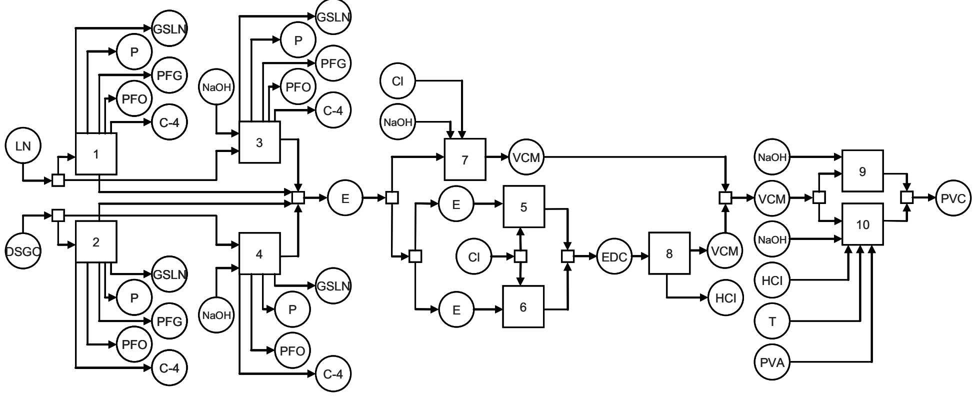

Fig. 2. PVC complex possible production alternatives

to the ethylene plant in our study are light naphtha (LN) and gas oil (GO). The selection of the feedstocks and hence the process technologies is decided upon based on the optimal balance and trade-off between the refinery and petrochemical markets. The process technologies considered in this study for the production of PVC are list in Table 2. The overall topology of all petrochemical technologies for the PVC production is shown in Fig. 2. The modeling system GAMS (Brooke et al., 1996) is used for setting up the optimization models and the MILP problems were solved with CPLEX (CPLEX Optimization Inc., 1993).

Table 2 Major products and processes in PVC complex

Product	Price ($/ton)	Process Technology	Index	Min. Prod. (10^3 ton/yr)
Ethylene (E)	$\mathcal{N}(1570,10)$	Pyrolysis of naphtha (LS)	1	250
		Pyrolysis of gas oil (LS)	2	250
		Steam cracking of naphtha (HS)	3	250
		Steam cracking of gas oil (HS)	4	250
Ethylene Dichloride (EDC)	$\mathcal{N}(378,10)$	Chlorination of ethylene	5	180
		Oxychlorination of ethylene	6	180
Vinyl chloride monomer (VCM)	$\mathcal{N}(1230,10)$	Chlorination and Oxychlorination of ethylene	7	250
		Dehydrochlorination of ethylene dichloride	8	125
Polyvinyl chloride (PVC)	$\mathcal{N}(1600,10)$	Bulk polymerization	9	50
		Suspension polymerization	10	90

In our study, we considered uncertainty in the imported crude oil price, refinery product price, petrochemical product price, refinery market demand, and petrochemical lower level product demand. In the presentation of the results, we focus on demonstrating the sample average approximation computational results as we vary the sample sizes and compare their solution accuracy and the CPU time required for solving the models.

Table 3 Computational results of stochastic model

		Lower bound sample size=N		
		1000	2000	3000
UB Samples	Number of Samples (R=30)			
N'=5000	LB estimate: $\bar{v}_N$	8802837	8804092	8804456
	LB error: $\tilde{\varepsilon}_l$ (α =0.975)	3420	2423	1813
	UB estimate: $\hat{v}_{N'}$	8805915	8805279	8805578
	UB error: $\tilde{\varepsilon}_u$ (α =0.975)	7776	7715	7778
	95% Conf. Interval	[0,14274]	[0,11324]	[0,10713]
	CPU (sec)	65	112	146
N'=10000	LB estimate: $\bar{v}_N$	8800071	8802080	8804305
	LB error: $\tilde{\varepsilon}_l$ (α =0.975)	3356	2527	2010
	UB estimate: $\hat{v}_{N'}$	8803310	8803204	8803414
	UB error: $\tilde{\varepsilon}_u$ (α =0.975)	5473	5833	5410
	95% Conf. Interval	[0,12068]	[0,9484]	[0,7420]
	CPU (sec)	196	224	263
N'=20000	LB estimate: $\bar{v}_N$	8796058	8801812	8802511
	LB error: $\tilde{\varepsilon}_l$ (α =0.975)	3092	2345	1755
	UB estimate: $\hat{v}_{N'}$	8802099	8804121	8802032

UB error: $\tilde{\varepsilon}_u$ (α =0.975)	3837	3886	3880
95% Conf. Interval	[0,12970]	[0,8540]	[0,5635]
CPU (sec)	1058	1070	1114

The problem was solved for different sample sizes N and N' to illustrate the variation of optimality gap confidence intervals, while fixing the number of replications R to 30. The replication number R need not be very large to get an insight of $\overline{v}_N$ variability. Table 4 shows different confidence interval values of the optimality gap when the sample size of N assumes values of 1000, 2000, and 3000 while varying N' between 5000, 10000, and 20000 samples. As the sample sizes N and N' were limited to these values due to computational considerations. In our case study, we ran into memory limitations when N and N' values exceeded 3000 and 20000, respectively. The solution of the three refineries network and the PVC complex using the SAA scheme with $N=$ 3000 and N'=20000 required 1114 CPU sec to converge to the optimal solution.

Table 4. Model results integrated network

	Process variables		Results (10^3 ton/yr) R1	R2	R3
Refinery	**Crude Oil Supply**		4500	12000	9900
	Production levels	Crude unit	4500	12000	9900
		Reformer	612.5	1824.6	1784.6
		Isomerization	160	-	450
		FCC	378	1174.2	-
		Hydrocracker	-	1740.4	2400
		Delayed coker	-	-	1440
		Des Gas oil	1300	3000	2400
		Des cycle gas oil	168.6	600	-
		Des ATK	-	1200	1654.8
		Des Distillates	-	-	366.2
	Intermediate streams exchange	From **R1** VGO	-	-	576.1 to HCU
		From **R2** LN	-	-	112.4 to Isom
		From **R3** VGO	-	274.8 to FCC	-
	Exports	PG95		439.8	
		JP4		1101.9	
		GO6		2044.2	
		HFO		1907.8	
		ATK		1887.6	
		Coke		110.7	
		Diesel		5.1	
Petrochemical	**Refinery feed to PVC complex**	Gas oil	788.6	1037.0	71.3
	Production levels	S. Crack GO (4)		486.8	
		Cl & OxyCl E (7)		475.4	
		Bulk polym. (9)		220.0	
	Final	PVC		220.0	
Total cost ($/yr)				$8,802,000	

Table 4 depicts the results of the optimal integration network between the three refineries and the PVC petrochemical complex. As shown in Table 5, the proposed model designed the refinery network and operating policies and also devised the optimal production plan for the PVC complex from all available process technologies. The model selected gas oil as the refinery feedstock to the petrochemical complex. PVC production was proposed by first high severity steam cracking of gas oil to produce ethylene. Vinyl chloride monomer (VCM) is then produced through the chlorination and oxychlorination of ethylene and finally, VCM is converted to PVC by bulk polymerization. The annual production cost across the refineries and the PVC complex was $8,802,000.

REFERENCES

Al-Qahtani, K., and Elkamel, A. (2008). Multisite Facility Network Integration Design and Coordination: An Application to the Refining Industry. *Computers & Chemical Engineering*, 32, 2198.

Al-Qahtani, K., Elkamel, A. and Ponnambalam, K. (2008). Robust Optimization for Petrochemical Network Design under Uncertainty, *Industrial & Engineering Chemistry Research*, 47, 3912.

Brooke, A., Kendrick, D., and Meeraus, A., Raman, R. (1996). *GAMS—A User's Guide*, GAMS Development Corporation: Washington DC.

CPLEX Optimization, Inc. (1993). *Using the CPLEX Callable Library and CPLEX Mixed Integer Library*, CPLEX Optimization Inc: Incline Village, NV.

Goyal, V., and Ierapetritou, M. G. (2007). Stochastic MINLP optimization using simplicial approximation. *Computers and Chemical Engineering*, 31, 1081.

Mark, W. K., Morton, D. P., and Wood, R. K. (1999). Monte Carlo bounding techniques for determining solution quality in stochastic programs. *Operational Research Letters*, 24, 47.

Norkin, W. I., Pflug, G. Ch., and Ruszczysk, A. (1998). A branch and bound method for stochastic global optimization. *Mathematical Programming*, 83, 425.

Verweij, B., Ahmed, S., Kleywegt, A. J., Nemhauser, G., and Shapiro, A. (2003). The sample average approximation method applied to stochastic routing problems: A computational study. *Computational Optimization & Applications*, 24, 289.