A MATHEMATICAL PROGRAMMING MODEL FOR OPTIMUM ECONOMIC PLANNING OF THE SAUDI ARABIAN PETROCHEMICAL INDUSTRY

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ABSTRACT

A new mixed integer linear programming model is formulated and used to model the development of the petrochemical industry in Saudi Arabia. The proposed model features a new mathematical programming formulation, new products and processes, new variables and constraints, and more accurate estimates of production costs based on local conditions. The products considered in the model are classified into four main categories: aromatics, ethylene derivatives, propylene derivatives, and synthetic gas derivatives. The model is used to recommend petrochemical products, their respective capacities, and the corresponding production technologies. Utilization of results is discussed and sensitivity analysis is performed.

Keywords: *Petrochemical Industry, Integer Programming, Optimization, Industrial Planning*

الملخص

يقدم هذا البحث نموذجا رياضيا باعتماد برمجة الأعداد الصحيحة الخطية لتخطيط الصناعات البتروكيماوية في المملكة . ويحتوي هذا النموذج المقترح على صيغ رياضية جديدة تشمل مجاهيل ومعادلات جديدة ، وعددا من المنتجات وتقنيات التصنيع أكبر من الأعداد التي تمت دراستها سابقاً ، كما يشمل تقديراً أدق لتكاليف الإنتاج المحلية . وتقسم المنتجات التي تتم دراستها إلى أربعة أنواع رئيسية هي مشتقات الإيثيلين والبروبيلين والغاز المصنع والعطريات . يتم استخدام النموذج لتحديد المنتجات التي سوف يتم إنتاجها وكمية الإنتاج والتقنية الملائمة . كما تجري مناقشة النتائج التي يقترحها النموذج لتنمية الصناعات البتروكيماوية السعودية .

1. INTRODUCTION

One of the unique characteristics of the petrochemical industry is the great interaction between feedstocks, technologies, and products and byproducts. For the production of many petrochemicals, there may be more than one process technology involving different combinations of feedstocks and by-products. Several alternative derivatives (with different capacities) can be derived from a certain petrochemical feedstock. The supply/demand situation and competitive production depends on the specific opportunity and is sometimes location specific. Also the available capital and feedstock quantity is limited. Obviously, all of these factors complicate the selection of the optimal opportunities. This requires establishment of a model for the development of the petrochemical industry to find the optimal structure of this industry.

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 its attendant potential for higher value-added products as well as the other 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, new large size private companies have been established in Saudi Arabia to undertake the construction and operation of petrochemical plants.

In order to obtain an estimated structure for the petrochemical industry in the Gulf Cooperation Council countries (GCC), [Wagialla et al. 1986] suggested a strategy for the Gulf region based strictly on satisfying the endogenous demand; it does not address the exogenous factors. [Al-Fadli et al. 1988] developed a network model for the optimal planning of petroleum refinery production in Saudi Arabia. By extension, the model considered the production of a limited number (eight) of basic petrochemicals. [Sayar et al. 1988] used the results of linear programming to suggest a plan for the optimal petrochemical industry in the GCC member states in order to meet the local demand in the first place and to cover a small part of the world demand.

[Bok et al. 1998] developed a multi-period mixed integer nonlinear model aimed at planning the long-range capacity expansion for chemical processing networks under uncertain demand forecast scenarios. They found that it is effective when they applied it to the case of investment planning in Korean petrochemical industry. [Bardesi et al. 1997] analyzed the role of multi-national corporations and foreign direct investment (FDI) on growth of Saudi Arabia's petrochemical industry, using polynomial distributed lag models to estimate the effects of FDI on imports and exports.

[Al-Sharrah et al. 2001] developed a model with an environmental objective so that only profitable and environmentally friendly processes are chosen. They selected the optimal set of processes meeting the objective function of sustainability. They quantified sustainability by a health index of the chemicals and represented increasing profit by process added value. They applied the model to plan Kuwait petrochemical industry.

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[Al-Amer et al., 1998] presented a modeling approach adopted for the future development of Saudi integrated 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 model incorporates the minimum economic production restrictions for each process. This work involves the modification of the latter model to incorporate new and different variables and constraints, and more accurate estimates of production costs based on local conditions. The new model has been used for screening and selection of the optimum petrochemical products for the Saudi petrochemical industry.

2. PRODUCTS INCLUDED IN THIS STUDY

In recent years, there has been a lot of interest from local companies and investors in new petrochemical products as the industry want to diversify its product portfolio and thus are competing for new and attractive projects. The petrochemical products included in this study are the ones believed in general, to enjoy high market growth and/or are missing from the regional production chain. It should be mentioned in here that no market analysis was done in this study. Also it is assumed that the technology is available.

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. It must be pointed out that phenol is classified as both a propylene derivative and a BTX derivative. The individual products within each category are listed below.

2.1. Propylene derivatives

- Polypropylene homopolymer
- Polypropylene copolymer
- Polypropylene block copolymer
- Phenol
- Acrylic Acid
- Propylene Oxide
- N-Butanol
- Cumene

2.2. Ethylene derivatives

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

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2.3. Synthesis gas derivatives

- Acetic Acid
- Ammonia
- Formaldehyde
- Methanol

2.4. BTX derivatives

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

3. BINARY INTEGER LP MODEL

The model includes 162 binary (0-1) variables and 26 constraints. The formulation of this binary integer linear programming model is described below.

3.1. Parameters

b_{jp} = input coefficients of raw material p in process j
= tons consumed of raw material p per ton produced of main product of process j

C_{jk} = production cost ($/ton) of process j per unit of main product if capacity level is k

D = total available capital ($M)

E_i = export selling price of product i per unit ($/ton)

Q_{jk} = production of process j (tons of main product /year) at capacity level k

R_p = available feedstock of raw material p (tons/year)

S_i = set of all processes in which the main product is i

V_{jk} = investment cost for process j at capacity k ($M)

3.2. Subscripts

i = product or by-product number, $i = 1, \ldots, 23$ (23 = number of products)

j = process number, $j = 1, \ldots, 54$ (54 = number of processes)

k = capacity level indicator, $k = l, m, h$ ($k = l$: low, $k = m$: medium, $k = h$: high)

p = raw material number, $p = 1, \ldots, 2$ (2 = number of limited raw materials)

3.3. Variables

H_j = 0-1 variable, = 1 if process j with high capacity is used, = 0 otherwise

L_j = 0-1 variable, = 1 if process j with low capacity is used, = 0 otherwise

M_j = 0-1 variable, = 1 if process j with medium capacity is used, = 0 otherwise

3.4. Objective

The objective of the model is to maximize the total annual profit, which can be expressed as (1) below. Although costs C_{ik} and prices E_i may slightly fluctuate, their relative ratios remain fairly stable over time.

$$\text{Maximize } Z = \sum_{j=1}^{54} (E_j - C_{jl})Q_{jl}L_j + (E_j - C_{jm})Q_{jm}M_j + (E_j - C_{jh})Q_{jh}H_j \tag{1}$$

3.5. Raw material constraints

These constraints ensure the total annual consumption of each raw material p does not exceed its annual availability R_p. The two limited-availability raw materials used are propylene and ethylene.

$$\sum_{j=1}^{54} b_{jp}(Q_{jl}L_j + Q_jM_{jm} + Q_{jh}H_j) \le R_p, \qquad p = 1, 2 \tag{2}$$

3.6. Budget constraint

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

$$\sum_{j=1}^{54} (V_{jl}L_j + V_{jm}M_j + V_{jh}H_j) \le D \tag{3}$$

3.7. Unique production-process and production-level constraints

These constraints ensure that, for each product, only one production process is chosen. At the same time, these constraints ensure that only one production level is chosen (zero, low, medium, or high) for each process.

$$\sum_{j \in S_i} L_j + M_j + H_j \le 1, \qquad i = 1, \ldots, 23 \tag{4}$$

4. INPUT DATA

In this work, the above model is applied to the petrochemical products listed above. The information and data needed for this study include, selected technologies, data needed to calculate the production cost such as fixed cost, raw material and energy requirements etc., and product price. These are obtained from [SRI (1993), Petrochemical Processes (1999), and Peters and Timmerhaus (1991)]. Again, it should be noted in here that this study did not take into consideration the market information, i.e., supply/demand of the products. It is simply assumed that there is sufficient demand. However, when up to date information and resources for good market study are available, the demand can be incorporated in the model as a constraint. For each derivative, the following data and calculations have been obtained or done:

1. Select relevant technologies along with the necessary data to calculate the production cost. Tables 1-4 summarize these derivatives and corresponding technologies and capacities for propylene, ethylene, synthesis gas, and BTX.
2. Production cost is calculated for each product/technology/capacity for the year 2000 at Saudi location .The details of this calculation are explained below.
3. The model sums up the capital cost and quantity of raw material (used to calculate production cost as in Tables 1-4) of the selected product to satisfy the constraints on these parameters.
4. The product price is obtained by taking an average international price over ten years. The international prices are generally cyclical but do not have a particular trend. The ten-year period covers as much fluctuation as possible.

5. RESULTS AND DISCUSSION

5.1. Calculation of Production Cost

Tables 1-4 show the production cost for each product using each available technology at three production levels. For example, for polypropylene copolymer alone, we selected three technologies, and so the number of production cost calculations is 3×3= 9. The total number of production cost calculations for all products and associated technologies and capacities included in this work is 3×54 = 162. The following procedure is used to calculate production cost:

- Capital cost is updated to year 2000 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.
- An average price for the raw material at Saudi location is taken to be $320/ton for ethylene and $350/ton for propylene.
- The cost of utilities is taken for Saudi location and included.
- Total number of operating labor is estimated to be 4.5 times number of operating labor per shift.
- Other costs such as supervision, maintenance, and general expenses are estimated using typical percentages given in relevant references such as Peters and Timmerhaus (1991).
- More details on production cost calculations, including a sample table, can be found in Alfares and Al-Amer (2002).

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5.2. Recommended Optimal Products

In order to run the integer-programming model, the maximum values (constraints) of the available investment budget D and raw material availability R_1 (for propylene) and R_2 (for ethylene) were assumed to be two billion U.S. Dollars 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 potentially available feedstock of propylene and ethylene in Saudi Arabia (which is now exported as LPG). In order to have a broader perspective, it seemed worthwhile to also consider the midpoints of these values. Assuming equal availability R of both propylene and ethylene, the input values into the model are given as:

D = 1 or 2 ($ billion),

$R = R_1 = R_2 = 0.5$ or 1 (million tons/year)

There are four cases (combinations of values for the two parameters D and R). The model was run once for each combination, producing different optimum selections of products (and byproducts) and processes for each combination. One process (process number 36: acetic acid by Low pressure carbonylation, supported Rh. catalyst) is chosen under all parameter variations. The detailed results are presented in Table 5. Four products are always chosen under all parameter values: propylene copolymer, linear low-density polyethylene, acetic acid, and styrene.

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Table 1. Propylene data used in the model

Product No. i & Price E_i ($/ton)	Process No. j & Name	Propylene used/ton b_{j1}	Variable L_j, M_j, H_j	Capacity Q_{jk} 10^3 (ton/yr)	Prod. Cost C_{jk} ($/ton)	Investment V_{jk} ($M)
1. Polypropylene Copolymer 975	1. Amoco/Chisso	0.9480	L1	70	724	55.0
			M1	135	667	81.1
			H1	270	632	131.6
	2. BASF	0.9432	L2	75	757	58.0
			M2	150	692	85.1
			H2	300	654	132.4
	3. Himont	0.9490	L3	77.5	734	60.2
			M3	155	669	86.8
			H3	310	631	134.1
2. Polypropylene Block copolymer 975	4. Sumitomo (Gas Phase)	0.9546	L4	70	738	55.1
			M4	145	673	83.1
			H4	290	637	132.0
	5. UCC\Shell	0.9550	L5	47.5	804	43.3
			M5	95	734	66.8
			H5	190	686	104.3
3. Polypropylene Homopolymer 780	6. Borealis	1.0450	L6	40	962	66.2
			M6	80	815	92.8
			H6	160	754	153.2
	7. UCC\Shell	1.0500	L7	40	793	40.0
			M7	80	713	61.4
			H7	160	659	95.1
4. Phenol 735	8. from C6H6/C3H8 via cumene	0.5103	L8	45	839	106.6
			M8	90	641	151.7
			H8	180	527	231.5
5. Acrylic acid (Ester grade) 1450	9. Two-stage oxidation	0.6289	L9	40	961	82.8
			M9	80	820	125.4
			H9	160	744	207.0
6. Propylene Oxide 1130	10. Arco Process (styrene product)	0.8648	L10	90	1024	233.5
			M10	180	884	390.7
			H10	360	808	698.7
	11. Texaco (T butanol byproduct)	0.9546	L11	90	963	185.8
			M11	180	856	304.5
			H11	360	799	537.1
	12. Chlorohydrin	0.8265	L12	90	1064	119.0
			M12	180	972	179.4
			H12	360	919	289.2
	13. Arco Process (T butanol byproduct)	0.7875	L13	90	972	212.3
			M13	180	873	362.7
			H13	360	819	657.7
	14. Cell Liquor Neutralization	0.8101	L14	90	1176	109.8
			M14	180	1092	164.3
			H14	360	1042	263.1
	15. Shell Process (Styrene byproduct)	0.8782	L15	90	1034	221.7
			M15	180	728	376.1
			H15	360	665	672.7
7. N- Butanol 830	16. via Cobalt Hydrocarbonyl Catalyst	0.8150	L16	50	828	115.5
			M16	100	687	180.4
			H16	200	586	287.4
	17. via N Butryaldehyde Rh Catalyst	0.6994	L17	50	698	63.7
			M17	100	620	100.2
			H17	200	558	156.3
8. Cumene 450	18. from C6H6 & Propylene	0.3784	L18	60	609	23.1
			M18	120	517	33.2
			H18	240	503	50.7

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Table 2. Ethylene data used in the model

Product No. i & Price E_i ($/ton)	Process No. j & Name	Ethylene used/ton b_{j2}	Variable L_j, M_j, H_j	Capacity Q_{jk} 10^3 (ton/yr)	Prod. Cost C_{jk} ($/ton)	Investment V_{jk} ($M)
9. Poly Vinyl Chloride (PVC) 740	19. Suspension Polymerization		L19 M19 H19	100 200 400	676 626 593	117.6 186.0 307.5
	20. Bulk Polymerization		L20 M20 H20	50 100 300	660 631 546	62.5 114.0 209.6
10. PVC Dispersion 1250	21. Batch Emulsion Polymerization		L21 M21 H21	25 50 100	1145 966 860	73.1 101.1 148.0
	22. Continuous Emulsion Polymerization		L22 M22 H22	25 50 100	959 861 795	46.5 70.7 110.1
11. Vinyl Chloride 430	23. TOSOH Technology		L23 M23 H23	125 250 500	510 494 482	49.2 74.4 112.8
	24. Pyrolysis		L24 M24 H24	125 250 500	548 538 528	79.1 144.2 258.1
	25. Chlorination/ Oxychlorination	0.4678	L25 M25 H25	250 500 1000	406 390 377	134.0 229.9 392.2
12. Ethylene Glycol 600	26. Hydration of EO: all EO for EG	0.7267	L26 M26 H26	90 180 360	558 500 460	142.6 234.8 397.5
13. Vinyl Acetate 690	27. From ethylene and acetic acid	0.3930	L27 M27 H27	67.5 135 200	798 749 732	82.7 133.6 181.3
14. High Density Polyethylene 860	28. UCC Process	1.0200	L28 M28 H28	70 135 270	601 556 525	56.9 84.5 131.5
	29. Du Pont Process	1.02	L29 M29 H29	70 135 270	636 574 547	63.4 84.5 136.9
	30. Philips Process	1.02	L30 M30 H30	70 135 270	636 583 548	66.5 96.2 147.7
15. Linear Low Density Polyethylene 900	31. Dry Mode Gas phase Univation Process	0.9461	L31 M31 H31	100 200 400	557 534 521	51.4 83.0 144.5
	32. Bimodal grade mixed Mettallocene Ziegler catalyst	0.9387	L32 M32 H32	75 150 300	643 601 576	46.9 66.0 98.6
	33. Bimodal grade Unipol process	0.943	L33 M33 H33	122.5 245 490	751 710 686	82.4 116.6 175.6
16. Low Density Polyethylene 870	34. High pressure tubular reactor	1.06	L34 M34 H34	50 100 200	697 639 602	72.0 117.7 199.7

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Table 3. Synthesis gas data used in the model

Product No. i & Price E_i ($/ton)	Process No. j & Name	NG Feed* used/ton b_{j3}	Variable L_j, M_j, H_j	Capacity Q_{jk} 10^3 (ton/yr)	Prod. Cost C_{jk} ($/ton)	Investment V_{jk} ($M)
17. Acetic acid 480	35. Low pressure carbonylation. Rh catalyst solution		L35 M35 H35	182.5 365 540	346 305 290	125.6 195.9 259.6
	36. Low pressure carbonylation supported Rh. catalyst		L36 M36 H36	182.5 365 540	330 282 264	116.4 168.2 213.5
	37. Low pressure carbonylation Rh Halide catalyst		L37 M37 H37	180 360 550	359 306 281	133.2 196.3 248.9
18. Ammonia 160	38. ICI AMV Process	6.35	L38 M38 H38	300 430 590	161 151 144	210.9 278.2 356
	39. MW Kellog Process	5.928	L39 M39 H39	300 430 590	176 166 157	243.5 322.4 412.6
	40. ICI LCA Process	6.678	L40 M40 H40	105 170 340	184 161 139	87 119.5 196.7
19. Formaldehyde 500	41. From Methanol using Silver catalyst		L41 M41 H41	15 25 50	435 388 353	15.3 20.2 32.7
	42. From Methanol using Fe Mo catalyst		L42 M42 H42	15 25 50	458 423 388	17.9 26.2 44.9
20. Methanol 150	43. Lurgi process	7.867	L43 M43 H43	415 830 1660	133 116 111	224.6 365.5 682.1
	44. ICI process copper catalyst	7.778	L44 M44 H44	415 830 1660	136 121 117	228.5 384.6 727.6
	45. ICI LCM process	7.661	L45 M45 H45	415 830 1660	125 118 113	199.1 371.5 702.9

* Natural gas (NG) is assumed to be available in unlimited quantity

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Table 4. BTX data used in the model

Product No. i & Price E_i ($/ton)	Process No. j & Name	Ethylene used/ton b_{j2}	Variable L_j, M_j, H_j	Capacity Q_{jk} 10^3 (ton/yr)	Prod. Cost C_{jk} ($/ton)	Investment V_{jk} ($M)
21. Styrene	46. Liquid Phase	0.2891	L46	225	470	116.9
760	Alkyl/Adiabatic		M46	450	455	190
	Dehydrogenation		H46	680	450	265.1
	47. Liquid Phase	0.2878	L47	225	480	115.6
	Alkyl Oxidative		M47	450	466	191.8
	Reheating		H47	680	461	266.8
	48. Vapor phase	0.2843	L48	225	469	125.2
	Alkyl/adiabatic		M48	450	450	192.7
	Dehydrogenation		H48	680	445	269
	49. Vapor phase	0.2874	L49	225	474	125.2
	Alkyl/Isothermal		M49	450	458	202
	Dehydrogenation		H49	680	453	285.5
22. Pthalic	50. Attochem/		L50	13	748	26
Anhydride	Nippon		M50	25	655	40.8
700			H50	50	568	63.9
	51. from O-Xylene		L51	13	714	27.7
	by Alsuisse Italia		M51	25	614	39.6
	Process		H51	50	546	56.9
4. Phenol	52. Liquid Phase		L52	45	816	108.8
735	Oxidation of		M52	90	711	157.2
	Toluene		H52	180	659	251.6
23. PTA	53. Hydrolysis		L53	125	651	208.1
680	of Dimethyl		M53	250	583	308.6
	Terephthalate		H53	500	551	515.5
	54. from P-Xylene		L54	125	627	170.5
	Bromine promoted		M54	250	580	267.3
	air oxidation		H54	500	554	452.7

For each case of D and R, the total profit margin and the simple rate of return on investment (ROR) are shown in Table 5. The annual profit range is $674-1,101.57 millions, while the annual ROR range is 43.5-73.6%. The maximum profit is obtained in Case 4 (D = $2 billions and R = 1 million tons/year), and the maximum ROR is obtained in Case 2 (D = $1 billion and R = 1 million tons/year). These numbers indicate excellent and highly profitable investment opportunities for new petrochemical projects in Saudi Arabia.

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Table 5. Optimum solution for the four cases of budget D and raw material availability R

Case	1	2	3	4
D (\$$10^6$)	1,000	1,000	2,000	2,000
$R = R_1 = R_2$ (10^3 tons/year)	500	1,000	500	1,000
Profit (\$$10^6$/year)	674	735.98	869.76	1,101.57
Return on investment	67.4%	73.6%	43.5%	55.1%
Processes chosen	H1, M4, H9, H32, H36, H46	H3, H4, H28, H31, M36, M41, H48	H1, H9, H17, H20, H22, H32, H36, H41, H48, H51, H54	H3, H4, H7, H9, H17, H20, H22, H28, H31, M34, H36, M41, H48, H51
Range of D (\$$10^6$)	998.9 – 1002.7	999.5 – 1008	1938 – 2000.7	1997.5 – 2006
Range of R_1 (10^3 tons/year)	496 – 505	572 – ∞	497 – 517	981 – 1071
Range of R_2 (10^3 tons/year)	479 – 572	849 – ∞	476 – 521	955 – 1060

5.3. Sensitivity analysis

Table 5 displays the results of sensitivity analysis performed to test the sensitivity of the model to changes in the input values of parameters D , R_1, and R_2. For each of the four cases presented above, the values of R_1 and R_2 were fixed while determining the range of D for which the solution remains valid. A similar procedure was used for determining the ranges of R_1 and R_2, varying one parameter at a time while fixing the values of the two other parameters. The model was found to be fairly sensitive to the values of all three parameters, but most sensitive to investment budget D and least sensitive to ethylene availability R_2. In terms of the four cases, Case 1 is the most sensitive to parameter variation, while Case 2 is the least sensitive.

6. CONCLUSIONS

An efficient integer programming model has been formulated for planning and screening investment opportunities in new petrochemical products in Saudi Arabia. Production costs of the petrochemical products based on Saudi conditions using various technologies and capacities have been calculated and presented. The optimal solution from the model gave the recommended products under different scenarios of available capital and raw material. The recommended products include propylene copolymer, linear low-density polyethylene, acetic acid, and styrene. Sensitivity analysis was performed and revealed that the model was fairly sensitive to availability of capital and raw materials. The ranges of these parameters under which the results are valid are reported.

LP models such as the one presented in this paper can be used in the initial screening of alternative investment options, as the first stage of feasibility studies when there is a large number

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of opportunities. One of the objectives of this paper is to demonstrate the applicability of mathematical programming models to problems similar to those faced by SABIC.

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