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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With increasing natural gas production, sufficient quantity of natural gas liquids for an ethylene plant and subsequent olefin complex will be available. In this paper, the problem of selecting an optimal initial structure and policy for development of an olefin-based complex is addressed. The mathematical model used was formulated to capture the dynamic nature of the petrochemical market. The length of the planning time horizon is 17 years, during which economic parameters were allowed to vary. Uncertainty in the estimation of these parameters was taken into account. A multiobjective analysis was performed in order to address the objectives of the various interest groups involved.

It was found that the optimal policy for an olefin-based complex involves the immediate production 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 petrochemical industry, there are no existing major olefin-based plants in Trinidad and Tobago. However, with plans for increased local natural gas production, the feasibility of an olefin-based complex would no longer be constrained by the availability of sufficient natural gas liquids. It is therefore important at this stage to devise an initial structure for that complex which would ensure optimal use of resources.

For long-term viability of the olefin-based complex, a *multiperiodic* model is developed, 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 which plays an important role in planning of this nature.

A *multiobjective* analysis is performed in order to address the goals of the various interest groups involved, such as investors, government and populace.

Various tools are employed to measure the effects of uncertainty in the economic parameters (*e.g.*, sale prices).

In this paper, the same theory as that outlined in Part I (Furlonge and Young Hoon, 2000) is applied to the problem of finding an optimal initial structure and policy for the development of an olefin-based complex (outlined in Section 2). In this case, however, a rigorous sensitivity analysis on a market-based petrochemical model is performed, as described in Section 3. The break-even plant capacities are given in Section 4, and the optimum olefin-based market model is discussed in Section 5. Multiobjective and uncertainty analyses of various complexes (derived from the market-based model) are given in Section 6. Concluding remarks are made in Section 7. Finally, limitations of the study and recommendations for possible future work, including application of the methodology to other planning problems, are outlined in Section 8.

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* This is the correct version.

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2. General Olefin-based Petrochemical Complex

A wide range of petrochemicals are considered for inclusion into the olefin-based complex. The ethylene-based petrochemicals considered are polyethylene (PE); ethylbenzene (EB); styrene; polystyene (PS); vinyl chloride (VCM); polyvinylchloride (PVC); vinyl chloride monomer (VAM); ethylene oxide (EO); and ethylene glycol (EG). The list of propylene-based petrochemicals includes acrylonitrile (ACN); acrylonitrile-butadiene-styrene (ABSR); polypropylene (PP); isopropyl alcohol (Isopal); phenol and acetone (PhenAc); bisphenol-A; polycarbonate (PC); epoxy resin (EpoxyR); propylene oxide (PO); and propylene glycol (PG).

As with the study of the methane-based complex (*cf.* Part I), the optimum solution based solely on market restrictions (*i.e.*, market-based olefin complex) is determined. From this case, other complexes are derived.

The planning time horizon (of total length 17 years) for the olefin-based complex 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.

Domestic natural gas consumption in 1999 (*i.e.*, the start of the planning time horizon) is taken to be 953 MMscfd. Together with gas utilised in the local liquified natural gas plant, the total quantity of natural gas available for liquid extraction is currently about 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 plant, which affects the product mix and the plant viability, this was treated as a decision variable which was optimised.

3. Methodology

The mathematical model for the olefin-based petrochemical complex comprises constraints on capacity expansion, supply of raw materials and demand for products, as well as yield and material balances. The general form of these constraints is given in Part I, Section 2.1 (Furlonge and Young Hoon, 2000).

The techniques used for handling multiobjectivity and uncertainty were the same as those used in the methane-based complex (*cf.* Sections 2.2 and 2.3 respectively, Part I).

The objective function used in the optimisation was the sum of the net present value (NPV) of all the plants in the complex. Other objectives, which include NPV per investment, NPV per t/y of ethylene, taxes and employment, were brought into the analysis at the post-optimisation stage. Objective preference factors were assigned to each objective to denote its relative importance, and these were varied in the multiobjective analysis.

With respect to the uncertainty analysis, the selling prices, raw material costs, capital costs and operating costs were assumed to follow normal distributions (*cf.* Section 2.3.1, Part I). The mean and standard deviation of NPV were thus calculated, and used to rate different portfolios. The coefficient of variation (mean divided by standard deviation of NPV) and the security market line (plot of mean versus standard deviation of NPV) were used to compare the degree of uncertainty associated with each complex (*cf.* Section 2.3.2, Part I). In addition to these tools, a sensitivity analysis was also performed in this paper, as described in the next section.

3.1 Degree of Model Stability

A sensitivity analysis was performed on the olefin-based market model. Various Degrees of Model Stability (DOMS) were defined in order to assist in the evaluation 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 was not performed with the methane-based models since these were fairly fixed (based on the various policies for development), and due to their larger size and the level of interaction between the plants. It should be noted that the base case olefin complex, OLEFC 1, was not fixed.

The following conditions arose in performing the sensitivity analysis:

Condition 1 -	The optimum complex remains unchanged in terms of plant capacities/ production/sales of all petrochemicals for each period.
Condition 2 -	The NPV does not change.
Condition 3 -	The NPV changes.
Condition 4 -	The optimum complex changes in terms of plant capacities/production/sales of petrochemicals.

Based on the different combinations of these conditions which may arise, the following DOMS are possible:

DOMS 1 -	*Conditions 1* and *2 exist, e.g.*, due to small changes in the selling price of a petrochemical that is *not* part of the base case optimum complex.
DOMS II -	*Conditions 1* and *3 exist, e.g.*, due to small changes in the selling price of a petrochemical which *is* part of the base case optimum complex.

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

4. Break-even Plant Capacities

The basis for the profitability analyses (*e.g.*, cost of capital) is given in Section 3, Part I. The break-even plant capacities were determined from plots of NPV versus plant capacity. 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.

The break-even capacities (Mt/y) for the propylene-based petrochemical plants 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. Optimum Olefin-based Market Model

As in Part I, the olefin-based market model was first considered. It involved placing demand constraints (obtained from a market survey - given in Furlonge, 1998) in the optimisation. The results of the optimisation (shown in **Figure 1**) recommended the cracker which utilises the minimum ethane feed composition, and hence produces the maximum quantity of propylene. Clearly, the higher capital and operating costs associated with this option was offset by the profitability of the downstream products. Thus, even though the profitability of the ethylene cracker by itself is not at a maximum, the overall profitability of the entire complex *is* at a maximum.

The ethylene produced was partially consumed by an EB plant, a VCM plant and an EO plant. This left 152.6 Mt/yd of excess ethylene in period 1. It should be noted that no PE was built despite this available ethylene. Hence, it is more profitable to sell the excess ethylene than to build a 152.6 Mt/y PE plant which is close to the break-even capacity. In the second period, the excess ethylene is consumed by a second EO plant. However, for market reasons, it probably would have been better to build a different petrochemical plant.

A phenol/acetone plant built 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 worthwhile to note that no PP plant was built since the total amount of propylene available (83 Mt/y) is insufficient for a profitable P plant which has a break-even capacity of 95 Mt/y.

As with the methane-based market model, the olefin-based market model is an infeasible solution. However, it gave useful insights which were used to develop another complex - OLECF 1, as shown in **Figure 2**. 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 as part of OLEFC 1. In this case, no expansions occurred in period 2 since all the available ethylene and propylene were consumed in period 1.

Other olefin complexes (OLEFC 2, OLEFC 3 and OLECF 4) were developed based on a rigorous sensitivity analysis as described in the next section.

5.1 Sensitivity Analysis

Given the nature of petrochemical market forces, selling price is considered to contain the greatest uncertainty and is more unpredictable than capital and operating costs. Thus, the degree of model stability (as defined in Section 3.1) of OLEFC 1 with respect to the selling price of each petrochemical was evaluated. The results, shown in **Tables 1** and **2**, are discussed in Sections 5.1.1 to 5.1.6.

5.1.1 Olefin Cracker

It was found 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).

5.1.2 Ethylene Oxide and Ethylene Glycol

Ethylene oxide and ethylene glycol were found to be the most stable plants (see **Table 1**). 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 of 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).

5.1.3 Other Ethylene-based Plants

Of the ethylene-based products, polyethylene was the third most stable with respect to uncertainty in its selling price. (See **Table 1**). Even if its selling price averaged as low as US$846/t (which has a probability of occurring (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

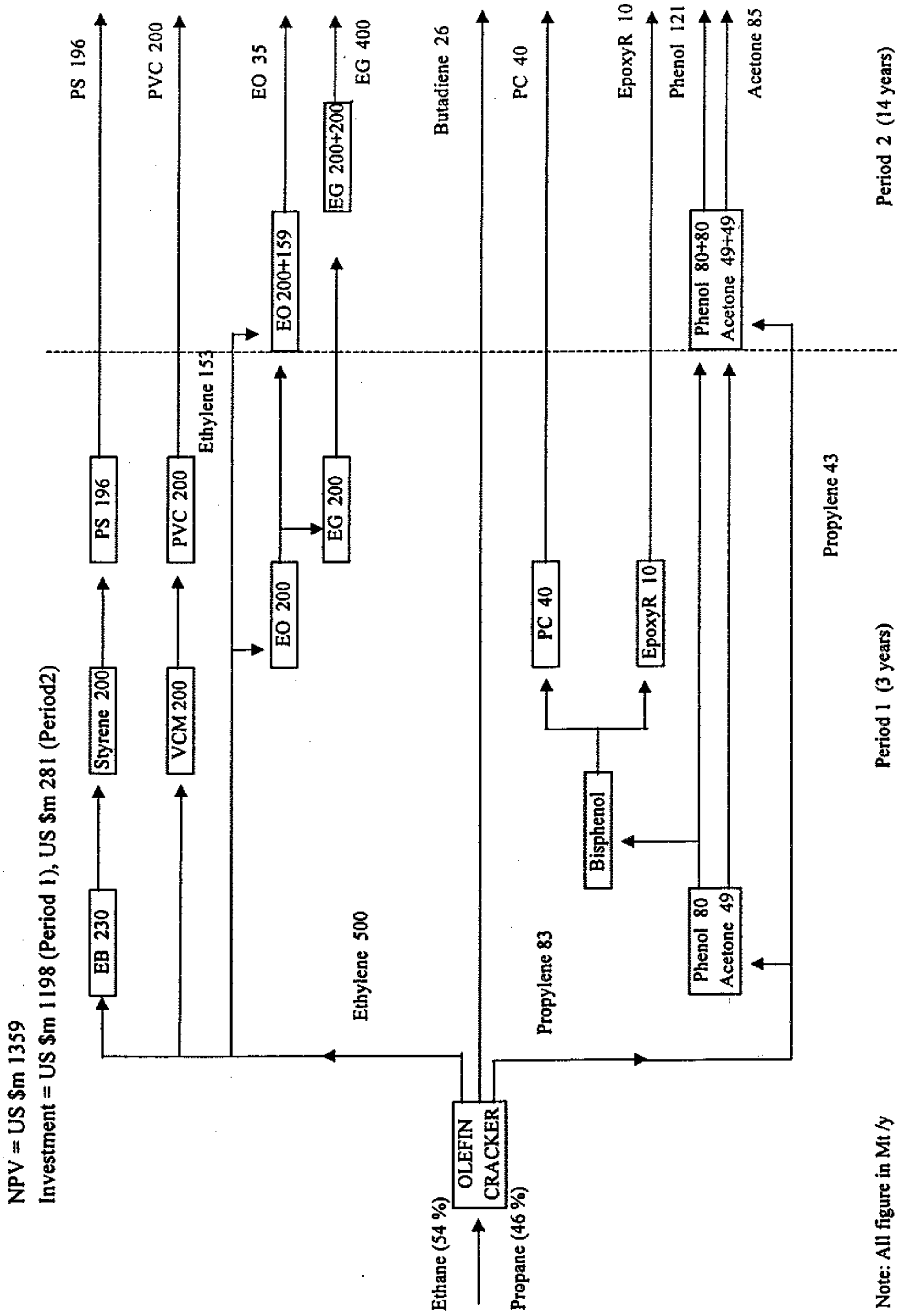

FIGURE 1: *Olefin-based Market Model*
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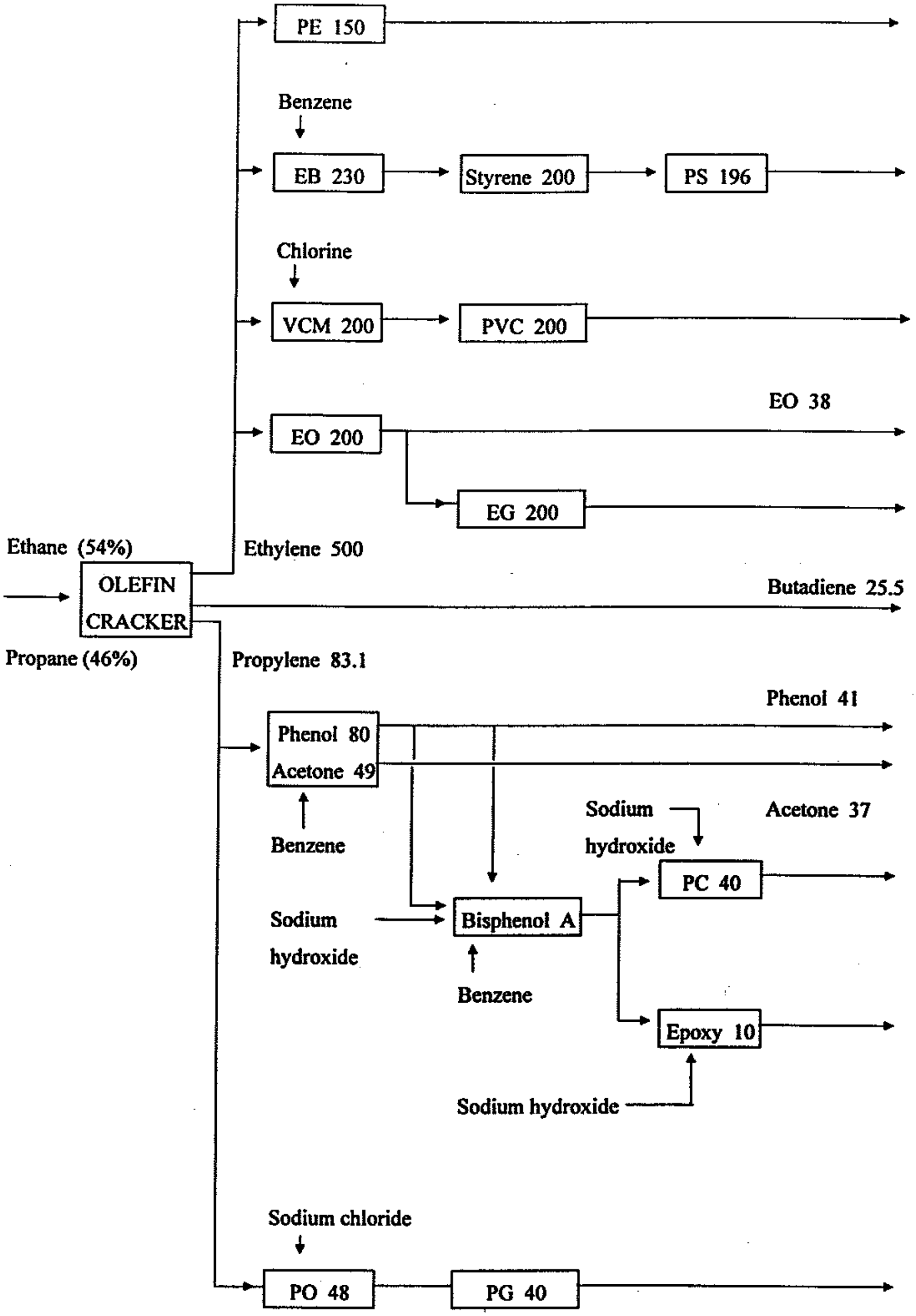


Note: All figures are in Mt/y

FIGURE 2: *Optimal Olefin-based Complex - OLEFC1*

TABLE 1: *Degree of Model Stability for OLEFC 1 with respect to Selling Price*

Selling Price	DOMS	Cause	Effect on Complex
PE	II	800 < SP (PE) < 1015	None
	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
VCM, PVC	II	SP (VCM) > 523 and SP (PVC) > 855	None
	III	SP (VCM) < 523 and SP (PVC) < 855	Q (VCM) decrease to 90.6 Q (PVC) decrease to 0 Q (PE) increase to 200
		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
EB, Styrene, PS	II	SP (PS) > 1238	None
	III	SP (PS) < 1238	Q (PS) decrease to 0
	II	SP (EB) > 515 SP (Styrene) > 882	None
	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
EO, EG	II	SP (EG) > 1157	None
	III	SP (EG) < 1157	Q (EG) decrease to 0
	II	SP (EO) > 890	None
	III	SP (EO) < 890	Q (EO) decrease to 162 Q (PE) increase to 185.36
PO, PG	II	SP (PG) > 1261	None
	III	SP (PG) < 1261	Q (PG) decrease to 0
	II	SP (PO) > 1080	None
	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

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, which 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 proved to be 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 plant capacity should be decreased to 35.5 Mt/y (which would not be viable and should therefore be omitted). Furthermore, no PVC plants should be built. The ethylene should be channeled to a 70 Mt/y VAM plant and a 200 Mt/y PE plant.

TABLE 2: *Degree of Model Stability for OLEFC 1 with respect to Selling Price*

Selling Price	DOMS	Cause	Effect on Complex
Phenol,	II	SP (PC) > 3510	None
Acetone,	III	SP (PC) < 3510	Q (PC) decrease to 0
PC,	II	SP (Epoxy resin) > 2700	None
Epoxy Resin	II	SP (Phenol) > 628 SP (Acetone) > 608	None
	III	SP (Phenol) < 628 SP (Acetone) < 608	Q (PhenAc) decrease to 39.16 Q (PO) increase to 71.8
VAM	I	SP (VAM) < 988 (104%)	None
	III	SP (VAM) > 988	Q (VAM) increase to 50 Mt/y Q (PE) decrease to 131.46
Ethylene, Propylene	I	SP of ethylene and propylene between optimistic and pessimistic values	None
Isopropyl	I	SP Isopropyl alcohol at optimistic value	None
Alcohol	I	SP (ACN) < 1239	None
ACN, ABSR	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	None
	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	None
PP	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

5.1.4 Epoxy Resin, Polycarbonate, Phenol and Acetone

Epoxy resin followed by polycarbonate were the two most stable propylene derivatives. Even if their pessimistic prices are realised, they still formed part of the optimal structure. If the selling price of phenol and acetone fell below 81% of their mean values (probability of 5% and 20% in periods 1 and 2 respectively for phenol, and 0.2% and 7.8% in periods 1 and 2 respectively for acetone) then a 39 Mt/y phenol/acetone plant is recommended instead of the 80 Mt/y plant. This would feed directly to the polycarbonate and epoxy resin plants, thus leaving no excess phenol.

5.1.5 Propylene Oxide and Propylene Glycol

A propylene glycol plant is suggested as long as its selling price averages above US$1261/t (probability of 60% in period 1 and 55% in period 2). An isopropyl alcohol plant entered 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 PO and PG plants should be built.

5.1.6 Acrylonitrile and ABSR

If the selling price of ABSR averages above US$1663/t (probability of 6% in period 1 and 21% in period 2), no PO and PG plants should be constructed. Instead, a 30Mt/y ACN plant should be built to feed a 50 Mt/y ABSR plant. A slightly smaller PS plant (186 Mt/y as opposed to 196 Mt/y) should be built 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 since the combined ACN and ABSR plants are profitable. This further exemplifies the fact that local losses are sometimes necessary for overall profitability.

Because of the limited availability of propylene (maximum of 83 Mt/y), neither an economically sized acrylonitrile plant (without associated 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 derivatives, places it in a strong position to be part of the optimal structure.

5.2 Formulation of other Complexes

In this section, the results of the sensitivity analysis discussed in the previous section, are summarised. Alternative feasible complexes are also devised.

Scenarios which promote the construction of a VAM plant include (*cf.* Section 5.1.3):

1. Below average (US$900/t) styrene price.
2. Weak PE price, *i.e*, below US$845/t (average used was US$900/t).
3. High VAM price, *i.e.*, above US$970/t (average used was US$950/t).
4. A local acetic acid plant which was shown in Part I to have a high profitability.

The above scenarios are not far from the base case; hence, it would be worthwhile to include a VAM plant in an alternative olefin complex (OLEFC 2), as shown in **Figure 3**.

Scenarios which discourage the construction of a styrene/PS plant (*cf* Section 5.1.3):

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

Scenarios which encourage a larger PE plant (*cf.* Sections 5.1.2 and 5.1.3):

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. High demand growth rates for PE (which is expected), and the existence of significant local and regional markets.

In light of the scenarios which encourage a larger PE plant and discourage a styrene/PS plant, a 184 Mt/y PE plant was included in OLEFC 2. The VCM and PVC plants were retained in this complex because of the size of teh market and its anticipated growth. The same optimal propylene-based plants as those in the OLEFC 1 structure were selected.

The profitability analysis revealed that PE surpassed PS in terms of NPV, for capacities greater than or equal to 300 Mt/y. Since PE plants are frequently built to such capacities, OLEFC 3 included a larger PE plant instead of a PS plant. (See **Figure 4**). Additional ethylene was obtained from a decrease in EO capacity and the exclusion of the EB plant. It should be noted that EO and EG maintain high profitabilities for smaller capacities (*cf.* Section 4).

As another possible combination, OLEFC 4 was developed which includes all ethylene-based resins (*i.e.*, PE, VCM, PVC, VAM and PS), as shown in **Figure 5**. No EO plant was built in this petrochemical model.

All the plants comprising complexes OLEFC 1, OLEFC 2, OLEFC 3 and OLEFC 4 are listed in **Table 3**.

6. Optimum Olefin-based Complex

In this section, multiobjectivity and uncertainty analyses of the various olefin-based complexes are performed (*cf.* Sections 6.1 and 6.2 respectively).

6.1 Multiobjective Analysis

The values of the various objectives (*e.g.*, NPV and NPV/investment) for each complex are shown in **Table 4**. With respect to the objective function used in the optimisation (*i.e.*, NPV), OLEFC 1 produced the greatest NPV followed by OLEFC 2, OLEFC 4 and OLEFC 3. NPV fell within the range US$m1065 and 1201; hence, 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 that according to NPV. (See **Table 5**).

Complex OLEFC 1, followed by OLEFC 4, OLEFC 2 and OLEFC 3 involved the greatest investment. In contrast, the complex which maximises the use of capital invested (*i.e.*, highest NPV/investment) was OLEFC 2, followed by complexes OLEFC 3, OLEFC 1 and OLEFC 4. Thus, as with the methane-based models, greater investment does not necessarily result in greater benefits. However, OLEFC 1 which required the largest investment did yield the highes NPV, NPV per t/y of ethylene, employment and taxes.

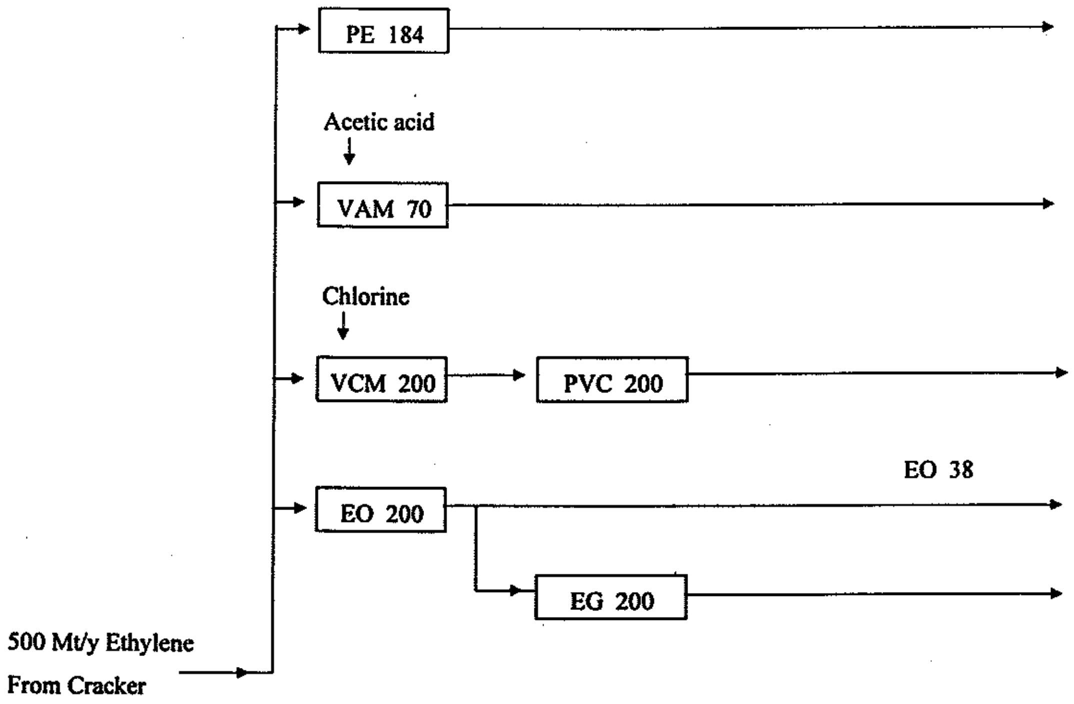
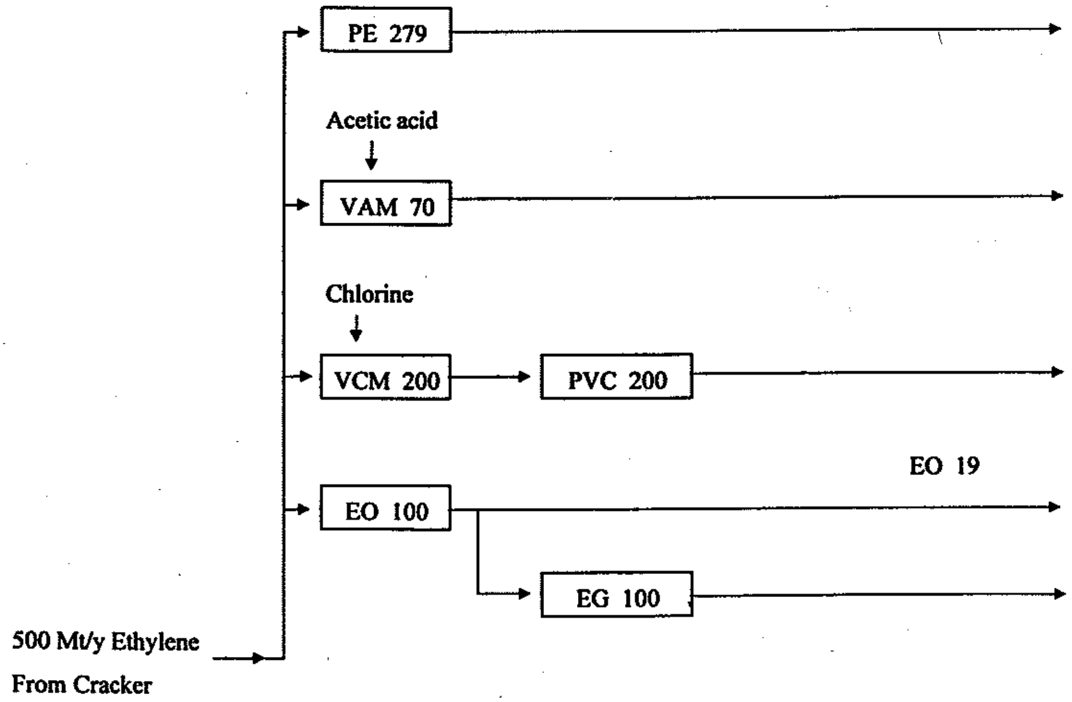


FIGURE 3: *Optimal Olefin-based Complex - OLEFC2*



Note : All figures in Mt/y

FIGURE 4: *Optimal Olefin-based Complex - OLEFC3*

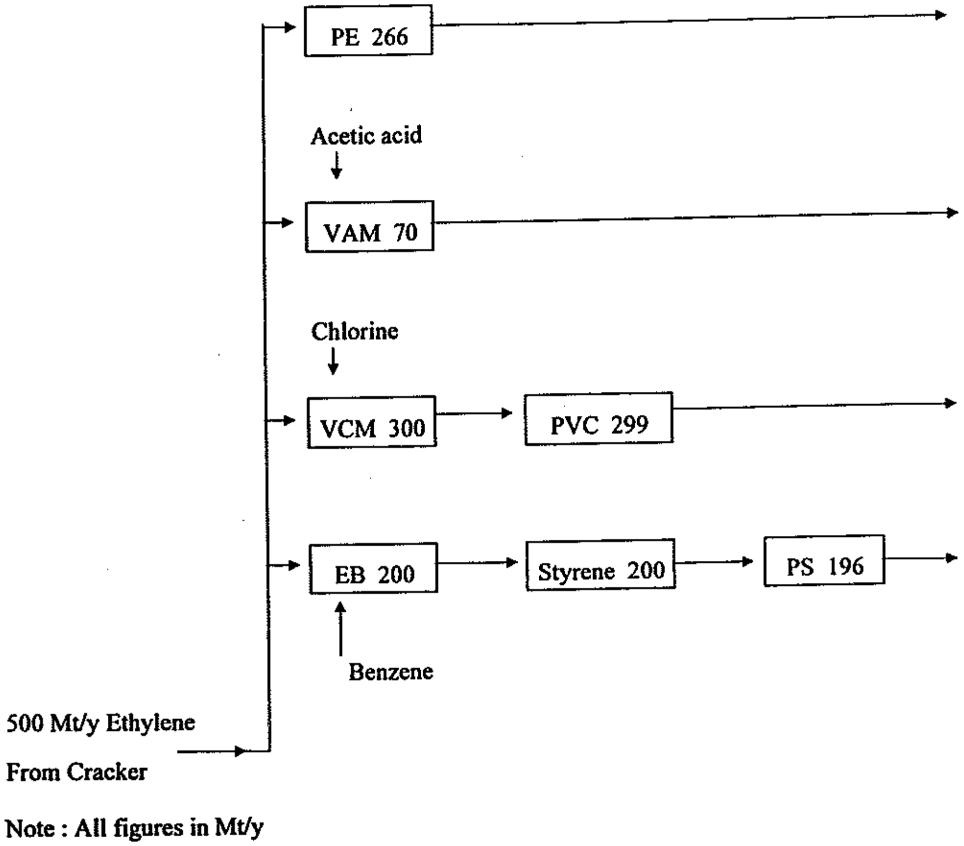


FIGURE 5: *Optimal Olefin-based Complex - OLEFC4*

The rank for employment was similar to that for NPV, except that OLEFC 4 moved above OLEFC 2 due to the higher operating costs associated with PS production as opposed to EO/EG production.

When equal weights were assigned to each objective (*i.e.*, Set #1), OLEFC 1 proved to be the best choice, followed by OLEFC 2, OLEFC 4 and OLEFC 3. See **Tables 6** and **7**. When resource utilisation (*i.e.*, NPV per t/y of ethylene and NPV per investment) were rated highly (*i.e.*, Sets #2 and 3), this rank remained unchanged. When employment and taxes were given high preference (*i.e.*, Sets #4 and 5), OLEFC 4 proved to be superior to OLEFC 2. In general, the rank remained stable regardless of the trade-off among the different objectives.

To summarise:

1. OLEFC 1 produced the highest NPV.
2. OLEFC 1 proved to be superior to the other petrochemical complexes based on the multiobjective analysis.
3. All of the optimal complexes used the ethylene plant which maximises the production of propylene.
4. All of the optimal complexes selected the policy of producing a blend of basic (*e.g.*, phenol), intermediate (*e.g.*, styrene) and consumer petrochemicals (*e.g.*, polycarbonate), *i.e.*, Policy 2 as defined in Section 4.2, Part I.

6.2 Effect of Uncertainty

The results of the statistical analysis for the various complexes are summarised in **Table 8**. As can be seen, the NPV range at high probabilities of occurrence is positive for all complexes except OLEFC 4. Furthermore, there is a chance that OLEFC 4 will yield the highest NPV, however, there is also a similar chance that it can yield the lowest NPV. Thus, the investment in OLEFC 4 is considered to be more risky than that in the other complexes.

The following relationships between the mean and standard deviation of NPV for the various complexes may be obtained from **Table 8**:

$$\mu_3 < \mu_4 < \mu_2 < \mu_1 \quad \text{.......................................} \quad (1)$$

$$\sigma_4 > \sigma_1 > \sigma_2 > \sigma_3 \quad \text{.......................................} \quad (2)$$

TABLE 3: *Structure of Various Olefin Complexes*

Petrochemical	OLEFC 1 Capacity, Mt/y	OLEFC 2 Capacity, Mt/y	OLEFC 3 Capacity, Mt/y	OLEFC 4 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 4: *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 5: *Rank of Olefin-based Complexes according to Each Objective*

NPV	NPV (US$)/ t/y Ethylene	NPV/ Investment	Employment Indicator	Tax	Overall/ Sum of Weights
OLEFC 1	OLEFC 1	OLEFC 2	OLEFC 1	OLEFC 1	OLEFC 1
OLEFC 2	OLEFC 2	OLEFC 3	OLEFC 4	OLEFC 2	OLEFC 2
OLEFC 4	OLEFC 4	OLEFC 1	OLEFC 2	OLEFC 4	OLEFC 4
OLEFC 3	OLEFC 3	OLEFC 4	OLEFC 3	OLEFC 3	OLEFC 3

TABLE 6: *Objective 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	0.20	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 7: *Rank of Complexes for Each Set of Preference Factors*

Rank #	Set #1	Set #2	Set #3	Set #4	Set #5
1	OLEFC 1	OLEFC 1	OLEFC 1	OLEFC 1	OLEFC 1
2	OLEFC 2	OLEFC 2	OLEFC 2	OLEFC 2	OLEFC 4
3	OLEFC 4	OLEFC 4	OLEFC 4	OLEFC 4	OLEFC 2
4	OLEFC 3	OLEFC 3	OLEFC 3	OLEFC 3	OLEFC 3

TABLE 8: *Results of Statistical Analysis for Various Olefin-based 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	1200.0	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

Since,

$$\sigma_4 > \sigma_1 > \sigma_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

and,

$$\mu_4 < \mu_2 < \mu_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

complex OLEFC 4 is inferior to complexes OLEFC 1 and OLEFC 2, which supports the previous findings.

Complex OLEFC 3 has the lowest standard deviation (least risky) and the lowest mean NPV (lowest returns), which implies that it cannot be determined, based on this criterion, whether it is more desirable than other complexes. Only if the decision-maker is risk averse, will he select complex OLEFC 3. Conversely, if he has a liking for risk, he will choose complex OLEFC 1, since it yields the highest returns, even though it incorporates the second highest risk.

If the decision-maker is not extremist, that is, 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 6**). On this basis, it is still very difficult to distinguish between complexes OLEFC 1, OLEFC 2 and OLEFC 3. However, it is clear that complex OLEFC 4 is not only inferior to complexes OLEFC 1 and OLEFC 2 (as determined earlier) but also to complex OLEFC 3, 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 OLEFC 1, OLEFC 2 and OLEFC 3. (See **Table 9**). Complex OLEFC 1 produced the highest return to risk ratio followed by complexes OLEFC 2, OLEFC 3 and OLEFC 4. Therefore, the overall rank (shown in **Table 10**) is that of the cautious (non-extremist) decision-maker.

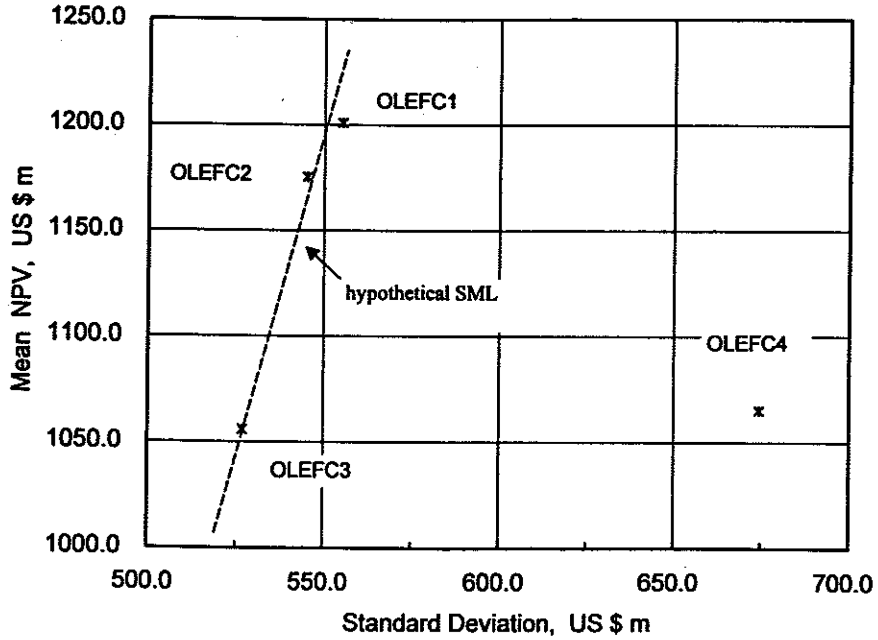


FIGURE 6: *Plot of Mean versus Standard Deviation of NPV for Olefin-based Complexes*

To summarise, the rank for the multiobjective analysis was, in fact, similar to that obtained in the uncertainty analysis, which again emphasises the superiority of OLEFC 1.

7. Conclusions

This paper applied a rigorous methodology for long-term planning to determine an optimal initial structure of an olefin-based petrochemical complex in Trinidad and Tobago. The following are the main conclusions drawn:-

1. With the quantity of natural gas production being about 1425 MMscfd, a viable 500,000 t/y ethylene cracker is possible based on ethane and propane extraction.

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

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

4. The multiobjective analysis revealed that the optimal olefin-based complex should include the following ethylene-based plants:

   - ✓ Polyethylene
   - ✓ Styrene
   - ✓ Vinyl chloride monomer
   - ✓ Ethylene oxide
   - ✓ Ethylbenzene
   - ✓ Polystyrene
   - ✓ Polyvinyl chloride
   - ✓ Ethylene glycol

   and the following propylene-based plants:

   - ✓ Phenol/acetone
   - ✓ Polycarbonate
   - ✓ Propylene oxide
   - ✓ Bisphenol
   - ✓ Epoxy resin
   - ✓ Propylene glycol

   This structure also involved the least risk since it 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 as part of the olefin complex.

8. Limitations of Study and Future Work

It is expected that 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

TABLE 9: *Rank of Olefin-based Complexes according to Various Statistical Measures*

Rank	Mean NPV	Standard Deviation	Coefficient of Variation
1	OLEFC 1	OLEFC 4	OLEFC 1
2	OLEFC 2	OLEFC 1	OLEFC 2
3	OLEFC 4	OLEFC 2	OLEFC 3
4	OLEFC 3	OLEFC 3	OLEFC 4

TABLE 10: *Overall Rank of the Olefin Complexes*

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

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 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 petrochemical industry. However, 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 so doing, one may take better advantage of the multiperiodic/dynamic model 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. Furthermore, 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 local petrochemical industry. This could be a critical factor since a number of important issues are involved in site selection, including the 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 utilise a better employment indicator than the one was used here. For example, an estimate of the number of employees in various fields (*e.g.*, administrative, plant operation and maintenance) 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. This would allow changes to be made to the current optimal solution, thereby giving a new long-term structure and policy for development. Other management tools may be used to more fully explore each structure, such as what-if scenarios and decision tree analyses.

The methodology presented in this study, *i.e.*, Part I (Furlonge and Young Hoon, 2000) and Part II, which includes 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, may be applied to:

a) An entire natural gas industry (including gas used in liquefied natural gas and metals production, electricity generation, commercial and light manufacturing, and transportation) to determine the overall optimum utilisation of natural gas.

b) An oil refinery to determine the optimal feed mix, product blend and capacity expansions.

c) An entire energy sector (Furlonge, 1996) to determine the optimum supply/demand balance of natural gas, petroleum, and other sources of energy in various end-use sectors including industrial, electricity generation, transportation, residential, and commercial sectors.

Nomenclature

ABSR	acrylonitrile-butadiene-styrene
ACN	acrylonitrile
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$m)
OLEFC 1	Olefin Complex 1
OLEFC 2	Olefin Complex 2
OLEFC 3	Olefin Complex 3
OLEFC 4	Olefin Complex 4
PC	polycarbonate
PE	polyethylene
PG	propylene glycol
PhenAc	phenol/acetone
PO	propylene oxide
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride
SML	security market line
SP	selling price (US$/t)
Sty	styrene
tscf	trillion standard cubic feet
t/y	tonnes per year
VAM	vinyl acetate monomer
VCM	vinyl chloride monomer
μ	mean/expected value (US$m)
σ	standard deviation (US$m)

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