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Towards the Development of an Optimal Long-Term Structure and Policy for the Development of Trinidad and Tobago's Petrochemical Industry

Part 11. The Olefin-based Complex

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By the year 2000, Trinidad and Tobago's natural gas production would be sufficient to support a 500,000 t y ethylene plant. In this paper, the problem of selecting an initial optimal structure and policy for development of an olefin-based complex is addressed. The mathematical model used is formulated to capture the dynamic nature of the petrochemical market. The planning time horizon extends until 2015, during which economic parameters were allowed to vary. Uncertainty in the estimation of these parameters is taken into account. The study recognises that planning on this scale must satisfy various interest groups which may have conflicting goals. As a result, a multiobjective analysis was performed. It was found that the optimal policy for an olefin-based complex involves the immediate product of a blend of basic, intermediate and end-products. Based on the range of feed compositions considered, the ethylene plant should produce the maximum amount of propylene possible.

1. Introduction

Unlike the methane-based complex which has an existing structure already in place, the olefin-based complex is non-existent at the present time. With plans for increased natural gas production, there exists the possibility for an olefin-based complex. As a result, it is important to derive an initial structure for that complex which ensures optimal use of resources.

For long-term viability of the olefin-based complex, a *multiperiodic* model is used, which captures the dynamic nature of the industry. A *mixed integer linear programming* (MILP) model is used since it takes into account economies of scale.

A *multiobjective* analysis is used to take into account the goals of various interest groups involved in the planning process. These include investors, government and populace.

The presence of *uncertainty* in the data used has a significant effect on the solutions obtained and must therefore be treated appropriately. Various tools are employed to measure the effects of uncertainty.

In this paper, the same theory outlined in *Part I* is applied to the problem of finding an optimal long-term structure and policy for development of an olefin-based complex. The paper ends with some remarks about issues on the implementation of development policies, limitations of the study and recommendations for possible future work.

2. Model for the Olefin-Based Complex

The mathematical model comprises constraints on capacity expansions, supply of raw materials, demand for products, yield and material balances. The general form of these constraints is given in *Part I, Section 2.1.*

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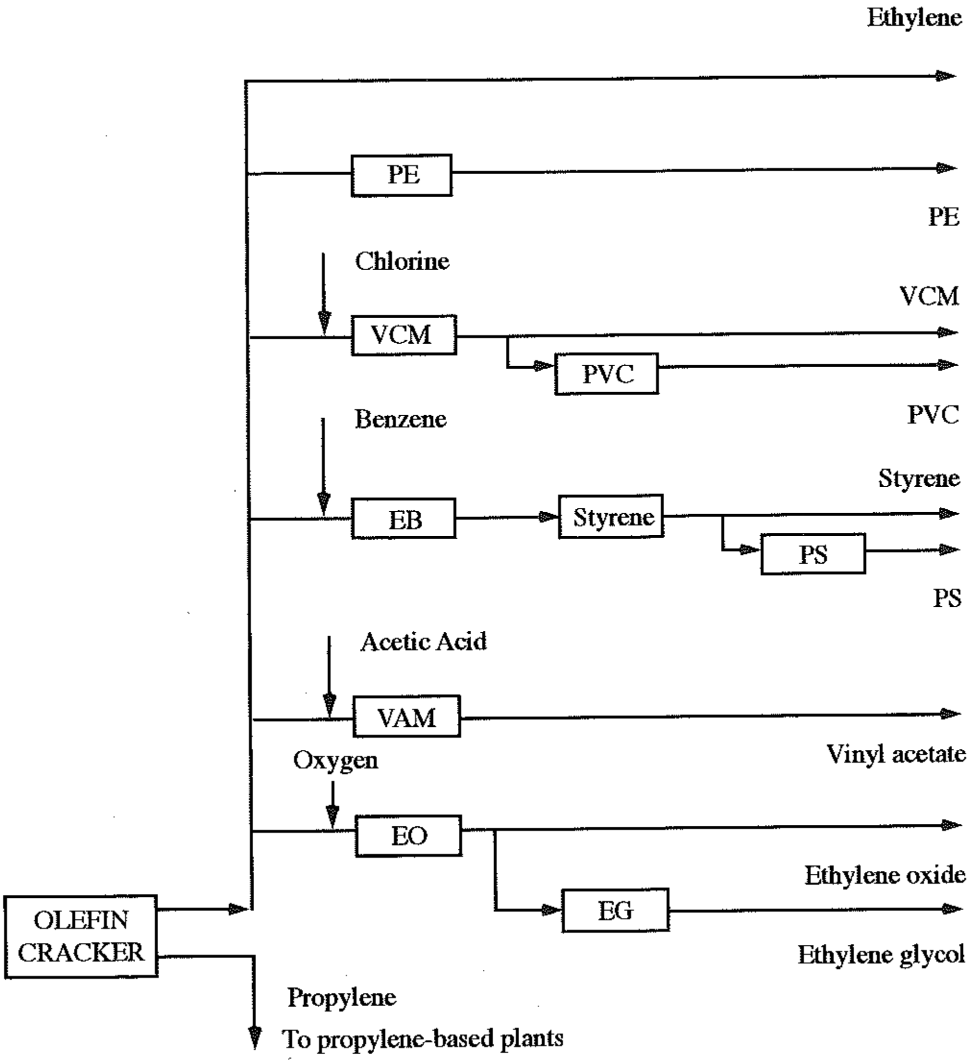


FIGURE 1: *Ethylene-based Petrochemical Complex*

The petrochemicals considered for inclusion into the olefin-based complex are given in **Figures 1** and **2**. As with the methane-based complex, the optimum solution based on solely on market restrictions (*i.e.*, market-based olefin complex) is determined. From this, other models are derived.

The time horizon used for the olefin-based complex is given in **Table 1**. It comprises just two periods (with investments possible in both periods) since the primary objective in this case is to select an initial long-term structure.

The current and anticipated (1999) natural gas consumption is taken to be 953 MMscfd (Petroleum Economist, Dec. 1994 and National Gas Company, 1993). Together with the liquified natural gas plant soon to come on-stream, the total quantity of natural gas available for liquid extraction is approximately 1425 MMscfd. This quantity contains about 590 Mt/y of ethane and 360 Mt/y of propane. Since there is a decision to be made on the choice of the composition of the gas (comprising ethane and propane) to be fed to the ethylene cracker, which affects its viability, this was treated as a decision variable which was optimised.

3. Methodology

The techniques used for handling multiobjectivity and uncertainty were the same as those used in the methane-based complex (*cf.* Sections 3.1 and 3.2, Part I).

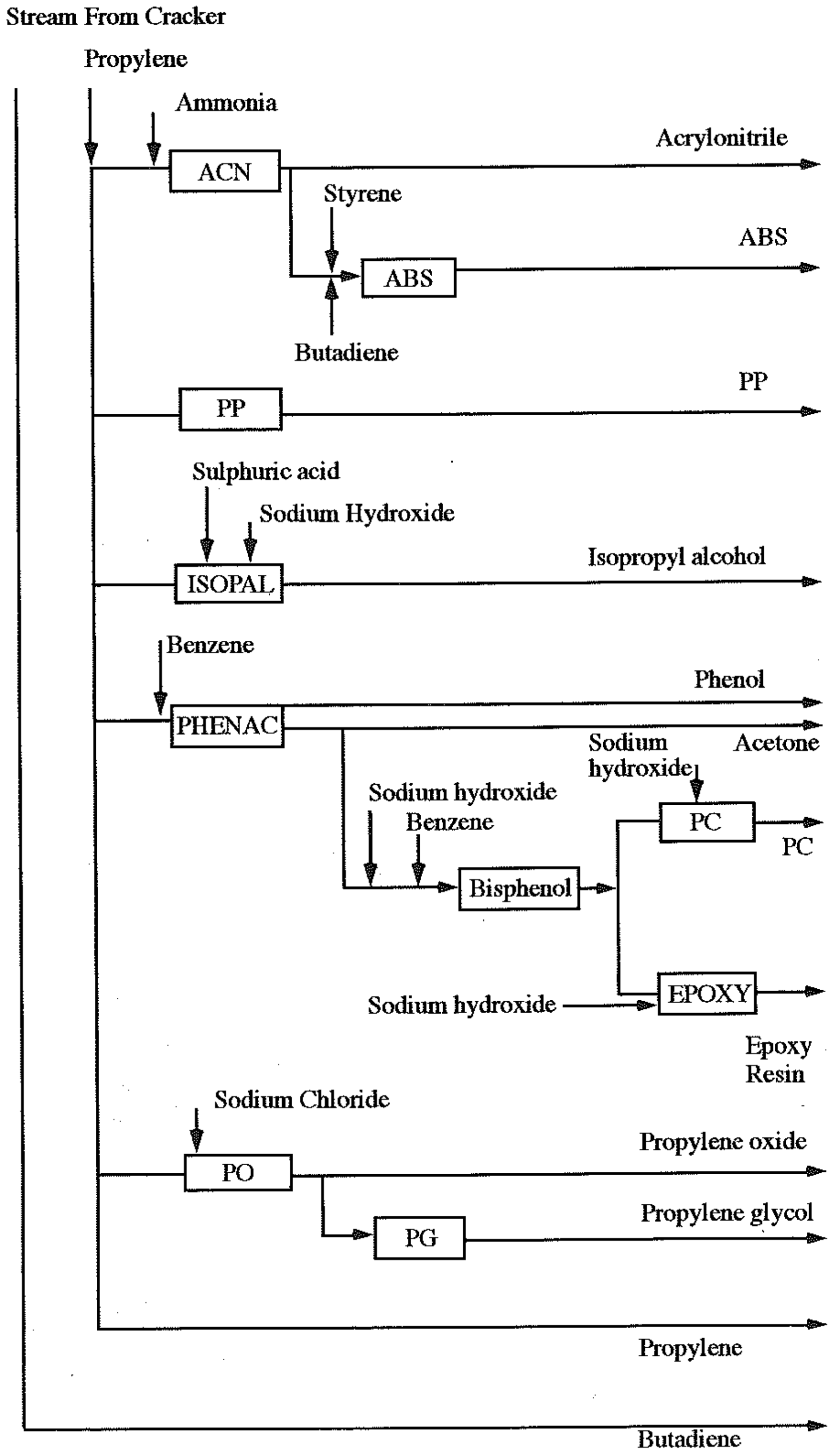


FIGURE 2: *Propylene-based Petrochemical Complex*

TABLE 1: *Time Horizon for the Olefin-based Complex*

Period	Year Starting	Year Ending	Length of Period
1	1999	2001	3
2	2002	2015	14

The objective function used in the optimisation was the sum of the net present value (NPV) of all the plants. Other objectives, which include NPV per investment, NPV per tscf of natural gas, taxes and employment, were brought into the analysis at the post-optimisation stage. Weights were assigned to each objective to denote its relative importance.

The coefficient of variation (expected value divided by standard deviation) and the security market line (plot of mean versus standard deviation) were used to compare the degree of uncertainty associated with each model. Another tool which was used is described in the next section.

3.1 Degree of Model Stability

A sensitivity analysis was performed on the olefin-based complex. Various Degrees of Model Stability (DOMS) were defined in order to assist in the interpretation of the results of the sensitivity analysis. The sensitivity analysis was performed with respect to sale price (*i.e.* the sale price of each petrochemical was perturbed to different degrees to determine the effect on the optimum structure). DOMS analysis could not be performed with the methane-based models since these were more or less fixed (based on the various policies for development) and because of their larger size and level of interaction between plants. The base case olefin complex, OLEFC1 was not fixed.

The following cases arose in performing the sensitivity analysis:

Condition 1 - The network remains unchanged in terms of plant capacities, production or sales of all petrochemicals for each period.

Condition 2 - The NPV does not change.

Condition 3 - The NPV changes.

Condition 4 - The network changes in terms of plant capacities, production or sales of petrochemicals.

The following DOMS were defined:

DOMS I - *Conditions 1* and *2 exist, e.g.*, may be due to small changes in the selling price of a petrochemical that is not a part of the current structure.

DOMS II - *Conditions 1* and *3 exist, e.g.*, may be due to small changes in the selling price of a petrochemical which is part of the current structure.

DOMS III - *Conditions 3* and *4 exist, e.g.*, may be due to large changes in the selling price of petrochemicals which may or may not be part of the current structure.

4. Break-even Plant Capacities

The plots of NPV versus plant capacity for each of the ethylene-based and propylene-based petrochemicals are shown in **Figure 3a** and **3b** respectively. From **Figure 3a**, the break-even capacities (Mt/y) for the ethylene-based petrochemical plants were found to be: PE - 160; EB - 100; Styrene - 180; PS - 100; VCM - 225; PVC - 70; VAM - 63; EO - 60; and EG - 45.

From **Figure 3b**, the break-even capacities (Mt/y) for the propylene-based petrochemicals were found to be: ACN - 107; ABSR - 50; PP - 95; Isopal - 10; PhenAc - 10; Bisphenol - 7; PC - 5; EpoxyR - 1; PO - 45; and PG - 10.

5. Olefin-based Market Model

The first olefin-based market model considered was the market model, on which was placed demand constraints (obtained from a market survey - given in Furlonge, 1998). The optimal market-based model (shown in **Figure 4**) recommended the cracker which utilises the minimum ethane feed composition, so that the maximum quantity of propylene is produced. Clearly, the higher cost associated with this option was offset by the downstream products from the product mix. The ethylene produced was partially consumed by an EB plant, a VCM plant and an ethylene oxide plant; 152.6 Mt/y excess ethylene remained in period 1. This large quantity is undesirable since export of ethylene by shipment would prove to be uneconomical since it requires refrigeration and pressurisation. Ethylene would be too valuable to be sold as LPG. It should be noted that no PE was built despite the excess available ethylene. Hence, it turns out that it is more profitable to sell the excess ethylene than to build a 152.5 Mt/y PE plant which is close to the break-even capacity. In the second period, the excess

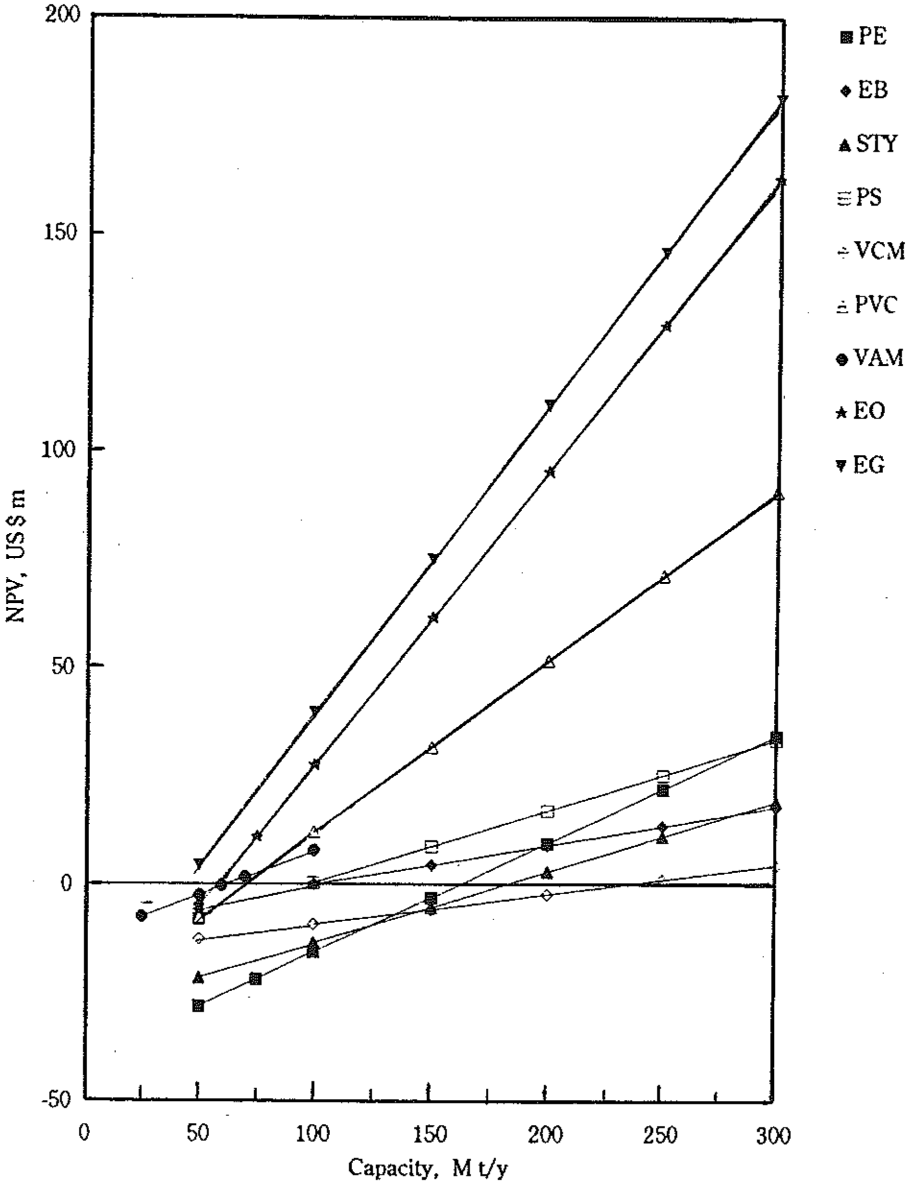


FIGURE 3a: *NPV vs Capacity for Ethylene-based Plants*

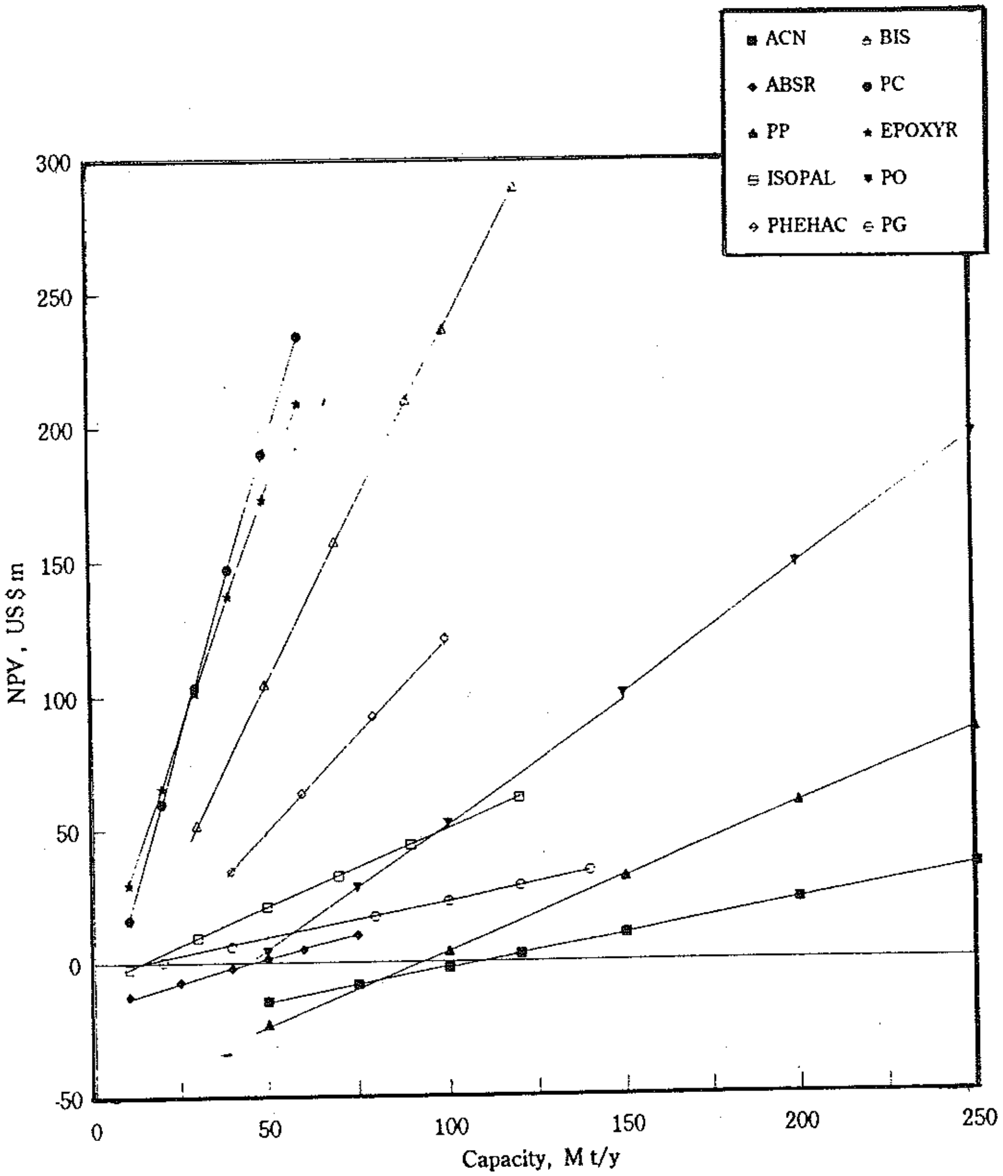


FIGURE 3b: *Graph of NPV vs. Capacity for Propylene-based Plants*

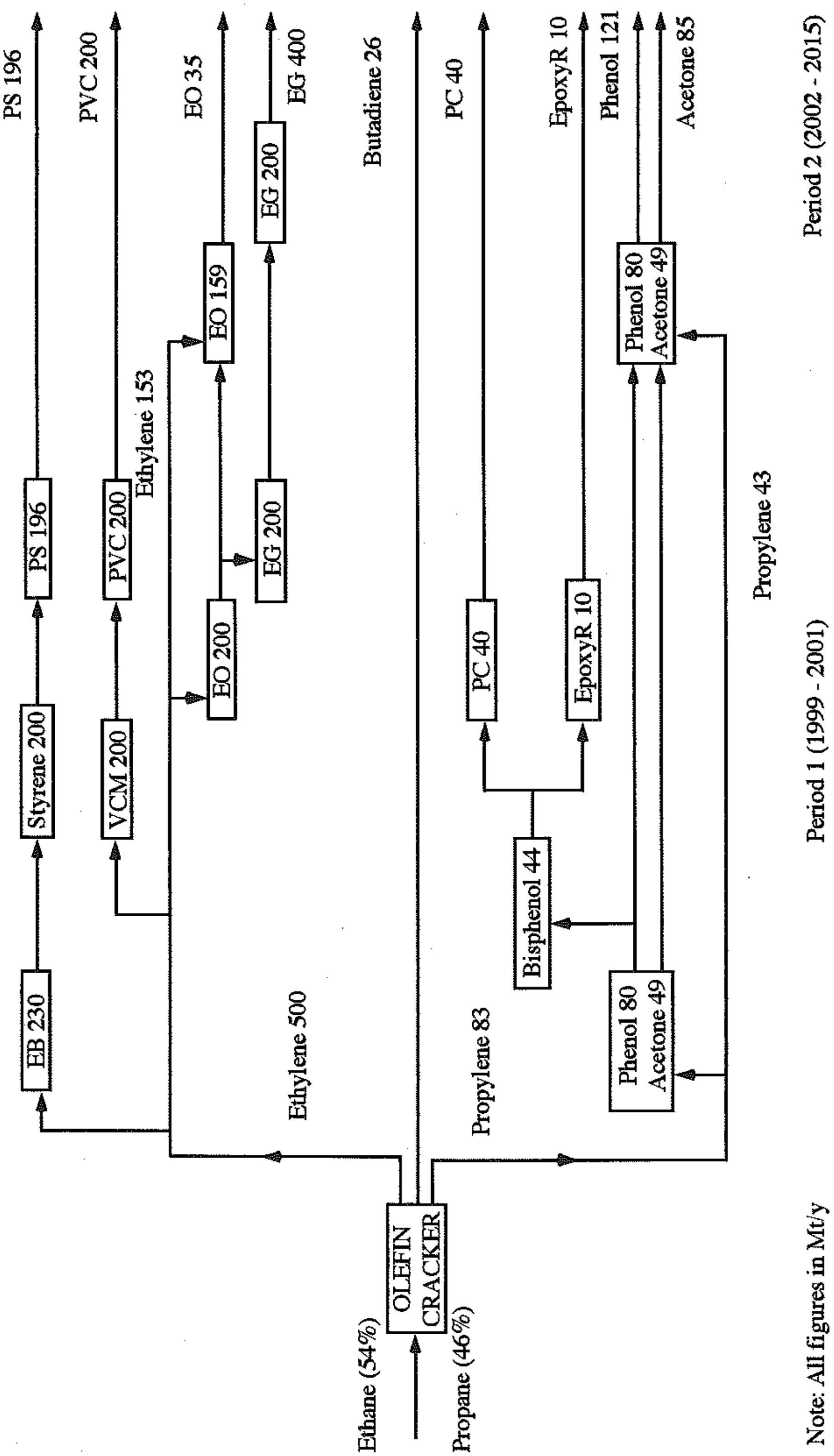


FIGURE 4: *Olefin-based Market Model*
NPV = US $m 1359
Investment = US $m 1198 (Period 1), US $m 281 (Period 2)

ethylene is consumed by a second EO plant. For market reasons, it probably would have been better to build a different petrochemical than to build another EO plant.

A phenol/acetone plant in each period consumed almost all the available propylene; half of the maximum available quantity of propylene was used in period 1 and all in period 2. It is apparent that the optimal structure favoured downstream production (with the selection of polystyrene, PVC, polycarbonate and epoxy resin plants). It is noteworthy that no PP plant was built since the total amount of propylene available (83 Mt/y) is insufficient for a profitable PP plant which has a break-even capacity of 95 Mt/y.

As with the methane-based market model, the olefin market model is an infeasible solution, however, it gave useful insights which were used to develop another complex - OLECF1 (see **Figure 5**). The latter allowed a maximum of one plant per petrochemical and eliminated unused ethylene and propylene. Apart from the petrochemicals selected by the market-based model, a 150 Mt/y polyethylene plant, a 48 Mt/y propylene oxide plant and a 40 Mt/y propylene glycol plant were also selected. In this case, no expansions occurred in period 2 since all the available ethylene and propylene were consumed in period 1.

Several possible olefin complexes (OLEFC2, OLEFC3 and OLEFC4) were developed based on a more rigorous approach to handling uncertainty in the data was adopted, *i.e.*, DOMS.

5.1 Degree of Model Stability

Selling price, because of the nature of the market forces, contained the greatest uncertainty and was more unpredictable than capital and operating costs. As a result, the degree of model stability (*cf.* Section 3.1) of OLEFC1 with respect to selling price was evaluated. (See **Tables 2** and **3**).

Ethylene oxide and ethylene glycol were the most stable plants. Ethylene glycol remains in the optimal complex as long as its selling price averages above US$1157/t, which has a high probability of occurring (83% in period 1 and 68% in period 2). If the selling price of EO falls below US$890/t, which is highly unlikely (probability 2% and 16% in periods 1 and 2 respectively), then a smaller EO plant (162 Mt/y) as opposed to 200 Mt/y) should be built. All of this capacity is used to feed the EG plant (200 Mt/y capacity). The additional available ethylene is dedicated to a larger PE plant (185 Mt/y).

Of the ethylene-based products, polyethylene was the third most stable with respect to uncertainty in its selling price. Even if the selling price averaged as low as US$846/t (which has a probability of occurring of 36% in period 1 and 43% in period 2), a PE plant (150 Mt/y) still proved to be a viable investment, and should therefore be part of the petrochemical complex.

In the event that the selling price of PE averaged below US$846/t, a 70 Mt/y VAM plant is recommended with a small decrease of 25 Mt/y in PE capacity. A VAM plant may also enter into the optimal complex if its selling price averaged above US$969/t (just 2% above the base value of US$950/t, and has a probability of occurrence of 35% and 42% in periods 1 and 2 respectively). If the styrene plant is not to be built, a VAM plant is suggested along with a larger PE plant.

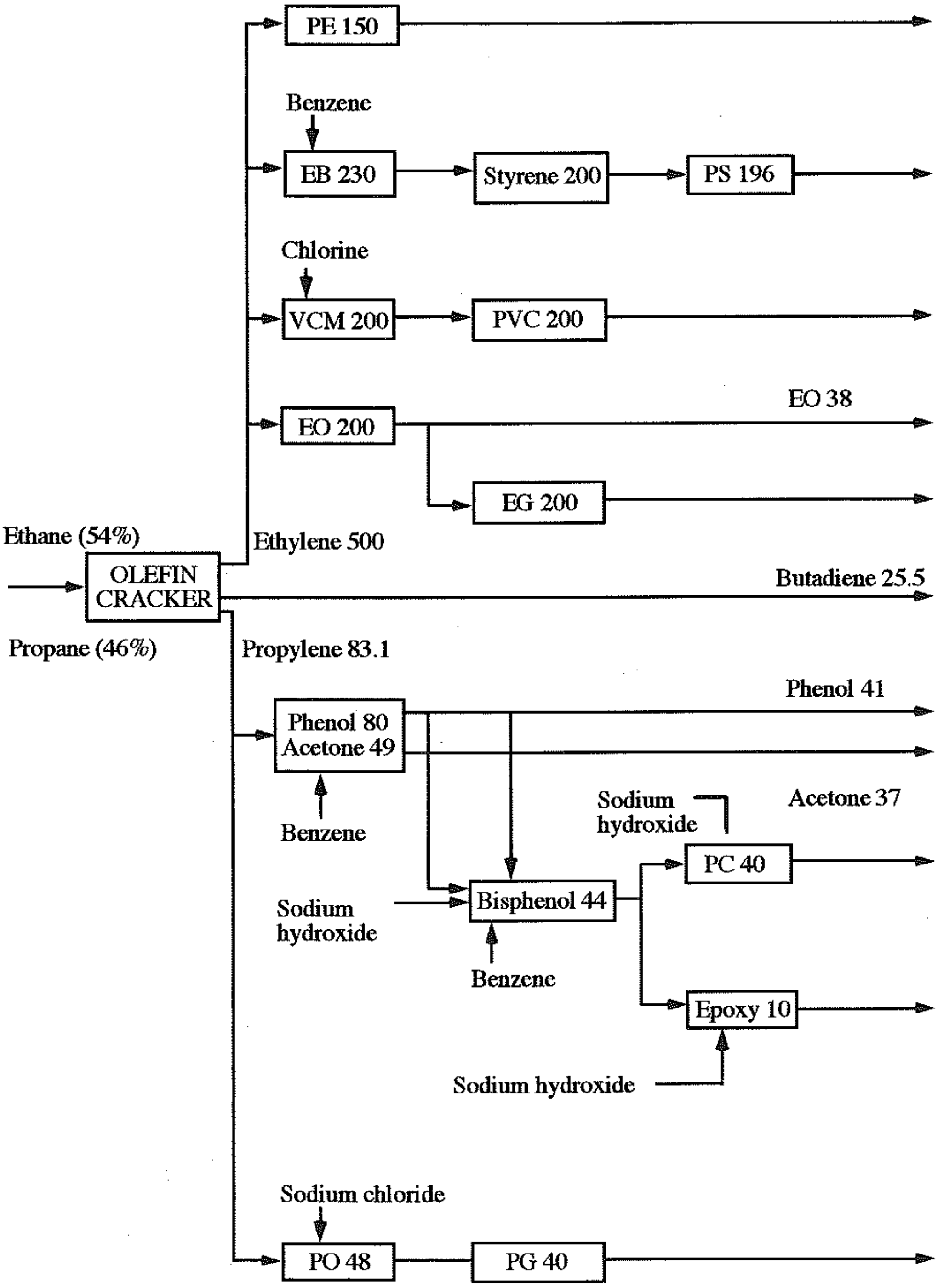
If the selling price of PE averages above US$1015/t (probability of 22% in period 1 and 35% in period 2), then a larger capacity is suggested (200 Mt/y instead of 150 Mt/y) at the expense of EB, styrene and PS. These three petrochemicals are the most unstable. If the price of PS falls below US$1238/t (a probability of 47% in period 1 and 49% in period 2), then a PS plant should not be built. If the prices of EB and styrene were to fall below US$515/t and US$882/t (US$10 and US$18 respectively below the mean values) then these plants should be omitted. In this case, a larger PE plant (184.4 Mt/y) may be built together with a VAM plant.

A 200 Mt/y PE plant may also be built if the selling price of VCM and PVC averages below US$523/t (probability of 36% in period 1 and 43% in period 2), and US$855/t (probability of 33% in period 1 and 41% in period 2) respectively. In this situation, the VCM capacity should be decreased to 35.5 Mt/y (which would not be viable and should be omitted), and no PVC plant should be built. The ethylene should be channelled to a 70 Mt/y VAM plant and a 200 Mt/y PE plant.

It should be noted that regardless of the selling price of ethylene (between the optimistic and pessimistic values), propylene and all other petrochemicals, the olefin cracker involving the minimum composition of ethane in the feed was selected (*i.e.*, maximum propylene production).

Epoxy resin followed by polycarbonate were the two most stable petrochemicals based on propylene. If their pessimistic prices were to be realised, they should still form part of the optimal structure. Thus the phenol/acetone plant should also form part of the optimal structure. If the selling price of phenol and acetone fell below 81% of their mean values (probability 4.7% in period 1 and 20% in periods 2 for phenol, and 0.2% in period 1 and 7.8% in period 2 for acetone), then a 39 Mt/y phenol/acetone plant is recommended to feed the polycarbonate and epoxy resin plants, no excess phenol is to be produced.

A propylene glycol plant is suggested as long as its selling price averages above US$1261/t (probability of



Note: All figures are in Mt/y

FIGURE 5: *Optimal Olefin-based Complex - OLEFC 1*

TABLE 2: *Degree of Model Stability for OLEFC 1*

DOMS	Cause	Effect
II	800 < SP (PE) < 1015	
III	SP (PE) > 1015	No EB Q (PE) increase to 200
III	SP (PE) < 800	Q (VAM) increase to 50 Q (PE) increase to 131.46
II	SP (VCM) > 523 and SP (PVC) > 855	
III	SP (VCM) < 523 and SP (PVC) < 855	Q (VCM) decrease to 90.6 Q (PVC) decrease to 0 Q (PE) increase to 200
III	SP (VCM) < 512 and SP (PVC) < 837	Q (VCM) decrease to 51.26 Q (PVC) decrease to 0 Q (PE) increase to 200 Q (VAM) increase to 50 Mt/y
II	SP (PS) > 1238	
III	SP (PS) < 1238	Q (PS) decrease to 0
II	SP (EB) > 515 SP (STYRENE) > 882	
III	SP (EB) < 515 SP (STYRENE) < 882	Q (EB / STYRENE / PS) decrease to 0 Q (PE) increase to 191.7 Q (VAM) increase to 50
II	SP (EG) > 1157	
III	SP (EG) < 1157	Q (EG) decrease to 0
II	SP (EO) > 890	
III	SP (EO) < 890	Q (EO) decrease to 162 Q (PE) increase to 185.36
II	SP (PG) > 1261	
III	SP (PG) < 1261	Q (PG) decrease to 0
II	SP (PO) > 1080	
III	SP (PO) < 1080	Q (PG) decrease to 0 Q (PO) decrease to 0 Q (ISOPAL) increase to 30 Q (ACN) increase to 16.2

TABLE 3: *Degree of Model Stability for OLEFC 1*

DOMS	Cause	Effect
II	SP (PC) > 3510	
III	SP (PC) < 3510	Q (PC) decrease to 0
II	SP (Epoxy resin) > 2700	
II	SP (Phenol) > 628	
	SP (Acetone) > 608	
III	SP (Phenol) < 628	Q (PhenAc) decrease to 39.16
	SP (Acetone) < 608	Q (PO) increase to 71.8
I	SP VAM < 988 (104%)	
III	SP VAM > 988	Q (VAM) increase to 50 Mt/y Q (PE) decrease to 131.46
I	ALL SP of ethylene and propylene between optimistic and pessimistic	
I	SP Isopropyl alcohol at optimistic	
I	SP ACN < 1239	
III	SP ACN > 1239	Q (ACN) increase to 36.03 Q (ABSR) increase to 50 Q (PO) decrease to 0 Q (PG) decrease to 0 Q (PS) decrease to 185.69
I	SP ABSR < 1663	
III	SP ABSR > 1663	Q (ACN) increase to 36.03 Q (ABSR) increase to 50 Q (PO) decrease to 0 Q (PG) decrease to 0 Q (PS) decrease to 185.69
I	SP PP < 1147	
III	SP PP > 1147	Q (PP) increase to 44.9 Q (PG) decrease to 0 Q (PO) decrease to 0
III	SP PP = 1250 (optimistic)	Q (PP) increase to 44.9 Q (PG) decrease to 0 Q (PO) decrease to 0 Phenol/Acetone not replaced

60% in period 1 and 55% in period 2). An isopropyl alcohol plant should enter the structure if the selling price of propylene oxide averages below US$1080 (probability of 21% in period 1 and 34% in period 2), in which case no propylene oxide and propylene glycol plants should be built. The latter situation may also arise if the selling price of ABSR averages above US$1663/t (probability 5.7% in period 1 and 21% in period 2), in this case, a 30 Mt/y ACN plant should be built to feed a 50 Mt/y ABSR plant. A slightly smaller PS plant (186 Mt/y) would be required due to the styrene needs of the ABSR plant. It was observed that, even though a 30 Mt/y ACN plant is not profitable by itself, it was selected. This exemplifies the fact that local losses are sometimes required for global profitability (*i.e.*, the combined ACN and ABSR plants are profitable).

Because of the limited availability of propylene (maximum of 83 Mt/y), neither an economic size acrylonitrile plant (without downstream plants) nor a polypropylene plant can be built. The phenol/acetone plant, as well as the propylene oxide plant requires small quantities of propylene. The high profitability of the phenol/acetone plant together with its downstream consumers cements its place in the optimal structure, so that insufficient propylene would be available for either an acrylonitrile plant or a polypropylene plant.

5.2 Formulation of Other Complexes

Scenarios which encourage the construction of a VAM plant:

1. Below average styrene price (US$900/t) .
2. Weak PE price, *i.e.*, below US$845/t (average used was US$900/t).
3. Healthy VAM price, *i.e.*, above US$970/t (average used was US$950/t).
4. A local acetic acid plant.

The above scenarios are not far from the base case, so it would be worthwhile to include a VAM plant in an alternative olefin complex (OLEFC2) shown in **Figure 6**.

Scenarios which discourage the construction of a styrene/PS plant:

1. PE price above US$1015/t.
2. Styrene price below US$880/t.

Scenarios which promote a larger PE plant:

1. Good PE price (above US$1015/t).
2. Below average styrene price.
3. Low ethylene oxide price, *i.e.*, below US$890/t (average used was US$1000/t).
4. Low VCM and PVC price (below US$520/t and US$850/t respectively).
5. Growing demand for PE (as is expected), and the existence of a local and regional market.

In light of the scenarios which encourage a larger PE plant and discourage a styrene plant, a 184 Mt/y PE plant was included in OLEFC2. The VCM and PVC plants were retained in this model because of the size of the market and its anticipated growth. The same optimal proplylene-based as OLEFC1 structure was used.

The profitability analysis revealed that PE surpassed PS in terms of NPV, for capacities greater than or equal to 300 Mt/y. PE plants are frequently built to such capacities. Therefore, OLEFC3 included this option. (See **Figure 7**). Additional ethylene was obtained from a decrease in EO capacity and the exclusion of the ethylbenzene plant. EO and EG maintain their high profitability for smaller capacities.

As another possible combination, OLEFC4 was developed which includes all ethylene-based resins (PE, VCM, PVC, VAM and PS), as shown in **Figure 8**. No ethylene oxide plant was built in this model. All the plants included in OLEFC1, OLEFC2, OLEFC3 and OLEFC4 are given in **Table 4**.

6. Optimum Network and Policy

6.1 *Multiobjective Analysis*

The values of the various attributes for each complex are shown in **Tables 5** to **7**. With respect to the objective function, NPV, OLEFC1 produced the greatest NPV followed by OLEFC2, OLEFC4 and OLEFC3. NPV fell within the range US$m1065 and 1201, so that all complexes may be considered to be lucrative portfolios. In terms of NPV per t/y of ethylene and taxes, the rank is the same as the rank according to NPV. The complex which maximises the use of capital invested was OLEFC2, followed by complexes OLEFC3, OLEFC1 and OLEFC4. As with the methane-based models, greater investment does not necessarily mean that greater benefits are accrued. However, OLEFC 1 which required the largest investment did yield the highest NPV, NPV per t/y of ethylene, employment and taxes. The rank for employment was similar to that of NPV, except that OLEFC4 moved above OLEFC2 due to the higher operating costs associated with PS production as opposed to ethylene oxide/ethylene glycol.

When equal weights were assigned to the attributes, OLEFC1 proved to be the best choice, followed by OLEFC2, OLEFC4 and OLEFC3 in that order. (See **Tables 8 to 10**). When resource utilisation (NPV per t/y of ethylene

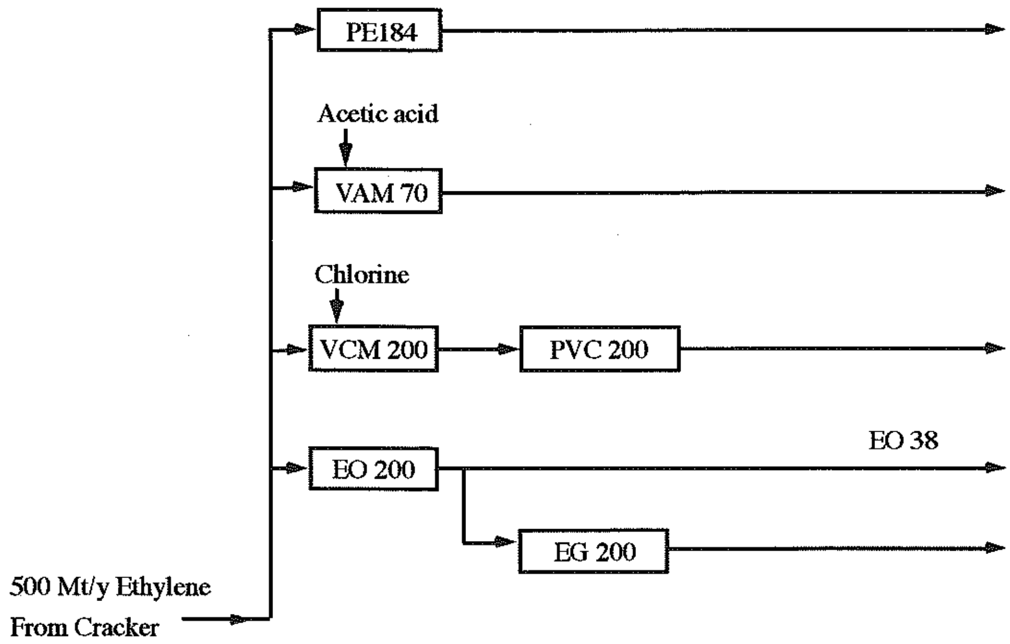
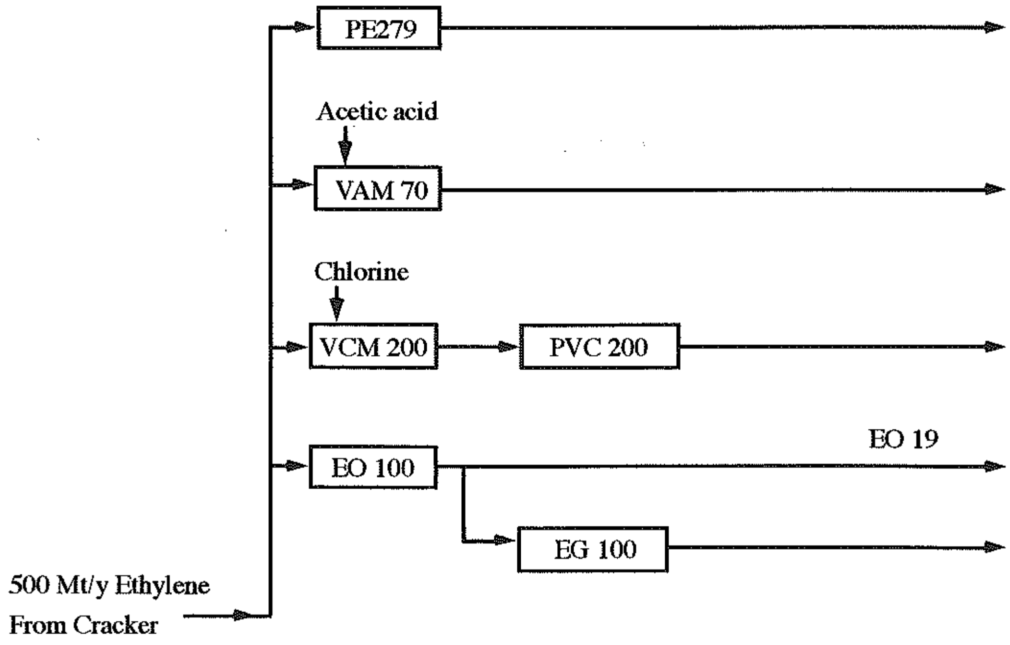


FIGURE 6: *Optimal Olefin-based Complex - OLEFC 2*



Note: All figures are in Mt/y

FIGURE 7: *Optimal Olefin-based Complex - OLEFC 3*

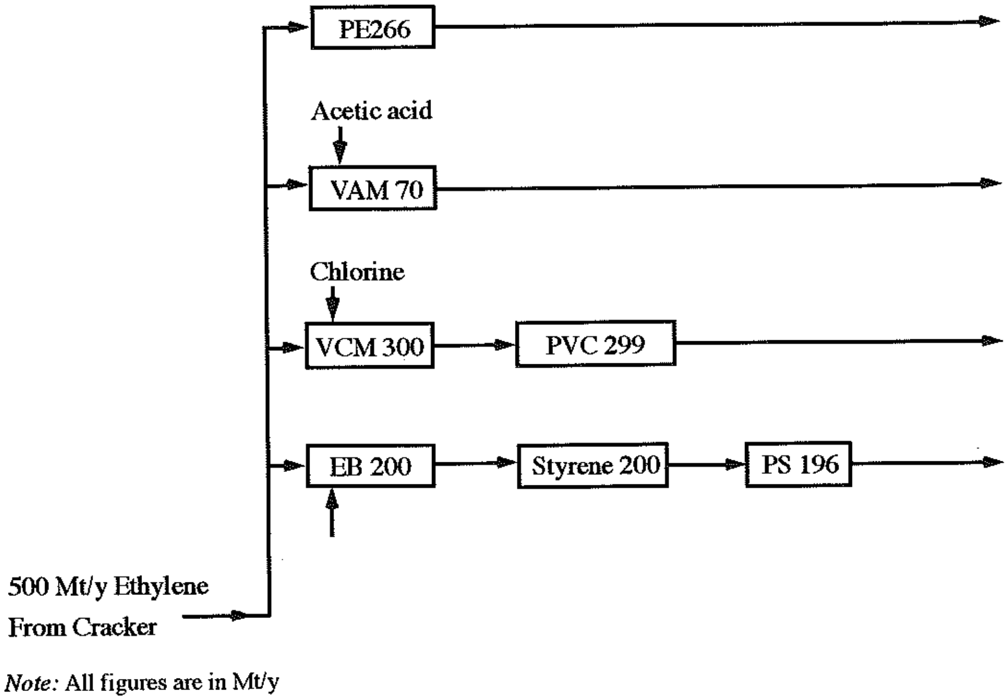


FIGURE 8: *Optimal Olefin-based Complex - OLEFC 4*

and NPV per investment) were rated highly, this rank remained unchanged. When employment and labour were given high preference, OLEFC4 proved to be superior to OLEFC2. In general, the rank remained stable regardless of the trade-off among the different objectives.

To summarise:

1. OLEFC1 produced the highest NPV.
2. OLEFC1 proved to be superior to the other petrochemical complexes based on the multiobjective analysis.
3. All optimal models used the ethylene plant which maximises the production of propylene.
4. All optimal models selected the policy of immediate downstream production while producing a blend of basic, intermediate and consumer petrochemicals, (*i.e.*, Policy 2 as defined in Section 2.3, Part I.

6.2 Effect of Uncertainty

The "probability" curve (shown in **Figure 9**) followed the same trend as the one generated for the methane-based complexes. Complexes OLEFC1, OLEFC2 and OLEFC3 are entirely enclosed by complex OLEFC4 for probabilities greater than 75%, and the mean NPV of complex OLEFC4 is lower than that of complexes OLEFC1 and OLEFC2. On this basis, complex OLEFC4 is inferior to complexes OLEFC1 and OLEFC2.

Relationships 1 and 2 were obtained from **Table 11** and **Figure 9**:

$$\mu_3 < \mu_4 < \mu_2 < \mu_1 \qquad (1)$$

$$\sigma_4 > \sigma_1 > \sigma_2 > \sigma_3 \qquad (2)$$

Since,

$$\sigma_4 > \sigma_1 > \sigma_2 \qquad (3)$$

and,

$$\mu_4 < \mu_2 < \mu_1 \qquad (4)$$

complex OLEFC4 is inferior to complexes OLEFC1 and OLEFC2, which supports the previous findings.

TABLE 4: *Structure of Various Olefin Complexes*

Petrochemical	OLEFC1 Capacity, Mt/y	OLEFC2 Capacity, Mt/y	OLEFC3 Capacity, Mt/y	OLEFC4 Capacity, Mt/y
EthylCrac	500	500	500	500
PE	150	184	279	266
EB	230	0	0	230
STYRENE	200	0	0	200
PS	196	0	0	196
VCM	200	200	200	300
PVC	199	199	199	299
VAM	0	70	70	70
EO	200	200	100	0
EG	200	200	100	0
ACN	0	0	0	0
ABSR	0	0	0	0
PP	0	0	0	0
ISOPAL	0	0	0	0
PHENAC	80	80	80	80
BIS	44	44	44	44
PC	40	40	40	40
EPOXYR	10	10	10	10
PO	48	48	48	48
PG	40	40	40	40

* EthylCrac represents the ethylene cracker which uses 54% ethane in the feed.

TABLE 5: *Summary of Results for Various Olefin-based Complexes*

Complex	NPV US$m	Investment US$m	Labour US$m	Tax US$m	NPV (US$) t/y Ethylene	NPV / Investment
OLEFC 1	1201	1400	966	1175	2402	0.86
OLEFC 2	1175	1237	724	1100	2350	0.95
OLEFC 3	1056	1200	660	1021	2111	0.88
OLEFC 4	1065	1327	911	1074	2130	0.80

TABLE 6: *Rank of Models for Equal Atribute Preferences*

NPV	NPV (US$) / t/y Ethylene	NPV / Investment	Employment Indicator	Tax	Sum of Weights
OLEFC1	OLEFC1	OLEFC2	OLEFC1	OLEFC1	OLEFC1
OLEFC2	OLEFC2	OLEFC3	OLEFC4	OLEFC2	OLEFC2
OLEFC4	OLEFC4	OLEFC1	OLEFC2	OLEFC4	OLEFC4
OLEFC3	OLEFC3	OLEFC4	OLEFC3	OLEFC3	OLEFC3

TABLE 7: *Weight Assignments of Olefin-based Models*

Complex	NPV	NPV (US$) / t/y Ethylene	NPV / Investment	Employment Indicator	Tax	Sum of Weights / 5
OLEFC1	1.00	1.00	0.90	1.00	1.00	4.90
OLEFC2	0.98	0.98	1.00	0.75	0.94	4.64
OLEFC3	0.88	0.88	0.93	0.68	0.87	4.24
OLEFC4	0.89	0.89	0.84	0.94	0.91	4.48

TABLE 8: *Attribute Preference Factors (k values)*

Attribute	Set #1	Set #2	Set #3	Set #4	Set #5
NPV	0.20	0.10	0.10	0.10	0.10
NPV / t/y of ethylene	0.20	0.25	0.30	0.20	0.15
NPV / Investment	0.20	0.25	0.30	0.20	0.15
Employment	0.20	0.20	0.15	0.25	0.30
Taxes	0.20	0.20	0.15	0.25	0.30

TABLE 9: *Sum of Weights for each Set of Attribute Preference Factors*

Complex	Set #1	Set #2	Set #3	Set #4	Set #5
OLEFC1	0.981	0.976	0.971	0.981	0.985
OLEFC2	0.928	0.930	0.944	0.915	0.900
OLEFC3	0.847	0.850	0.862	0.837	0.824
OLEFC4	0.895	0.893	0.887	0.899	0.906

TABLE 10: *Rank of Complexes for each Set of Preference Factors*

Rank #	Set #1	Set #2	Set #3	Set #4	Set #5
1	OLEFC1	OLEFC1	OLEFC1	OLEFC1	OLEFC1
2	OLEFC2	OLEFC2	OLEFC2	OLEFC2	OLEFC4
3	OLEFC4	OLEFC4	OLEFC4	OLEFC4	OLEFC2
4	OLEFC3	OLEFC3	OLEFC3	OLEFC3	OLEFC3

TABLE 11: *Results of Statistical Analysis for Various Olefin Complexes*

Model	Investment US$m	Mean NPV US$m	Standard Deviation US$m	68% Confidence Interval		95% Confidence Interval		Coefficient of Variation
				Upper	Lower	Upper	Lower	
OLEFC 1	1400	1200.9	555.2	1756.2	645.7	2311.4	90.5	2.163
OLEFC 2	1237	1175.2	545.2	1720.4	630.0	2265.6	84.8	2.156
OLEFC 3	1200	1055.7	527.0	1582.6	528.7	2109.6	1.7	2.003
OLEFC 4	1327	1065.0	674.5	1739.6	390.5	2414.1	-284.0	1.579

Complex OLEFC3 has the lowest standard deviation (least risky) and the lowest mean NPV (lowest returns), which implies that it cannot be determined, based on this criteria, whether it is more desirable than other complexes. Only if the decision-maker(s) is risk averse, will he select complex OLEFC3. Conversely, if he has a liking for risk, he will choose complex OLEFC1, since it yields the highest returns, even though it incorporates the second highest risk.

If the decision-maker is not extremist, i.e., he neither has a great liking for risk nor is he risk averse, then he must turn to some other criterion. In the plot of NPV versus standard deviation, a hypothetical security market line (SML) may be drawn, based simply on the best straight line through the points. (See **Figure 10**). On this basis, it is still very difficult to distinguish between complexes OLEFC1, OLEFC2 and OLEFC3. However, it is clear that complex OLEFC4 is not only inferior to complexes OLEFC1 and OLEFC2 (as determined earlier) but also to complex OLEFC3, since it lies furthest away from the SML in the high risk/reject region.

If the coefficient of variation is examined, one can distinguish between complexes OLEFC1, OLEFC2 and OLEFC3. (See **Table 12**). Complex OLEFC1 produced the highest return to risk ratio followed by complexes OLEFC2, OLEFC3 and OLEFC4. Therefore, the rank shown in **Table 13** is that of the cautious (non-extremist) decision-maker.

The rank for the multiobjective analysis was, in fact, similar to that obtained in the uncertainty analysis, which again emphasises the superiority of OLEFC1.

7. Conclusions

(1) By the year 2000, the level of natural gas production will be about 1500 MMscfd. A 500,000 t/y ethylene cracker will be possible, based on ethane and propane extraction from natural gas.

TABLE 12: *Rank of Olefin Complexes for Various Statistical Measures*

Rank	Mean NPV	Standard Deviation	Coefficient of Variation
1	OLEFC1	OLEFC4	OLEFC1
2	OLEFC2	OLEFC1	OLEFC2
3	OLEFC4	OLEFC2	OLEFC3
4	OLEFC3	OLEFC3	OLEFC3

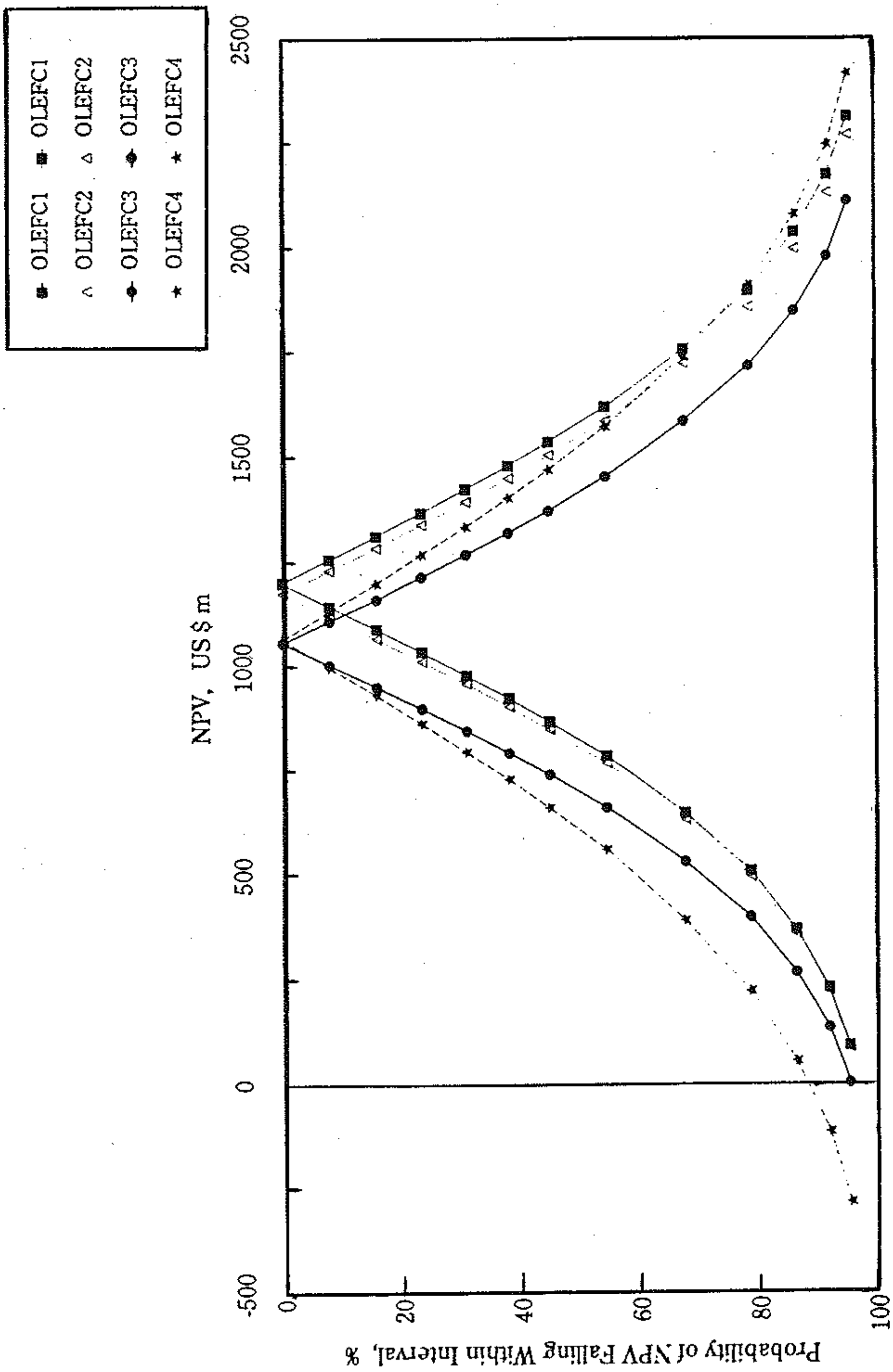


FIGURE 9: *Variation of Confidence Interval with Probability for Olefin Complexes*

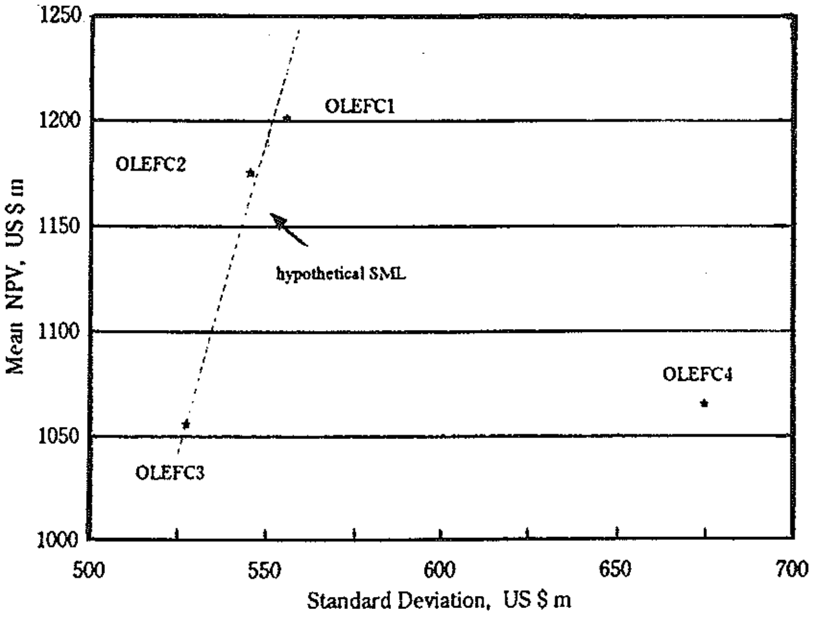


FIGURE 10: *Plot of Mean vs. Standard Deviation of NPV for Olefin Complexes*

(2) An ethylene cracker which maximises the production of propylene should be selected. However, the propylene thus produced is insufficient to justify a PP plant or an acrylonitrile plant (unless accompanied by downstream plants). A phenol/acetone plant which has numerous downstream possibilities is highly recommended. Propylene oxide/glycol is also recommended for propylene consumption.

(3) The optimal policy involves the construction of an olefin-based complex that produces immediately a blend of basic, intermediate and end-products.

TABLE 13: *Overall Rank of the Olefin Complexes*

	Based on	
Rank	Uncertainty Analysis	Multiobjective Analysis
1	OLEFC 1	OLEFC 1
2	OLEFC 2	OLEFC 2
3	OLEFC 3	OLEFC 4
4	OLEFC 4	OLEFC 3

(4) The multiobjective analysis revealed that the optimal olefin complex should include the following ethylene-based plants:
PE, ethylbenzene, styrene, PS, VCM, PVC, EO and EG;

and the following propylene-based plants: Phenol/acetone, bisphenol, polycarbonate, epoxy resin, propylene oxide and propylene glycol.

This structure also produced the greatest returns to risk ratio when compared to the other structures examined.

(5) If a local acetic acid plant becomes a reality, then efforts should be made to build a vinyl acetate plant provided plans for an olefin cracker materialises.

8. Limitations of Study and Future Work

The market, cost and technological data on which this study was based has a significant impact on the results obtained and on the conclusions drawn. The accuracy of the data depends on its source and on the estimation techniques employed. The data sources and techniques used here is considered to be suitable for planning of this magnitude and stage of development. For subsequent work however, certain measures should be taken to improve on the accuracy of the data.

Planning on such a large scale is multi-faceted, *i.e.*, there are many considerations which are pertinent to the expansion of the local petrochemical industry. It is difficult to quantify, and hence take into account each aspect in a mathematical programming approach. Environmental, land and labour considerations have not been rigorously treated. In order to address these limitations, the following recommendations for future work are suggested.

(1) A more comprehensive market survey should be done utilising more sophisticated forecasting techniques. In this way, one may take better advantage of the multiperiodic/dynamic model as presented in this study.

(2) In order to reduce uncertainty in the data, more reliable sources, as well as more detailed capital and operating cost estimation techniques should be used. Also, the technology to be used for the production of petrochemicals should also be a decision variable. In this study, the consumption of natural gas was measured as the amount used as feedstock; however, the quantity consumed as fuel by the petrochemical plants should also be taken into account.

(3) At a subsequent stage of planning, it is recommended that an environmental impact assessment be performed in order to ensure that integrity of the environment is maintained and that development is environmentally sustainable.

(4) A detailed assessment is required for the allocation of land for expansion of the petrochemical industry. This could be a critical factor since a number of important factors are involved in site selection, for instance, existence of deep-water harbours with adequate port facilities, proximity to villages, overcrowding in the estates and emergency considerations.

(5) A more in-depth study should use a better employment indicator than was used here. For example, an estimate of the number of employees in various fields (administrative, plant operation, services, maintenance, and so on) could be useful in assessing the supply and demand balance of labour.

(6) The entire long-term planning process should be repeated periodically when better estimates of future data are available, so that changes may be made to the previous optimal solution and a new long-term structure and strategy for development identified. Other management tools may be used to explore more fully each structure, *e.g.*, what-if scenarios and decision tree analyses.

(7) The multiperiodic MILP model, the technique for handling the multiobjective nature of planning and the methods for measuring the effect of uncertainty in the data as presented in this study may be applied to:

(a) The entire industrial sector in Trinidad and Tobago, including non-petrochemical users, namely the iron and steel industry, commercial and light manufacturing industry and other small consumers, to determine the optimal structure of the entire natural gas industry.

(b) The oil refinery to determine optimal product blend and capacity expansions.

(c) The entire energy sector (to determine the optimum utilisation of natural gas) including:

- ✓ Electricity generation (use of natural gas as a fuel)
- ✓ Industrial (use of natural gas as a fuel and a feedstock)
- ✓ Transportation (use of natural gas as a transport fuel, *i.e.*, compressed natural gas)
- ✓ Residential (use of natural gas as a fuel, *i.e.*, liquified petroleum gas)
- ✓ Commercial (use of natural gas as a fuel)

Nomenclature

Abbreviations

ABSR	acrylonitrile-butadiene-styrene
ACN	acrylonitrile
Bisph/Bis	bisphenol-A
DOMS	degrees of model stability
EB	ethylbenzene
EG	ethylene glycol
EO	ethylene oxide
Isopal	isopropyl alcohol
MMscfd	million standard cubic feet per day
NPV	net present value (US$m)
OLEFC1	Olefin Complex 1
OLEFC2	Olefin Complex 2
OLEFC3	Olefin Complex 3
OLEFC4	Olefin Complex 4
PC	polycarbonate
PE	polyethylene
PG	propylene glycol
PhenAc	phenol/acetone
PO	propylene oxide
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride
SML	security market line
Sty	styrene
tscf	trillion standard cubic feet
t/y	tonnes per year
VAM	vinyl acetate monomer
VCM	vinyl chloride monomer

Greek Letters

μ	mean/expected value (US$m)
σ	standard deviation (US$m)

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