A two-person non-zero-sum game model of the world oil market

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The world oil market is modelled as a two-person non-zero-sum game in normal form with each player having a continuum of strategies. The two players are the oil importing nations (OPIC) and the oil exporting nations (OPEC). The game is solved in the noncooperative sense using the equilibrium point solution concept due to Nash. The Nash equilibrium point solution yields an analytic expression for the optimal price per barrel of oil for OPEC and the optimal level of imports of oil for OPIC assuming noncooperation between the players. The cooperative solution to the game is also investigated using the von Neumann–Morgenstern negotiation set solution and Nash's bargaining point solution. Again, we give analytic expressions for the optimal price of a barrel of oil and the optimal level of imports of oil assuming that the players cooperate (negotiate, bargain, etc., for a binding agreement) in arriving at a solution.

Introduction

In the winter of 1973, some major oil exporting countries belonging to the OPEC cartel declared an embargo on oil exports to some of the western countries for political reasons. Elated by their success and the realization that they controlled a major share of the oil exports, they subsequently raised the price of oil four-fold and cut back production thus obtaining (in the face of an almost inelastic demand) increased revenues. Since then, the major oil importing countries have been trying to work out an optimal energy policy designed to obtain their energy needs at the lowest possible prices. Some of the strategies available to the oil importing countries are as follows:

(i) Decrease the consumption of oil
(ii) Increase the domestic production of oil
(iii) Invest heavily in research and development of a competitive and alternate source of energy
(iv) Form a counter-cartel of oil importing countries to coordinate their strategies against the OPEC cartel
(v) Attempt to split the oil cartel by bilateral dealings with the individual countries in the OPEC cartel or by playing one member country off against another
(vi) Take over the oil fields of the OPEC countries by military force
(vii) Stockpile large quantities of oil sufficient to outlast an oil embargo by OPEC over a long period of time
(viii) Shut off essential imports of the oil producing countries such as machinery, technology, spare parts for oil extracting and refining plants, food, arms, etc.
(ix) Block the investment of oil money (earned by OPEC with oil exports) into their (oil importing countries') economy
(x) Link the economies of the oil importing countries together so closely that OPEC nations would have a vested interest in the welfare of the oil importing countries and vice versa.

The strategies available to the oil exporting countries are as follows:

(i) Raise the price of oil even more for increased revenues from oil exports
(ii) Restrict production of oil so as to create a shortage in the oil market enabling them to sustain high prices
(iii) Protect itself from world inflation by tying the price of oil to the worldwide prices of other goods or reject payment in dollars (or other currency of the oil importing countries) and insist that the oil importing countries use a new 'Arab Dinar'.
(iv) Use excess capital accumulated from oil exports as a tool in breaking up any cartel of oil consuming nations
(v) Declare an embargo on oil exports
(vi) Organize other raw material producers under its auspices with the aim of bringing about a further transfer of wealth and goods to the underdeveloped world
(vii) Seek help from USSR and other communist countries to thwart any embargo or military intervention by the oil consuming nations.

We shall denote the oil importing countries by OPIC and oil exporting countries by OPEC, and make the follow-

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ing observations regarding the strategies of the OPIC and OPEC nations:

(1) Strategy (v) of OPEC can be countered to some extent by strategies (vii) and (viii) of OPIC
(2) Strategies (vi) and (viii) of OPIC can be counteracted by strategy (vii) of OPEC
(3) Strategy (vi) of OPIC though feasible under certain circumstances is only effective as a 'threat' in extreme circumstances (to prevent the collapse of the social and economic structure of the nation as a result of an extended embargo on oil exports by OPEC). In the same sense strategies (v) and (vi) are 'threat strategies' for OPEC
(4) Strategy (x) of OPIC is relevant in a 'cooperative' solution of the problem
(5) Strategies (iv) and (v) of OPIC and strategy (iv) of OPEC need to be investigated using the theory of n-person cooperative games[1]

In short, OPIC is interested in a policy that will ensure an adequate supply of oil at lowest possible prices and OPEC is interested in a policy that will give them the maximum revenues from their finite oil reserves in order to develop their underdeveloped economies.

The model

The world oil market is modelled as a two-person non-zero-sum game. Player 1 called OPIC represents the oil importing nations and player 2 called OPEC represents the oil exporting nations. Implicit in this formulation is the assumption that all major oil importing countries have formed a cartel and bargain collectively as one unit and that this cartel is the sole market for the oil exported by OPEC. A similar assumption is made about OPEC which monopolizes all the oil imported by OPIC.

We assume that OPIC needs a total of I million barrels of oil daily (mmbd) representing consumption required for a maximum growth of their economy. A part of this requirement can be met by domestic production of oil. By a large investment, the domestic production of oil can be increased by finding new sources, or just by working the existing oil wells harder using improved technology. Alternatively, the demand for oil can partly be satisfied by other fuels such as coal, nuclear fission, shale oil and other new sources that could be developed by large investment in research and development. Furthermore, the consumption of oil could be reduced by voluntary or mandatory methods such as rationing the supply of oil, an energy tax, etc. This may, however, result in a decrease in OPIC's economic growth. In short, the strategy for OPIC is to decide the quantity of oil imports. More formally, we denote the strategy space of OPIC:

$$\Sigma_1 = \{x \in E^1\colon\ 0 \leqslant x \leqslant \mathrm{I}\} \tag{1}$$

Associated with a strategy $x \in \Sigma_1$ is a monetary cost to OPIC, denoted by $f(x)$, for restricting its imports to x mmbd. $f(x)$ does not include the cost of imports. A sketch of a method of computing $f(x)$ is as follows.

Let $h(y)$ denote the total cost in million dollars daily (mm\$d) to ensure that domestic production of oil (or other sources of energy) is at least y mmbd. Let $g(z)$ denote the loss in million dollars daily in OPIC's GNP* if the total oil (energy) consumption is restricted to z mmbd. Then, we have:

$$f(x) = \min_{0 \leqslant y \leqslant I - x} [h(y) + g(y + x)] \tag{2}$$

We will assume that $f(x)$ is a nonincreasing, positive, real-valued function defined on the strategy space Σ_1 of OPIC.

Let the total proven oil reserves of OPEC be R million barrels. It costs OPEC an average of c dollars per barrel to extract the oil from the fields. The strategy for OPEC is to decide the price p of a barrel of oil exported to OPIC. Denote the strategy space of OPEC by Σ_2:

$$\Sigma_2 = \{p \in E^1\colon\ c \leqslant p < \infty\} \tag{3}$$

where E^1 is the Euclidean space of dimension one. Let Σ,

$$\Sigma = \Sigma_1 \times \Sigma_2 = \{(x, p)\ \ x \in \Sigma_1, p \in \Sigma_2\} \tag{4}$$

denote the set of all possible outcomes. Let $u_i\colon\ \Sigma \to E^1$ denote the utility (payoff) function of player i, $i = 1, 2$, defined on the set of all possible outcomes.

To complete the formulation of the world oil market as a game, we need to define the utility function of each player. Neglecting political, psychological and other considerations, we can define the utility functions purely in terms of monetary gains (or losses). Assuming that utility is linear in money, we have:

$$u_1(x, p) = -f(x) - px \tag{5}$$

for each outcome $(x, p) \in \Sigma$ (see *Figures 1* and *2*). The monetary payoff to OPEC resulting from the outcomes $(x, p) \in \Sigma$ is $(p - c)x$ mm\$d. We assume that OPEC's economy is sufficiently developed to absorb all revenues from oil exports. Again, assuming that utility is linear in money, we have:

$$u_2(x, p) = (p - c)x \tag{6}$$

for each $(x, p) \in \Sigma$. However, under a long-term policy, OPEC may be interested in obtaining the maximum revenue from its finite oil reserves of R million barrels. In this case, assuming that parameters of the problem (I, f, c) remain constant with time, we would have:

$$u_2(x, p) = \begin{cases} 0 & \text{if } x = 0 \\ \sum_{i=0}^{[R/x]} (p - c)x\beta^i & \text{if } x > 0 \end{cases} \tag{7}$$

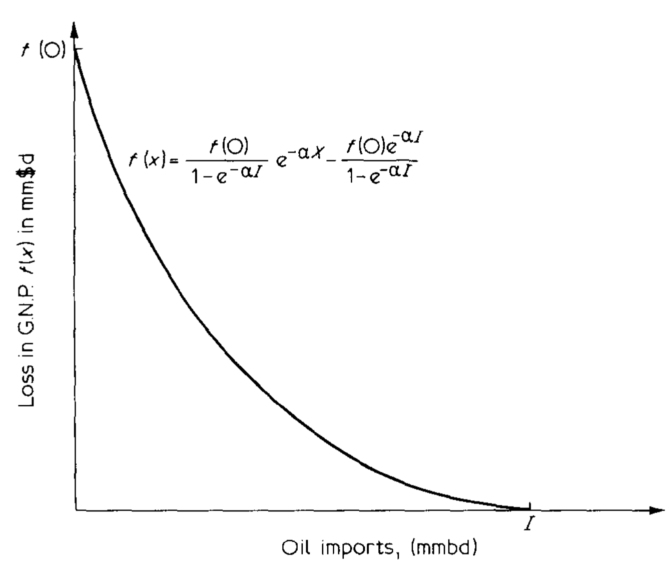

Figure 1 Exponential model of $f(x)$

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*Gross National Product. Other indicators of a nation's economic growth can also be used

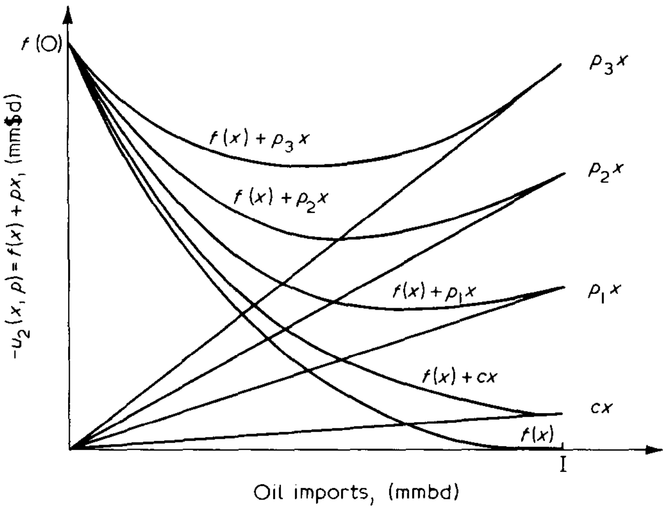

Figure 2 Utility function for OPIC

where $[R/x]$ denotes the largest integer $\leqslant R/x$ and β is the discount factor such that $0 < \beta < 1$. The sum:

$$\sum_{i=0}^{[R/x]} (p - c)\, x\beta^i$$

represents the discounted sum of revenues in million dollars that OPEC would earn from its total oil reserves of R million barrels given that outcome (x, p) is constant during this period (of $[R/x]$ days).

If the function f is completely known then the formulation of the world oil market as a two-person non-zero-sum game is complete. Determining an accurate nature of the function f is no trivial task. However, several studies have been made to determine the function $f(x)$ for the USA. (See Appendix for more details.)

In the next section, we show the Nash[2] equilibrium point solution of the game when played in the noncooperative sense. In this case, the nonincreasing assumption for the function f suffices to find the solution. Later in the paper, assuming an exponential model for $f(x)$, we solve the game in the cooperative sense and indicate the von Neumann–Morgenstern negotiation set (see von Neumann and Morgenstern[3]), and the Nash's bargaining point solution (see Nash[4]) of the game.

The noncooperative solution of the game

By a noncooperative game is meant a game in which there is no preplay communication or an absence of a binding agreement between the players. The game can be represented as shown below:

$$\begin{array}{lll} & & \text{OPEC} \\ & & c \leqslant p < \infty \\ \text{OPIC} & 0 \leqslant x \leqslant \mathrm{I} & [u_1(x,p), u_2(x,p)] \end{array}$$

First, we find all the Nash equilibrium points of the game.

Case 1. $u_2(x,p) = (p - c)x$ for each $(x,p) \in \Sigma$
Let (x^*, p^*) be an equilibrium. Then we have:

$$u_2(x^*, p^*) = (p^* - c)x^*$$

Since $u_2(x^*, p^*) \geqslant u_2(x^*, p^* + \Delta p)$ for all $\Delta p > 0$ (by definition of a Nash equilibrium), we have:

$$(p^* - c)x^* \geqslant (p^* + \Delta p - c)\,x^*$$

i.e.,

$$\Delta p x^* \leqslant 0 \qquad \text{for each } \Delta p > 0$$

Hence, we must have $x^* = 0$.
Now, we have $u_1(0, p^*) = -f(0)$. Also $u_1(0 + \Delta x, p^*) = -f(\Delta x) - p^*\Delta x$. Since $u_1(0, p^*) \geqslant u_1(0 + \Delta x, p^*)$ for each $\Delta x > 0$ we have:

$$-f(0) \geqslant -f(\Delta x) - p^*\Delta x \qquad \text{for each } \Delta x > 0$$

i.e.,

$$p^* \geqslant \frac{f(0) - f(x)}{\Delta x} \qquad \text{for each } \Delta x > 0$$

Define:

$$p_m = \sup_{0 < x \leqslant \mathrm{I}} \frac{f(0) - f(x)}{x} \tag{8}$$

then $(0, p^*)$ where $p^* \geqslant p_m$ is an equilibrium outcome.† All equilibrium outcomes have the same utility, namely:

$$u(0, p^*) = (u_1(0, p^*), u_2(0, p^*))$$
$$= (-f(0), 0) \qquad \text{for every } p^* \geqslant p_m.$$

Case 2

$$u_2(x,p) = \begin{cases} 0 & \text{if } x = 0 \\ \sum_{i=0}^{[R/x]} (p - c)\, x\beta^i & \text{if } x > 0 \end{cases}$$

A similar analysis shows that $(0, p^*)$ where $p^* \geqslant p_m$ is an equilibrium outcome with utility vector $(-f(0), 0)$.

Since every equilibrium pair of outcomes are interchangeable, the game is solvable in the sense of Nash and since every equilibrium pair has the same utility, $(0, p^*)$ where $p^* \geqslant p_m$ (resulting in payoffs $(-f(0), 0)$) is the solution of the noncooperative game.

The noncooperative solution is for OPIC to restrict its oil imports to zero and for OPEC to charge a very high $(p^* \geqslant p_m)$ price for its oil. The Arab oil embargo in the winter of 1973 was an outcome of the game at its equilibrium, i.e., $x = 0, p \to \infty$. It was forced by OPEC in order to demonstrate to the OPIC nations the disadvantages of a noncooperative situation (noncooperation here was on a political issue). Because of the large magnitude of $f(0)$, the utility at equilibrium is more distasteful to OPIC than to OPEC (assuming that interpersonal comparison of utilities is meaningful).

If the game is played once (i.e., for a period of one day) in a noncooperative sense then the equilibrium point is a viable solution concept. However, we have a situation where the same game (the parameters of the game, in reality, change with time) is repeated every day, every month and every year. In situations like these, even when there is no preplay communication, there is, nonetheless, a form of involuntary communication. The players signal to each other via their choice patterns on previous plays. The situation in the post-embargo period when OPEC increased their price four-fold and the United States reduced their

† If we assume that $f(x)$ is a bounded and differentiable function in the interval $[0, I]$, then p_m will always exist

growth in oil imports from OPEC can be explained as a kind of preliminary jockeying before the two players realized the advantages of a cooperative bargaining solution. The long period of time involved in the process is because both the players have sluggish policy-making processes that prevent them from making their policies optimal. Their interests involve numerous considerations. Sorting out those considerations is a complicated process and the result is perhaps a characteristic preference to pursue previous plicies rather than switch to new policies unless forced to do so. In recent years the OPEC and the OPIC nations have been bargaining for an outcome which would be mutually acceptable to both the players. The theory of two-person cooperative games indicates the kind of bargaining and 'solutions' under these circumstances. This is considered in the next section.

The cooperative solutions of the game

In a cooperative game, we assume that[5]:

(1) all agreements are binding and they are enforceable by the rules of the game, and
(2) a player's evaluation of the outcomes of the game are not disturbed by the preplay negotiations.

Since the solution depends on the function $f(x)$, we will assume an exponential model for $f(x)$ to illustrate the mechanism of finding the cooperative solutions of the game. Let us assume that (see *Figure 1*):

$$f(x) = (f(0)/(1 - e^{-\alpha I}))\, e^{-\alpha x} - (f(0)\, e^{-\alpha I}/(1 - e^{-\alpha I})) \quad \text{for each } 0 \leqslant x \leqslant I$$

where α is a positive constant. Note that the studies conducted by National Petroleum Council indicate an exponential type function for $f(x)$ for the United States. (See the Appendix for more details.) Hence our assumption may not be far removed from reality.

To simplify our analysis, we will assume that the utility payoff function for OPEC is as follows:

$$u_2(x,p) = \begin{cases} p & \text{if } x > 0 \\ 0 & \text{if } x = 0 \end{cases} \tag{9}$$

This utility function is in fact equivalent to the utility function represented in equation (6) and is obtained from (6) by a positive linear transformation (which is permissible for von Neumann–Morgenstern utilities.[3])

The von Neumann–Morgenstern negotiation set

Let:

$$A = \{(u_1(x,p), u_2(x,p)):\ (x,p) \in \Sigma\} \tag{10}$$

denote the set of all possible payoffs (see *Figure 3*). Due to the nature of the game, we do not consider randomization of strategies as feasible. Hence, we will consider only pure strategies. A point $(u_1, u_2) \in A$ is said to be dominated by a different point $(u_1', u_2') \in A$, $(u_1', u_2') \neq (u_1, u_2)$ if we have $u_1' \geqslant u_1$ and $u_2' \geqslant u_2$. The set of all undominated outcomes in A is called the Pareto-optimal set. Let us denote this set by P, i.e.:

$$P = \{(u_1, u_2) \in A \text{ there does not exist } (u_1', u_2') \in A \text{ such that } (u_1', u_2') \neq (u_1, u_2), u_1' \geqslant u_1 \text{ and } u_2' \geqslant u_2\} \tag{11}$$

Let v_1 and v_2 denote the maximin values for players 1 and 2 respectively. These values represent the amount each player can guarantee for himself by treating the game in a noncooperative manner. The negotiation set, denoted by N, is then defined as:

$$N = \{(u_1(x,p)\, u_2(x,p)) \in P:\ u_1(x,p) \geqslant v_1 \text{ and } u_2(x,p) \geqslant v_2\} \tag{12}$$

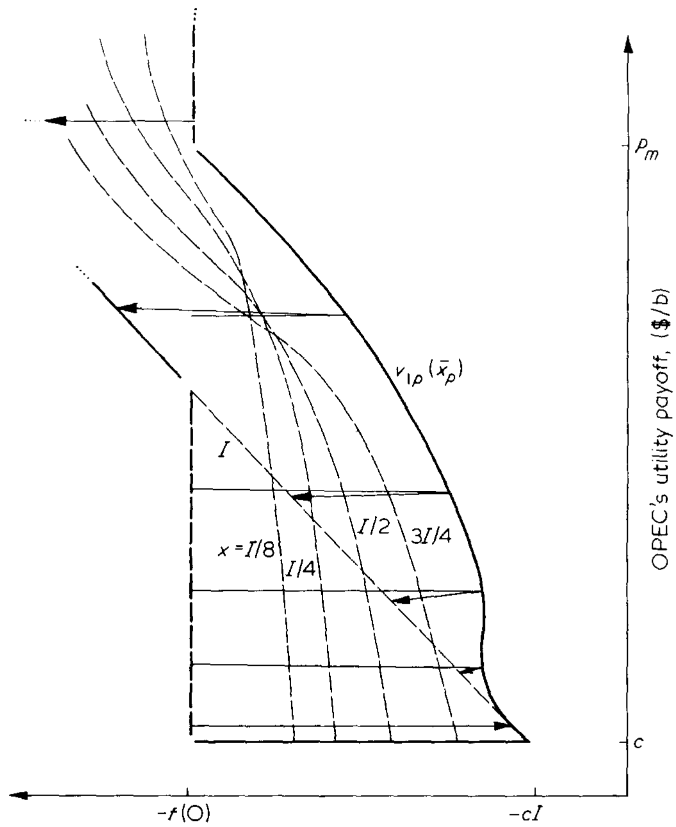

Figure 3 Geometrical representation of game in payoff space. (→), indicates changes in payoff for constant strategy p of OPEC and as $x = 0 \to I$. (– – –) indicates contour lines for constant strategy x of OPIC

As shown in the last section, for our game, $v_1 = -f(0)$ and $v_2 = 0$. The corresponding maximin strategy for OPIC is $x = 0$ and for OPEC is $p \geqslant p_m$.

Suppose OPEC chooses a fixed strategy $p \in \Sigma_2$. Then the payoff to OPIC if it chooses strategy $x \in \Sigma_1$, denoted by $v_{1p}(x)$, is:

$$v_{1p}(x) = u_1(x,p) = -f(x) - px = -K_1 e^{-\alpha x} - K_2 - px$$

where:

$$K_1 = f(0)/(1 - e^{-\alpha I})$$

and

$$K_2 = f(0)\, e^{-\alpha I}/(1 - e^{-\alpha I})$$

v_{1p} is a concave, continuous function of x. Let $\bar{x}_p$ denote the value of x at which v_{1p} is maximized. Then $\bar{x}_p$ is found by setting the first derivative of v_{1p} to zero. That is:

$$v_{1p}'(x) = \alpha K_1 e^{-\alpha x} - p = 0$$

i.e.:

$$\bar{x}_p = \begin{cases} \dfrac{1}{\alpha} \ln(\alpha K_1/p) & \text{if } \dfrac{1}{\alpha} \ln(\alpha K_1/p) \leqslant I \\[2ex] I & \text{if } \dfrac{1}{\alpha} \ln(\alpha K_1/p) > I \end{cases} \tag{13}$$

The payoff to OPIC at this strategy $\bar{x}_p$, is:

$$v_{1p}(\bar{x}_p) = \begin{cases} -\dfrac{p}{\alpha}\,[1 + \ln(\alpha K_1/p)] - K_2 & \text{if } \dfrac{1}{\alpha}\ln(\alpha K_1/p) \leqslant I \\ -pI & \text{if } \dfrac{1}{\alpha}\ln(\alpha K_1/p) > I \end{cases}$$

The value of P_m (see equation (8)) is given by:

$$P_m = \sup_{0<x\leqslant I} \frac{f(0) - f(x)}{x} = f'(0) = \alpha K_1$$

We can now describe the negotiations set of the game as (see *Figure 4*):

$$N = \{(v_{1p}(\bar{x}_p), p):\; c \leqslant p < p_m\}$$

The cooperative two-person theory of van Neumann and Morgenstern singles out the negotiation set as the 'cooperative solution' of the game. In other words, the players act jointly to discard all the dominated payoff pairs and all undominated payoffs which fail to give each of them at least the amount he could be sure of obtaining without cooperating with the other player.

The actual selection of a payoff from the multiplicity of points in the negotiation set N depends on certain psychological aspects of the players which are relevant to the bargaining context. We shall consider one such outcome – Nash's solution – in the next section.

Nash's bargaining point solution

The procedure for finding Nash's solution is as follows.

(i) Change the origin of measurement of utility for each player so that the maximin point (v_1, v_2) is transformed into $(0, 0)$ and let the resulting transformation of A be denoted by A'.

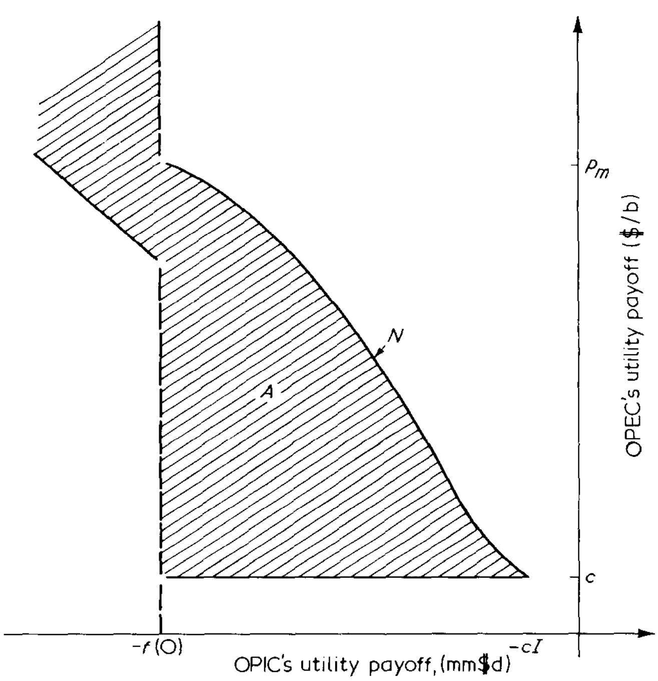

Figure 4 von Neumann–Morgenstern negotiation set

(ii) In region A', find the unique (if one exists) point $(u_1^{0'}, u_2^{0'})$ such that $u_1^{0'}u_2^{0'}$ is the maximum of all products $u_1'u_2'$ where $(u_1', u_2') \in A'$.

(iii) The Nash's solution to the game, denoted by (u_1^0, u_2^0) is obtained by inverting the utility transformation on $(u_1^{0'}, u_2^{0'})$. Using the above procedure, we wish to find the value of p at which:

$$\max_{c\leqslant p<p_m} (f(0) + v_{1p}(\bar{x}_p))(p)$$

is attained.

The value of p for which $(1/\alpha)\ln(\alpha K_1/p) = I$ is $p = \alpha K_1 e^{-\alpha I}$. So we need the value of p at which we attain:

$$\max\left\{ \max_{\alpha K_1 e^{-\alpha I}\leqslant p<p} \; pf(0) - \frac{p^2}{\alpha}[1 + \ln(\alpha K_1/p)] - pK_2 \atop \max_{c\leqslant p\leqslant \alpha K_1 e^{-\alpha I}} \; pf(0) - p^2 I \right\}$$

Let p_N be the value of p at which the above maximum is attained.

Case (i) $\alpha K_1 e^{-\alpha I} \leqslant p_N < p_m$

In this case, the Nash's solution is given by:

$$-\frac{p_N}{\alpha}(1 + \ln(\alpha K_1/p_N) - K_2, p_N) \in P \tag{14}$$

Case (ii) $c \leqslant P_N \leqslant \alpha K_1 e^{-\alpha I}$

In this case, Nash's solution is given by:

$$(-p_N I, p_N) \in P \tag{15}$$

Nash's solution can be explained on the basis of the following negotiation model (see Harsanyi[6]).

Consider a bargaining situation with the region A of possible payoffs and the status quo at the origin. Suppose that player 1 is holding out for a trade with utility payoffs (u_1', u_2') and 2 is demanding (u_1'', u_2'') where the two points are different and each is Pareto optimal. Who should make a concession? The argument is that player 1 should make a concession if:

$$\frac{u_1' - u_1''}{u_1'} \leqslant \frac{u_2'' - u_2'}{u_2''}$$

i.e.:

$$u_1'u_2' \leqslant u_1''u_2''$$

and vice versa. Concession need not necessarily mean accepting the opponent's demand; rather the conceding player can suggest an alternative trade which will not require him to make a further concession in the next round of negotiations. But, for this to be so, he must propose some (u_1''', u_2''') having a component product $u_1'''u_2'''$ at least as large as the component product of his opponent's demand and larger if possible. Clearly, this procedure raises the component product at each stage, and so it inexorably leads to the point for which the component product is a maximum – Nash's solution. The concession principle is based on the rationale that when the two demand are (u_1', u_2') and (u_1'', u_2''), then, roughly, $(u_1' - u_1'')/u_1'$ and $(u_2'' - u_2')/u_2''$ measure, respectively, the relative losses incurred when player 1 and 2 concede. The assumption, then, is that the player whose relative losses are the smaller will make the concessions.

Acknowledgements

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Appendix

Estimation of function $f(x)$ for the United States (see reference 7)

There are several stages of reactions which must be considered in assessing the ultimate economic impact of a shortfall in imports of oil. First, standby conservation measures would be invoked to reduce domestic consumption without significant economic consequences. The energy posture of the economy would be a major determinant of the extent to which such conservation measures would be effective. Thus, if the domestic policy heavily emphasized long-term conservation and austere demand restraint, then only minimal standby conservation reductions could be anticipated.

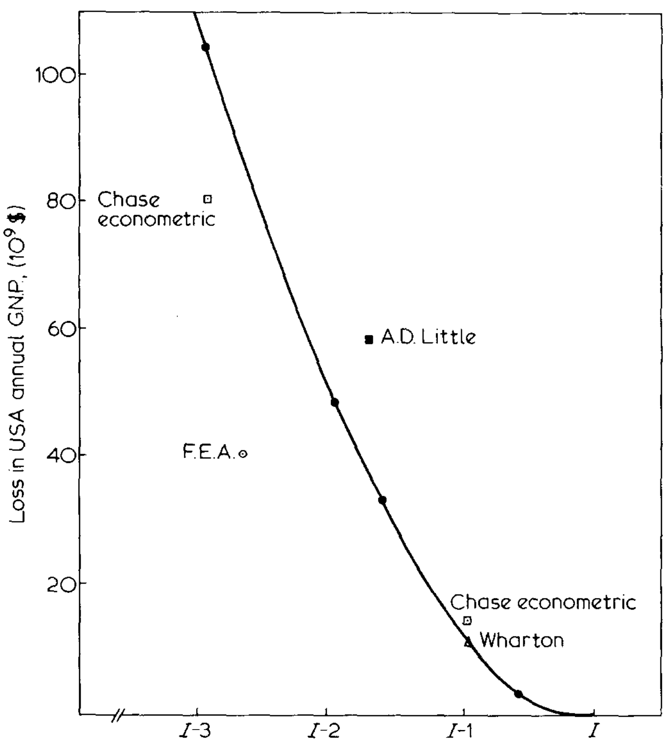

Figure 5 National Petroleum Council's shortfall impact estimate

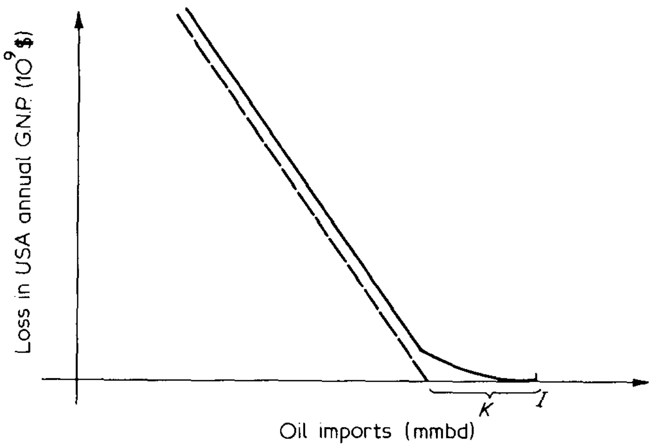

Figure 6 Federal Energy Administration's shortfall impact estimate. (—), estimated cost curve; (– – –), piecewise linear approximation.

The second stage would likely involve an emergency allocation programme to minimize the impact of a shortfall on vital industrial and commercial activities highly dependent on adequate supplies of energy.

The last stage of reaction would involve distribution of the shortfall among the various consuming and geographic sectors.

These stages reflect the aggregate effect of the shortfall on the economic (GNP) growth of the country.

The National Petroleum Council developed a summary graphical representation of such effects during the 1973 embargo (*Figure 5*).

The basic approximation made in deriving the impact of oil shortfalls in the United States by the Federal Energy Administration is represented by the linear curve indicated in *Figure 6*. The linear approximation is based on two key parameters of real world significance: (1) K, the substitution/standby conservation level (in mmbd oil equivalents) that the economy can withstand without a perceptible loss in GNP; and (2) M, the average multiplier effect used in estimating the value of GNP cost of each unit of oil shortfalls beyond the level K.

The approximate values of K and M are not easily determined for any economy at any time. The value of K could be less than 1 mmbd. The value of M is highly uncertain, but is estimated at \$30 to \$40 billion per mmbd per year based on analysis of the impact of the 1973–74 embargo.