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

Part 1. The Methane-based Complex

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In this paper, a rigorous methodology for long-term planning of industrial development involving a formal optimisation technique is presented. It is applied to finding an optimal long-term structure and policy for development of the petrochemical industry in Trinidad and Tobago. The mathematical model for the industry captured the dynamic nature of the petrochemical market. The length of the investment time horizon is 18 years, during which economic parameters were allowed to vary. Uncertainty in the estimation of these parameters was also taken into account. Since planning on this scale involves various interest groups (e.g., government, investor and populace) which may have conflicting goals, a multiobjective analysis was performed. The results of the case study suggest that the optimal policy for development of the methane-based industry in Trinidad and Tobago should involve a shift towards the production of downstream petrochemicals. The current structure of this industry is already poised for downstream manufacturing. Continued upstream production was shown to be the least lucrative policy and incorporated the greatest risk.

1. Introduction

With Trinidad and Tobago's proven reserves of natural gas standing at approximately 21 tscf and with the availability of primary petrochemicals (e.g., natural gas liquids, ammonia and methanol), the opportunity exists for the country to further develop its petrochemical industry. Apart from continued expansion of the already extensive methane-based primary petrochemical industry, there is scope for an olefin cracker and an olefin-based complex. The ultimate aim of this paper, therefore, is to devise a feasible and lucrative policy for the development of the local petrochemical industry using a rigorous mathematical approach.

In planning the development of any petrochemical industry, it is important that a long-term structure is selected and an appropriate policy is applied to ensure the attainment of that structure. As a result, various long-term structures and policies for development were examined in this study. The optimal policy selected by the optimisation outlines explicitly:

1) Petrochemicals to be produced from natural gas,
2) Process capacity expansion and shutdown patterns,
3) Investment patterns, and
4) Sale and purchase volumes

which maximises the chosen objective function.

In order to select a long-term structure, a *multiperiodic* mathematical model representing the industry

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was necessary since it captures the dynamism of the industry by allowing economic parameters, and demand and supply levels to vary periodically. The model involved several categories of petrochemicals (basic, intermediate and end-product) which may be produced from methane and from methane and from olefins (ethylene and propylene). The resulting system of equations decribing the model was linear. Because of the significant role economies of scale play in a problem of this nature, *a mixed integer linear programming* (MILP) model was necessary.

The petrochemical industry, in general, has historically been driven by economics and optimal use of resources. Thus, the objectives for selection of the best long-term structure and policy for development were net present value (NPV) which ensures viability, NPV per investment which ensures optimal use of indigenous resources. Other objectives include amount of taxes (i.e., corporate tax) generated and employment. Indeed, a *multiobjective* analysis was necessary because of the different and often conflicting objectives of the various interest groups involved. For instance, the investor is interested in profits, government is concerned with generating taxes and maximising benefits from the country's natural resources, and the populace requires employment.

The study took into account *uncertainty* which is inherent in technical and economic parameters, such as selling price. Various techniques were used to measure the effect of the uncertainty.

In this paper (Part I), the development of the local methane-based petrochemical industry is considered. Section 2 describes the methodology used for long-term planning. It includes the mathematical model and the techniques used in the multiobjectivity and uncertainty analyses. The different petrochemical plants and their break-even capacities are examined in Section 3. The planning time horizon and the different policies for development are discussed in Section 4. A market-based petrochemical model and the various policies for development are analysed in Sections 5 and 6 respectively. Finally, Section 7 gives the concluding remarks.

In a subsequent (Part II) paper (Furlonge and Young Hoon, 2000), the problem of selecting an optimal initial structure and policy for development of an olefin-based complex in Trinidad and Tobago is addressed. The methodology used in this case is essentially the same as that used in this paper. However, a sensitivity analysis was performed only in Part II. The limitations of the methodology and possible future work are also discussed in Part II.

2. Methodology for Long-Term Planning

2.1 Mathematical Model

There are three aims of the mathematical model. Firstly, it must represent the particular industry (i.e., the petrochemical complex in this case) in sufficient detail. This was accomplished by the (linear) equations (Stadtherr and Rudd, 1976) representing the various chemical transformations as well as various constraints, e.g., demand constraints. Secondly, since economies of scale play a significant role in planning of this nature, integer variables were required to facilitate the representation of fixed and variable components of capital and operating costs (Grossmann and Santibanez, 1980). Finally, since a long-term structure was sought, the model has to be valid for the entire time horizon. A multiperiodic model (Sahinidis *et al.*, 1989) was therefore used since it allows economic parameters to vary with time. The resulting set of equations for a general petrochemical complex forms a *multiperiodic MILP model*. It comprises of equality and inequality constraints, as well as an objective function.

2.1.1 Constraints

Capacity Limitations

Eq. 1 sets upper limits (QE_{it}^{U}) and lower limits (QE_{it}^{L}) on the capacity expansions (QE_{it}) for plant i in period t. QE_{it}^{U} was determined from a market survey and a profitability analysis. QE_{it}^{L} was kept at zero except when a policy was imposed onto the model, in which case a capacity above the break-even capacity was used as the lower limit. y_{it} is a binary variable which takes a value of "1" when a capacity expansion of plant i occurs in period t; otherwise, y_{it} is equal to "0". There are NP plants and NT time periods. Eq. 2 states that the plant capacity in period t is given by the capacity expansion in that period plus the existing capacity ($Q_{i,t-1}$).

$$y_{it}\,QE_{it}^{\,L} \le QE_{it} \le y_{it}\,QE_{it}^{\,U}$$

$$y_{it} = 0,1 \tag{1}$$

$$Q_{it} = Q_{i,t-1} + QE_{it} \tag{2}$$

Yield Constraints

The amount of main chemical m produced by plant i in period t (W_{imt}) cannot exceed the installed capacity (Q_{it}):

$$Q_{it} \geq W_{imt} \tag{3}$$

A linear material balance equation is used:

$$W_{ijt} = \mu_{ij} W_{imt} \tag{4}$$

μ_{ij} = mass balance coefficient relating chemicals j and m in process i

Supply Constraints
The amount of purchases of chemical j (P_{jt}) made in period t is restricted by a lower bound and an upper bound, a_{jt}^{L} and a_{jt}^{U} respectively:

$$a^{L}{}_{jt} \leq P_{jt} \leq a^{U}{}_{jt} \tag{5}$$

Demand Constraints
The amount of sales of chemical j in period t (S_{jt}) is bounded by lower and upper demand levels (determined from a market survey), $d^{L}{}_{jt}$ and $d^{U}{}_{jt}$ respectively:

$$d^{L}{}_{jt} \leq S_{jt} \leq d^{U}{}_{jt} \tag{6}$$

Material Balance Constraints
The amount of purchases and production must be equal to the amount of sales plus consumption of chemical j in period t:

$$P_{jt} + W_{jt} = S_{jt} + W_{jt} \tag{7}$$

2.1.2 Objective Function

The objective function used in the optimisation was NPV of the entire petrochemical complex:

Maximise

$$NPV = -\sum_{i=1}^{NP}\sum_{t=1}^{NT}(\alpha_{it} QE_{it} + y_{it}\,\beta_{it}) -$$

$$\sum_{i=1}^{NP}\sum_{t=1}^{NT}(\sigma_{it} W_{imt} + y_{it}\,\Theta_{it}) +$$

$$\sum_{i=1}^{NP}\sum_{j=1}^{NC}\sum_{i=1}^{NT}(\gamma_{ijt} W_{imt} - \Gamma_{ijt}\,P_{ijt}) \tag{8}$$

where, α_{it} = unit capital cost
β_{it} = constant of capital cost
σ_{it} = unit operating cost
Θ_{it} = constant of operating cost
γ_{ijt} = unit selling price
Γ_{ijt} = unit cost price

It should be noted that each of these costs were pre-multiplied by the appropriate present-value factors in order to determine the NPV. The techniques used for cost estimation are discussed in Section 3.

The present value of corporate taxes (PVTAX) was used as an objective in the multiobjective analysis and is given by:

PVTAX = Present value of (Total Sales - Total Raw Material Cost - Total Operating Cost - Depreciation) x 35% (9)

The depreciable life of a petrochemical plant was taken as 11 years. Straight line depreciation was used with a salvage value of 10% of the total capital cost. From Eq. 9, PVTAX =

$$0.35\sum_{i=1}^{NP}\sum_{j=1}^{NC}\sum_{i=1}^{NT}(\gamma_{ijt} W_{ijt} - \Gamma_{ijt}\,P_{ijt}) -$$

$$0.35\sum_{i=1}^{NP}\sum_{t=1}^{NT}(\sigma_{it} W_{imt} + y_{it}\,\Theta_{it}) -$$

$$\frac{0.35}{11} \text{ x } 0.9\sum_{i=1}^{NP}\sum_{t=1}^{NT}(\alpha_{it} QE_{it} + y_{it}\,\beta_{it}) \tag{10}$$

It was assumed that 10% of the total operating cost represents the cost of labour (Sinnot, 1993, and Peters and Timmerhaus, 1980). The present value of labour (PVLAB) was used as an employment indicator in the multiobjective analysis:

$$PVLAB = 0.1\sum_{i=1}^{NP}\sum_{t=1}^{NT}(\sigma_{it} W_{imt} + y_{it}\,\Theta_{it}) \tag{11}$$

The mathematical model was written in the General Algebraic Modelling System (GAMS) modelling tools, and the XA solver (Brooke *et al.*, 1988), which is based on a primal simplex method, was used for solution of the MILP problem.

2.2 Multiobjectivity

In planning of this nature, there are several interest groups, each with its own objective(s). This gives rise to a multiobjective problem. The following are the interest groups and their primary objective(s).

1) *Global consumer* - whose objective is to ensure that the demand for petrochemicals are met; consumer demand affects global capacity additions and petrochemical prices to a large degree.

2) *Investor* - whose objective is to invest in petrochemical plants that are most profitable; NPV, rate of return and payback time are measures of profitability.

3) *Government/policy-maker* - whose objectives include maximising benefits from the country's natural resources while satisfying all of the various interest groups.

4) *Populace* - whose objectives include utilities, housing and jobs.

In order to quantify the objectives of the various groups, the following variables were used:

a) Net Present Value (NPV), US$m.

b) NPV per investment, US$m / US$m.

c) NPV per trillion standard cubic feet of natural gas (NPV/tscf), US$m/tscf.

d) Taxes, US$m.

e) Employment, US$m.

It should be noted that the multiobjective problem existsonly because there is no solution for which all objectives are optimised simultaneously. The methodology involved examining a preferred set of feasible solutions and selecting the superior complex/policy. The primary objective used was NPV, i.e., the objective function in the optimisation problem was NPV. The optimisation problem was therefore treated as a single objective problem, and multiobjectivity was incorporated at the post-optimisation stage. Having optimised a structure with respect to NPV, the values of the other objectives were obtained.

The different structures were rated using a weight (or relative performance measure) w_φ for each objective φ. Consider a set of structures, X, Y and Z. If Y has the highest NPV, then for structure X,

$$w_{npv} = \frac{NPV\ of\ X}{Maximum\ NPV} = \frac{NPV\ of\ X}{NPV\ of\ Y} \qquad (12)$$

This method of assigning weights eliminates some subjectivity from rating structures which is a clear advantage over most other techniques for treating multiobjective problems.

Each objective was assigned a preference factor (Sophos *et al.*, 1980), k_φ, also referred to as a value trade-off factor, which was indicative of the relative level of importance of objective φ, where,

$$\sum_{\varphi=1}^{5} k_\varphi = 1 \qquad (13)$$

The selection of k_φ values is a subjective task, since it is incumbent upon the decision-maker to rate the relative importance of each objective. Having selected these k_φ values, an overall weight, W, for each optimal structure can be calculated:

$$W = \sum_{\varphi=1}^{5} k_\varphi \cdot w_\varphi \qquad (14)$$

The overall weight, W, was used as a guide as to which structure gives the best compromise solution. Several possible petrochemical structures/policies (cf. Section 4.2) were examined and ranked based on a particular set of k_φ values. It would be useful to determine the sensitivity of this rank to changes in k_φ values, i.e., when the relative importance of the objectives are varied. Hence, several sets of k_φ values were used to further reduce the subjectivity in rating objectives and to determine the most flexible structure.

2.3 Uncertainty Analysis

The aim of the uncertainty analysis was to determine the probability density function (PDF) of NPV (Section 2.3.1), and to use the mean and standard deviation to rate different portfolios (Section 2.3.2).

2.3.1 Determination of PDF of NPV

It was assumed that the uncertainty in sale prices, raw material costs, capital costs and operating costs are continuous random variables which follow normal distributions. For a given mean (μ), and lower and upper limits to each random variable, the standard deviation (σ) was computed by assuming that the probability of the variable falling within the given limits was 95.5% (i.e., $\pm 2\sigma$); more detail is given in Furlonge (1998). For instance, it is assumed that the sale price of ammonia has a 95.5% probability of falling in the range US$100/t and US$200/t. The mean NPV is therefore US$150/t, and the standard deviation is US$25/t. The certainty of the price falling within this range is expected to decrease with time; thus, a linear decrease in the standard deviaiton with time was assumed (see **Figure 1**).

The following section outlines the tools (based on the mean and standard deviation of NPV) used in rating different portfolios.

2.3.2 Uncertainty Tools for Portfolio Assessment

Consider a hypothetical problem in which one has to decide between two portfolios, A and B, based on NPV. The basic criterion for selection is as follows:

Case 1:

If $\mu_A > \mu_B$ and $\sigma_A = \sigma_B$, then choose A

Case 2:

If $\mu_A = \mu_B$ and $\sigma_A > \sigma_B$, then choose B

Case 3:

If $\mu_A > \mu_B$ and $\sigma_B > \sigma_A$, then choose A

For the above cases, it is clear which project should be selected; however, there is a further situation which may exist:

Case 4:

If $\mu_A > \mu_B$ and $\sigma_A > \sigma_B$,

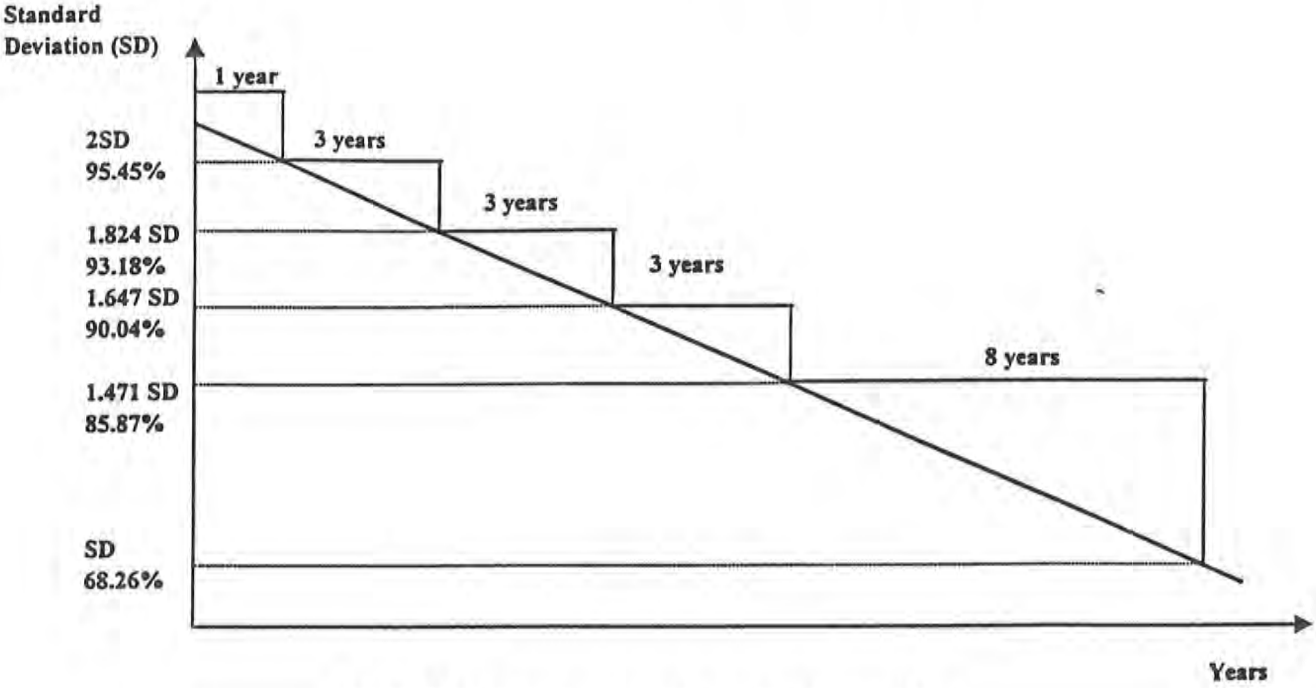


FIGURE 1: *Linear Decrease in Standard Deviation with Time*

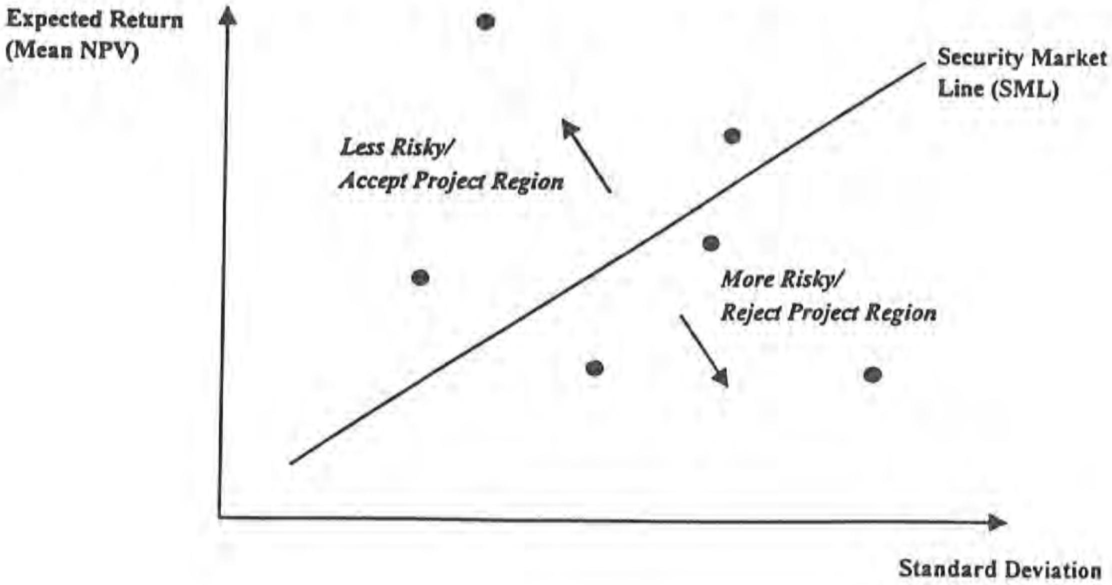


FIGURE 2: *Plot of Mean versus Standard Deviation*

For this situation, there must be a trade-off between risk and expected value. However, the decision-maker need not make an entirely subjective decision. There are two tools which may be used:

(1) The *coefficient of variation*, defined as the expected value (i.e., mean) divided by the standard deviation of NPV (Brigham and Gapenski, 1991).

(2) The *security market line* (SML), which is a plot of mean versus standard deviation (Brigham and Gapenski, 1991), as shown in **Figure 2.** This line may be produced based on historical data that is similar in nature.

Portfolios with higher coefficients of variation would be more attractive since they yield higher NPV per unit risk. Similarly, portfolios which lie above the SML are more favourable than those below. Both of these techniques were applied together with the comparison of the means and standard deviations. However, a hypothetical SML, based on the best straight line through the points representing the different models, was used.

3. Break-Even Plant Capacities

The structure of the local petrochemical industry in 1997 (start of first period) comprised 2150 Mt/y of ammonia capacity, 590 Mt/y of urea capacity, 1510 Mt/y of methanol capacity, 6 Mt/y of formaldehyde capacity and 12.5 Mt/y of urea-formaldehyde capacity.

The list of petrochemicals considered for inclusion in future local development comprises ammonia, methanol, urea, formaldehyde, urea-formaldehyde, melamine, melamine-formaldehyde, methyl methacrylate (MMA), methyl tertiary butyl ether (MTBE) and acetic acid.

In order to ensure profitability of individual petrochemical plants, each plant must be above a minimum cdapacity, i.e., break-even capacity, where the NPV is zero. The profitability analyses performed in this study were based on a plant life of 15 years and a cost of capital of 15%. Capital and operating cost estimates were obtained from various sources including Trevino *et al.* (1981), Chem. Systems Ltd. (1990), European Chemical News (various issues) and Hydrocarbon Processing (various issues). The following formula was used for calculating the total fixed capital cost (TFC) in year t for a plant of capacity Q (Peters and Timmerhaus, 1980):

$$TFC = TFC\ (Q\,/\,Q')^{n}\ (I\,/\,I') \tag{15}$$

where TFC_t' is the total fixed capital cost in year t' for a plant of capacity Q'. I and I' are the chemical engineering plant cost indices for year t and t' respectively. n is the scaling exponent for the particular type of chemical plant. The operating costs (comprising mainly of utility, raw material and maintenance costs) were calculated based on data obtained from the literature. Greater detail of the techniques, and economic and technological data is given in Furlonge (1998).

The break-even capacity which were obtained from plots of NPV versus plant capacity are as follows: ammonia - 500 Mt/y; urea - 335 Mt/y; melamine - 26 Mt/y; melamine-formaldehyde - 6 Mt/y; methanol - 300 Mt/y; formaldehyde - 50 Mt/y; urea-formaldehyde - 6 Mt/y; acetic acid - 20 Mt/y; MTBE - 450 Mt/y; and MMA - 9 Mt/y. Geneerally, any plant that is built must be above its break-even capacity.

4. Methane-Based Petrochemical Complex

4.1 Planning Time Horizon

The multiperiodic nature of the mathematical model described in Section 2.1 requires the definition of a time horizon. The time horizon spans a fixed number of years which must be sufficiently long for a reasonable rate of development. However, it should not be too long so as to negate the findings of the market survey, introduce a high degree of uncertainty in the data, nor fall out of range of the current technological age.

The time horizon, of total length 18 years, was segmented into five periods, as shown in **Table 1**. It should be noted that it is possible to push the entire horizon back a few years, provided this does not invalidate the data, e.g., the initial structure of the industry must be the unchanged. Thus, the mathematical model is insensitive to the year in which the horizon begins, i.e., Period 1 may start in the year 2000 say, if it is thought that the horizon selected begins too early. It should be noted that the NPV pertains to the year in which the horizon begins.

4.2 Policies for Development

Four basic policies for development of the petrochemical industry (Jimenez *et al.*, 1982), which were applied during the planning time horizon defined in Section 4.1, were considered. Various possible complexes were also formulated from these basic policies.

Policy 1: *Develop gradually an industry that is dedicated to the production of downstream petrochemicals.*

In the case of Policy 1 Model 1, the first period of investment (i.e., period 2) was used to increase the local capacity of basic petrochemicals (i.e., ammonia and methanol) and add the intermediate petrochemicals (i.e., urea, formaldehyde and acetic acid). An MTBE plant was also allocated period 2. The possibility of MTBE expansions in further periods was included. In period 3, the complex ventured further downstream to melamine, urea-formaldehyde and MMA. Because of the high profitability of acetic acid, a maximum of one plant was assigned to each period of investment. Melamine-formaldehyde entered the structure in period 4; a urea-formaldehyde expansion also occurred in this period, see **Figure 3**.

As a variation, Policy 1 Model 2 which included another MMA plant in period 4 was developed. Policy 1 Model 3 included two ammonia plants and two methanol plants in period 2, together with one MMA plant in period 4.

Policy 2: *Build, as early as possible, an industry that is dedicated to downstream production.*

In Policy 2 Model 1, period 2 included the possibility of expansions of all 10 petrochemicals. However, expansions in period 3 are solely for the downstream petrochemicals, i.e., urea-formaldehyde, melamine-formaldehyde, MMA and acetic acid. Only an acetic acid expansion is allowed in period 4.

Policy 2 Model 2 included the option of a second melamine plant in period 3, as shown in **Figure 4**.

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

Period	Year Starting	Year Ending	Length of Period	Rationale
1	1997	1997	1	Pre-investment period
2	1998	2000	3	First period of investment
3	2002	2003	3	Second period of investment
4	2004	2006	3	Final period of investment
5	2007	2014	8	This period allows plants built in period 4 to run for their depreciable life (11 years)

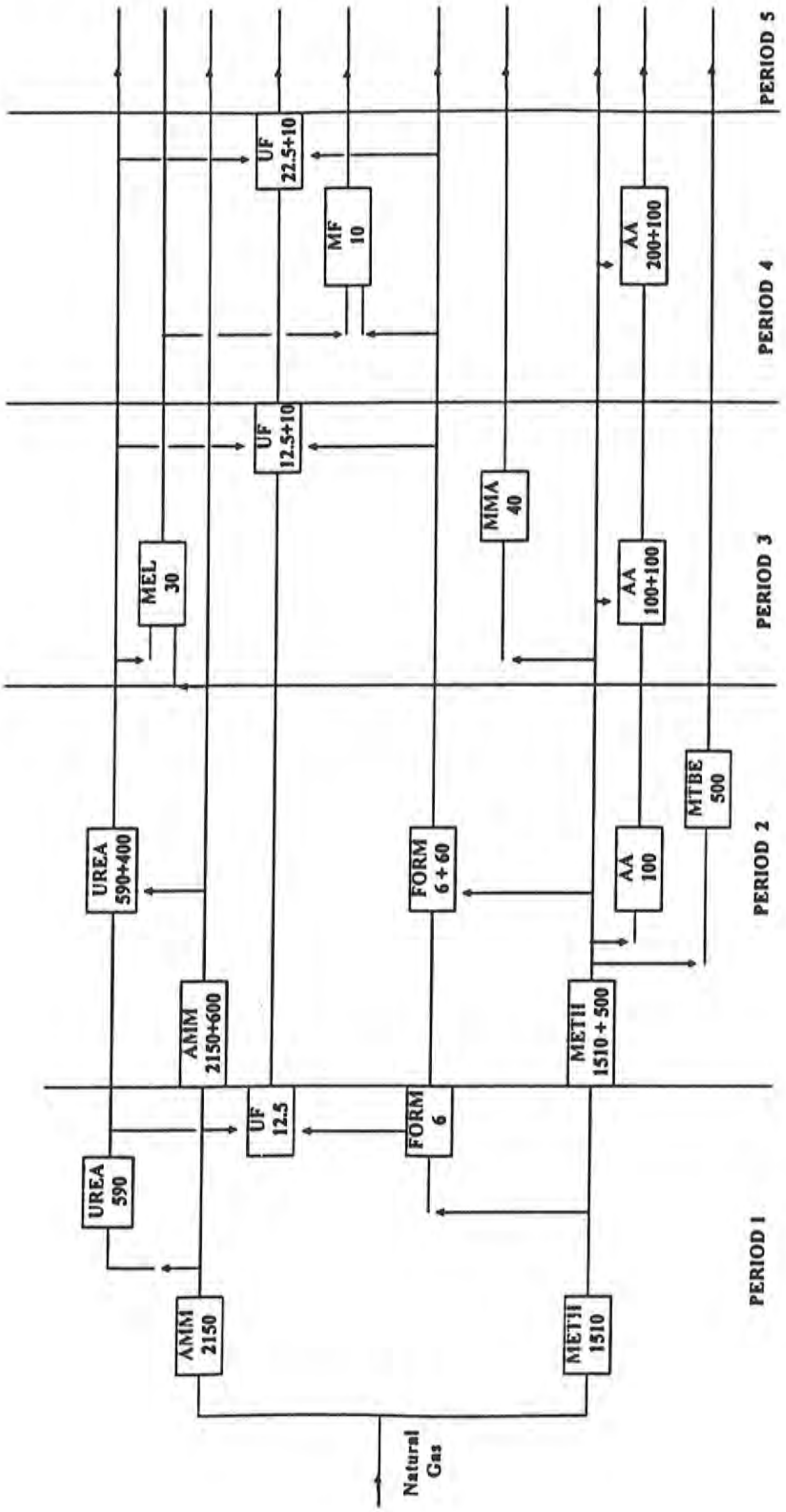


FIGURE 3: *Block Diagram of Policy 1 Model 1*

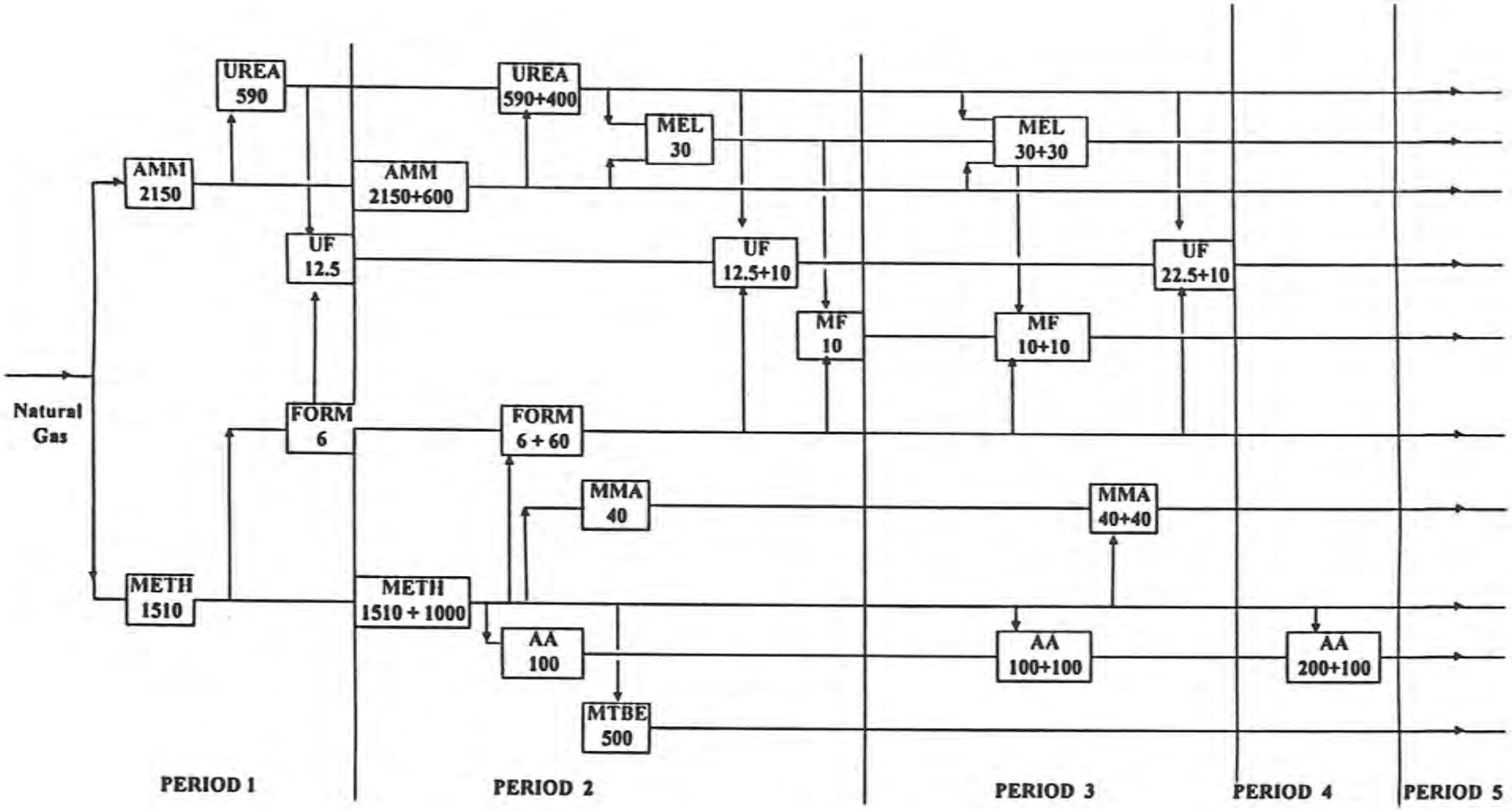


FIGURE 4: *Block Diagram of Policy 2 Model 2. (No Melamine Expansion occurs in Period 3 of Policy 2 Model 1)*

Policy 3: *Develop an industry that produces a blend of basic, intermediate and end-product petrochemicals.*

This policy was not as dedicated to downstream production as was Policy 1; instead, it continued to build basic and intermediate petrochemical plants in excess of downstream requirements, see **Figure 5**. Policy 3 Model 1 involved the construction of one ammonia plant and one methanol plant in each period. The option to build one MTBE plant in each period was allowed.

Policy 3 Model 2 generally followed the same policy, but included the option of constructing more downstream plants in later periods, i.e., a second MMA plant in period3, and extra urea-formaldehyde and melamine-formaldehyde plants in period 4.

Policy 4: *Continue to build an industry that is dedicated to upstream production.*

In Policy 4 Model 1, two ammonia plants and two methanol plants were constructed in each period of investment. A urea plant was allocated to period 2, see **Figure 6**.

Policy 4 Model 2 included the possibility of producing acetic acid in each period and MTBE in period 2. The local industry has been focused on upstream production since its inception. It has only ventured downstream as far as urea and urea-formaldehyde (one plant each). There were tentative plans to build an acetic acid plant and an MTBE plant; Policy 4 Model 2 represented this strategy.

It should be noted that the nine structures delineated above, certainly do not depict all the possible combinations; however, they do cover a number of different possibilities in a systematic manner. As a result, useful deductions can be made from them, and a general policy for development can thus be detected.

5. Optimum Methane-Based Market Model

The first petrochemical model considered did not conform to any one of the policies described in Section 4.2. Instead, the bounds on the demand levels (obtained from a market survey) were the only constraints placed on the optimisation. This model is thus referred to as a methane-based market model.

Data for the market survey was obtained from several sources including European Chemical News and Hydrocarbon Processing. The aim of the market survey was to determine the number of petrochemical plants that periodically come on-stream worldwide, and hence, determine the possible local capacity expansions. The approach involved finding the current global capacity and projected demand growth rates. This information can easily be used to calculate the number of plants that will come on-stream within each period of the time horizon. It was assumed that between 5% and 30% of global expansion can be built locally. Typically, this corresponds to one or two local plants per three-year period out of a global expansion corresponding to as much as 5 to 10 plants in some cases.

The optimum methane-based market model is depicted in **Figure 7**. This model generated an NPV of US$m 2,152 with an investment of US$m 2,902. All projects which yield a positive NPV were selected by the optimiser.

The resulting optimum network included 25 new plants constructed over a 7-year period. Such rapid development may raise concerns about the provision of the necessary infrastructure. Hence, this network cannot be a feasible solution since it is not pragmatic. However, it was used to develop and rate other more practical complexes.

Profitability and market considerations have therefore proven to be inadequate in determining the path that should be taken towards developing the local methane-based petrochemical industry. Instead, various policies for development (*cf.* Section 4.2) were imposed on the mathematical model (*cf.* Section 2.1). Optimisation was then carried out, the result of which are discussed in the next section.

6. Optimal Policy for the Methane-Based Complex

The results of the optimisation, including the NPV and investment for each of the different petrochemical models (described in Section 4.2) are given in **Table 2**. NPV fell within the range US$m 1,840 and 2,152 for all models (see **Figure 8**). This suggests that all the models should be attractive to investors and there is no clear superiority of one model over another in terms of NPV. However, the corresponding range of investment was US$m 1,043 to 3,016, with Policies 1 and 2 generally requiring the lowest investment and Policy 4 the highest. The narrow range of the NPV, compared to the wide range of investment suggests that the amount of money invested is not as significant as where it is invested.

Essentially, the local petrochemical industry has been concentrating on upstream production since its inception, apart from urea and urea-formaldehyde production. There are tentative plans to build an acetic acid plant and an MTBE plant. Policy 4 Models 1 and 2 represented this policy. The results indicate that this policy generally produced the most taxes (up to 30% more) and greatest employment (up to 20% more) see **Table 2**. However, it consumed significantly more resources, such that its NPV/tscf and NPV/investment proved to be the penultimate lowest (up to 52% lower) and

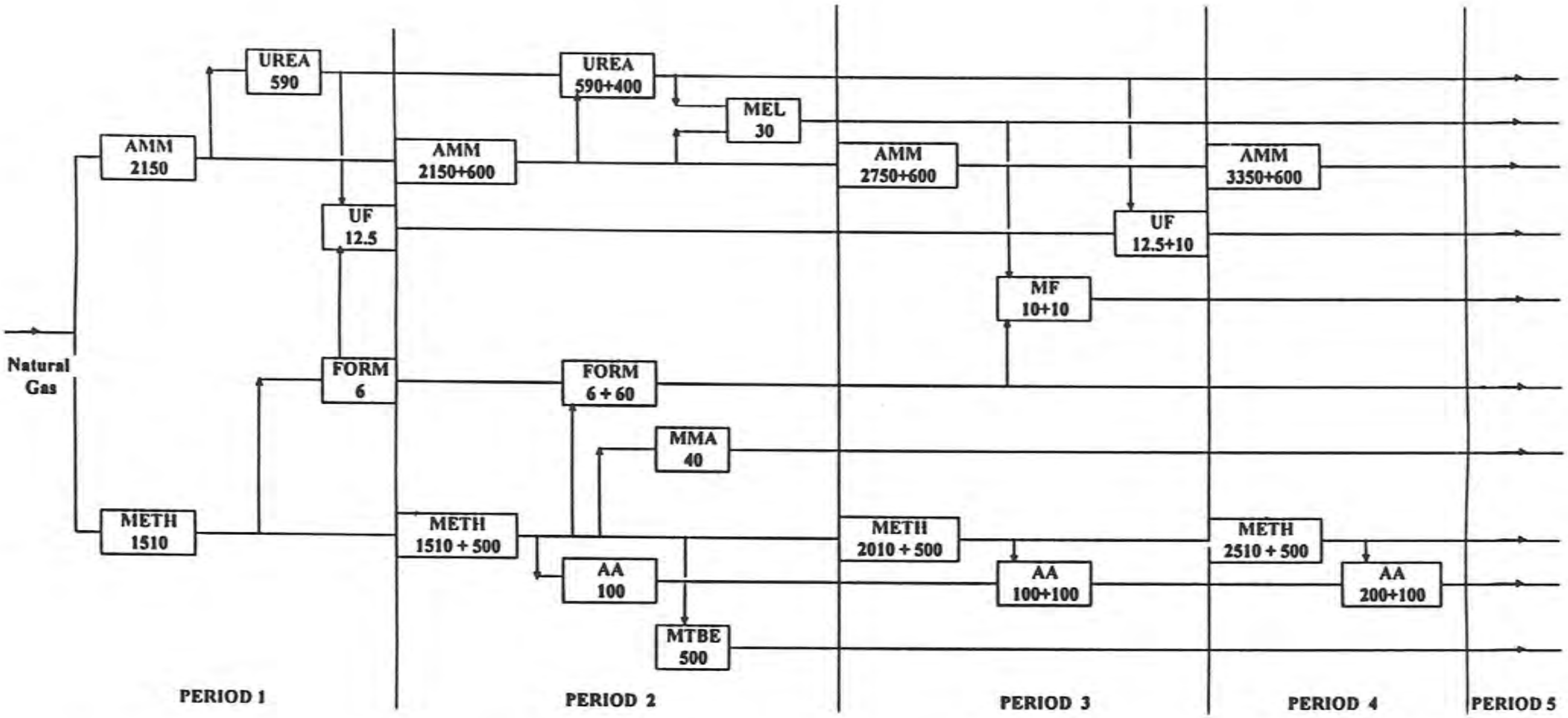


FIGURE 5: *Block Diagram of Policy 3 Model 1*

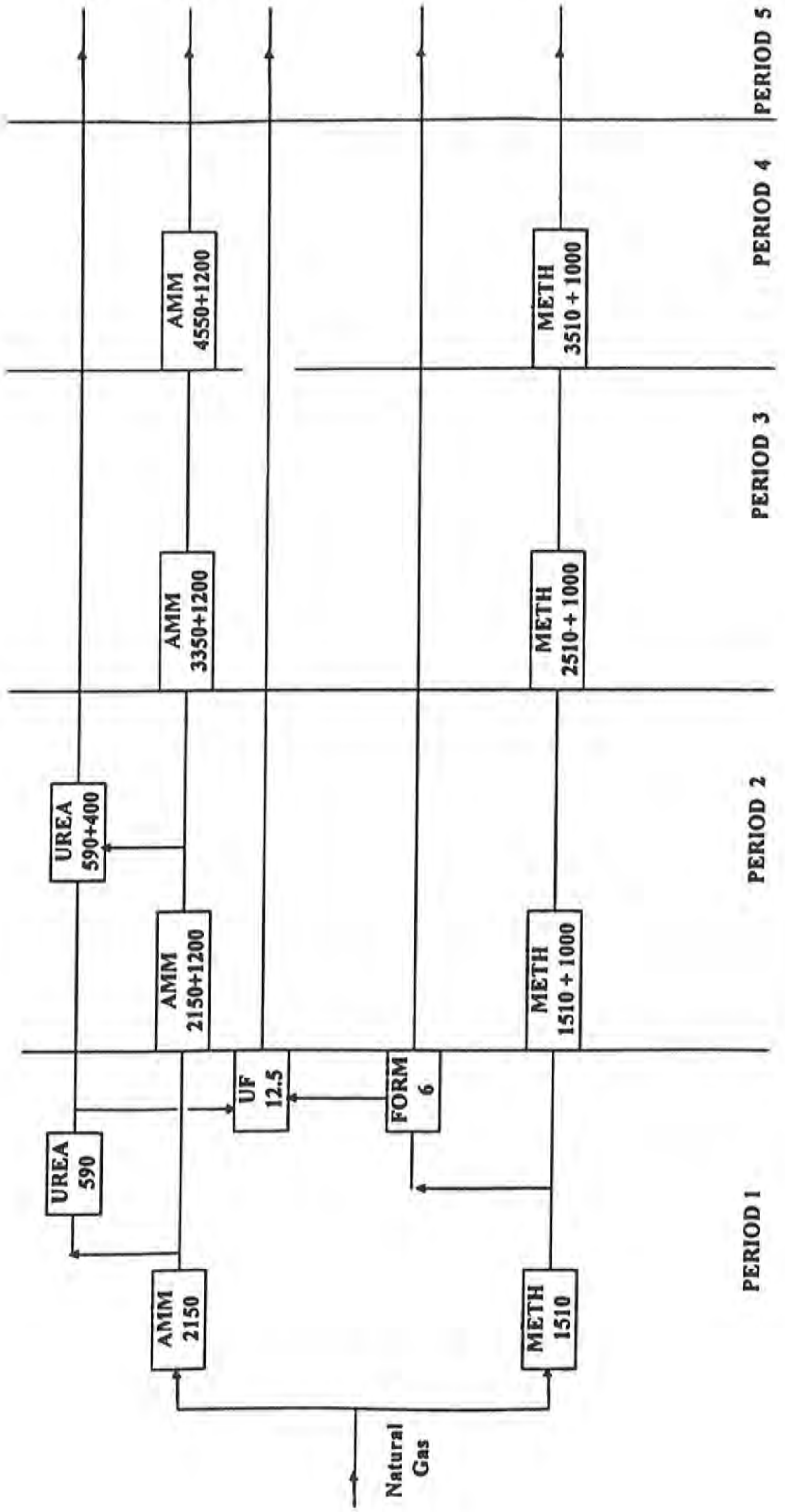


FIGURE 6: *Block Diagram of Policy 4 Model 1*

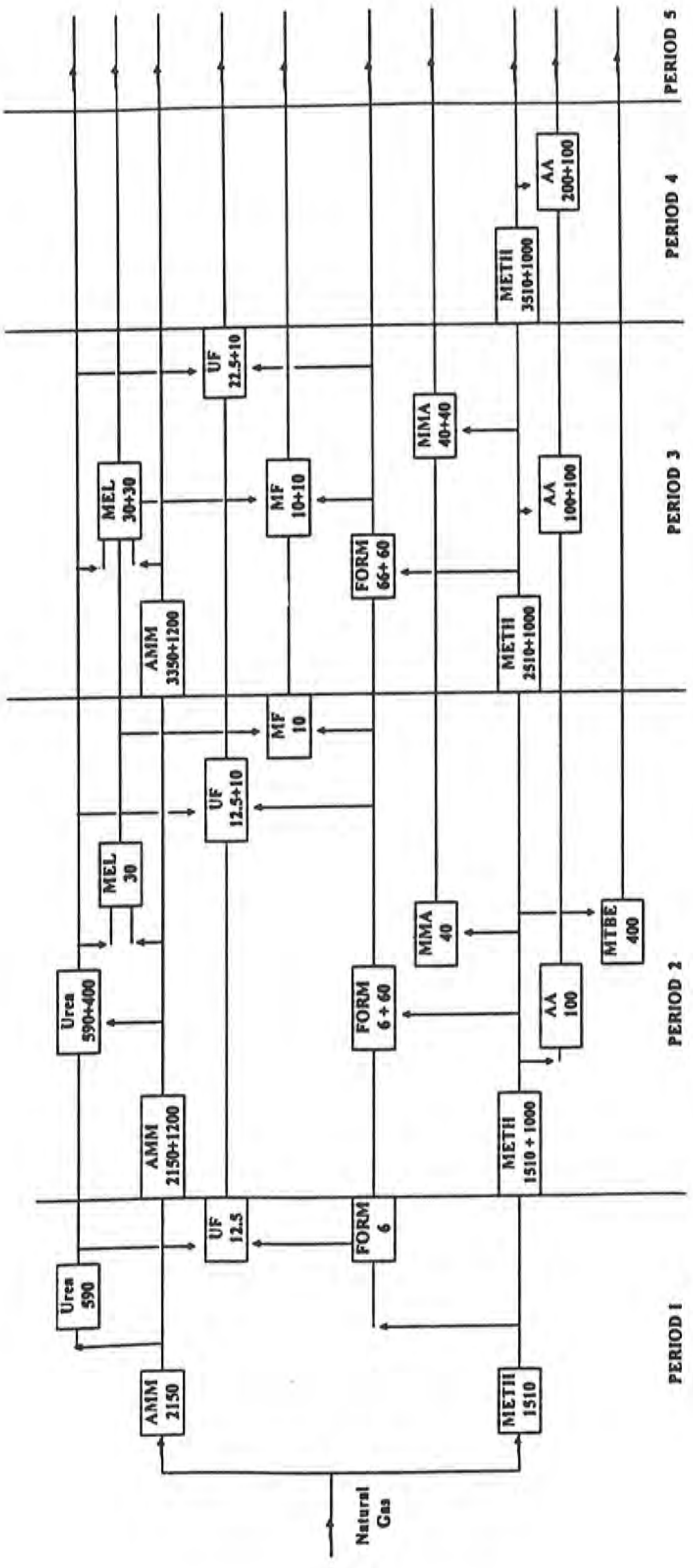
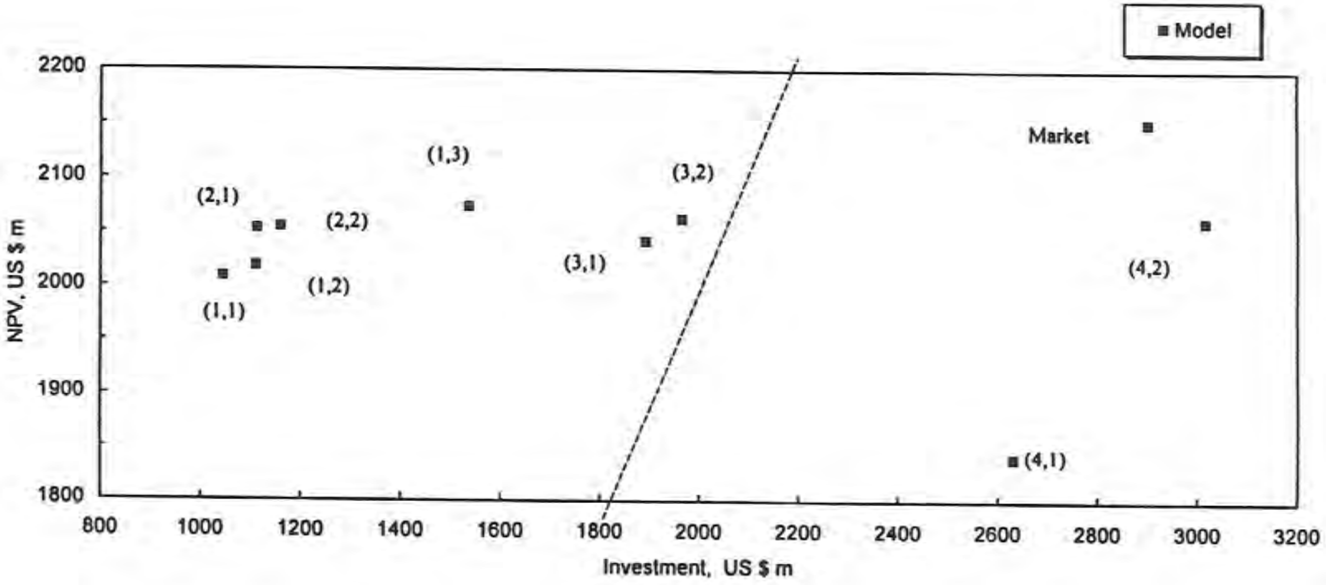


FIGURE 7: *Optimum Methane-Based Market Model (All Figures in Mt/y)*



(x,y) - model coordinates

e.g. (1,2) represents Policy 1, Model 2

FIGURE 8: *NPV vs Investment for Various Methane-Based Models*

TABLE 2: *Value of Objectives for Methane-Based Petrochemical Models*

MODEL	Investment (US$m)	Total Natural Gas (tscf)	NPV (US$m)	NPV/tscf (US$m/tscf)	NPV/ Invest. (US$m/ US$m)	PV of Taxes (US$m)	Employment (US$m)
Market	2,902.0	3.008	2,152.1	715	0.742	1,974.9	458
POL1 MOD1	1,043.9	1.758	2,009.0	1,143	1.925	1,407.7	341.2
POL1 MOD2	1,110.2	1.758	2,018.5	1,148	1.818	1,424.4	347.3
POL1 MOD3	1,536.6	2.146	2,073.4	966	1.349	1,608.4	376.8
POL2 MOD1	1,112.3	1.758	2,052.9	1,168	1.846	1,459.9	369.9
POL2 MOD2	1,159.2	1.758	2,054.5	1,169	1.772	1,471.9	376.3
POL3 MOD1	1,891.4	2.329	2,041.8	877	1.080	1,611.7	384.8
POL3 MOD2	1,965.1	2.329	2,062.7	886	1.050	1,640.1	397.7
POL4 MOD1	2,631.4	3.288	1,840.1	560	0.699	1,676.8	326.9
POL4 MOD2	3,016.4	3.288	2,061.7	627	0.683	1,913.4	407.9

TABLE 3: *Rank of Petrochemical Models for each Sect of Objective Preference Factors*

Rank #	NPV	NPV/tscf	NPV Investment	PV of Taxes	Employment	Overall/ Sum of Weights
1	Market	POL2 MOD2	POL1 MOD1	Market	Market	POL2 MOD1
2	POL1 MOD3	POL2 MOD1	POL2 MOD1	POL4 MOD2	POL4 MOD2	POL2 MOD2
3	POL3 MOD2	POL1 MOD2	POL1 MOD2	POL4 MOD1	POL3 MOD2	POL1 MOD1
4	POL4 MOD2	POL1 MOD1	POL2 MOD2	POL3 MOD2	POL3 MOD1	POL1 MOD2
5	POL2 MOD2	POL1 MOD3	POL1 MOD3	POL3 MOD1	POL1 MOD3	POL1 MOD3
6	POL2 MOD1	POL3 MOD2	POL3 MOD1	POL1 MOD3	POL2 MOD2	POL3 MOD2
7	POL3 MOD1	POL3 MOD1	POL3 MOD2	POL2 MOD2	POL2 MOD1	POL3 MOD1
8	POL1 MOD2	Market	Market	POL2 MOD1	POL1 MOD2	Market
9	POL1 MOD1	POL4 MOD2	POL4 MOD1	POL1 MOD2	POL1 MOD1	POL4 MOD2
10	POL4 MOD1	POL4 MOD1	POL4 MOD2	POL1 MOD1	POL4 MOD1	POL4 MOD1

lowest (up to 65% lower) respectively of all the models. Overall, this policy proved to be the least desirable.

It may also be observed that Policy 4 Model 1, and Policy 3 Models 1 and 2 performed in a similar manner to Policy 4 Model 2. Together with the market model, Policies 3 and 4 consumed the greatest financial and natural gas resources and generally produced the greatest NPV's, taxes and employment figures (see **Table 2**). However, these petrochemical models ranked the lowest in terms of NPV/ tscf, NPV/investment and in the overall ranking, see **Table 3**. This suggests that the optimum utilisation of resources (i.e., benefits per unit of consumption) is not achieved by the maximum consumption of resources. Policy 4 Model 1, which continued to build ammonia and methanol plants, utilises considerable amounts of natural gas (3.29 tscf over the 18-year planning horizon) and foreign/local investment, but such a policy does not maximise the benefits from the use of these resources.

TABLE 4: *Objective Preference Factors (k values)*

Attribute	Set #1	Set #2	Set #3	Set #4	Set #5
NPV	0.2	0.1	0.1	0.1	0.1
NPV/tscf	0.2	0.25	0.2	0.15	0.3
NPV/Investment	0.2	0.25	0.2	0.15	0.3
Taxes	0.2	0.2	0.25	0.3	0.15
Employment	0.2	0.2	0.25	0.3	0.15

Policy 3, which involves the production of a blend of petrochemicals, also proved to be inferior to Policies 1 and 2. Policies 1 and 2 (Models 1 and 2 in each case) consumed less natural gas (1.76 tscf compared to 2.33 tscf for Policy 3) and involved the smallest investment, yet they produced the highest NPV/tscf and NPV/investment (see **Table 3**). The results therefore indicate that more benefits are derived from the primary raw material (i.e., natural gas) when more downstream plants are built. Furthermore, a profitability analysis revealed that individual downstream petrochemical plants generally produce higher NPV's per unit of investment; hence, any strategy which involves the production of downstream petrochemicals would maximise the use of investment.

So far, each objective has been compared separately. In the next section, a multiobjective analysis, which takes into account all objectives simultaneously, is performed.

6.1 Multiobjective Analysis

The values of the objectives for each of the petrochemical models are given in **Table 2**. When each objective was assigned equal importance (see last column of **Table 3**), Policy 2 proved to be the best policy for development, followed by Policy 1, the market model, Policy 3 and Policy 4. This rank indicates that the local petrochemical industry should change its course of development and venture into the production of downstream products.

The above rank was based on equally valued objectives (i.e., $k_\varphi = 0.2$ for all objectives). Since the objective preference factors require a subjective judgement, the stability of the present rank to changes in these factors was examined. The significance of the NPV criterion was decreased for two reasons:

1) The decision-maker may consider the other criteria more important, since the highest NPV does not ensure maximum use of resources (as shown earlier), and
2) The NPV for the 10 petrochemical models were very close, all falling within the range US$m 1,840 and US$m 2,152, with eight of them falling between US$m 2,009 and US$m 2,073.

Five sets of objective preference factors were considered, as shown in **Table 4**. In Set #1, the objectives were rated equally, as described earlier. In Sets #2 and #5, NPV/tscf and NPV/investment were given greater preference over taxes and employment. Apart from the position of the market-based model, the rank remained stable in Set #2 and #5, as shown in **Table 5**. This suggests that Policies 1 and 2 remain superior when utilisation of resources is given greater importance than other objectives. When NPV/tscf is the only objective ($k_{NPV/tscf} = 1$), Policies 1 and 2 remain superior, as can be seen from **Table 3**. The trend is similar for the objective NPV/investment.

In Sets #3 and #4, taxes and employment were assigned higher value trade-off factors (see **Table 4**). As shown in **Table 5**, the rank of the petrochemical models for Set #3 remained unchanged from the base case (Set #1). In Set #4, Policy 2 Model 2 moved ahead of Policy 2 Model 1. The market-based model also moved higher. Apart from these minor changes, the rank proved to be stable even though Policies 3 and 4 produced greater taxes than Policies 1 and 2.

A development policy which has been promoted locally (i.e., Policy 4 Model 2) generated the greatest taxes and employment. However, even when these two objectives were weighted heavily, this policy did not prove to be the best solution. Its NPV/investment and NPV/tscf were very low compared to Policies 1 and 2 (see **Table 2**) and the latter yields employment figures which were only US$m 66.7 and US$m 38 (16% and 9%) respectively lower than Policy 4 Model 2. The difference in tax collected was US$m 506 for Policy 1 (26% less than Policy 4 Model 2) and US$m 453 for Policy 2 (24% less than Policy 4 Model 2). Hence, Policies 1 and 2 still performed well in terms of taxes and employment, whereas Policy 4 Model 1 consumed

TABLE 5: *Rank of Petrochemical Models for each Sect of Objective Preference Factors*

Rank #	Set #1	Set #2	Set #3	Set #4	Set #5
1	POL2 MOD1	POL2 MOD1	POL2 MOD1	POL2 MOD2	POL2 MOD1
2	POL2 MOD2	POL2 MOD2	POL2 MOD2	POL2 MOD1	POL2 MOD2
3	POL1 MOD1	POL1 MOD1	POL1 MOD1	Market	POL1 MOD1
4	POL1 MOD2	POL1 MOD2	POL1 MOD2	POL1 MOD1	POL1 MOD2
5	POL1 MOD3	POL1 MOD3	POL1 MOD3	POL1 MOD2	POL1 MOD3
6	Market	POL3 MOD2	Market	POL1 MOD3	POL3 MOD2
7	POL3 MOD2	POL3 MOD1	POL3 MOD2	POL3 MOD2	POL3 MOD1
8	POL3 MOD1	Market	POL3 MOD1	POL3 MOD1	Market
9	POL4 MOD2	POL4 MOD2	POL4 MOD2	POL4 MOD2	POL4 MOD2
10	POL4 MOD1	POL4 MOD1	POL4 MOD1	POL4 MOD1	POL4 MOD1

almost two times the amount of natural gas and investment than Policies 1 and 2 without a concomitant increase in its NPV, taxes and employment.

In general, Policies 1 and 2 maintained their superiority over Policies 3 and 4 regardless of the relative importance of the objectives. It is therefore suggested that the petrochemical industry is already geared to embark on a course for the production of downstream petrochemicals and this is the direction which should be taken if long-term viability is to be achieved.

6.2 Effect of Uncertainty

In this section, the effect of uncertainty on the rank of the various policies is examined.

The probability density function of the NPV was determined using the method described in Section 2.3.1; the results are summarised in **Table 6**. Since it was assumed that the input parameters follow a normal distribution, the NPV also conformed to the same distribution. The mean and standard deviation were used to measure the relative

TABLE 6: *Results of Statistical Analysis for Various Methane-Based Petrochemical Models*

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	
POL1 MOD1	1,043.9	2,009.0	278.8	2,287.8	1,730.2	2,566.7	1,451.4	7.21
POL1 MOD2	1,110.2	2,018.5	282.2	2,300.6	1,736.0	2,582.8	1,454.0	7.15
POL1 MOD3	1,536.6	2,073.4	364.7	2,438.1	1,708.6	2,802.8	1,343.9	5.69
POL2 MOD1	1,112.3	2,052.9	286.1	2,339.0	1,766.8	2,625.1	1,480.7	7.18
POL2 MOD2	1,159.2	2,054.5	280.0	2,334.5	1,774.5	2,614.6	1,494.4	7.34
POL3 MOD1	1,891.4	2,041.8	343.1	2,384.9	1,698.7	2,728.0	1,355.6	5.95
POL3 MOD2	1,965.1	2,062.7	343.5	2,406.2	1,719.2	2,749.7	1,375.7	6.01
POL4 MOD1	2,631.4	1,840.1	485.9	2,326.0	1,354.2	2,811.9	868.3	3.79
POL4 MOD2	3,016.4	2,061.7	525.8	2,587.5	1,535.8	3,113.3	1,010.0	3.92
*POL1 MOD1	1,043.9	2,009.0	379.5	2.388.5	1,629.6	2,767.9	1,250.1	5.29

* Result when the probability associated with the periods were changed to 90%, 86%, 81%, 74% and 48% in periods 1 to 5 respectively.

uncertainty associated with each model, as described in Section 2.3.2.

The results revealed that Case 4, (cf. Section 2.3.2) applies to this situaiton (see **Table 7**), since the ranks with respect to the mean and standard deviation of NPV do not coincide. Therefore, other uncertainty tools were required to discern which petrochemical model incorporated the least risk.

Based on the rank according to standard deviation, Policies 3 and 4 contained greater uncertainty than Policies 1 and 2 (excluding Policy 1 Model 3). Policies 1 and 2 also produced greater coefficients of variation than Policies 3 and 4. In fact, the ranks were very similar to the ranks obtained in the multiobjective analysis (compare **Tables 5** and **7**).

Figure 9 shows the positions of the various complexes on a mean versus standard deviation diagram. A hypothetical security market line (SML) was drawn, based simply on the positions of the points. It is clear that Policy 4 (upstream production) is inferior to the other policies since it lies far into the reject region.

Figure 10 is an enlargement of **Figure 9**; the former indicates that Policy 2 is superior to the other policies, since it lies the furthest away from the hypothetical SML in the less risky/accept region.

In general, the result of the multiobjective and uncertainty analyses were very similar, in that Policies 1 and 2 (which focus more on downstream production) were better than Policies 3 and 4 (which involve greater upstream production).

6.2.1 Effect of Subjective Judgement

It should be noted that there are other more sophisticated techniques for finding the PDF of a random variable; Monte Carlo simulation is a popular method. Such techniques involve sampling and thousands of runs in order to determine the PDF of NPV; clearly, there are time and computational constraints associated with such methods given the large number of random variable involved. One may ask, how much would the results have changed if such techniques were applied instead, and is it worth the additional time and resources for this stage of planning?

A simple test was performed to determine the effect of probability of the range of values (cf. Section 2.3.1) for the independent random variables (e.g., selling price) on the standard deviation of NPV (i.e., dependent random variable). The probability was decreased from 95.5% (2σ), 93.2% (1.82σ), 90.0% (1.65σ), 85.9% (1.47σ), 80.5% (1.29σ), 73.7% (1.12σ) and 48.4% (0.65σ) respectively. This has caused the standard deviation of NV for Policy 1 Model 1 to change by about US$m 100. As shown in **Table 6**, the upper limit of NPV corresponding to a 95% confidence interval increased by 7.8%, and the lower limit decreased by 13.8%; for a 68% confidence interval, the changes were 4.4% and 5.8% respectively. These changes were relatively small; hence, the probability of the input data for each period did not have a significant effect on the confidence intervals of the NPV.

TABLE 7: *Rank of Methane-Based Petrochemical Models according to Various Statistical Measures*

Rank	Highest Mean NPV	Lowest Standard Deviation	Highest Coefficient of Variation
1	POL1 MOD3	POL1 MOD1	POL2 MOD2
2	POL3 MOD2	POL2 MOD2	POL1 MOD1
3	POL4 MOD2	POL1 MOD2	POL2 MOD1
4	POL2 MOD2	POL2 MOD1	POL1 MOD2
5	POL2 MOD1	POL3 MOD1	POL3 MOD2
6	POL3 MOD1	POL3 MOD2	POL3 MOD1
7	POL1 MOD2	POL1 MOD3	POL1 MOD3
8	POL1 MOD1	POL4 MOD1	POL4 MOD2
9	POL4 MOD1	POL4 MOD2	POL4 MOD1

The results obtained, together with the findings of Rose (1976), lead to the conclusion that the accuracy of the probability need not be very high and that subjective judgements must be made in investments decision-making. Furthermore, their effect on the ultimate decision is not significant depending on the stage of the planning and the degree of accuracy required. It is important, though, to test the effect of the subjective judgement as was done here.

7. Conclusions

In this study, a methodology for long-term planning which incorporates economies of scale, market dynamics, multiobjectivity and uncertainty was presented. The major findings and general remarks regarding the application of this method to the methane-based petrochemical industry of Trinidad and Tobago are given in Sections 7.1 and 7.2 respectively.

7.1 Major Findings

(1) All policies for development considered in this study generated similar NPV's, and should all be attractive to investors.

(2) Policies of development for the methane-based industry involving a

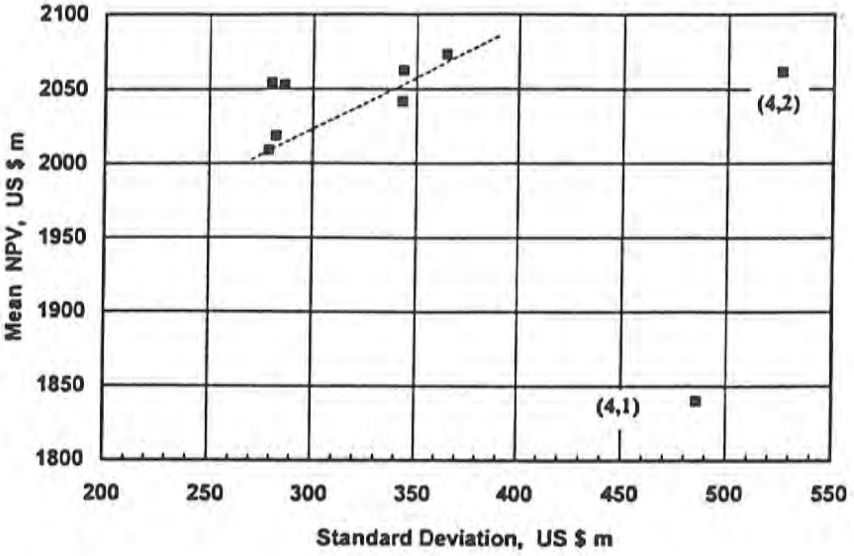


FIGURE 9: *Plot of Mean vs Standard Deviation of NPV for Various Methane-Based Complexes*

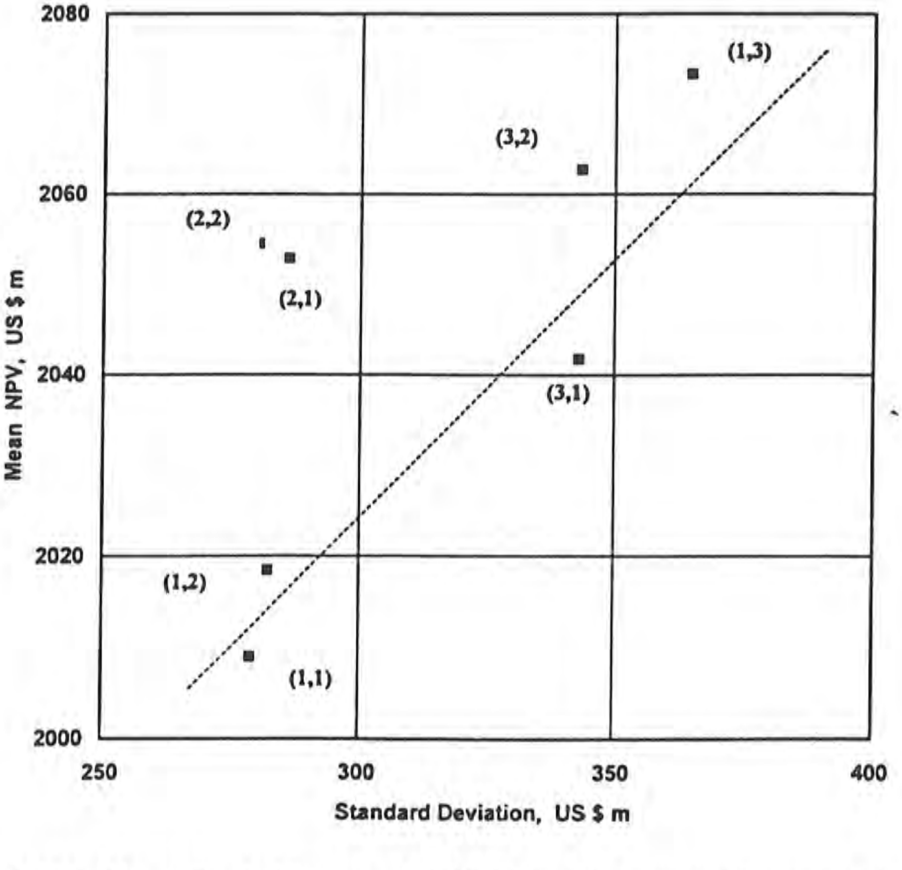


FIGURE 10: *Plot of Mean vs Standard Deviation of NPV for Various Methane-Based Complexes (Excluding Policy 4)*

shift towards the production of downstream petrochemicals proved to be superior to policies which encourage further upstream expansions in ammonia and methanol.

(3) Plans for the methane-based industry involving further ammonia and methanol plants together with an acetic acid plant and an MTBE plant was proven to be the least viable option and incorporated the greatest risk.

(4) Given that the best policies suggested an immediate shift to downstream production (rather than continued ammonia and methanol expansions), this suggests that the current structure of the methane-based industry is already poised for embarking on a path of downstream production. This could lead to a well-integrated industry (e.g., that given by Policies 1 and 2) within a 10-year period. Such an industry produces an optimum blend of basic, intermediate and consumer petrochemicals, which ensures that maximum local benefits are accrued from the consumption of resources.

(5) One viable long-term structure could include the following expansions: three acetic acid plants built three years apart, one ammonia plant, one methanol plant, one formaldehyde plant, at least one urea-formaldehyde plant, one melamine plant, at least one melamine-formaldehyde plant, one MTBE plant and at least one MMA plant.

(6) Policies which encourage downstream production proved to be the least risky and yielded the highest returns (mean NPV) to risk (standard deviation) ratio.

7.2 General Remarks

(1) Due to the conflicting objectives of the various interest groups (i.e., investor, government and populace), maximum NPV does not ensure optimum use of financial and indigenous resources.

(2) The progress of the local petrochemical industry should not be measured by the size of investment that is made, since the greatest NPV per investment, as well as NPV per tscf of natural gas consumed are not achieved by the greatest investment. Rather, it is achieved by carefulselection of the most profitable petrochemicals and the application of a suitable policy for development.

(3) A policy for development based on the maximisation of natural gas consumption does not ensure that optimum use is being made of the gas since the corresponding benefits (such as NPV) per unit amount of natural gas consumed is not a maximum.

Nomenclature

a	supply of raw material (t/y)
AA	acetic acid
Amm	ammonia
d	petrochemical demand (t/y)
Formal/Form	formaldehyde
i	petrochemical plant
j	chemical
k_{φ}	preference factor of objective φ
Mel	melamine
Mel-Form/MF	melamine-formaldehyde
Meth	methanol
MMA	methyl methacrylate
MTBE	methyl tertiary butyl ether
NC	number of chemicals
NP	number of processes
NT	number of periods
NPV	net present value (US$m)
P	amount of purchases (t/t)
POL1 MOD1	Policy 1 Model 1
POL1 MOD2	Policy 1 Model 2
POL1 MOD3	Policy 1 Model 3
POL2 MOD1	Policy 2 Model 1
POL2 MOD2	Policy 2 Model 2
POL3 MOD1	Policy 3 Model 1
POL3 MOD2	Policy 3 Model 2
POL4 MOD1	Policy 4 Model 1
POL4 MOD2	Policy 4 Model 2
PVLAB	present value of labour (US$m)
PVTAX	present value of taxes (US$m)
Q	plant capacity (t/y)
QE	capacity expansion (t/y)
S	sales of chemical (t/y)
t	time period

tscf	trillion standard cubic feet
t/y	tonnes per year
UF/Uresa-Form	ureas-formaldehyde
w_φ	weight of objective φ
W	overall weight
W_j	amount of chemical j produced or consumed (t/y)
W_m	amount of main product produced (t/y)
y	binary variable denoting capacity expansion decision
α	unit capital cost (US$/t)
β	constant of capital cost (US$m)
φ	objective
γ	unit selling price (US$/t)
Γ	unit cost price (US$/t)
Θ	constant of operating cost (US$/y)
μ_{ij}	mass balance coefficient for process i and chemical j
μ_{NPV}	mean/expected value of NPV (US$m)
σ_{NPV}	standard deviation of NPV (US$m)

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