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GENERAL RESEARCH

Planning an Integrated Petrochemical Business Portfolio for Long-Range Financial Stability

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This paper is an extension of a research on sustainable planning of the petrochemical industry. We have previously quantified sustainability to pollution prevention represented by a health index of the chemicals and increased profit represented by a process added value. In the present study, a model with an environmental objective and strategic constraints is considered. The objective in the new model is still quantified in the same fashion as that in our previous model. However, in addition to material balance, supply/demand, and economic constraints, a new constraint set is introduced. This set represents a strategic tool in the form of the Boston Consulting Group growth/share matrix and is used as a product selection criteria to give a competitive advantage to the industry and to direct products with good growth potenial. The ultimate results would be sustainable and financially stable businesses. The model is tested on a case study of planning the development of Kuwait's petrochemical industry. Results give an optimal development structure for different scenarios but also provide a tool for long-range growth and financial stability.

Introduction

The development of a petrochemical industry is basically finding the best route in a complex network connecting feedstocks to final products. The objective of this study is to develop a model that translates the network into mathematical relations and plans for the projected development. In the model, it is assumed that the overall industry seeks to utilize its available resources in an optimal way with respect to the criteria of sustainability and under good planning strategies.

Many mathematical programming models have emerged over the years to plan for the petrochemical industry. Stadtherr and Rudd[1] defined the intermediate chemicals as a network and formulated the behavior of the petrochemical industry as a system of linear equations. Other researchers have presented variants to the linear programming model of Stadtherr and Rudd[1] with different objective functions. Rudd,[2] Al-Fadli et al.,[3] and Fathi-Afshar et al.[4] selected the minimization of the total production cost; other studies, those of Sokic and Stevancevic[5] and Stadtherr and Rudd,[6] selected the minimization of feedstock consumption.

Multiobjective analysis in the modeling of the petrochemical industry has also been considered. Fathi-Afshar and Yang[7] considered a dual objective of minimizing cost and gross toxicity. Sophos et al.[8] considered the minimization of entropy creation (lost work) and feedstock consumption.

The linear programming for planning the petrochemical industry may recommend the production of a single chemical using more than one technology with unacceptably low production rates.[9] This caused a shift to mixed-integer linear programming (MILP) models. A MILP model was proposed by Jimemez et al.[10] and Jimemez and Rudd[11] to study the Mexican petrochemical industry with a fixed charge operating cost as an objective function. The model selects a process to be installed if the production cost of its product reaches a favorable level with respect to the cost of importing the chemical. The development of the petrochemical industry in the Kingdom of Saudi Arabia was also studied with a MILP model. Al-Amir et al.[12] proposed a MILP model similar to the Jimenez et al.[10] model but with a small modification in process capacity constraints. The objective function was the maximization of the total annual profit. A MILP model was recently proposed by Al-Sharrah et al.[9] with sustainability as the objective and applied to a case study on the development of Kuwait's petrochemical industry. The model gave an optimal structure for the development of the industry and proved that simple indicators can represent sustainability well. Sustainability is defined as "economic development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs".[13] Within the petrochemical industry, support for the concept of sustainable development is based on the following:[14] (i) protection and improvement of the quality of the environment; (ii) prudent management of available resources including the development of new, clean, and energy-efficient technology; (iii) the transition toward a cleaner and more sustainable mix of energy sources

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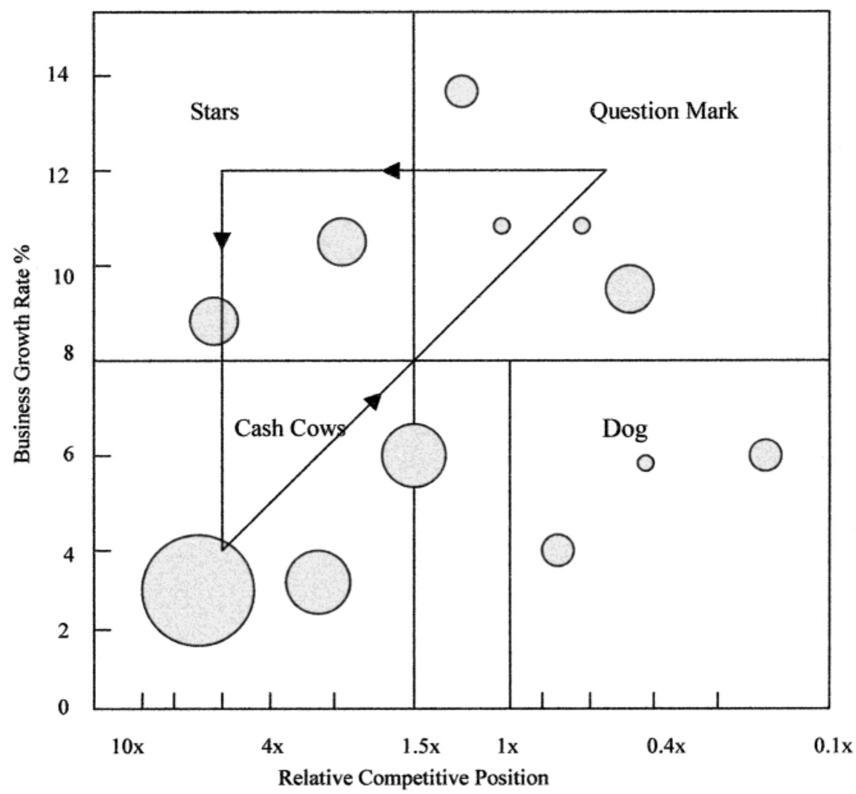

Figure 1. BCG business portfolio matrix.

and consumption patterns (including a switch from high-carbon to low-carbon fuels).

In this study, the economics, represented by the added value, and the health, represented by a health index, were used to represent the sustainability of the planned petrochemical industry. A strategic constraint will be added to the sustainability formula to incorporate the financial aspect of sustainability. A business in order to be sustainable must be financially stable. We will show below how to incorporate a simple strategic tool to represent financial stability.

Manufacturing Strategy and Product Selection Tools

Manufacturing strategy is an area of growing concern in most industries. It is simply an effective use of resources to maintain a strong competitive position in the market. For any manufacturing firm to stay competitive in the more globally oriented market of today, the understanding of strategic, tactical, and operational issues concerning the link between markets, products, and production is fundamental.[15]

Nowadays, there is a shift in strategic thinking arising from the increasing importance of technology and innovation to the overall strategy of the industry. These aspects of the industry's activity can no longer be treated as a tactical issue. The resource development and environmental interactions are increasingly dependent on the availability of innovative products, processes, and services. Therefore, to achieve its corporate and business objectives, the industry needs to have an innovation and technology strategy and to integrate these into its corporate and business strategies. The importance of innovation and technology strategy in this decade is far greater than that in any other period in the past 50 years. It is this period of low and stable inflation coupled with financial markets collapse that would give rise to major and radical technology innovations.[16]

The main step in developing a strategy is to prepare a list of all of the products that are in the portfolio of the industry for which a strategy is being prepared. It is then necessary to identify the development and competitive advantage the industry is able to achieve through these products. This is best done through the use of some form of strategic product selection tools that can show the industry's strength and weakness, opportunities, and threats. Selecting products is a part of product engineering that deals with the research methodologies, tools, and strategies.

From our knowledge of chemical engineering fields, process engineering in the last several decades attained a high degree of scientific maturity.[17] The other field, product engineering, is a younger, less mature area where we answer the question of what products do we produce and how are they produced? Tools used for product selection are usually an assessment of quantitative and qualitative information together with human expert judgment.

A classic product selection tool is the Boston Consulting Group (BCG) Business Portfolio Matrix, as shown in Figure 1. Although developed for a multidivisional firm, it can be used in a firm with a multiproduct portfolio; the contribution of the product to the competitive position of the firm is similar to that of the business. It is a simple four-square grid. One axis is the "relative competitive position" usually measured by market share, and the other is the "business growth rate" expressed as a percentage. Businesses are placed in the quarters according to an assessment of their performance. In Figure 1 the size of the circle is proportional to the size of the business involved. The names given to each quarter are supposed to reflect the nature of the business.

Stars are those businesses (products) that are growing rapidly and have high investment demand.

Cash cows are those business (products) which have low growth and high market share; they usually have a superior market position with low costs, low growth rates, and low demands for investment funds. This enables them to generate large cash surpluses.

Dogs are those businesses (products) that usually have a high cost-competitive position, so that in times of high inflation they may not have sufficient cash to maintain their businesses.

Question marks or problem children are those businesses (products) with a high cash need; their potential for cash generation is low because they only currently have a low market share. Radical innovations normally fall in this category.

In short, the BCG matrix is a strategic tool that is used to maintain financial sustainability of business. To use the matrix, a firm would determine the values of each dimension for each of its products, and when it is placed in the matrix, this would provide an overview of the company portfolio. It would indicate whether the parts of the business were concentrated in one area. The theory suggests that portfolios should be reasonably balanced among stars, cash cows, and question marks and that this is the desired direction for continued success and profitability. A company may develop a product in a high-growth market, which initially has a low market share (question mark). The company should plan to increase the market share and thus move the product into the star category. While the product remains a star, it is unlikely to release cash. Given that the market is still growing rapidly, the cash generated, and maybe more, will be required for a new plant to satisfy the increases in demand. As the market growth rate slows down, less cash is required for reinvestment and thus the product automatically becomes a cash cow, with the cash being released rather than used for reinvestment. As the growth slows even further, the theory enables revitalization to the question mark stage and so the cycle begins again. Dogs are low-market-share products in a declining industry, and so the firm should exit from these businesses unless there is a special reason for not doing so.

If there are too many stars, a cash crisis may result; if there are too many cash cows, future profitability may be in jeopardy; and if there are too many question marks, current profitability may be affected.

Use of the BCG portfolio enables the scope and competitive advantage of each product to be established and the strategy for each business to be identified. Also it is a useful analytical device for organizing ideas about the industry products and moving funds to balance the financial viability of the business. Therefore, it is considered as a good product selection tool in the sense of assessing financial sustainability. Details of the BCG matrix theory can be found in work by Koch.[18]

Another strategic tool used in planning and product selection is the bill of material (BOM).[15] Normally, the end product is broken down into a number of intermediate products and additives. This creates a list of items, each with its own BOM representing the items needed to produce an item. Therefore, any production planning should be accompanied with BOMs for successful operation. In strategic planning, the striving for flatter BOM, or in other words a shorter internal supply chain, and simpler products is increasingly used.[15]

The changing market and increased product variety proposed an important strategic tool in the manufacturing systems, which is flexibility. Flexibility can support the industry strategies as a competitive weapon. Persentili and Alptekin[19] quantified flexibility as being inversely related to the sensitivity to change (STC). The lower the sensitivity of the product to the globally changing environment, the higher the flexibility. Changes affecting products may include price, demand, environmental constraints, feedstock availability, etc. The original formulation of STC has two components: penalty for change and probability of change. The definition of STC is made in the general form as[19]

$$\text{STC} = \text{penalty} \times \text{probability}$$

In this study, the BCG strategic tool is used as a constraint together with other material, economics, and supply/demand constraints in order to guide the product selection process toward long-range growth and financial stability. The next section will give a detailed representation of the model.

Model Development

Following the notation in our previous model,[9] let N be the number of chemicals involved in the operation of M processes, X_j the annual level of production of process j, Q_i the total amount produced of chemical i, F_i the amount of chemical i as a feedstock, and a_{ij} the output coefficient of material i in process j. The main constraints that govern the operation of the petrochemical network are the material balance constraints:

$$F_i + \sum_{j=1}^{M} a_{ij} X_j = Q_i \qquad i = 1, 2, ..., N \tag{1}$$

These constraints ensure that the total quantity produced of each material i is equal to the sum of all amounts produced (or consumed) by all processes plus its quantity as a feedstock.

The products in the planned petrochemical industry will be governed by their demands in the petrochemical market, according to the country's share in that market. Constraints on Q_i for all products are needed, and they are formulated as

$$Q_i \le D_i U \qquad i = 1, 2, ..., N \tag{2}$$

where D_i is the world demand for chemical i and it is multiplied by the country's share in the petrochemical market; U represents valid upper limits on the country's share.

Introducing the binary variables Y_j for each process j will help in the selection requirement of the planning procedure. Y_j will be equal to 1 only if process j is selected and 0 if process j is not selected. Also, if process j is selected, the production level must be at least equal to the process minimum economic capacity B_j. For each process j, we can write the following constraint:

$$B_j Y_j \le X_j \le K Y_j \qquad j = 1, 2, ..., M \tag{3}$$

where K is a valid upper bound.

The proposed improvement of a petrochemical industry is directed toward building new plants to produce petrochemicals, so it is logical for many countries that only one process should be selected to produce a single chemical. Then we should include the following constraints for all chemicals:

$$\sum Y_j \leq 1 \qquad j \in J \tag{4}$$

where J is the group of processes that produce a single chemical.

The supply of feedstock limitations will impose additional constraints on the selection and planning, i.e.,

$$F_i \leq S_i \qquad i \in I_2 \tag{5}$$

where S_i is the supply availability of feed chemical i. The above constraint only applies for the set I_2 of some main feedstock chemicals.

The strategic constraint is represented by the BCG matrix described previously. According to this strategic tool, the industry portfolio should be reasonably balanced among stars, cash cows, and question marks. Knowing the age and growth rate of all chemicals in the model, they are easily classified as stars, cash cows, question marks, or dogs by defining the vertical and horizontal lines that cuts Figure 1, forming the squares. This classification can be applied to the processes included in the model by appropriately defining associated coefficients. For instance, let

$$\text{stars}_j = \begin{cases} 1 & \text{if process } j \text{ is producing a star chemical} \\ 0 & \text{otherwise} \end{cases}$$

Similar definitions are cash cows$_j$, question marks$_j$, and dogs$_j$. The BCG constraint for a balanced distribution of chemicals, or processes, in the industry portfolio is quantified as a specified number G representing the difference between the number of processes in the stars, cash cows, and question marks and a small number of processes in the dogs square:

$$\left|\sum_{j=1}^{M} \text{stars}_j \times Y_j - \sum_{j=1}^{M} \text{cash cows}_j \times Y_j\right| \leq G \tag{7}$$

$$\left|\sum_{j=1}^{M} \text{stars}_j \times Y_j - \sum_{j=1}^{M} \text{question marks}_j \times Y_j\right| \leq G \tag{8}$$

$$\left|\sum_{j=1}^{M} \text{question marks}_j \times Y_j - \sum_{j=1}^{M} \text{cash cows}_j \times Y_j\right| \leq G \tag{9}$$

$$\left|\sum_{j=1}^{M} \text{dogs}_j \times Y_j\right| \leq G \tag{10}$$

Note that eq 10 places an upper limit on the number of processes that fall into the category dogs. This limit does not necessarily have to be the same limit, G, that represents the difference between the number of processes in the categories stars, cash cows, and question marks.

An additional economic constraint is required for the limit on the investment budget. If cap$_j$ is the capital investment cost for constructing plant j and Bg is the available budget, then the constraint is formulated as

$$\sum_{j=1}^{M} \text{cap}_j \times Y_i \leq \text{Bg} \tag{11}$$

Now, we need to define the objective function that represents sustainability. The proposed method to quantify the sustainability aspect is to define a composite objective that represents both environmental and economic aspects. We proceeed in the same fashion as that in our previous work[9] and write the objective function in two parts: a toxicity objective Z_1

$$\min Z_1 = \sum_{j=1}^{M} \sum_{i=1}^{N} a_{ij} H_i X_j \tag{6}$$

and an economical profit Z_2

$$\max Z_2 = \sum_{j=1}^{M} \sum_{i=1}^{N} a_{ij} C_i X_j \tag{7}$$

Both parts should be appropriately scaled before being used within the composite objective. H_i in eq 6 represents the health index of chemical i as defined by the National Fire Protection Association,[20] while C_i in eq 7 represents the price of chemical i.

Illustrative Case Study

The same case study presented earlier[9] on the development of Kuwait's petrochemical industry will be used here to illustrate the present model. A petrochemical network of 83 processes linking the production and consumption of 65 chemicals was proposed for the development of the industry. A simplified network is illustrated in Figure 2. The data needed for the case study were collected from SRI[21] reports, Kuwait Petrochemical Industry Company (KPIC) annual reports, and NFPA[20] standards. More details can be found in work by Al-Sharrah et al.[9]

The BCG matrix is divided into its corresponding squares by first defining a mature age for the chemicals (vertical line) and a moderate growth rate (horizontal line); in this study, 70 years and 3% growth rate were used according to a general study of the history of the petrochemical market. Data for the age and growth rate of chemicals are taken from different sources, and accordingly they were classified as stars, cash cows, question marks, or dogs. Table 1 shows growth rates and ages of some products selected by the model solution.

To solve the model, the second part of the objective function is transformed to minimization by multiplying by a negative sign, and then the two parts are normalized and added to form one minimization objective. The model was solved using the commercial optimization package GAMS.[22] The solution indicated the selection of 23 processes out of the 83 processes that form the petrochemical network. The selected chemical products and their respective net production rates are shown in Table 1 and the corresponding BCG is shown in Figure 3.

It is noticed that the BCG matrix (Figure 3) is reasonably distributed between the cash cows, question marks, and stars squares with some products in the dogs square. These dogs products are, namely, acrylonitrile, ABS, and chlorobenzene. Acrylonitrile is used in the production of acrylic fibers and ABS (Acryloni-

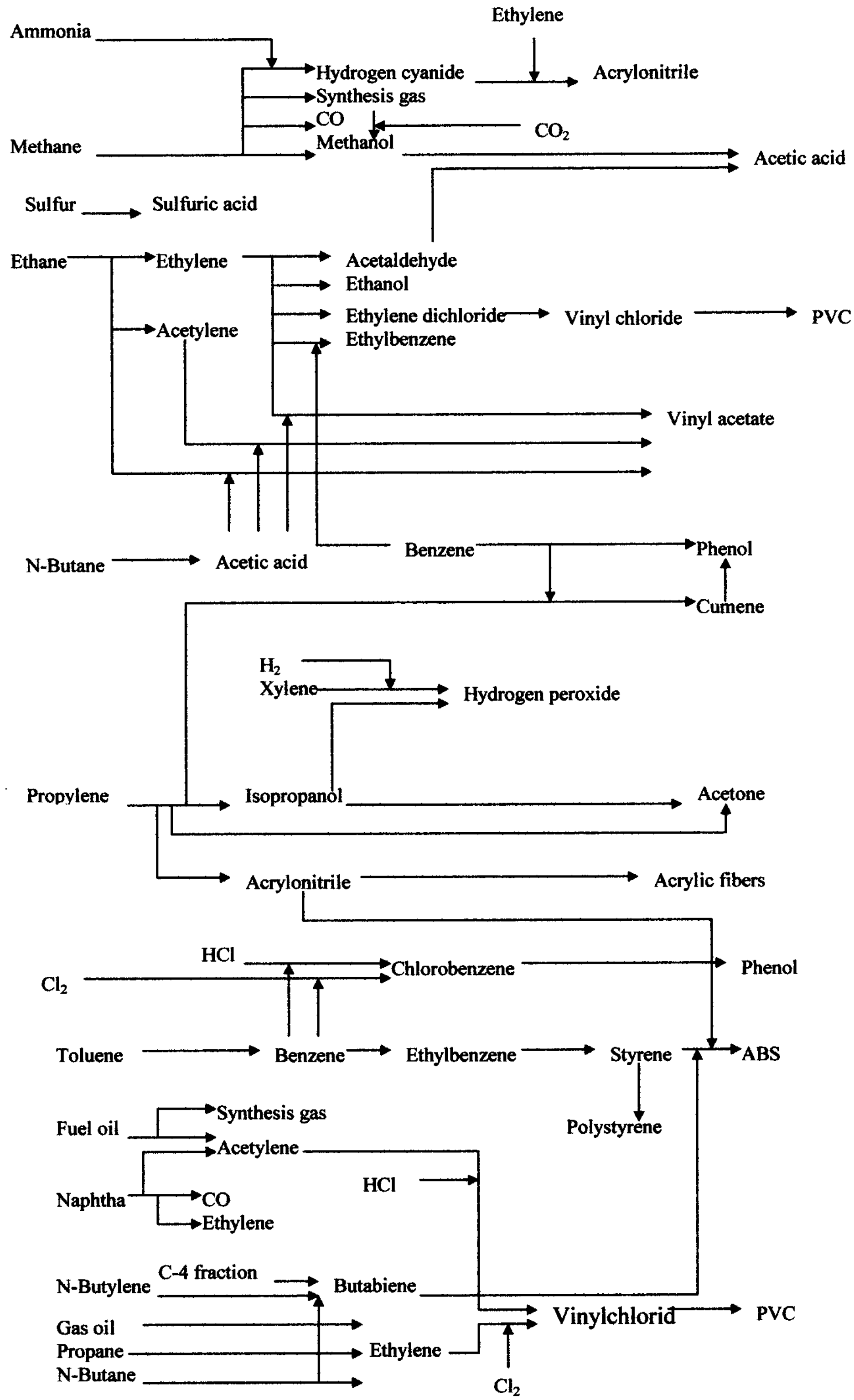

Figure 2. Simplified network of processes in the model.

trile-butadiene-styrene) that have good health indices; in addition, ABS has a very high added value. Chlorobenzene is a reasonable health and added value chemical. The distribution of products in the BCG matrix is not with clear spread because of the close ages and growth rates of chemicals in the petrochemical industry.

When the model was solved without the inclusion of the BCG constraint set, as was done in the previous work,[9] the result was process selection without any strategic plan. The BCG matrix of the solution indicated that the proposed planning was positioned mainly in the cash cows square, which means only immediate profitability.

A sensitivity analysis was carried out to study the effect of changing the parameter *G* in the model. This parameter needed to be specified in the model in order to restrict the difference between the number of processes in the stars, cash cows, and question marks and to impose a small number of processes in the dogs

Table 1. Model Optimal Solution

chemical/process selected	chemical age (yr)	chemical growth rate (%)	net production[a] (10^3 tons/yr)
acetaldehyde by the two-step oxidation from ethylene	85	3	80
acetic acid by low-pressure carbonylation of methanol	86	3	240
acetone by the dehydrogenation of 2-propanol	49	3	151.552
acetylene by the pyrolysis of naphtha (one-stage partial oxidation)	100	1	6
acrylic fibers by the batch suspension polymerization	39	6	113.02
acrylonitrile by ammoxidation of propylene	49	2	68.8
ABS by suspension/emulsion polymerization	59	1.6	164
benzene by hydrodealkylation of toluene	149	2.9	0
butadiene by extractive distillation	70	2	105.2
carbon monoxide from naphtha	85	4	0
chlorobenzene by oxychlorination of benzene	47	2	80
ethylbenzene by the alkylation of benzene	69	3	238.437
ethylene by steam cracking of ethane−propane (50/50 wt %)	70	2.5	278.87
hydrogen peroxide by autoxidation of 2-propanol	74	8	28
2-propanol by the hydration of propylene	79	2	26.4
methanol from methane (medium pressure)	76	4	206.847
polystyrene (crystal grade) by bulk polymerization	61	3	11.57
polystyrene (expandable beads) by suspension polymerization	61	3	68.604
polystyrene (impact grade) by bulk suspension polymerization	61	3	308.36
poly(vinyl acetate) by solution polymerization	60	3	80
poly(vinyl chloride) by bulk polymerization	69	4	272.156
propylene (chemical grade) from propylene refinery grade			398.837
styrene from ethylbenzene by the hydroperoxide process	74	5	244.8
sulfuric acid be the double absorption process	101	1	289.345
vinyl acetate by the reaction of acetylene and acetic acid	74	3	63.504
vinyl chloride by the hydrochlorination of acetylene	74	3	323.2

[a] Zero net production corresponds to an intermediate chemical (i.e., produced and then consumed in the network).

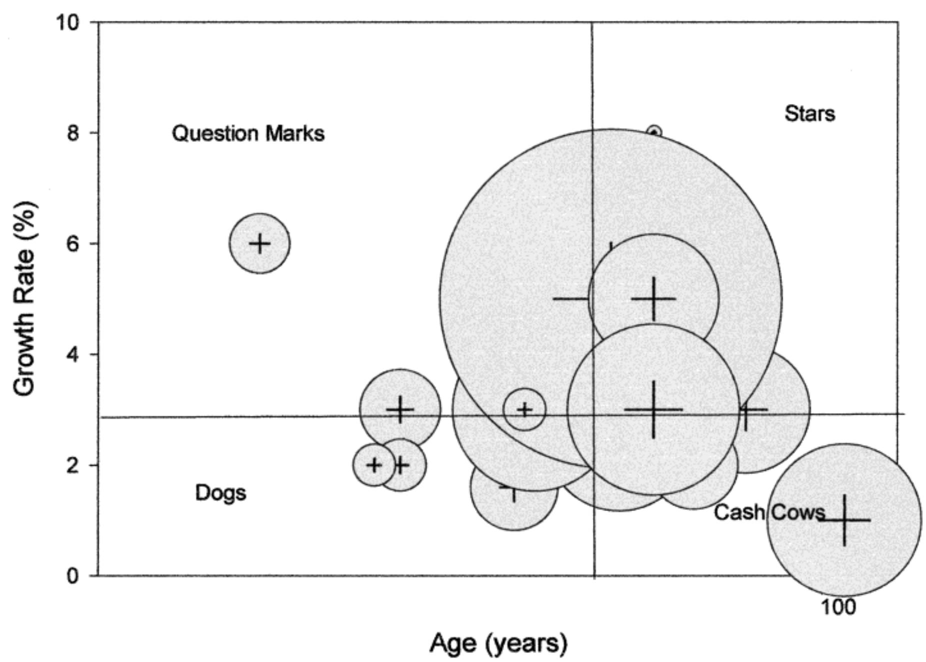

Figure 3. Optimal solution of the BCG matrix.

Table 2. Effect of BCG Distribution on the Model Solution

distribution number G	objective function value at optimal solution	no. of iterations
2	no optimal solution	reached over 10 000
3	−893.228	5602
4	−901.274	1345
5	−964.29	348

square. In the first model solution, that number was set to 4. Changing this number has a significant effect on the model solution. Table 2 outlines these effects. Because the overall objective function is minimization, relaxing the "G constraint" will improve the objective function because of an increase in the feasible solution area. A very low G gives a tight limit on the model selection and, as can be expected, an infeasible solution.

The ability of the model to adapt to changes or recommendations by decision makers was also tested. In the case of Kuwait's petrochemical industry, it already includes the chemicals benzene, methanol, and propylene. To include this information in the model, the inequality in eq 4 should be replaced by an equal sign only for these three chemicals. The model will then suggest strategic ways to supplement the existing industry. Solution of the model in this mode resulted in an objective function that is worse by only 0.8% of the objective of the original case.

Concluding Remarks

Product selection is a new challenge for the chemical engineer because of its important role in strategic planning. The petrochemical industry is one of the most important areas for the application of product selection. It is a complex industry that will not easily adapt to future changes. Therefore, early studies of plans and strategies are essential. The BCG growth/share matrix concept proved to be a good strategic product selection tool that can be quantified easily and then incorporated into planning models.

A MILP model based on the BCG matrix was presented for the development of the petrochemical industry. The objective of the model was based on sustainability, while the constraint set was based on material balance, demand and supply, budget, and growth strategy represented by the BCG matrix. The model proved to be useful in directing the industry to long-range growth and financial stability.

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