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AN OPTIMIZATION MODEL FOR GUIDING THE PETROCHEMICAL INDUSTRY DEVELOPMENT IN SAUDI ARABIA

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A mixed integer linear programming model is formulated for determining the optimum plan for the expansion of the Saudi Arabian petrochemical industry. The products selected for consideration fall into four categories: propylene derivatives, ethylene derivatives, synthesis gas derivatives, and aromatic derivatives. The model incorporates new variables and constraints, and realistic estimates of production costs, which are calculated based on local conditions in Saudi Arabia. For each production process, the unit production cost is assumed to be a function of production capacity. The input data for each product includes relevant production technologies, capacities, local production costs, and selling price. The solution of the model gives the recommended products under different scenarios of available capital investment and feedstock. The results are reported and analyzed.

Keywords: Optimization; Integer programming models; Petrochemical industry; Industrial development; Investment models

1 INTRODUCTION

Saudi Arabia has a small domestic petrochemical market and a large raw materials resource base, and hence the Kingdom's development of the petrochemical industry is a logical consequence of this situation. The industry is export-oriented, with emphasis on higher value-added products to maximize the economic benefits of industrialization. Saudi Arabian Basic Industries Corporation (SABIC) was established in 1976 to undertake and lead the development of the petrochemical industry. In recent years, there has been a lot of interest from local companies and investors in diversifying petrochemical production as the industry is competing for new and attractive projects. Therefore, this paper presents a model for the optimum planning of the future development of the Saudi petrochemical industry.

For the production of many petrochemicals, there may be more than one process technology involving different combinations of feed stocks and co-products. Several alternative derivatives (with different capacities) can be derived from a certain petrochemical feedstock. Since the available capital and feedstock quantity are limited, it is very important to formulate

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the best development strategy that will give the highest benefit to the national economy and propel the industrialization process. This requires a theoretical basis (model) for planning, in order to find the optimal structure of the petrochemical industry.

This paper presents a modeling approach adopted for the future development of Saudi Arabia's integrated petrochemical industry. The model considers a number of petrochemical products that are mainly aimed for export to the international market and not limited to domestic consumption only. The formulation incorporates new variables and constraints, and more accurate estimates of production costs based on local conditions. The unit production cost is assumed to be a function of the production level. This model is used to select the optimum set of products and associated technologies for the Saudi petrochemical industry.

The model includes both continuous and integer variables that indicate the process chosen for each product and the associated production level. The objective of the model is to maximize the total annual profit. The constraints include at least three types of restrictions: (1) limited raw material availability, (2) limited investment budget, and (3) unique production-level for each product. Additional constraints are easily incorporated to reflect other realistic investment considerations.

2 LITERATURE REVIEW

The pioneering work of Rudd [12] showed that a cost-minimization linear programming (LP) model gives a good representation of the petrochemical industry, which is useful for estimating the relative attractiveness of new technologies, the cost requirement and the potential impact on the global petrochemical industry. Several previous studies presented different approaches for modeling and optimizing the petrochemical industry in Saudi Arabia and the Persian Gulf region. Wagialla *et al.* [15] developed a model to obtain an estimated structure for the petrochemical industry in the Gulf countries, including Saudi Arabia. Wagialla *et al.*'s suggested strategy for the Gulf region is strictly based on satisfying the endogenous demand; it does not address the exogenous factors.

Sayar *et al.* [13] used linear programming to suggest a plan for the optimal petrochemical industry in the Gulf states in order to meet the local demand in the first place and to cover a small part of the world demand. It was found that the raw materials cost is dominant and labor cost has no significant effect on the production cost. Al-Fadli *et al.* [3] constructed a network model for the optimal planning of petroleum refinery production in Saudi Arabia. The model considered only a very small number (eight) of basic petrochemicals. Bardesi *et al.* [7] analyzed the role of multi-national corporations and foreign direct investment (FDI) on the growth of Saudi Arabia's petrochemical industry. They examined the time lags involved in this growth process, which reflect stages of project completion, FDI inflow, construction work, and other factors. Two approaches were used in this analysis. First, the activities of the Saudi Basic Industries Corporation (SABIC) were recorded. Second, polynomial distributed lag models were used to estimate the effects of FDI on the imports and exports of Saudi Arabia.

Duffuaa *et al.* [9] constructed a linear programming model to study the impact of oil production on gas supply to vital petrochemical industries in Saudi Arabia. Oil production level determines the availability of associated natural gas (mainly ethane and methane). The model integrates oil production with gas processing and distribution to optimize the allocation of oil production to different fields. The model determines the minimum oil production level needed to satisfy the petrochemical industry's requirements for natural gas, and also international demands for different types of crude oil.

Bok *et al.* [8] developed a model aimed at planning the long-range capacity expansion for chemical processing networks under uncertain demand forecast scenarios. This optimization problem involves capacity expansion timing and sizing of each chemical processing unit to maximize the expected net present value, while considering the deviation of net present values and the excess capacity over a given time horizon. They used a multi-period mixed integer nonlinear programming model. They found that it is effective when they applied it to the case of investment planning in the Korean petrochemical industry.

Al-Amer *et al.* [2] presented a modeling approach adopted for the future development of Saudi Arabia's petrochemical industry. Their model considers a relatively large number of petrochemical products that are mainly aimed for export to the international market and not limited to domestic consumption only. The mixed integer programming model incorporates the minimum economic production quantity restriction for each process. Al-Amer [1] applied a binary integer programming model to the optimum screening and planning of propylene derivatives and associated processes in Saudi Arabia. Alfares [4] presented a mixed integer programming model for the economic planning of investment in ethylene derivatives.

Zhou *et al.* [17] constructed a goal programming (GP) model for optimizing the whole supply chain of continuous process industries with sustainability considerations. They defined sustainability as a combination of multiple and possibly conflicting social, economic, and environmental objectives. The analytic hierarchy process (AHP) is used to assign priorities to goals and weights to constraint deviations. The objective of the integer programming model formulated by Al-Sharrah *et al.* [6] is also to maximize sustainability, which is defined as the combination of two objective functions: minimizing the toxicity index of selected products, and maximizing the profitability of chosen processes. The constraints include material balance, demand lower and upper bounds, process minimum economic production quantity, unique process per product, and feedstock availability. As a case study, the model was applied to the petrochemical industry in Kuwait.

Several authors discuss the growing trends of petrochemical industries in Saudi Arabia and the Gulf region. For example, Al-Sa'doun [5] describes the strategic plan of Saudi Arabia's petrochemical industry to face competition mainly by increasing capacity and diversifying its product mix. Williams [16] describes recent gas projects in the Middle East, highlighting the rapid expansion of petrochemical industry in Saudi Arabia using natural gas as feedstock.

3 PRODUCTS CHOSEN

Saudi Arabia has large resources of both petroleum and natural gas. Although the petroleum industry is highly developed, the petrochemical industry based on natural gas is relatively new and has a tremendous growth potential. Drawing on that potential, twenty three (23) petrochemical products and fifty four (54) production processes have been chosen on the basis of economic advantage, international demand, and environmental impact. The chosen products are classified into four categories: propylene derivatives, ethylene derivatives, synthesis gas derivatives, and aromatics or BTX (benzene, toluene, and xylene) derivatives. The individual products within each category are listed below. It should be noted here that phenol could be considered as a derivative of both propylene and BTX.

Propylene derivatives

– Polypropylene (homopolymer, copolymer, and block copolymer)
– Phenol*
– Acrylic Acid
– Propylene Oxide
– N-Butanol
– Cumene

Ethylene derivatives

- Poly Vinyl Chloride (PVC) and Poly Vinyl Chloride (PVC) Dispersion
- Vinyl Chloride Monomer (VCM)
- Ethylene Glycol (EG)
- Vinyl Acetate
- Polyethylene (high density, linear low density, and low density)

Synthesis gas derivatives

- Acetic Acid
- Ammonia
- Formaldehyde
- Methanol

BTX derivatives

- Styrene
- Phthalic Anhydride
- Phenol*
- Purified Terephthalic Acid (PTA)

4 MIXED INTEGER LP MODEL

The model includes both continuous and binary (0–1) integer variables. The formulation of this mixed integer linear programming model is described below.

4.1 Parameters

$b_{j,t}$ = tons consumed of raw material t/tons produced of X_j
B = total available budget ($)
C_{kj} = production cost of process j per unit of X_j if capacity level is k ($/ton)
D_i = total annual demand of product i (tons/year)
E_i = export selling price of product i per unit ($/ton)
h_j = high-capacity production level of process j (tons of main product/year)
l_j = low-capacity production level of process j (tons of main product/year)
m_j = medium-capacity production level of process j (tons of main product/year)
S_i = set of all processes in which the main product is i
R_t = available feedstock of raw material t (tons/year)
V_{kj} = investment cost for process j at capacity k ($)

4.2 Subscripts

i = product or by-product number, $i = 1, \ldots, I$ (I = number of products)
j = process number, $j = 1, \ldots, J$ (J = number of processes)
k = capacity level indicator ($k = l$: low, $k = m$: medium, $k = h$: high)
t = raw material number, $t = 1, \ldots, T$ (T = number of limited raw materials)

4.3 Variables

X_j = production level of process j (tons of main product of process j per year)

4.4 Objective

The objective of the model is to maximize the total annual profit P. Let E_j = export selling price of the main product of process j (\$/ton). Then, the objective can be expressed as follows: maximize profit P = sum of (sale price − production cost) of all products, or

$$\text{Maximize } P = \sum_{j=1}^{J} E_j X_j - C(X_j) \tag{1}$$

For each production process (j), the data provided by the SRI [14] provides information with respect to three distinct levels of production: low (l_j), medium (m_j), and high (h_j). The low production level (l_j) corresponds to the minimum economic production quantity of the given process. The medium production level (m_j) corresponds to the typical mid-level production quantity. Finally, the high production level (h_j) corresponds to the maximum production quantity of the given process technology. The SRI data allows the accurate calculation of the local production cost only at these three discrete production levels. Let these costs be denoted by C_{lj}, C_{mj}, C_{hj} for production levels l_j, m_j, and h_j, respectively. A fourth level may be added: $X_j = 0$, since naturally $C(0) = 0$.

For the remaining values of production level (X_j), a piece-wise linear cost function is assumed: $C(X_j)$, as shown in Figure 1.

The cost function $C(X_j)$ is nonlinear and non-continuous at $X_j = 0$ and $X_j = m_j$. Although it may not be obvious from Figure 1, it is clear that $C(0) = V(0) = 0$. Thus, the function $C(X_j)$ exists in two separate regions: $X_j = 0$, and $l_j \leq X_j \leq h_j$. In order to represent $C(X_j)$ in linear terms, two binary variables (Y_j, Z_j) are introduced:

$$Y_j = \begin{cases} 1, & X_j \leq m_j \\ 0, & X_j > m_j \end{cases} \tag{2}$$

$$Z_j = \begin{cases} 1, & X_j > 0 \\ 0, & X_j = 0 \end{cases} \tag{3}$$

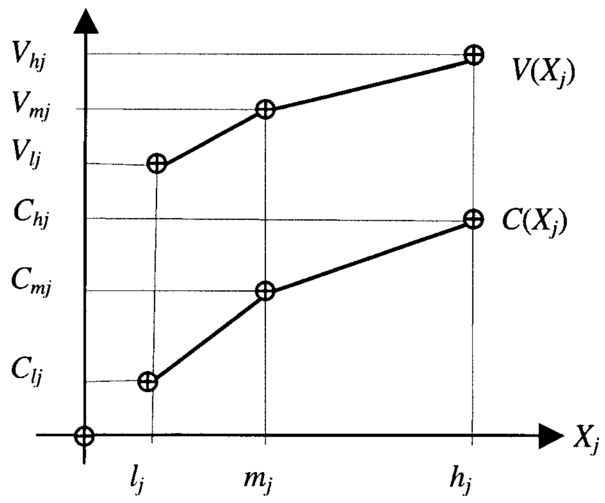

FIGURE 1 Production and investment costs $C(X_j)$ as functions of production level X_j. The small circles denote points in which $C(X_j)$ is accurately known.

Now, the objective can be written as Eq. (4), with additional continuous variables (L_j, M_j, H_j) and additional constraints (5)–(10) needed to complete the linear transformation.

$$\text{Maximize } P = \sum_{j=1}^{J} E_j X_j - (C_{lj} L_j + C_{mj} M_j + C_{hj} H_j) \tag{4}$$

Subject to

$$X_j = l_j L_j + m_j M_j + h_j H_j \tag{5}$$

$$\mathrm{L}_j \leq Y_j \tag{6}$$

$$H_j \leq 1 - Y_j \tag{7}$$

$$L_j + M_j + H_j = Z_j \tag{8}$$

$$X_j \leq NZ_j, \quad N \text{ is a large number (as in the big-M method)} \tag{9}$$

$$X_j, L_j, M_j, H_j \geq 0, \quad Y_j, Z_j = 0 \text{ or } 1 \tag{10}$$

Constraint (5) expresses X_j as a linear combination of three variables (L_j, M_j, H_j). Variables L_j, M_j, and H_j represent the proportions of using production levels l_j, m_j, and h_j, respectively. For example, $L_j = 1$ means that a low (l_j) production level is chosen, while $M_j = H_j = 0.5$ means that a production level exactly between medium (m_j) and high (h_j) is chosen. Constraints (6) and (7) ensure that $L_j = 0$ if $X_j \geq m_j$ and that $H_j = 0$ if $X_j \leq m_j$. Constraints (8) and (9) restrict the sum of (L_j, M_j, H_j) to be equal to 1 if $X_j > 0$, and equal to 0 if $X_j = 0$.

4.5 Raw Material Constraints

This constraint ensures that the total annual consumption of the raw material t does not exceed its annual availability. Two main raw materials are assumed in this study to have limited availability, namely ethylene and propylene.

$$\sum_{j=1}^{J} b_{j,t} X_j \leq R_t, \quad t = 1, \ldots, T \tag{11}$$

4.6 Budget Constraints

This constraint ensures that the initial investment expenditure does not exceed the available budget.

$$\sum_{j=1}^{J} V(X_j) \leq B \tag{12}$$

Using the SRI reports data, the initial investment values (V_{lj}, V_{mj}, V_{hj}) can be obtained at three values of X_j: l_j, m_j, and h_j, respectively. Assuming a piece-wise linear investment cost function $V(X_j)$, as shown in Figure 1, the initial budget constraint (12) can be written as:

$$\sum_{j=1}^{J} V_{lj} L_j + V_{mj} M_j + V_{hj} H_j \leq B \tag{13}$$

4.7 Demand Constraints

These constraints ensure that, for each product, the production level does not exceed the expected annual demand.

$$\sum_{j \in S_i} X_j \leq D_i \quad i = 1, \ldots, I \tag{14}$$

4.8 Unique Process Constraints

These constraints ensure that only one production process (technology) is chosen for each product. These constraints are optional, depending on the given investor's preferences and investment strategy.

$$\sum_{j \in S_i} Z_j \leq 1 \quad i = 1, \ldots, I \tag{15}$$

5 INPUT DATA

The above model was applied to all the petrochemical products listed above. The information needed for this study is obtained from Peters and Timmerhaus [10] and the SRI Report [14]. This information includes available technologies, data needed to calculate the production cost such as fixed cost, raw material, catalyst, and energy requirements etc., and product prices. It should be noted here that demand for the products is not easy to obtain, and thus it is not explicitly taken into consideration. It is simply assumed that there is sufficient demand for each product to cover the whole production quantity. For each product, the following data and calculations are needed:

- A search for available technologies along with the necessary data to calculate the production cost is done. Tables I–IV respectively summarize chosen products and corresponding technologies and capacities for propylene, ethylene, synthesis gas, and aromatics.
- Production cost is calculated for each product/technology/capacity for the year 2001 at the Saudi location. Details of this calculation are discussed below.
- The model sums up the capital cost and quantity of raw material used in order to satisfy the constraints on these parameters.
- The product price is obtained by averaging prices over the last five years.

5.1 Calculation of Production Cost

The local production cost had to be calculated for each product using each available technology at three production levels (C_{lj}, C_{mj}, C_{hj}). For example, for propylene oxide alone, there are six technologies, and hence the number of production cost calculations is $3 \times 6 = 18$. The total number of production cost calculations for all products and associated technologies and capacities is $3 \times 54 = 162$. One Excel sheet has been constructed for making each production cost calculation. In calculating local production cost, the following procedure is used:

- Capital cost is updated to year 2001 by using the cost index ratio. This is multiplied by the Saudi location factor of 1.1 to find the estimated cost for Saudi location. The cost of utilities is taken for the Saudi location.

TABLE I Data for Propylene Products and Processes Used by the Model.

Product	Sale price ($/ton) E_j	Process no. j	Process name	Propylene used/ton $b_{j,2}$	Capacity (10^3 ton/yr) l_j	m_j	h_j	Production cost ($\$10^6$/yr) C_{lj}	C_{mj}	C_{hj}	Investment ($\$10^6$) V_{lj}	V_{mj}	V_{hj}
Polypropylene copolymer	975	1	Amoco/Chisso	0.9480	70	135	270	50.7	90.1	170.7	55.0	81.1	131.6
		2	BASF	0.9432	75	150	300	56.8	103.8	196.2	58.0	85.1	132.4
		3	Himont	0.9490	77.5	155	310	56.9	103.7	195.7	60.2	86.8	134.1
Polypropylene block copolymer	975	4	Sumitomo (gas phase)	0.9546	70	145	290	51.7	97.6	184.8	55.1	83.1	132.0
		5	UCC/Shell	0.9550	47.5	95	190	38.2	69.8	130.4	43.3	66.8	104.3
Polypropylene homopolymer	780	6	Borealis	1.0450	40	80	160	38.5	65.2	120.7	66.2	92.8	153.2
		7	UCC/Shell	1.0500	40	80	160	31.8	57.1	105.5	40.0	61.4	95.1
Phenol	735	8	From C6H6/C3H8 via cumene	0.5103	45	90	180	37.8	57.7	94.9	106.6	151.7	231.5
Acrylic acid (ester grade)	1450	9	Two-stage oxidation	0.6289	40	80	160	38.5	65.6	119.1	82.8	125.4	207.0
Propylene oxide	1130	10	Arco process (styrene product)	0.8648	90	180	360	92.2	159.2	290.9	233.5	390.7	698.7
		11	Texaco (T butanol byproduct)	0.9546	90	180	360	86.7	154.1	287.7	185.8	304.5	537.1
		12	Chlorohydrin	0.8265	90	180	360	95.8	175	330.9	119.0	179.4	289.2
		13	Arco process (T butanol byproduct)	0.7875	90	180	360	87.5	157.2	294.9	212.3	362.7	657.7
		14	Cell liquor neutralization	0.8101	90	180	360	105.9	196.6	375.2	109.8	164.3	263.1
		15	Shell process (styrene byproduct)	0.8782	90	180	360	93.1	131.1	239.4	221.7	376.1	672.7
N-butanol	830	16	Via Cobalt hydrocarbonyl catalyst	0.8150	50	100	200	41.4	68.7	117.2	115.5	180.4	287.4
		17	Via *N* butryaldehyde Rh catalyst	0.6994	50	100	200	34.9	62	111.6	63.7	100.2	156.3
Cumene	450	18	From C6H6 and Propylene	0.3784	60	120	240	36.6	62.1	120.8	23.1	33.2	50.7

TABLE II Data for Ethylene Products and Processes Used by the Model.

Product	Sale price ($/ton) E_j	Process no j	Process name	Ethylene used/ton $b_{j,1}$	Capacity (10^3 ton/yr) l_j	m_j	h_j	Production cost ($\$10^6$/yr) C_{lj}	C_{mj}	C_{hj}	Investment ($\$10^6$) V_{lj}	V_{mj}	V_{hj}
Poly vinyl chloride	740	19	Suspension polymerization		100	200	400	67.6	125.2	237.2	117.6	186.0	307.5
		20	Bulk polymerization		50	100	300	33	63.1	163.8	62.5	114.0	209.6
Poly vinyl chloride (dispersion)	1250	21	Batch emulsion polymerization		25	50	100	28.7	48.3	86	73.1	101.1	148.0
		22	Continuous emulsion polymerization		25	50	100	24	43.1	79.5	46.5	70.7	110.1
Vinyl chloride	430	23	TOSOH technology		125	250	500	63.8	123.5	241	49.2	74.4	112.8
		24	Pyrolysis		125	250	500	68.5	134.5	264	79.1	144.2	258.1
		25	Chlorination/ Oxychlorination	0.4678	250	500	1000	101.5	195	377	134.0	229.9	392.2
Ethylene glycol	600	26	Hydration of EO all EO for EG	0.7267	90	180	360	50.3	90	165.6	142.6	234.8	397.5
Vinyl acetate	690	27	From ethylene and acetic acid	0.3930	67.5	135	200	53.9	101.2	146.4	82.7	133.6	181.3
High density polyethylene	860	28	UCC process	1.0200	70	135	270	42.1	75.1	141.8	56.9	84.5	131.5
		29	Du Pont process	1.02	70	135	270	44.6	77.5	147.7	63.4	84.5	136.9
		30	Philips process	1.02	70	135	270	44.6	78.8	148	66.5	96.2	147.7
Linear low density polyethylene	900	31	Dry mode gas phase univation process	0.9461	100	200	400	55.7	106.8	208.4	51.4	83.0	144.5
		32	Bimodal grade by mixed mettallocene/ Ziegler catalyst	0.9387	75	150	300	48.3	90.2	172.8	46.9	66.0	98.6
		33	Bimodal grade by unipol process	0.943	122.5	245	490	92	174	336.2	82.4	116.6	175.6
Low density polyethylene	870	34	High pressure tubular reactor	1.06	50	100	200	34.9	63.9	120.4	72.0	117.7	199.7

TABLE III Data for Synthesis Gas Products and Processes Used by the Model.

Product	Sale price ($/ton)	Process no j	Process name	Methane used/ton	Capacity (10^3 ton/yr)			Production cost ($\$10^6$/yr)			Investment ($\$10^6$)		
	E_j			$b_{j,3}$	l_j	m_j	h_j	C_{lj}	C_{mj}	C_{hj}	V_{lj}	V_{mj}	V_{hj}
Acetic acid	480	35	Low pressure carbonylation (Rh. catalyst solution)		182.5	365	540	63.2	111.4	156.6	125.6	195.9	259.6
		36	Low pressure carbonylation supported Rh. catalyst		182.5	365	540	60.3	103	142.6	116.4	168.2	213.5
		37	Low pressure carbonylation Rh. halide catalyst		180	360	550	64.7	110.2	154.6	133.2	196.3	248.9
Ammonia	160	38	ICI AMV process	6.35	300	430	590	48.3	65	85	210.9	278.2	356
		39	MW Kellog process	5.928	300	430	590	52.8	71.4	92.7	243.5	322.4	412.6
		40	ICI LCA process	6.678	105	170	340	19.4	27.4	47.3	87	119.5	196.7
Formaldehyde 1	500	41	From methanol using silver catalyst		15	25	50	6.6	9.7	17.7	15.3	20.2	32.7
		42	From methanol using Fe Mo catalyst		15	25	50	6.9	10.6	19.4	17.9	26.2	44.9
Methanol	150	43	Lurgi process	7.867	415	830	1660	55.2	96.3	184.3	224.6	365.5	682.1
		44	ICI process copper catalyst	7.778	415	830	1660	56.5	100.5	194.3	228.5	384.6	727.6
		45	ICI LCM process	7.661	415	830	1660	51.9	98	187.6	199.1	371.5	702.9

TABLE IV Data for Aromatics (BTX) Products and Processes Used by the Model.

Product	Sale price ($/ton) E_j	Process no j	Process name	Ethylene used/ton $b_{j,1}$	Capacity (10^3 ton/yr) l_j	m_j	h_j	Production cost ($\$10^6$/yr) C_{lj}	C_{mj}	C_{hj}	Investment ($\$10^6$) V_{lj}	V_{mj}	V_{hj}
Styrene	760	46	Liquid phase alkyl/ adiabatic dehydrogenation	0.2891	225	450	680	105.8	204.8	306	116.9	190	265.1
		47	Liquid phase alkyl oxidative reheating	0.2878	225	450	680	108	209.7	313.5	115.6	191.8	266.8
		48	Vapor phase alkyl/ adiabatic dehydrogenation	0.2843	225	450	680	105.6	202.5	302.6	125.2	192.7	269
		49	Vapor phase alkyl/ isothermal dehydrogenation	0.2874	225	450	680	106.7	206.1	308.1	125.2	202	285.5
Pthalic anhydride	700	50	Attochem/Nippon		12.5	25	50	9.4	16.4	28.4	26	40.8	63.9
		51	from O-Xylene by Alsuisse Italia process		12.5	25	50	9	15.4	27.3	27.7	39.6	56.9
Phenol	735	52	Liquid phase oxidation of toluene		45	90	180	36.8	64	118.7	108.8	157.2	251.6
PTA	680	53	Hydrolysis of dimethyl terephthalate		125	250	500	81.4	145.8	275.5	208.1	308.6	515.5
		54	from P-xylene by bromine promoted air oxidation		125	250	500	78.4	145	277	170.5	267.3	452.7

- An average price for the raw materials at the Saudi location is taken to be \$320/ton for ethylene and \$350/ton for propylene. The average prices of all products are shown in Tables I–IV.
- The annual salary per laborer in Saudi Arabia is assumed as \$18,000.
- Other costs such as supervision, maintenance, and general expenses are estimated using typical percentages similar to those used in Peters and Timmerhaus [10].

The items used in calculating production cost for each process include:

- Total fixed capital (initial investment cost, which is also considered as a constraint in the model).
- Raw materials, including catalysts.
- Utilities, including cooling water, electricity, natural gas, fuel, and steam.
- Operating labor, including supervision, maintenance, operations, laboratories, patents and royalties, and research and development.
- Financial cost, including depreciation, taxes, insurance, interest, and rent.
- Other miscellaneous items such as plant overhead, administration, and distribution and sales.

6 INTEGER PROGRAMMING RESULTS

In order to explore different alternatives, the model was run with and without unique process constraints (15). In order to run the mixed integer programming (MIP) model, the maximum values of the available investment budget B and available raw materials R_1 (ethylene) and R_2 (propylene) were assumed to be two billion U.S. Dollars (including Government and commercial loans), and one million tons per year respectively. These two values are representative of the available capital for a large size company (similar to SABIC) and of the available feedstocks of ethylene and propylene in Saudi Arabia. In order to have a broader perspective, it seemed worthwhile to also consider the midpoints of the maximum values of these two values. Assuming the available amounts of ethylene and propylene are equal, define R as the available amount of each raw material. Therefore, input values into the IP model are given as:

$$B = 1 \text{ or } 2 \text{ (\$ billion)}$$
$$R = R_1 = R_2 = 0.5 \text{ or } 1 \text{ (million tons/year)}$$

Thus, there are four combinations of values for the two parameters B and R. The model was run once for each combination, producing different optimum selections of products and processes for each of the four combinations. Each budget-raw material availability combination was run twice, with and without unique process constraints (15). The branch-and-bound integer programming algorithm of LINDO® software was used to obtain optimum solutions. The results with and without constraints (15) are summarized in Tables V and VI, respectively. Detailed discussion of these results is given below.

6.1 Case 1: Unique Process Constraints (15) Included

This case reflects a cautious investment approach, in which no more than one (main) production process in chosen for each product. This approach allows the investor to concentrate on only one process per selected product, thus making the investment easier to manage.

TABLE V Results with Unique Process Constraints (15) Included.

B ($\$10^6$)	1000	1000	2000	2000
R_1 (10^3 tons/year)	500	1000	500	1000
R_2 (10^3 tons/year)	500	1000	500	1000
Profit ($\$10^6$/year)	692.8337	759.7366	894.2706	1111.476
Processes chosen:	3 (310)	3 (310)	3 (273.4)	3 (310)
Process number j and	4 (122.9)	4 (290)	9 (160)	4 (290)
(capacity X_j in tons/year)				
	9 (140.8)	9 (142.3)	17 (200)	7 (160)
	31 (324.1)	28 (270)	20 (300)	9 (160)
	36 (540)	31 (400)	22 (100)	17 (200)
	48 (680)	48 (680)	31 (324.1)	20 (300)
			36 (540)	22 (100)
			41 (50)	28 (270)
			48 (680)	31 (400)
			51 (50)	34 (144.2)
			54 (500)	36 (540)
				41 (50)
				48 (680)
Range of B ($\$10^6$)	1000–1000	1000–1000	1952–2005	1989.3–2012
Range of R_1 (10^3 tons/year)	500–500	847.2–∞	500–500	1000–1000
Range of R_2 (10^3 tons/year)	500–500	660.5–∞	500–500	979.5–1046

However, this added restriction tends to lower the total profit since it excludes some potentially maximum-profit solutions. The optimum solutions are summarized in Table V. The following optimum solutions are obtained for the four budget B and raw material availability R combinations:

6.1.1 *B = \$1 Billion, R = 0.5 Million Tons/Year*

The total annual profit is \$692,833,700. The annual return on investment is 69%. The optimum selection includes six products and processes: propylene copolymer, propylene block copolymer, acrylic acid, linear-low density polyethylene, acetic acid, and styrene.

TABLE VI Results with Unique Process Constraints (15) Excluded.

B ($\$10^6$)	1000	1000	2000	2000
R_1 (10^3 tons/year)	500	1000	500	1000
R_2 (10^3 tons/year)	500	1000	500	1000
Profit ($\$10^6$/year)	726.0068	834.3011	1173.108	1452.819
Processes chosen:	1 (217.1)	3 (310)	1 (111)	2 (300)
Process number j and	3 (310)	4 (290)	3 (310)	3 (310)
(capacity X_j in tons/year)	41 (50)	31 (382.7)	9 (160)	4 (290)
	46 (613.4)	32 (300)	22 (100)	9 (160)
	48 (680)	46 (563.6)	35 (540)	31 (231.4)
	49 (450)	48 (680)	36 (540)	36 (540)
			37 (550)	46 (680)
			41 (50)	47 (680)
			46 (613.4)	48 (680)
			48 (680)	49 (680)
			49 (450)	
Range of B ($\$10^6$)	993–1001	1000–1000	1991.7–2006	1998.1–2012
Range of R_1 (10^3 tons/year)	500–500	1000–1000	500–500	1000–1000
Range of R_2 (10^3 tons/year)	500–500	571–∞	500–500	954.6–1084

6.1.2 B = \$1 Billion, R = 1 Million Tons/Year

The total annual profit is \$759,736,600. The annual return on investment is 76%. The optimum selection includes six products and processes: propylene copolymer, propylene block copolymer, acrylic acid, high density polyethylene, linear-low density polyethylene, and styrene.

6.1.3 B = \$2 Billion, R = 0.5 Million Tons/Year

The total annual profit is \$894,270,600. The annual return on investment is 45%. The optimum selection includes eleven products and processes: propylene copolymer, acrylic acid, *N*-butanol, polyvinyl chloride, polyvinyl chloride (dispersion), linear-low density polyethylene, acetic acid, formaldehyde, styrene, pthalic anhydride, and purified terephthalic acid (PTA).

6.1.4 B = \$2 Billion, R = 1 Million Tons/Year

The total annual profit is \$1,111,476,000. The annual return on investment is 56%. The optimum selection includes thirteen products and processes: propylene copolymer, propylene block copolymer, propylene homopolymer, acrylic acid, *N*-butanol, polyvinyl chloride, polyvinyl chloride (dispersion), high density polyethylene, linear-low density polyethylene, low density polyethylene, acetic acid, formaldehyde, and styrene.

From the above solutions, if unique process constraints are included, then the following four products and corresponding processes are always chosen under all parameter values:

- propylene copolymer (process number 3: Himont process),
- acrylic acid (process number 9: two-stage oxidation),
- linear-low density polyethylene (process number 31: dry mode gas phase Univation process), and
- styrene (process number 48: vapor phase alkyl/adiabatic dehydrogenation).

6.2 Case 2: Unique Process Constraints (15) Excluded

Relaxing unique process constraints (15) corresponds to an open investment strategy, in which more than one (main) production process can be chosen for each product. This approach would be taken by the investor who is willing to spend the extra effort in return for the maximum profit. The optimum solutions are shown in Table VI. The following optimum solutions are obtained for the four budget B and raw material availability R combinations:

6.2.1 B = \$1 Billion, R = 0.5 Million Tons/Year

The total annual profit is \$726,006,800. The annual return on investment is 73%. The optimum selection includes three products using six processes: propylene copolymer (processes 1 and 3), formaldehyde (process 41), and styrene (processes 46, 48, and 49).

6.2.2 B = \$1 Billion, R = 1 Million Tons/Year

The total annual profit is \$834,301,100. The annual return on investment is 83%. The optimum selection includes four products using six processes: propylene copolymer (process 1), propylene block copolymer (process 4), linear-low density polyethylene (processes 31 and 32), and styrene (processes 46 and 48).

6.2.3 $B = \$2$ Billion, $R = 0.5$ Million Tons/Year

The total annual profit is $1,173,108,000. The annual return on investment is 59%. The optimum selection includes six products using eleven processes: propylene copolymer (processes 1 and 3), acrylic acid (process 9), polyvinyl chloride dispersion (process 22), acetic acid (processes 35, 36, and 37), formaldehyde (process 41), and styrene (processes 46, 48, and 49).

6.2.4 $B = \$2$ Billion, $R = 1$ Million Tons/Year

The total annual profit is $1,452,819,000. The annual return on investment is 73%. The optimum selection includes six products using ten processes: propylene copolymer (processes 2 and 3), propylene block copolymer (process 4), acrylic acid (process 9), linear-low density polyethylene (process 31), acetic acid (process 36), and styrene (processes 46, 47, 48, and 49).

As can be seen from the above solutions, if unique process constraints are not included, then two products and three processes are always chosen under all parameter values:

- propylene copolymer (process number 3: Himont process), and
- styrene
  - (process number 46: liquid phase alkyl/adiabatic dehydrogenation)
  - (process number 48: vapor phase alkyl/adiabatic dehydrogenation)

6.3 Sensitivity Analysis

Sensitivity analysis was performed to test the sensitivity of the model to changes in the input values of parameters B, R_1 and R_2. First, the values of R_1 and R_2 were fixed while determining the range of B for which the solution remains valid. A similar procedure was used for determining the ranges of both R_1 and R_2, fixing the value of the other two parameters while varying the given parameter one at a time. For each of the two cases discussed above, validity ranges for the values of B, R_1 and R_2 are shown in Tables V and VI. The model was found to be fairly sensitive to the values of all three parameters, but slightly more sensitive for case 2 when constraints (15) are excluded. The following observations can be made for each case:

6.3.1 Unique Process Constraints (15) Included

Validity ranges for the values of B, R_1 and R_2 are given in Table V. The model is most sensitive to parameter variations for the combination $B = \$1$ billion and $R = 0.5$ million tons/year (zero tolerance for changes in all three parameters B, R_1 and R_2). The model is least sensitive for the combination $B = \$1$ billion and $R = 1$ million tons/year (non-zero tolerance and infinite upper bounds for two parameters: R_1 and R_2). The model is most sensitive to variations in the value of R_1 (zero tolerance for three combinations of B and R) and least sensitive to variations in the value of R_2 (non-zero tolerance for two combinations of B and R_2, including one infinite upper bound).

6.3.2 Unique Process Constraints (15) Excluded

Validity ranges for the values of B, R_1 and R_2 are given in Table VI. The model is most sensitive to parameter variations for the combination $B = \$1$ billion and $R = 0.5$ million tons/year (zero tolerance for changes in R_1 and R_2 with minimum tolerance for changes in B). The model is least sensitive for the combination $B = \$2$ billion and $R = 1$ million tons/year (non-zero tolerance for both B and R_2). The model is most sensitive to variations in the value of R_1 (zero tolerance for all four combinations of B and R), and least sensitive to variations in the value of B (non-zero tolerance for three combinations of B and R).

7 CONCLUSIONS

A simple and efficient model has been formulated for the planning and screening of investment opportunities in petrochemical products in Saudi Arabia. This mixed integer linear programming model has several new and unique features. The unit production cost is assumed to be an increasing function of the production quantity. Both the investment cost and the total production cost for each process are assumed to be piece-wise linear functions of the production quantity. New transformations are applied to represent these functions in linear terms suitable for efficient linear programming solution.

Current local production costs in Saudi Arabia of the relevant petrochemical products using various technologies and capacities have been calculated and presented. Typical values of both the investment capital and available raw material have been assumed, using two alternative investment strategies. According to the model results, the investment opportunities in petrochemical production are very profitable, regardless of the investment strategy and raw material availability. The annual return on a one-billion-dollar investment ranges from 69% to 83%, while the annual return on a two-billion-dollar investment ranges from 45% to 73%.

The model recommended several products that included: propylene copolymer, acrylic acid, linear-low density polyethylene, and styrene. It is clear that the most promising investment opportunities are associated with two processes: the Himont process for producing propylene copolymer, and the vapor phase alkyl/adiabatic dehydrogenation process for producing styrene. Sensitivity analysis was performed and revealed that the model was fairly sensitive to availability of both capital and raw materials (ethylene and propylene).

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