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OPEC BEHAVIOR

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ABSTRACT

This thesis aims to contribute to a further understanding of the real dynamics of OPEC production behavior and its impacts on the world oil market. A literature review in this area shows that the existing studies on OPEC still have some major deficiencies in theoretical interpretation and empirical estimation technique. After a brief background review in chapter 1, chapter 2 tests Griffin's market-sharing cartel model on the post-Griffin time horizon with a simultaneous system of equations, and an innovative hypothesis of OPEC's behavior (Saudi Arabia in particular) is then proposed based on the estimation results. Chapter 3 first provides a conceptual analysis of OPEC behavior under the framework of non-cooperative collusion with imperfect information. An empirical model is then constructed and estimated.

The results of the empirical studies in this thesis strongly support the hypothesis that OPEC has operated as a market-sharing cartel since the early 1980s. In addition, the results also provide some support of the theory of non-cooperative collusion under imperfect information. OPEC members collude under normal circumstances and behave competitively at times in response to imperfect market signals of cartel compliance and some internal attributes. Periodic joint competition conduct plays an important role in sustaining the collusion in the long run. Saudi Arabia acts as the leader of the cartel, accommodating intermediate unfavorable market development and punishing others with a tit-for-tat strategy in extreme circumstances.

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Chapter 1

INTRODUCTION

Over the past half century, and in the foreseeable future, oil will be the most important energy source powering human society. Since the first oil crisis in the early 1970s, people have seen a frequently and dramatically fluctuating oil market and its enormous impacts on the world's economic development. People usually connect any oil price change with the Organization of Petroleum Exporting Countries (OPEC). Successfully or not, OPEC tries to affect oil prices as a unified group, with its more than 40% share of world output, about 50% share of the world oil trade, and extremely low production costs. Therefore, there has been considerable curiosity and concern about OPEC's behavior and its role in the international oil market.

Economists have formulated many contradictory hypotheses about OPEC's behavior, from many different points of views. While almost all statistical tests have rejected the non-cartel hypothesis, the tests on various cartel models still arouse notable controversy. A literature review in this area has led me to believe that the existing studies on OPEC still have some major deficiencies in theoretical interpretation and empirical estimation technique. This dissertation aims to contribute to a further understanding of the real dynamics of OPEC production behavior and its impacts on the world oil market.

This dissertation is composed of three chapters. The first chapter briefly describes OPEC's history and the theoretical and empirical controversy over OPEC's behavior, and then outlines deficiencies in the existing empirical studies and works in chapters 2 and 3. Chapter 2 tests Griffin's market-sharing cartel model on the post-Griffin time horizon with a simultaneous system of equations, and an innovative hypothesis of OPEC's behavior (Saudi Arabia in particular) is then proposed based on the estimation results. Chapter 3 first provides a conceptual analysis of OPEC behavior under the framework of non-cooperative collusion with imperfect information. An empirical model is then constructed and estimated.

1.1 A Brief History of OPEC

Oil has been an important commodity in international trade since the 1860s. Before World War II, the most important participants in the world oil market were major international companies. At the end of World War II, the so-called "seven sisters"-- Esso, BP, Shell, Gulf, Standard Oil of California, Texaco and Mobil--controlled virtually all the crude oil involved in international trade. The highly concentrated market and the major companies' overlapping interests in the ownership of oil properties limited competition and made the oil industry considerably profitable. In 1947, the price of oil was around $2.20/barrel, while exporter government taxes were less than $0.50/barrel and production costs were in the range of $0.10 to $0.20/barrel. The considerable economic rents, albeit insignificant compared to today's OPEC profits, attracted new entrants, which exerted increasingly competition pressure on the existing majors. By 1970, an essentially competitive world oil price level had been established. From 1947 to 1970, crude oil prices fell from $2.20 to $1.30/barrel and company profit margins after production costs fell from $1.80 to 20 cents per barrel (Griffin, 1986). The dramatic decline in profitability of the international oil companies turned out to be a major stimulus to the creation of OPEC because, prior to 1960, exporter country tax receipts were tied to company profits.

On September 14, 1960, five major oil exporters--Iran, Iraq, Kuwait, Saudi Arabia and Venezuela--announced the formation of OPEC, with the intent of collusive restraint of producer competition in the world oil market. Thereafter, it was augmented by Qatar in 1961, Indonesia and Libya in 1962, Abu Dhabi (whose membership was supplanted by the U.A.E. in 1974) in 1967, Algeria in 1969, Nigeria in 1971, and Ecuador and Gabon in 1973. OPEC was composed of thirteen members prior to the first oil crisis in 1973. Ecuador and Gabon left OPEC later in 1992 and 1995, respectively.

OPEC in 1960 lacked the strength to act as a truly effective cartel but succeeded in gradually gaining market power from the major oil companies. OPEC countries in the 1960s sought to alter the inherited obligations that limited their control over the development and pricing of oil. They changed the tax system to increase tax revenue per barrel from oil companies and stepped toward nationalization of concessions. Political events in the 1960s, such as the Arab-Israeli War of June 1967, and the Libyan revolution in September 1969 also strengthened OPEC's power. These events completely changed the political climate and gave the Middle Eastern members of OPEC a greater degree of resolve and certainty in their dealings with the oil companies and with the Western powers.

The market conditions also changed radically in the late 1960s and early 1970s. The single most important factor was the virtual disappearance of excess production capacity outside the cartel. Economic and income growth had increased dramatically in

Western countries, while production peaked in most areas outside OPEC in the late 1960s. In the second half of 1973, OPEC began to wield its unprecedented power. It raised the tax reference price unilaterally from $3 to $7, then to the $10 range, rejecting any pleas for compromise or negotiation. The panic buying triggered by the alleged oil embargo from Arabian producers thrust the market into upheaval. This was the so-called "first oil crisis."

After 1973 OPEC members moved rapidly toward nationalization of their companies' properties. Following the upheaval of 1973-1974, the period from 1975 to 1978 was relatively tranquil in terms of price and output. As shown in Figure 1.1, price fluctuation was rather mild over this period. Later in 1978, the "second oil crisis" began to unfold, triggered by the Iranian revolution and precipitated by opportunistic behavior from other OPEC members. The political unrest in Iran caused its production to drop from 6 MMB/D in September 1978 to 2.4 MMB/D by December 1978. Initially, other OPEC producers increased their production, to an amount that made up the bulk of the Iranian production shortfall. However, shortly thereafter Saudi Arabia suddenly reduced its production ceiling twice, and prices soared from $18.50 to over $40 per barrel. Later, rather than raising production sufficiently to force the spot price down to the official Saudi marker price, the Saudis adjusted their official price upward. Because of the skyrocketing prices, oil demand began to drop sharply, together with rising production from non-OPEC areas, resulting in substantial reduction in OPEC's production and its market share, as shown in Figure 1.2.

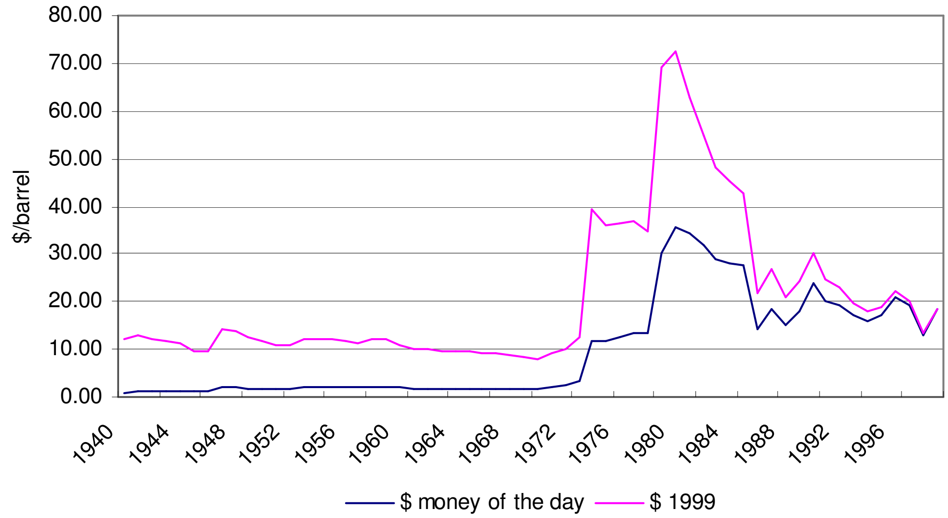

Figure 1.1 World Oil Prices, 1949-2000.

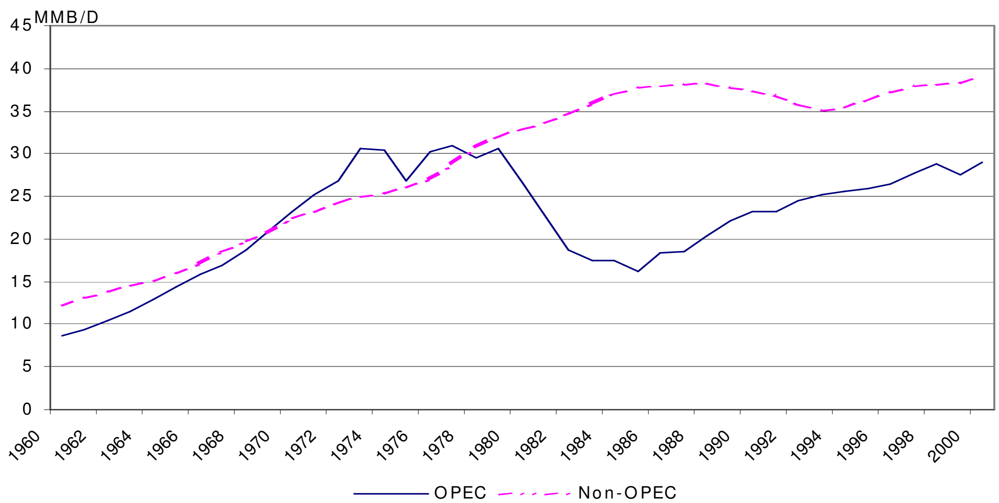

Figure 1.2 OPEC and Non-OPEC Supply, 1960-2000.

The period from 1981 through 1986 provided OPEC with its first major test. Cartel cohesion was rather easy to attain from 1973 to 1980 since the market was tight. However, after the second oil crisis, the market developed in the direction of weakening the cartel's power.

World oil consumption was sharply depressed under the skyrocketing prices, particularly after consumers were given sufficient time to adjust to the higher prices. Supply from the non-OPEC area was also stimulated by high prices. As shown in Figure 1.2, the non-OPEC supply increased dramatically after the first oil crisis. The two forces combined just made it impossible for OPEC to sustain prices without cutting its production and market share significantly.

In March 1982, OPEC approved a market-sharing formula that set the total production and individual country quotas and appointed Saudi Arabia as the swing producer to equalize OPEC production and market demand at the targeted market price. However, in the early days of this scheme, OPEC members obviously were not used to the instrument of production control since traditionally they had eschewed any collective production controls, viewing their production decisions as sovereign matters. The weak adherence to the quotas from many members and sharp decline in the production and market share of Saudi Arabia triggered the Saudis to lower the official prices sequentially and led them to renounce the role of "swing producer" in 1986. The outcome of the Saudis' reprisal would be the collapse of prices when others did not take the situation seriously. In 1986, the world oil price slumped from $27 at the beginning of the year to less than $10 in July (see Figure 1.3).

The clear message sent by the Saudis and the market response made the cheaters realize that the threat was so real and detrimental that they had to take the new quota seriously. The lesson of 1986 taught OPEC members that there is no quick fix to causing both prices and volumes to magically increase. OPEC would obtain higher revenues only if it showed a reasonable degree of discipline. This requires strong leadership. Saudi Arabia has to balance its strategy for price maintenance with that for volume maintenance, which requires some compromise on price aspirations. With the exception of the short unrest caused by the Gulf War, the market became tranquil to some extent from1986 to November 1997, when OPEC seriously misjudged the demand growth and mistakenly increased its total production ceiling by 2.5 MMB/D. The price plunged to around $10 in late 1998 and early 1999. OPEC rallied in 1999–2000 and successfully pushed prices upward but overshot its target to over $30 in 2000 (see Figure 1.3).

This study will focus on OPEC's behavior pattern during the time horizon from 1982 to 2002, a period during which coordinated production control, the quota system, was in effect. The statistical tests will provide evidence of whether the coordination was truly effective and whether each individual member's behavior went with the cartel collusion.

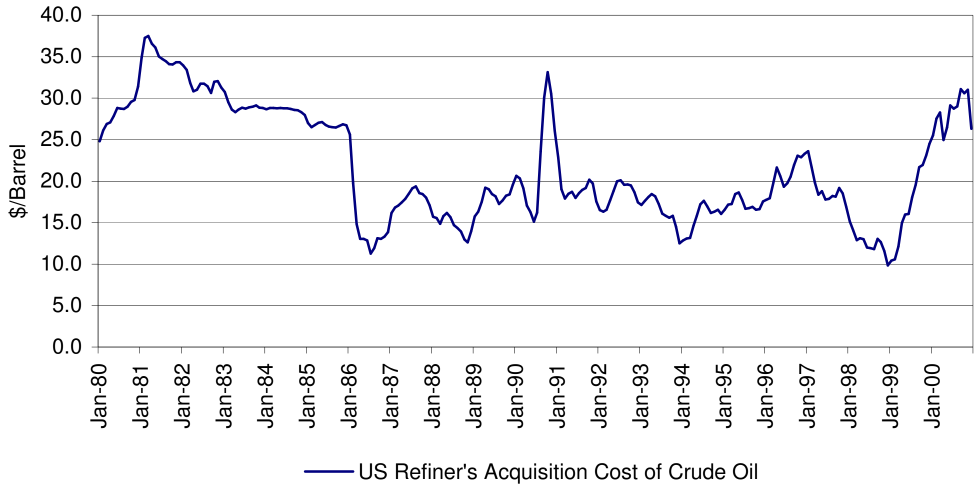

Figure 1.3 U.S. Refiner's Acquisition Cost of Crude Oil

1.2 Hypotheses about OPEC's Behavior

Economists have formulated many hypotheses on OPEC's behavior from different points of view. Basically, they can be categorized as cartel and non-cartel models. Widely quoted non-cartel models include the competitive model (MacAvoy, 1982), target investment model (Cremer and Salehi-Isfahani, 1980; Teece, 1982), regime of property rights (Johany, 1978; Mead, 1979). Cartel models usually refer to the market-sharing model, dominant firm model (Adelman, 1982) and cooperative profit maximizer model (Pindyck, 1978).

Non-cartel Model

Competitive Model

MacAvoy (1982) explained the increases in oil prices in the 1970s by focusing on supply and demand rather than cartel behavior. He believed that prices had inevitably risen because of the scarcity of the oil reserve and market forces decided the price in the absence of any monopolist power of OPEC. He argued that a naturally fixed physical endowment of oil, coupled with rising consumption, puts greater strain on limited productive resources. Accordingly, under these circumstances prices would keep rising.

However, the reality is that the market is in a glut state at most times. Adelman's study (1986) shows that the marginal cost, which can measure the scarcity of oil, cannot be reconciled with a price determined by scarcity. First of all, the marginal cost among different regions varies enormously. This situation offends the principle of competitive markets: marginal cost of all participants should be within the neighborhood of the market price. Also, in a competitive market, lower cost production should gradually displace high-cost production. However, in the real world, high-cost areas like North America increased their investment and maintained or increased output after 1973 while the reserves in low-cost areas, especially the Persian Gulf, have been little depleted. In addition, cost only constitutes a small fraction of the price, so it is vastly profitable to expand output enormously in the great bulk of world oil reserves. Therefore, the oil price pattern should not be a reflection of increasing scarcity. MacAvoy's competitive model failed to foresee the collapse of oil prices in the 1980s.

Target Investment Model

The target investment model (Teece, 1982) suggests that OPEC countries make their oil production decisions in reference to the requirements of their national budgets. Their budgetary needs are a function of their economy's capacity to absorb productive investments. Since many OPEC countries are well under-developed, they do not have adequate infrastructure to support rapid escalation in consumption and investment levels.

They would only need revenue sufficient to make investments that could generate a certain level of return. The oil production decisions are made in order to meet the investment target. Increases in oil prices will require less production to meet the target; conversely, if prices fall, producers will increase production for the same investment target.

The target investment model provided some seemingly plausible explanation for price increases in 1973-1974 and 1978-1979, following stabilization at high levels. However, the price decrease of $5 in 1983 did not lead to a production increase. Instead, during this period the major OPEC producers cut oil production.

Property Rights Transfer Model

In the first half of the 1970s, the transfer of property rights from giant oil companies to host governments was another dramatic event that changed the world oil market structure. Based on this fact, Johany (1978) and Mead (1979) developed the theory of property rights transfer to explain the oil price pattern. Johany and Mead argue that the host governments are more farsighted than oil companies, i.e., they have lower discount rates, so they have more incentive to hoard the oil for future profit. Therefore, the transfer of property rights in the 1970s should be responsible for production cuts and price rises. The theory argues that the companies were predicting the impending loss of property rights and thus employed a high production rate to gain profit as fast as possible. In contrast, the governments think more about the future and are more likely to cut production.

However, the reality of the oil market does not fully support this theory. First, according to the exhaustible resource theory on which the property rights transfer model is based, the price should rise gradually in a moderate way because of the gradual depletion of resources. What really happened was that the price soared in a short time and some time later it fell enormously. This can be more plausibly explained by an exercise of market power followed by the collapse of the collusive scheme.

The other critical issue is that the governments may be more short-sighted than companies and should have an even higher discount rate than companies as asserted by Adelman (Griffin and Teece, 1982, p. 39): *Countries always wanted more production than companies.*

Companies respond to the capital market while governments respond to their political status. The instability of the political structure in the host countries, especially in those of the Middle East, and their desires to be wealthier in order to obtain more political and economical power made the governments try to gain as much and quickly as possible from oil production. In addition, the theory could not offer any plausible interpretation of the price rise in 1978-1979 since the transfer of ownership had long taken place and hence further reductions in the discount rate could not have occurred.

Cartel Model

In spite of being challenged by alternative explanations such as target revenue or property right transfer, OPEC's cartel-like behavior is the most widely accepted explanation for the dramatic price increases of the 1970s and price fluctuations in the 1980s and 1990s. The cartel can take on many variant forms with different characteristics and impacts on the market. Although every cartel is unique, the common attributes of any effective cartel are collusion among members for deliberate restraint on their production and a consistent higher-than-competitive price level.

Ideally, an ideal cartel can act as a monopolist operating a number of plants. The multiplant monopoly cartel assumes that it is a cartel authority rather than each cartel member who makes price and output decisions such that the cartel as a whole obtains the maximum possible monopoly profits from the market, and cartel members do not compete with each other and share the total profits in a predetermined manner.

Under these assumptions, the cartel authority actually acts as a monopolist. The marginal cost curve is determined by using up the lowest cost area production first, regardless of which member country the producing area belongs to. Given the market demand curve for the cartel's production, the cartel authority calculates the marginal revenue pattern and equates it to the jointly decided marginal cost curve. The equilibrium will set the cartel's profit-maximizing output level and the corresponding monopoly price. The central determination of price and output by the cartel authority can guarantee maximum profit to the organization as a whole. Under this framework, the producers with high marginal cost might not produce at all if their marginal cost is higher than the cartel's marginal revenue. Therefore, a unanimously accepted profit-share arrangement should be predetermined and post-enforced.

However, such a perfect cartel cannot be sustained in the reality of OPEC, which is composed of constituent nations. Although OPEC has a committee and holds members' oil ministers' meetings regularly to discuss the production and price policy, each member maintains control over its own production. Furthermore, it is practically impossible to implement side payments from low-cost producers to high-cost producers because they are too costly to negotiate and enforce.

Adelman (1982) suggests that the OPEC cartel is somewhere between two polar cases: dominant firm and fully collaborated output combination. In the dominant firm model, the large producer (usually assumed to be Saudi Arabia) would act as the residual-firm monopolist and the other producers operate as fringe firms. The dominant producer sets the price, allows the other OPEC nations to sell all they wish, and supplies the remaining demand. The dominant producer is thus the "swing producer", absorbing the demand and supply fluctuations in order to maintain the monopoly price. Such an arrangement creates no cheating problems. However, it does run the risk of inducing sufficient new production, outside of the dominant producer, to make the strategy nonviable for him. The fringe firms maximize profits individually given their individual marginal cost and the market price set by the dominant firm. The large producer then makes up the difference between demand for OPEC and output from other producers, varying its production to control the price.

The dominant model is easy to operate if OPEC, especially the leading producer, has an overwhelming market share of the world market. Therefore, the stability of the cartel does not depend on the strengths and weaknesses of cartel cohesion. Rather, it turns on whether world supply and demand at the dominant price results in sufficient demand for the dominant producer's production to satisfy its objectives.

One of the other common forms of cartel is a market-sharing cartel, in which the members decide on the share of the market or level of production that each is to obtain as a cartel member. In order to achieve this objective the members may then get together regularly to decide the collusive actions in light of changing market conditions.

Since each member country in OPEC retains sovereign power over its own production rate and no individual one (except, possibly, Saudi Arabia) has the power to fix the price favorable to the cartel, it is very likely that the member countries take the market-sharing strategy as the way to achieve the cartel objective. The members collude to restrain their production for higher prices and gain extra profit. Theoretically, if the cartel members have similar marginal cost curves, the ideal market-sharing strategy can achieve the same goals as the joint profit-maximizing ideal cartel model, outcomes of which are equivalent to those of a monopolist operating a number of plants.

The assumption of identical marginal costs may not be too unrealistic since, compared to the market prices, the marginal cost in most OPEC countries are small, especially among the dominant Middle East producers. Some studies show that marginal production costs in the Middle East range from 15 to 35 cents per barrel (Griffin and Steele, 1986). Members outside the Persian Gulf area have much higher but still considerably low costs of about $1 to $2 (Griffin, 1986). The more realistic threat to the stability of the market-sharing cartel is the temptation for tremendous extra profits for individual members that gain a higher market share by cheating on the quota. Like any cartel, some OPEC members have strong incentives to deviate from the collusion to benefit from the cartel price sustained by others' compliance with the quota, while some members who can benefit most from the high price (the members with low cost, low population and high reserve and production level) would like to sustain the price by greater compliance with the quota.

1.3 Controversy about Econometric Tests on OPEC's Cartel Behavior

Beginning with Griffin in his widely cited article, "OPEC Behavior: A Test of Alternative Hypotheses" (1985), numerous empirical studies have been undertaken to test a variety of hypotheses about OPEC behavior, such as Jones (1990), Dahl and Yücel (1991), Griffin et al. (1994, 1997), Al-Sultan (1995), Alhajji and Huettner (2000), Ramcharran (2001, 2002), and Yang (2003). A literature survey of the econometrics model of OPEC behavior developed over the past two decades shows that all of the non-cartel models have been tested and rejected (Griffin, 1985; Jones, 1990; Dahl and Yücel, 1991; Alhajji, 2000). In contrast, the cartel hypothesis is still controversial. Griffin (1985) and Jones (1990) support the partial market-sharing cartel model; Dahl and Yücel (1991) assert that there is no evidence for dynamic optimization and coordination in the form of strict cartel behavior or swing production among OPEC countries, and loose coordination or duopoly is consistent with OPEC behavior; Alhajji (2000, 2002) claims OPEC does not work as a cartel, but that Saudi Arabia is the dominant firm and the other members are the competitive fringe.

1.4 Deficiencies of Existing Empirical Work and Goals of This Study

Most previous empirical studies on OPEC behavior test the hypothesis of whether OPEC works as a joint profit maximization organization. However, as OPEC works with limited data and limited power and is almost unable to predict precisely the market response to its production decisions, it should not be a surprise that the ideal joint profit maximization conditions are not met in econometric tests with historic statistical data.

In addition, from the oligopoly theory point of view, a cartel is not stable at the joint profit maximization level because of the inherent proclivity to cheat. On the other hand, a cartel in a repeated game is unlikely to fall in the Cournot equilibrium as there are other sustainable equilibriums where every firm in the cartel can obtain larger payoffs than the Cournot floor. It is widely accepted that the world oil market is not competitive and the price level is constantly higher than the Cournot equilibrium outcome. Intuitively, it is sensible to think that some sort of OPEC collusion sustains the price above a competitive level while being far below the monopolistic level.

Therefore, rather than testing whether OPEC or a group of OPEC countries works as a joint profit-maximization organization, this dissertation intends to answer two fundamental questions with empirical evidence: do OPEC countries collude, and how do they collude if they do?

Griffin (1985) suggested that OPEC countries collude as a market-sharing cartel and provided some econometric evidence for the hypothesis for 1971-1983. Griffin's empirical model has some appealing properties. Empirically, the model is much less data-demanding than the profit maximization cartel model as it does not involve the cumbersome concept of user cost, for which neither direct data nor data on reliable proxies are available. More importantly, the market-sharing cartel model resembles reality. Initiated in early 1982, OPEC instituted a quota allocation system to coordinate members' crude oil production. Later on, OPEC formally acknowledged that its policy was to sustain its market share. Griffin's empirical model can help in examinations of how well the market-sharing scheme works and how individual producers perform in this form of collusion.

Griffin (1985) specified his single equation model for testing the market-sharing cartel model as follows:

Individual country production (S_{it}) is some fraction ($\alpha_i^{'}$) of other OPEC members' production ($S_{nit} = S_{opect} - S_{it}$):

$$S_{it} = \alpha_i^{'} S_{nit} \tag{1.1}$$

The market-share coefficient ($\alpha_i^{'}$) is assumed to be a function of price:

$$\alpha_i^{'} = \alpha_i P_t^{\gamma_i} \tag{1.2}$$

Hence, the market-share cartel model can be expressed as:

$$S_{it} = \alpha_i P_t^{\gamma_i} S_{nit}^{\beta_i} \; ; \tag{1.3}$$

The empirical model to be estimated follows directly from the above equation by taking the log-linear functional form:

$$\ln S_{it} = \alpha_i + \gamma_i \ln P_t + \beta_i \ln S_{nit} + \varepsilon_{it} \tag{1.3'}$$

Three tests were performed by Griffin: (1) constant market sharing ($\beta_i = 1, \gamma_i = 0$), in which market share among members is not affected by the oil price; (2) market sharing ($\beta_i = 1, \gamma_i \neq 0$), representing market share change over time according to price; and (3) partial market sharing ($\beta_i > 0, \gamma_i \neq 0$). The latter would suggest a looser cartel model since market-sharing considerations partially affect production decisions, but production cutbacks need not be proportional. Producing members also adjust their outputs according to price.

The results of the hypothesis tests from Griffin's single equation market-sharing model are summarized in Table 1.1

Table 1.1 Summary of Hypothesis Tests from Griffin's Market-sharing Model

Hypothesis	Do Not Reject (Number)	Do Not Reject (Countries)	Reject (Number)
Constant Market Sharing ($\gamma = 0, \beta = 1$)	1	Not documented	10
Market Sharing ($\gamma \neq 0, \beta = 1$)	5	Qatar, U.A.E., Libya, Iran, Nigeria	6
Partial Market Sharing $\gamma \neq 0, \beta > 0$	11	All Members	0

Griffin claimed that, according to these results: "based on this evidence, OPEC appears to be a real cartel with at least partially effective output coordination…. In sum, the evidence favoring a partial market-sharing model is impressive." (Griffin, 1985).

Griffin's tests of the market-sharing model only cover a period of generally tight markets and rising prices (1971:I-1983:III), during which there was no market sharing agreement among OPEC producers and OPEC's asserted policy was to sustain a favorable price. In a later similar study, Jones (1990) only extended the test period to 1988:IV, and could not capture OPEC's behavior in the 1990s. Ever since the second oil crisis, the world oil market has experienced tremendous volatilities, such as price collapses in 1986 and 1997/98, and the following price rebounds, as well as the relatively tranquil period from 1987 to 1990 and 1992 to 1997. Researchers are very interested in studying whether OPEC follows the form of a market-sharing cartel in the post-Griffin period.

Chapter 2 aims to provide new statistical evidence with a modified estimation approach and new data series following Griffin's approach. The results will be compared to those of Griffin to see whether OPEC has improved its collaboration in a rather loose market condition.

Another primary deficiency of existing studies is that the empirical models are based on the monolithic behavior assumption, i.e., those models assume that OPEC producers' production strategy does not vary over time. Previous researchers only applied some simplistic game theoretic concepts due to their appealing tractability, such as Cournot-Nash, joint-profit-maximizer, and dominant firm/competitive fringe, to analyze the rather complex dynamics of the world oil market and OPEC's conduct. The empirical tests have shown that OPEC countries do not fit neatly into these simplistic models. It is surprising that the latest development in oligopoly studies, the game theoretic framework, has not been introduced in the analysis of probably the most famous cartel--OPEC.

The theory of non-cooperative collusion under uncertainty initialized by Green and Porter (1984) has some appealing properties that fit OPEC's conduct. Green and Porter propose a dynamic game theoretical model in which a cartel employs an enforcement mechanism to detect and deter cheating to sustain an extent of collusion with imperfect information. They assume an individual firm's production strategy (either collusive or Cournot) is unobservable, and the market information is imperfect to indicate rival's production behavior (there is stochastic demand noise, in particular). Firms observe market price (probably as well as other indicators, like market share) as a signal of the competitors' conduct. Green and Porter state that collusion can be enforced by production strategy switches from collusive behavior to Cournot behavior as triggered by the imperfect signal. Because the stochastic component in demand can draw the price down below the trigger price, competition wars will be triggered from time to time as a means to deter cheating although members may not actually cheat[1]. One important prediction of Green and Porter's model is that periodic switches between collusive and Cournot output level should be observed and can be empirically distinguished.

Oil market and OPEC structure have some critical features in conformity to Green and Porter's model.

First, although OPEC has an explicit agreement on production quotas, members have never come to institute a mechanism to enforce the agreement and are mostly self-disciplined. In addition, there are no side payments in OPEC, and thus members basically produce to their own interests. Therefore, collusion, if there is any, is likely to be non-cooperatively supported.

Second, the oil market is highly volatile from both supply and demand viewpoints. The uncertainties of non-OPEC supply and world oil demand make market price an imperfect signal of OPEC production behavior. In addition, as the fairness of the quota allocation is constantly questioned and the predetermined quota level may not sufficiently conform to the volatile market demand, deviations from quota may not be necessarily deemed as a violation of the collusion and thus cannot act as a perfect signal of members' production strategy. Moreover, market information errors (such as an

[1] In the equilibrium, it is optimal for the firms to behave collusively in normal demand periods and the competition war is only triggered by the price dip caused by downward demand shock. See details in Green and Porter (1983).

individual member's output level[2] and market demand), which are common in the world oil market can also undermine the correlations of any signals with members' behavior.

Third, the anecdotal evidence seems to support the conjecture of production behavior switching over time. For example, when formal production quotas were first instituted, Saudi Arabia was cast as a "swing producer" to balance the supply and demand according to the market. A simple visual observation of Saudi Arabia's output trend reveals that the country was mostly likely to take the role of swing producer for the period 1983 to August 1985, as it cut its output level from above 6 million barrels/day in mid-1983 to 2.3 million barrels/day in August 1985 and the price moderately fluctuated between $26.90 and $28.90 per barrel. In August 1985, Saudi Arabia officially threatened to abandon the role of swing producer and to turn to a strategy that maintained its market share. Thereafter, Saudi Arabia had an obvious shift in its production strategy and its output level increased to 6.4 million barrels/day twelve months after its abandonment of the swing producer strategy. In the process, prices plunged from around $28.00 to $8.00 per barrel.

The varying production behaviors of OPEC members have been recognized by some researchers for a long time. For example, Adelman (1993) states:

> The cartel (OPEC) oscillates between two models: (1) the largest firm sets output, and all others produce ad lib. (2) All firms participate in setting an output total, and dividing it.... Both are

[2] Alhajji (2000) notes OPEC's quota violation monitoring is for a short period of time and does not involve certification of exports. In addition, there is no timely accurate report on non-OPEC producers' output level. Akacem and Fleisher III (1996) note that complete direct monitoring of rivals' behavior is prohibitively costly for OPEC.

> unstable: in (1), the dominant firm will try to make others share the burden; in (2), cheating may force the dominant firm willy-nilly into (1) (Adelman, 1993, p. 287).

Geroski, Ulph and Ulph (1987) and Griffin and Neilson (1994) have employed econometric methods to analyze OPEC's behavior under the framework of varying production behaviors over time, but the analysis on this direction is still limited and many interesting questions still have not been answered.

Geroski, Ulph and Ulph (1987) developed an empirical model in which the pricing conduct of OPEC producers is allowed to vary over time in response to both endogenous and exogenous factors. There are *n* producers in OPEC and the objective function of producer *i,* $V_i(P_t)$ is modeled as:

$$V_i(P_t) = \delta_{it}\pi_i^L(P_t) + (1-\delta_{it})\pi_i^S(P_t) + \theta_{it}\sum_{j\neq i}\pi_j^L(P_t) \qquad (1.4)$$

where $P_t = (P_{1t}, \ldots P_{nt})$ is a vector of strategic variables-differentiated prices in this model, and $\pi_i^L(P_t)$ and $\pi_i^S(P_t)$ are the long-run and short-run profits of producer *i,* respectively, $\sum_{j\neq i}\pi_j^L(P_t)$ is the long-run profit of producers other than *i.* Two aspects of varying conduct are captured in the model: one is that financial as well as some other constraints may cause producers to vary their pricing conducts to the extent that they give weight to long-run or short-run profits. This aspect is captured by the coefficient δ_{it} as in the above objective function. The second aspect is that producers may vary between cooperative and non-cooperative behavior in response to whether they think that rivals have been acting cooperatively or not, as captured by the coefficient θ_{it} --the weight producer *i* attaches to the long-run profits of other producers. The authors note that variation in the parameters δ_{it} and θ_{it} represents a wide range of equilibriums, from full cooperation to perfect competition: if both $\delta_{it} = 1$ and $\theta_{it} = 1$ for all *i,* then OPEC's decision problem is simply the maximization of joint long-run profits. If $\theta_{it} = 0$, producer *i* only takes its own profits into consideration, and equilibrium would be non-cooperative. To examine the determinants on varying conducts, δ_{it} and θ_{it} are modeled in correlation with a set of exogenous and endogenous variables.

Geroski, Ulph and Ulph (1987) employed the model to examine four groups[3] of OPEC producers' pricing conduct from 1966 to 1981. While the estimated values of δ_{it} are generally constant (indicating no conduct varying with respect to changes in internal financial needs)[4], the estimates on θ_{it} enable the authors to reject the hypothesis of constant conduct and provide an interesting interpretation of OPEC's pricing conducts during the two sharp price rises between 1973 and the early 1980s. According to the estimates on θ_{it}, jumps in the willingness of producers to cooperate are observed in 1973 and 1979; the authors stated that OPEC producers' pricing conduct was likely to switch from non-cooperative to cooperative in conformity with the two sharp price rises at those two points of time.

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[3] Fringe Group: Indonesia, Venezuela, Iran, Nigeria; High Absorber Group: Algeria, Libya, Iraq; Low Absorber Group: Kuwait, UAE, Group 4: Saudi Arabia.

[4] The authors admit that the estimates of δ_{it} are indeed too large in size to be truly consistent with the model.

The world oil market and OPEC have experienced drastic structural change after the study period of Geroski, Ulph and Ulph's work. In the early 1980s, depressed world oil demand and surprising growth in non-OPEC output had drastically undermined the market power of OPEC. OPEC gradually lost its control of the market price, instituted the quota mechanism in April 1982, and finally gave up the price defending policy and turned to maintain its market share instead. Therefore, after the early 1980s, output level rather than price became OPEC's strategic variable by which to affect the oil market. The pricing model proposed by Geroski, Ulph and Ulph (1987) should not apply to OPEC's behavior from then on. As noted above, OPEC production conduct seems to still vary over time. Thus, studying the varying conduct feature of the post-Geroski et al study time horizon is of great interest.

Following the anecdotal evidence, Griffin and Neilson (1994) artificially split their study period of 1983-1990 into two sub-periods. From 1983 to August 1985, Saudi Arabia took the role of swing producer, balancing the demand and supply to stabilize the price at a collusive level predetermined at OPEC ministerial meetings. Thereafter, Saudi Arabia employed a tit-for-tat behavior to punish the others' cheating from quota.

Griffin and Neilson did not directly estimate the production characteristics of the swing producer strategy compared to those for the tit-for-tat strategy. Rather, they tested the applicability of the swing producer model from 1983 to August 1985 according to the proposition that under the swing producer strategy, prices should fluctuate around Saudi's official price and they should be less volatile than prices under the tit-for-tat strategy. The empirical estimates on price variations of the two sub-periods provided some evidence that the swing producer strategy prevailed from 1983 to August 1985.

Griffin and Neilson also fitted the following equation to test the tit-for-tat strategy:

$$Q^{SA} - Q^{SA}_{quota} = \gamma_0 + \gamma_1(Q^{oo} - Q^{oo}_{quota}) + \gamma_2(Q^{oo} - Q^{oo}_{quota})^2 \qquad (1.5)$$

The negative coefficient on γ_1 coupled with a positive coefficient on γ_2 would imply a threshold above which Saudis would adopt the tit-for-tat strategy; otherwise, they act as a swing producer. Their estimates show that in the period from August 1985 to 1990, Saudi Arabia did allow mild cheating and exerted severe punishments when cheating escalated above a threshold. In addition, the tit-for-tat model did not show any explanatory power in the assumed swing producer period.

Griffin and Neilson's (1994) work has obvious limits in several respects. First, the study period is limited to 1983-1990. The Saudi Arabian production behavior shift is assumed to have occurred only once in August 1985 and its conduct is implicitly assumed to be constant during the two sub-periods. This artificial division needs to be further verified and whether the conduct shift only occurred once is in question. In addition, how Saudi Arabia behaved post-1990 and whether its conduct varied is of great interest to researchers.

Second, only the hypothesis about Saudi Arabia's production behavior shift is tested, and the question of whether other producers' behavior also varies over time is still open. This is important because OPEC is much more than Saudi Arabia alone, and Saudi Arabia's strategy should be in response to strategies chosen by other producers.

Third, Griffin and Neilson only verify the existence of shifts in OPEC's (indeed only Saudi Arabia's) production strategy, but the characteristics of Saudi Arabia's different strategies as well as those of other producers are not identified. In addition, only quota violation is considered a factor triggering Saudi Arabia's conduct switching. As noted in Yang (2003), being the leader of OPEC, the Saudis should also look at other market conditions, such as total world oil demand change, price level, etc., when it chooses a production strategy. The other possible triggers of production behavior switching stand to be specified and tested.

Chapter 3 attempts to explain OPEC's behavior with a dynamic game theoretic model similar to the one proposed by Green and Porter (1984). The empirical model is then constructed, and tests are made for the occurrence and timing of production regime switches of each producer and for the possible triggers of the regime shifts from collusion to competition.

Chapter 2

OPEC BEHAVIOR: REVISITING THE MARKET-SHARING CARTEL MODEL

2.1 Empirical Model Specification

2.1.1 Simultaneous Bias Problem in the Estimation of Griffin's Market-Sharing Cartel

Griffin only utilized Ordinary Least Square (*OLS*) to estimate the single market-sharing equation (*1.3*). To obtain consistent estimates for the coefficient of the equation with *OLS,* it is assumed that the explanatory variables P_t and S_{nit} are uncorrelated with the error term ε_{it}. This assumption indicates that P_t and S_{nit} are exogenous and predetermined, and ε_{it} represents factors that influence S_{it} other than these two variables and are assumed to be independent and identically distributed with mean zero and variance σ^2. However, this assumption is a little restrictive because:

a. OPEC producers are believed to determine the price P_t whereas the assumption considers P_t predetermined as given, a hypothesis consistent with competitive behavior.

b. The production of any OPEC producer other than producer *i* is hypothesized in the model to be determined by the production of other OPEC producers including producer *i*. Therefore, S_{nit} should be considered endogenous rather than exogenous regressors.

To illustrate the difficulties with endogenous regressors in estimation, consider the simplified market-sharing model with only two OPEC producers: Core Producer *c* and Non-core Producer *nc*. For simplicity, omit the factor price *P* and use the pure market-sharing model as suggested by Griffin. The two producers' supply functions take the forms with S_{ct} denoting the log of production of the core producer and S_{nt} denoting the log of production of the non-core producer. Note that this chapter will simply use the original variables to represent the log of the real value of corresponding variables hereafter. For example, equation (*2.1*),

$$\ln S_{ct} = \beta_1 \ln S_{nt} + \ln \varepsilon_{ct} \qquad (2.1)$$

is simply written as

$$S_{ct} = \beta_1 S_{nt} + \varepsilon_{ct} \qquad (2.2)$$

$$S_{nt} = \beta_2 S_{ct} + \varepsilon_{nt} \qquad (2.3)$$

Obviously, both S_{ct} and S_{nt} are endogenous variables. Substitute (*2.2*) into (*2.3*), obtaining:

$$S_{ct} = \beta_1 \beta_2 S_{ct} + \beta_1 \varepsilon_{nt} + \varepsilon_{ct} \qquad (2.4)$$

Rearranging,

$$S_{ct} = \frac{\beta_1 \varepsilon_{nt} + \varepsilon_{ct}}{1 - \beta_1 \beta_2} \qquad (2.5)$$

Substituting this back into (*2.3*),

$$S_{nt} = \frac{\beta_1\beta_2\varepsilon_n + \beta_2\varepsilon_{ct}}{1-\beta_1\beta_2} + \varepsilon_{nt} \qquad (2.6)$$

Consider the consequences of trying to estimate (*2.2*) by *OLS*. A regression of core producers' production on non-core producer's production will produce the estimate:

$$\hat{\beta}_{1T} = \frac{(1/T)\sum_{t=1}^{T} S_{ct}S_{nt}}{(1/T)\sum_{t=1}^{T} S_{nt}^2} \qquad (2.7)$$

Substituting (*2.5*) and (*2.6*) into the numerator in (*2.7*) results in:

$$(1/T)\sum_{t=1}^{T} S_{ct}S_{nt} = (1/T)\sum_{t=1}^{T} (\frac{\beta_1\varepsilon_{nt} + \varepsilon_{ct}}{1-\beta_1\beta_2})(\frac{\beta_2\varepsilon_{ct} + \varepsilon_{nt}}{1-\beta_1\beta_2})$$

$$= (1/T)\sum_{t=1}^{T}\left[\frac{\beta_1(\varepsilon_{nt})^2 + \beta_2(\varepsilon_{ct})^2 + (1+\beta_1\beta_2(\varepsilon_{nt}\varepsilon_{ct}))}{(1-\beta_1\beta_2)^2}\right]$$

$$\xrightarrow{p} \frac{\beta_1\sigma_n^2 + \beta_2\sigma_c^2}{(1-\beta_1\beta_2)^2} \qquad (2.8)$$

Similarly, for the denominator,

$$(1/T)\sum_{t=1}^{T} S_{nt}^2 = (1/T)\sum_{t=1}^{T} (\frac{\beta_2\varepsilon_{ct} + \varepsilon_{nt}}{1-\beta_1\beta_2})^2$$

$$\xrightarrow{p} \frac{\sigma_n^2 + \beta_2^2\sigma_c^2}{(1-\beta_1\beta_2)^2} \qquad (2.9)$$

Hence,

$$\hat{\beta}_{iT} \xrightarrow{p} \left[\frac{\sigma_n^2 + \beta_2^2\sigma_c^2}{(1-\beta_1\beta_2)^2}\right]^{-1}\left[\frac{\beta_1\sigma_n^2 + \beta_2\sigma_c^2}{(1-\beta_1\beta_2)^2}\right] = \frac{\beta_1\sigma_n^2 + \beta_2\sigma_c^2}{\sigma_n^2 + \beta_2^2\sigma_c^2} \qquad (2.10)$$

OLS regression does not give the core producer's elasticity β_1. If the error in the core producers' supply function is negligible ($\sigma_c^2 \longrightarrow 0$) or if the error term in the non-core producers' supply function has a large enough variance ($\sigma_n^2 \longrightarrow \infty$), then (*2.10*) indicates that *OLS* would give a consistent estimate of the core producer's elasticity β_1. But when these are not the case, the *OLS* estimates would represent a biased estimation, a phenomenon known as simultaneous equations bias.

2.1.2 Simultaneous-equation System Model

To address the problems stated in the last section, a simultaneous-equation system model is constructed as follows.

Three types of components are specified in the simultaneous equations model. The first is a world crude oil demand function. Economic theories and empirical studies indicate explicitly that oil demand depends on the price change and income increase. Almost all oil demand studies apply these two variables as explanatory variables in the demand function. I thus assume the world oil demand Q_{wt} to be a function of the real price of crude oil P_t and the Gross Domestic Production (GDP_t). In addition, as a result of inertia, people do not change their oil consumption behavior immediately following a price or income change; therefore, I involve the lagged demand Q_{wt-1} into the function:

$$Q_{wt} = w_0 + w_1 P_t + w_2 GDP_t + w_3 Q_{wt-1} + \varepsilon_{wt-1} \qquad (2.11)$$

Second, I consider the supply of non-OPEC producers. Because we are interested in OPEC members only, I consider supply from non-OPEC producers as a whole. The real price of crude oil P_t is obviously an explanatory variable that should be involved in the function. Some researchers usually make efforts to introduce some type of cost variable into the non-OPEC function. Theoretically, as price takers, non-OPEC producers' production level should depend on the given market price and their own marginal cost. Unfortunately, it is practically difficult to distinguish explicitly the cost of oil producers, let alone successive cost data. Proxies are selected to represent the cost but the credibility is highly implausible. As a long-standing point of Adelman, tax and other government interventions may exert more impacts on oil supply in most non-OPEC oil producers since the real cost of supply is actually quite low so that it is unlikely to be a major factor affecting the supply. Therefore, in my model, I do not introduce a cost variable and consider it a part of the disturbance. Again, the production level in the past period is taken into consideration. I specify the non-OPEC oil supply function as:

$$S_{nopt} = nop_0 + nop_1 P_t + nop_2 S_{nopt-1} + \varepsilon_{nopt} \qquad (2.12)$$

The third is the supply function for each OPEC member. To describe OPEC's allegedly collusive behavior, the market-sharing equation following Griffin's thinking is applied in the simultaneous-equation system as described above:

$$S_{it} = \alpha_i + \gamma_i P_t + \beta_i S_{nit} + \varepsilon_{it} \qquad (2.13)$$

The market clearing condition for this simultaneous model is:

$$Q_{wt} = S_{nopt} + \sum_{i=1}^{n=11} S_{it} \qquad (2.14)$$

2.1.3 Consistent Estimates from Two-Stage Least Square Estimation (*2SLS)*

As analyzed in section 1.2.1, a single market-sharing equation cannot result in consistent estimation. Thus, a simultaneous equations system is introduced and estimated with the Two-Stage Least Square method. To simplify the illustration that consistent estimates can be obtained with *2SLS*, only two groups of OPEC producers are incorporated in the system, namely, core OPEC producers and non-core producers. The simultaneous equations system can be written as:

$$S_{copt} = cop_0 + cop_1 P_t + cop_2 S_{ncopt} + \varepsilon_{copt} \quad (2.15)$$

$$S_{ncopt} = ncop_0 + ncop_1 P_t + ncop_2 S_{copt} + \varepsilon_{ncopt} \quad (2.16)$$

$$S_{nopt} = nop_0 + nop_1 P_t + nop_2 S_{nopt-1} + \varepsilon_{nopt} \quad (2.17)$$

$$Q_{wt} = w_0 + w_1 P_t + w_2 GDP_t + w_3 Q_{wt-1} + \varepsilon_{wt-1} \quad (2.18)$$

Suppose the objective is to estimate the coefficient vector *COP* of the supply function of core OPEC producers in the system. The explanatory variables P_t and S_{ncopt} obviously are endogenous variables. Estimation of *COP* requires variables known as instruments, which are correlated with the endogenous explanatory variables but uncorrelated with the regression disturbance ε_{copt}. The predetermined explanatory variables S_{nopt-1} in equation (*2.17*), and GDP_t and Q_{wt-1} can be naturally taken as instrumental variables for price (P_t). Assuming the production of core OPEC producers at current period (S_{copt}) is independent of the production of non-core OPEC producers at last period ($S_{ncopt-1}$), $S_{ncopt-1}$ can serve as an instrument for S_{ncopt}. Denoting the vector of endogenous explanatory variables as $Z_t^{'} = [1, P_t, S_{ncopt}]$, the vector of coefficients as

$COP = [cop_0, cop_1, cop_2]$ and the vector of instruments as

$X_t^{'} = [1, GDP_t, Q_{wt-1}, S_{nopt-1}, S_{ncopt-1}]$, the supply function of core OPEC producers can be written as:

$$S_{copt} = Z_t^{'} \cdot COP + \varepsilon_{copt} \qquad (2.19)$$

and the explanatory variables Z_t can be expressed as a function of instruments:

$$Z_t = \delta' \cdot X_t + e_t \qquad (2.20)$$

where $\delta = [1, \delta_p, \delta_{ncop}]$.

Using an *OLS* regression of Z_t on X_t, the fitted values for the regression are given by

$$\hat{Z}_t = \hat{\delta}' \cdot X_t = [\delta_0, \hat{\delta}_p, \hat{\delta}_{ncop}]' \cdot [1, GDP_t, Q_{wt-1}, S_{nopt-1}, S_{ncopt-1}], \qquad (2.21)$$

where

$$\hat{\delta}_p = \left[\sum_{t=1}^{T} X_t X_t^{'}\right]^{-1} \left[\sum_{t=1}^{T} X_t P_t\right],$$

$$\hat{\delta}_{ncop} = \left[\sum_{t=1}^{T} X_t X_t^{'}\right]^{-1} \left[\sum_{t=1}^{T} X_t S_{ncopt}\right].$$

The two-stage least squares (*2SLS*) estimate of *COP* is found from an *OLS* regression of S_{copt} on $\hat{Z}_t$:

$$C\hat{O}P_{2SLS} = \left[\sum_{t=1}^{T} \hat{Z}_t \cdot \hat{Z}_t^{'}\right]^{-1} \left[\sum_{t=1}^{T} \hat{Z}_t S_{copt}\right] = \left[\sum_{t=1}^{T} \hat{Z}_t \cdot Z_t^{'}\right]^{-1} \left[\sum_{t=1}^{T} \hat{Z}_t S_{copt}\right], \qquad (2.22)$$

since $\sum_{t=1}^{T} \hat{z}_{jt} z_{it} = \sum_{t=1}^{T} \hat{z}_{jt} (\hat{z}_{it} + \hat{e}_{it}) = \sum_{t=1}^{T} \hat{z}_{jt} \hat{z}_{it}$ and hence $\sum_{t=1}^{T} \hat{Z}_t \cdot \hat{Z}_t^{'} = \sum_{t=1}^{T} \hat{Z}_t \cdot Z_t^{'}$

Substituting [*2.19*] into [*2.15*]:

$$C\hat{O}P_{2SLS} = \left[\sum_{t=1}^{T} \hat{Z}_t \cdot Z_t^{'}\right]^{-1} \left[\sum_{t=1}^{T} \hat{Z}_t (Z_t^{'} \cdot COP + \varepsilon_{copt})\right]$$

$$= COP + \left[\sum_{t=1}^{T} \hat{Z}_t \cdot Z_t^{'}\right]^{-1} \left[\sum_{t=1}^{T} \hat{Z}_t \cdot \varepsilon_{copt}\right]$$

$$= COP + \left[(1/T)\sum_{t=1}^{T} \hat{Z}_t \cdot Z_t^{'}\right]^{-1} \left[(1/T)\sum_{t=1}^{T} \hat{Z}_t \cdot \varepsilon_{copt}\right] \qquad (2.23)$$

The consistency of the 2SLS estimator can be shown as follows. From (*2.20*) and (*2.21*), the first term in the matrix product (*2.23*):

$$\left[(1/T)\sum_{t=1}^{T} \hat{Z}_t \cdot Z_t^{'}\right] = \hat{\delta}^{'}(1/T)\sum_{t=1}^{T} X_t Z_t^{'}$$

$$= \left[(1/t)\sum_{t=1}^{T} X_t X_t^{'}\right]^{-1} \left[(1/T)\sum_{t=1}^{T} Z_t X_t^{'}\right]\left[(1/T)\sum_{t=1}^{T} X_t Z_t^{'}\right]$$

$$\xrightarrow{P} \left[E(X_t X_t^{'})\right]^{-1} \left[E(Z_t X_t^{'})\right]\left[E(X_t Z_t^{'})\right]$$

The second term in the matrix product in (*2.23*):

$$\left[(1/T)\sum_{t=1}^{T} \hat{Z}_t \cdot \varepsilon_{copt}\right] = \hat{\delta}'(1/T)\sum_{t=1}^{T} X_t \varepsilon_{copt}$$

$$\xrightarrow{P} \left[E(X_t X_t^{'})\right]^{-1} \left[E(Z_t X_t^{'})\right]\left[E(X_t \varepsilon_{copt})\right]$$

$$= 0$$

since $E(X_t \varepsilon_{copt}) = 0$ under the assumption of correlation between X_t and ε_{copt}.

Therefore,

$C\hat{O}P_{2SLS} \xrightarrow{p} COP$, which indicates the 2SLS estimator is consistent.

2.2 Issues in Empirical Tests

2.2.1 Estimation of the Empirical Model

The consistency of the estimates from *2SLS* was discussed in section 2.1. The entire system of equations is as follows:

World oil demand function:

$$Q_{wt} = w_0 + w_1 P_t + w_2 GDP_t + w_3 Q_{wt-1} + \varepsilon_{wt-1}; \qquad (2.24)$$

Non-OPEC supply function:

$$S_{nopt} = nop_0 + nop_1 P_t + nop_2 S_{nopt-1} + \varepsilon_{nopt}; \qquad (2.25)$$

Supply function of individual OPEC members:

Supply from i member except Kuwait and Iraq,

$$S_{it} = \alpha_i + \gamma_i P_t + \beta_i S_{nit} + \varepsilon_{it}; \qquad (2.26)$$

Supply from Iraq,

$$S_{iraqt} = \alpha_{iraq} + \gamma_{iraq} + \beta_{iraq} S_{niraq} + \delta_{iraq} d_{iraq} + \varepsilon_{iraqt}; \qquad (2.27)$$

Supply from Kuwait,

$$S_{kuwaitt} = \alpha_{kuwait} + \gamma_{kuwait} + \beta_{kuwait} S_{nkuwait} + \delta_{kuwait} d_{kuwait} + \varepsilon_{kuwaitt}; \qquad (2.28)$$

Note that dummy variables are added in Iraq's and Kuwait's supply function. This is due to the first Gulf War. The war only lasted several months from August 1990 to February 1991; however, its impacts on the two involved producers, especially Iraq, have not entirely vanished. It took Kuwait about three years to return to its pre-war production level. Iraq was exporting oil under the UN's Oil for Food program after the war and so has not been in OPEC's quota allocation system ever since. I add dummy variables to incorporate this issue into the model. The values of d_{iraq} are set to zero before the third quarter of 1990 and to one thereafter. The values of d_{kuwait} are set to zero before the third quarter of 1990 and after the second quarter of 1993, and are set to one in between.

Now, my simultaneous equations model consists of 1 demand equation, 1 non-OPEC supply equation, and 11 OPEC members' supply equations.

The selection of instrumental variables is one of the most critical issues in applying *2SLS* to estimate a simultaneous system. Instrumental variables should be correlated with the endogenous explanatory variables but uncorrelated with the regression disturbance. In the estimation of individual producer's supply function, the predetermined explanatory variables S_{nopt-1}, GDP_t, Q_{wt-1} and the dummy variables can be naturally taken as instrumental variables. It is reasonable to assume that the production of one producer in the current period is independent of any other individual producer's production in the last period; therefore, the other individual producer's production in the last period is taken as instrumental variables. Note that the member's own production at last period is correlated with its production during the current period and hence should not be included as an instrumental variable. For example, to estimate the supply function of Saudi Arabia, the instrumental variable vector is $X_t^{'} = [1, GDP_t, Q_{wt-1}, S_{nopt-1}, S_{it-1}, d_{jt}]$, where i represents the individual producers except Saudi Arabia and j represents Iraq and Kuwait.

2.2.2 Hypothesis Test and Result Interpretation

One disadvantage of Griffin's market-sharing model is that the hypotheses to be tested are not explicitly specified because they do not represent a specific cartel model. Griffin suggested that a positive coefficient of other producers' production (β_i) would explicitly indicate market-sharing behavior. However, a positive β_i may just indicate a parallel action rather than a market-sharing oriented strategy. A proportional production adjustment to other members' production change may not be so crucial as to indicate a strict market-sharing policy. Rather, I believe that the coefficient of price may be more meaningful in determining whether the producer's behavior is consistent with the market-sharing strategy.

Therefore, it is not appropriate to group the hypothesis results into three variants, namely, (1) constant market sharing ($\beta_i = 1$, $\gamma_i = 0$), (2) market sharing ($\beta_i = 1$, $\gamma_i \neq 0$), and (3) partial market sharing ($\beta_i > 0$, $\gamma_i \neq 0$). This grouping in Griffin's paper resulted in some odd mixtures. For example, Saudi Arabia ($\beta_i = 0.74$, $\gamma_i = 0.29$), Venezuela ($\beta_i = 0.17$, $\gamma_i = -0.25$) and Indonesia ($\beta_i = 0.56$, $\gamma_i = 0.26$) are not rejected in the partial market-sharing hypothesis. However, the coefficients strongly indicate different behaviors among these three nations. Indonesia more likely acts as a competitive producer, happening to positively adjust its production with other members' production changes. Venezuela's negative coefficient for price indicates a preference for higher prices and its relatively low coefficient of other members' production may just have statistical meaning without indicating partial coordination with other producers.

In this thesis, the hypothesis of $\beta_i = 1$, $\gamma_i = 0$ is tested and a different grouping and interpretations are provided.

2.2.3 Data Collection

For comparative purposes, quarterly data for the period 1984:I through 2000:IV were utilized. Quarterly data, as opposed to annual data, allow a closer examination of short-run production adjustments in response to price and other factors.

Quarterly world crude oil demand and supply are assumed to be equal since only OECD stock changes data are available for part of my estimation period. Also, experiments incorporating OECD stock changes in the model indicated trivial effects. Quarterly crude oil production volumes, in thousand of barrels, were published in the *Energy Statistical Sourcebook* of the *Oil and Gas Journal* energy database.

The price series is a weighted average of free on board (f.o.b.) costs of U.S. crude oil imports from OPEC members, which represents the actual price paid by the international oil companies to the producing countries. The real price of oil was then derived by deflating the nominal price by the inflation index published by the Bureau of Labor Statistics on its website.

Quarterly data on the OECD real gross domestic product (GDP) at 1990 purchasing power parity levels, in billions of U.S. dollars, were obtained from the OECD's *Quarterly National Accounts.*

2.3 Regression Results From *2SLS* and *OLS*

The simultaneous equation system was estimated using the two-stage least squares method over the post-Griffin sample period (1984:I – 2000:IV). Table 2.1 displays the estimated coefficients for the market-sharing model. Two hypothesis tests were carried out: the coefficient for price is equal to zero ($\gamma_i = 0$) and the coefficient for other producers' production is equal to one ($\beta_i = 1$). The summary of hypothesis tests is shown in the last column of Table 2.2.

Table 2.1 Two-Stage Least Square Estimates

Country	P_i (γ_i)	S_{it} (β_i)	Adjusted R^2	Hypothesis Test (5% level)	Significance Level ($\gamma = 0, \beta = 1$)
Algeria	.051 (.026)	.472 (.035)	.83	$\gamma > 0$ $0 < \beta < 1$	*.047* *.000*
Indonesia	.0096 (.032)	.223 (.042)	.44	$\gamma = 0$ $0 < \beta < 1$	*.761* *.000*
Iran	.079 (.077)	1.219 (.108)	.78	$\gamma = 0$ $\beta > 1$	*.307* *.044*
Iraq	.252 (.579)	4.491 (1.219)	.39	$\gamma = 0$ $\beta > 1$	*.579* *.004*
Kuwait	-.561 (.439)	.565 (.586)	.59	$\gamma = 0$ $\beta = 1$	*.201* *.458*
Libya	.076 (.053)	.697 (.073)	.71	$\gamma = 0$ $0 < \beta < 1$	*.153* *.000*
Nigeria	.149 (.055)	1.028 (.076)	.81	$\gamma > 0$ $\beta = 1$	*.007* *.717*
Qatar	.168 (.139)	1.557 (.174)	.73	$\gamma = 0$ $\beta > 1$	*.226* *.001*
Saudi Arabia	-.305 (.133)	1.235 (.222)	.59	$\gamma < 0$ $\beta = 1$	*.022* *.290*
U.A.E.	-.005 (.079)	1.278 (.112)	.81	$\gamma = 0$ $\beta > 1$	*.954* *.013*
Venezuela	.017 (.066)	1.147 (0.09)	.84	$\gamma = 0$ $\beta = 1$	*.796* *.103*

Table 2.2 Summary of Hypothesis Tests

Hypothesis	Test Result	
	Number of Countries	Countries
Constant Market ($\gamma = 0, \beta = 1$)	2	Kuwait, Venezuela
Partial Market Sharing ($\gamma > 0, \beta = 1$)	1	Nigeria
Partial Market Sharing ($\gamma > 0, 0 < \beta < 1$)	1	Algeria
Market Sharing ($\gamma = 0, \beta > 0$)	6	Indonesia, Iran, Iraq, Libya, Qatar, U.A.E.
Market Sharing and Price Making ($\gamma < 0, \beta > 1$)	1	Saudi Arabia

As a point of interest, I also re-estimated each equation using the ordinary least-squares method. This was done to see the extent to which the *OLS* estimates are biased. Tables 2.3 and 2.4 display the estimation results from *OLS*. Table 2.5 presents the comparison between the estimators from the two methods.

Table 2.3 Ordinary Least Square Estimates

Country	P_i (γ_i)	S_{it} (β_i)	Adjusted R^2	Hypothesis Test (5% level)	Significance Level (γ = 0, β = 1)
Algeria	.061 (.017)	.479 (.030)	.82	$\gamma > 0$ $0 < \beta < 1$	*.001* *.000*
Indonesia	.002 (.021)	.208 (.035)	.42	$\gamma = 0$ $0 < \beta < 1$	*.924* *.000*
Iran	.064 (.187)	1.152 (.088)	.78	$\gamma = 0$ $\beta = 1$*	*.187* *.082*
Iraq	-.186 (.279)	3.135 (.962)	.40	$\gamma = 0$ $\beta > 1$	*.505* *.027*
Kuwait	-.144 (.264)	.954 (.466)	.59	$\gamma = 0$ $\beta = 1$	*.583* *.922*
Libya	.073 (.036)	.705 (.06)	.72	$\gamma > 0$* $0 < \beta < 1$	*.041* *.000*
Nigeria	.060 (.035)	.93 (.061)	.83	$\gamma = 0$* $\beta = 1$	*.090* *.254*
Qatar	.230 (.073)	1.579 (.129)	.72	$\gamma > 0$* $\beta > 1$	*.002* *.000*
Saudi Arabia	-.137 (.090)	1.388 (.188)	.60	$\gamma = 0$* $\beta > 1$*	*.127* *.039*
U.A.E.	-.019 (.053)	1.2282 (.096)	.81	$\gamma = 0$ $\beta > 1$	*.724* *.003*
Venezuela	.020 (.042)	1.129 (0.07)	.84	$\gamma = 0$ $\beta = 1$	*.629* *.082*

*Note: * Different with results from 2SLS*

Table 2.4 Summary of Hypothesis Tests from *OLS* Estimation

Hypothesis	Test Result	
	Number of Countries	Countries
Constant Market ($\gamma = 0, \beta = 1$)	4	Kuwait, Venezuela, Nigeria, Iran
Partial Market Sharing ($\gamma \neq 0, \beta > 1$)	1	Qatar
Partial Market Sharing ($\gamma \neq 0, 0 < \beta < 1$)	2	Algeria, Libya
Market Sharing ($\gamma = 0, \beta > 0$)	4	Indonesia, Iraq, U.A.E., Saudi Arabia
Market Sharing and Price Setting ($\gamma < 0, \beta > 1$)	0	

Table 2.5 Significance Level of Comparison between 2SLS and OLS

Country	H_0 $\gamma_{2sls} = \gamma_{OLS}$	H_0 $\beta_{2sls} = \beta_{OLS}$
Algeria	.651	.901
Indonesia	.458	.485
Iran	.561	.307
Iraq	.316	.049*
Kuwait	.115	.415
Libya	.780	.978
Nigeria	.009*	.100*
Qatar	.188	.644
Saudi Arabia	.063*	.421
U.A.E.	.820	.936
Venezuela	.796	.760

*Note: * Indicates rejection of the hypothesis at 10% significance level*

2.3.1 Comparison of the Two Estimation Methods

Basically, the comparison of the two methods shows that *OLS* estimators are surprisingly close to the structural *2SLS* estimators, although the two methods do present some different hypothesis test results. One reason for the similarity of the two methods may be attributed to the finite samples. Asymptotically, *2SLS* must dominate *OLS,* as demonstrated in section 2.1. In this study, the sample size is 68 and may not fully represent the asymptotical properties. The other reason may be the cancel-out effects in those biasing terms when *OLS* estimators are applied.

Although the closeness of the two estimates predominates, one prominent difference in the comparison still suggests that the results from *2SLS* are superior to results from *OLS*. The hypothesis that the price coefficients of Saudi Arabia as estimated from the two methods are equal can be rejected with very high confidence. In *2SLS,* Saudi Arabia has a significant negative price coefficient while *OLS* suggests that Saudi Arabia's price coefficient is not significantly different from zero. The significantly negative price coefficient is more reasonable and just presents the uniqueness of Saudi Arabia's status in OPEC. The differences in the other hypothesis tests for Iran, Qatar, Libya, and Nigeria also indicate that results from *2SLS* can provide a more plausible explanation. Therefore, I will use the estimation results from *2SLS* in further analysis.

2.3.2 Comparison with the Results of Griffin's Market-Sharing Study

Comparing the results of this study with previous studies will provide some enlightening insights on OPEC's market-sharing behavior. Griffin (1985) initialized the market-sharing model and estimated the model by the data from 1971:I to 1983:III.Table 2.6 provides a comparison of the two studies.

Table 2.6 Comparison Between This Study and Griffin's

	Yang (2003) (1984:I - 2000:IV)			Griffin (1985) (1971:I - 1983:III)		
Country	P_i (γ_i)	S_{it} (β_i)	Adjusted R^2	P_i (γ_i)	S_{it} (β_i)	Adjusted R^2
Algeria	0.05	0.47	0.83	0.005	0.74	0.69
	(0.03)	(0.04)		(0.02)	0.07	
Indonesia	0.01	0.22	0.44	0.26	0.56	0.83
	(0.03)	(0.04)		(0.02)	(0.06)	
Iran	0.08	1.22	0.78	0.05	0.88	0.69
	(0.08)	(0.11)		(0.02)	(0.15)	
Iraq	0.25	4.49	0.39	0.29	-0.06	0.49
	(0.58)	(1.22)		(0.05)	(0.48)	
Kuwait	-0.56	0.57	0.59	-0.39	1.41	0.90
	(0.44)	(0.59)		(0.03)	(0.12)	
Libya	0.08	0.70	0.71	-0.27	0.72	0.59
	(0.05)	(0.07)		(0.05)	(0.18)	
Nigeria	0.15	1.03	0.81	0.10	1.13	0.68
	(0.06)	(0.08)		(0.03)	(0.11)	
Qatar	0.17	1.56	0.73	-0.03	0.88	0.73
	(0.14)	(0.17)		0.02	(0.08)	
Saudi Arabia	-0.31	1.24	0.59	0.29	0.74	0.49
	(0.13)	(0.22)		0.04	0.13	
U.A.E.	-0.01	1.28	0.81	0.20	1.00	0.80
	(0.08)	(0.11)		(0.02)	(0.08)	
Venezuela	0.02	1.15	0.84	-0.25	0.17	0.75
	(0.07)	(0.09)		(0.02)	(0.08)	

New Interpretation of Griffin's Results

The comparison in Table 2.6 shows that OPEC's behavior during the post-Griffin period was notably more homogeneous than that in the period tested by Griffin. The homogeneity should indicate better strategy coordination among OPEC members. One prominent difference between the results of the two studies is that most OPEC producers have insignificant price coefficients and only Saudi Arabia has a significant negative price coefficient in this study, while Griffin’s estimates show frequent statistically significant price terms. This is important because market shares changing with price indicate a deviation from coordinated strategies.

Although Griffin claims that his results impressively favor the partial market-sharing model, the tests for a competitive model in the same study ironically do not reject the competitive behavior for six out of eleven producers. Griffin’s results also show little regularity in grouping OPEC producers with some very odd mixtures. For example, among the widely recognized cartel core of Kuwait, Qatar, the U.A.E. and Saudi Arabia, only the U.A.E. and Qatar are grouped into the market-sharing variant while the others are grouped into the partial market-sharing variant, and Kuwait has significant negative coefficients on price while Saudi Arabia and the U.A.E. have significant positive ones. As another example, which Griffin mentioned in his paper: “Of those countries found to increase market share in response to rising prices, we find a curious mixture ranging from Saudi Arabia to Indonesia” (Griffin, 1985). All of these make it difficult to find a plausible interpretation under the framework of an effectively coordinated market-sharing strategy.

In addition, Griffin considered whether the coefficient for market share equal to unity was a crucial criterion to use in grouping the producers, arguing that a proportional production adjustment against other producers’ production indicates a constant market share strategy. However, the frequent significant price effects on market share as well as the heterogeneity of the coefficients on market share ranging from –0.06 to 1.41 seriously discredit the argument.

Combined with the fact that there were no official guidelines (quota allocation) for the market-sharing strategy during the period tested by Griffin, the estimation results can hardly support the hypothesis that the cartel worked under the scheme of effective market sharing. Therefore, it is actually more plausible to interpret Griffin's results as rejecting an effective market-sharing strategy than favoring one.

2.3.3 New Grouping of OPEC Producers

Contrary to the vague grouping in Griffin's study, the results of this study enable us to re-group the OPEC producers in a more meaningful way. One of the prominent properties of the results is that eight out of eleven producers have an insignificant coefficient for price, with Saudi Arabia having the only significant negative coefficient. This property strongly indicates a more effective coordination in their production control strategy, and the foremost role of OPEC as a whole and Saudi Arabia in particular in affecting oil prices. My grouping largely depends on the price coefficient but considers the market share coefficient as well.

Three groups are determined as follows:

Cartel Leader and Swing Producer: Saudi Arabia

Market Share Participant: Iran, Kuwait, Libya, Qatar, Venezuela, and U.A.E.

Partial Market Share Participant: Nigeria, Algeria, and Indonesia

Iraq is not assigned to any of the above groups because of the odd statistical estimation results and its current status as an OPEC outsider.

Cartel Leader and Swing Producer: Saudi Arabia

It is well known that Saudi Arabia is the most important producer and plays a key role in OPEC's production and pricing policies. Saudi Arabia can prevent prices from rising by raising its production given its mass surplus capacity. Conversely, Saudi Arabia can prevent prices from falling if it is willing to substantially reduce its production. My results show that Saudi Arabia does behave like the cartel's leader and the price setter. Only Saudi Arabia has a significant negative coefficient for price, and the hypothesis that its market-share coefficient is equal to one cannot be rejected. The negative price coefficient tells us that Saudi Arabia adjusts its production inversely to the price and indicates that it actually sets the prices, a behavior strongly inconsistent with competitive producers. The positive and close to one coefficient for market-share indicates that Saudi Arabia does not act as a dominant producer, which should adjust its production inversely with other producers' production. It also cannot be explained as a full swing producer.

After the price collapse and dramatic drop in its production and market share in 1986, Saudi Arabia announced that it had abandoned its role as swing producer. However, without a swing supplier there was no way, except by an accidental quirk of supply/demand equalization, that every member could precisely meet his quota. Figure 2.1 shows the Saudis' oil production and their quota. Basically, Saudi Arabia adjusts its production higher or lower against the quota with relatively high compliance, a behavior indicating a market-sharing oriented strategy.

The estimates results suggest that Saudi Arabia's production strategy can be explained as follows: Saudi Arabia works as a moderate swing producer adjusting its production in the neighborhood of the quota so that it can maintain the oil price within a favorable range to the cartel's stability and to its long-term profit under moderate conditions. In the meantime it will not overburden itself when market situations are extremely detrimental to it.

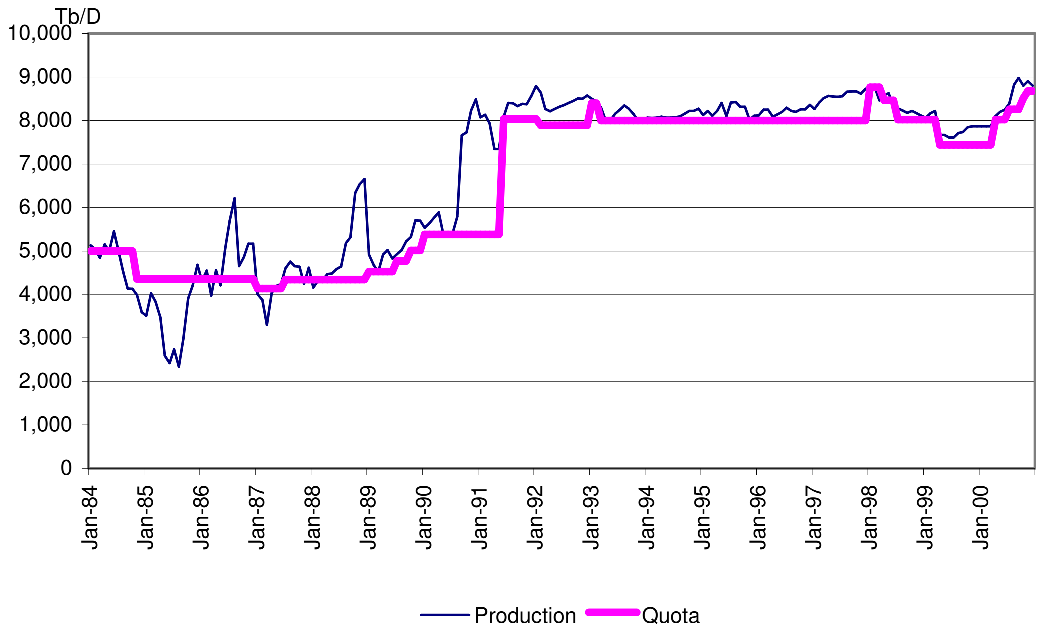

Figure 2.1 Saudi Arabia Oil Production and Quota, 1984-2000

Market-Share Participator: Kuwait, U.A.E, Qatar, Libya, Iran, and Venezuela

All market-share participators have an insignificant coefficient for price and their market-share coefficients are close to one.

The three Gulf producers -Kuwait, the U.A.E., and Qatar- have common characteristics: vast oil reserves; relatively small populations; more flexible economic development plans; and the ability to withstand the threat of lower revenues. Hence, they are widely considered firmly supportive of the market share policy. Among them, the U.A.E. and Qatar have coefficients on market share higher than unity in the tests. Interestingly, in Griffin's study, Kuwait also shows this property. This may suggest that these producers are willing to take a greater degree of the production cut burden under the slack market conditions and falling prices, and bear more than their share when cartel-wide production increases. This behavior indicates that the Gulf producers are willing to see oil prices fall to a favorable range, not too high and not too low.

When the quota system was initialized in the early 1980s, Iran and Libya as well as Algeria were opposed to the market share policy and wanted to see fixed and higher prices with more strict production restraints. However, they did not have the power to achieve the higher prices either by reducing their own production without coordinated production control from others or disciplining the cartel for lower production quota. Their consistence with market share strategy indicates that they had to compromise their own ideal objective with the one they could practically obtain.

Partial Market Share Participants: Nigeria, Algeria and Indonesia

These three countries all have large populations, relatively low GDP per capita and high absorptive capacity. The three partial market share participants are assumed to behave more like competitive producers. They essentially select their outputs at the point that equates price to marginal costs with the constraints of production capacity, while they also take into consideration their market-share in OPEC when they make their production decision.

Algeria and Nigeria have significant positive coefficients on price. Algeria is notorious for its consistently low compliance with its quota (see Figure 2.2). Its relatively low coefficient for market share is more likely to be an indication of a coincidental parallel action with other OPEC producers' production adjustments.

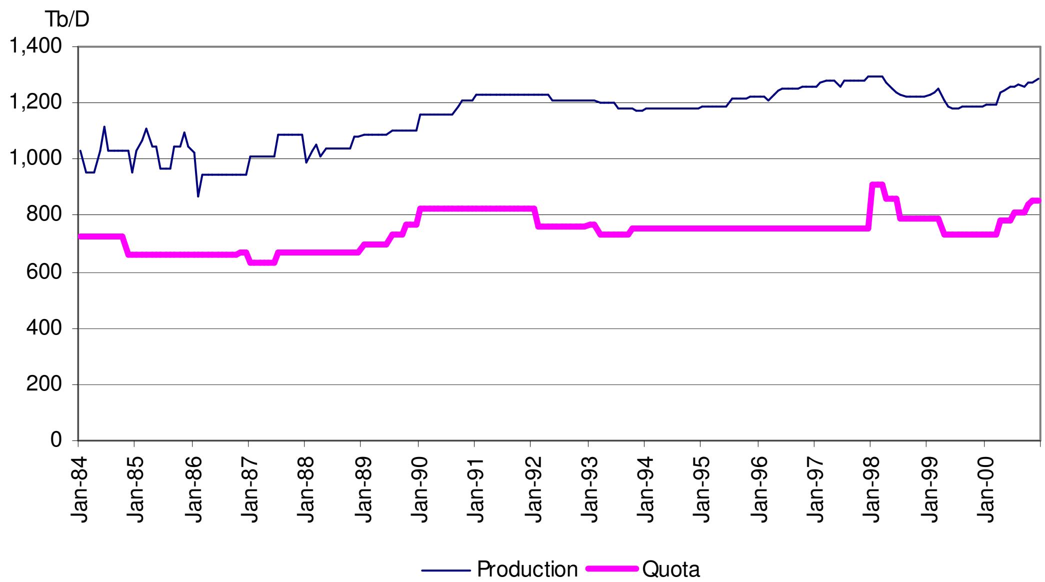

Figure 2.2 Algeria Oil Production and Quota, 1984-2000

Its peculiar location and target market reveal that Nigeria can hardly be a constant market-share strategy follower in OPEC. Eighty percent of Nigerian exports are destined for the Atlantic Basin market (West Europe and U.S. East Coast). In the days of slump demand and increased non-OPEC North Sea supply, Gulf crude streams become less attractive in the Atlantic Basin, and Nigeria basically competes with non-OPEC Atlantic crudes (North Sea and U.S.) and works as a dominant producer in the area to some extent. Therefore, Nigeria has to consider this specific market condition when it makes its production decision. Nigeria's production dropped more than half from its peak level to well below 1 MMB/D in early 1982 when it stuck with OPEC's fixed price and price differential policy as the demand in the Atlantic area dropped and the non-OPEC North Sea crude stream increased substantially. This miserable experience made Nigeria realize that its full cohesion with OPEC production/price policy was not in its best interest. The estimation results show that Nigeria adjusts its production positively with the price as opposed to the price-inelastic behavior of its peers in the Middle East.

It is well known that Indonesia has the very lowest ratio of reserve to production. Figure 2.3 shows that Indonesia has problems in expanding its oil production capacity and maintaining its level of production and exports. Although Indonesia has an insignificant coefficient for price, the impressively low market-share coefficient indicates that Indonesia may be restrained in increasing its production by its capacity constraint when other producers increase production to catch more market share, making them reluctant to cut production when coordinated cuts are needed to accommodate slack market conditions. In addition, the relatively low R-squared value indicates that other important factors are affecting Indonesia's oil production decision, which also means a deviation from a constant market-sharing strategy.

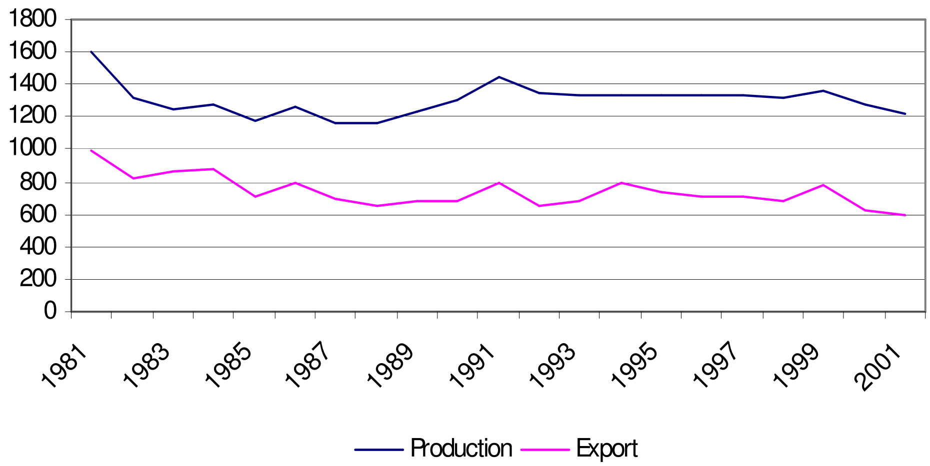

Figure 2.3 Indonesia Oil Production and Export, 1981-2001

In summary, the estimation results of this study strongly support the hypothesis that OPEC has operated as a market-share cartel since the early 1980s. The comparison between Griffin's study and the one described here indicates that OPEC was far from mature as a cartel in terms of effectively coordinated production control from 1973 to 1983 as many researchers have claimed; rather, the unprecedented market power gained by OPEC from nationalization and price rigidity may be more important factors in explaining the ease of increasing price dramatically in 1973-1974 and 1979 with moderate coordinated actions. The enormous structural changes in the oil market in the early 1980s required more effective coordination from OPEC to maintain a favorable market for the cartel. The statistical tests in this study show that OPEC did improve coordination on production control in response to changing market conditions. The majority of OPEC producers demonstrate substantially coordinated behavior in making their production decisions and Saudi Arabia takes leadership in the cartel, a crucial factor in the success and stability of the cartel.

2.4 Dynamics of OPEC Behavior

One of the most prominent findings of this study is that only Saudi Arabia has a significant negative coefficient for price. This strongly indicates that Saudi Arabia is the price-setter, i.e., when Saudi Arabia increases its production, the price will go down and vice versa. It is intriguing to know the basis upon which Saudi Arabia makes its production decisions.

Many researchers hold the supposition that Saudi Arabia is a dominant producer that maximizes its own profits by setting its marginal revenue equal to marginal cost with respect to the demand curve, assuming the other competitive fringe producers set their production level with given prices. However, this supposition would not be consistent with the proposition that Saudi Arabia sets its production inversely against the price.

Saudi Arabia acts as a leader in OPEC by having the greatest surplus production capacity and the ability to adjust its production to correspond the market price with market conditions. As the leading member of OPEC, Saudi Arabia not only decides its production according to its market share as formalized by the quota mechanism but also has to take the role of swing producer. Doing so decides its production inversely against the market price trend in most circumstances as shown in the statistical tests. The constant dominant producer behavior is not sufficient to explain this behavior. As a dominant producer, Saudi Arabia would face the residual demand schedule determined by the difference between total demand for OPEC and supply from other OPEC producers except Saudi Arabia itself. Facing this residual demand schedule, according to the dominant firm model, the Saudis would determine their production at a level that makes the marginal revenue equal to marginal cost. The following graphs demonstrate that the dominant firm model is not consistent with the proposition that Saudi Arabia's production changes inversely with price.

Either the decrease in total demand for OPEC or the increase in supply from other OPEC producers reduce the residual demand for Saudi Arabia's oil. For simplicity's sake, I assume that the basic scenario for other OPEC producers' supply pattern is price inelastic as shown in Figure 2.4. According to this assumption, other OPEC producers stay with their predetermined market share and do not adjust their production level according to the market price. As shown in section 2.3, the hypothesis of the coefficient of price equal to zero cannot be rejected for all other OPEC producers except Algeria and Nigeria, so the assumption here is plausible.

Now, as shown in Figure 2.4, when supply from non-OPEC producers increases greatly or the total world oil demand decreases dramatically, total demand for OPEC shifts left from D_{OPEC} to D_{OPEC}'. Assuming other OPEC producers do not reduce their production and stick instead with their production level, the residual demand for Saudi Arabia's supply would shift left from D_{SA} to D_{SA}' correspondingly, as does the marginal revenue curve from MR_{SA} to MR_{SA}'. According to the dominant firm model, Saudi Arabia decides its production level at the point where marginal revenue equals marginal cost to maximize its profit; therefore, the production level would shift from Q_{SA} to Q_{SA}'. However, the price level would not increase as indicated by the inverse changes between

Saudi Arabia's production and market price. Rather, the price would decrease from P_{SA} to P_{SA}', indicating a positive relationship between Saudi Arabia's production and market price.

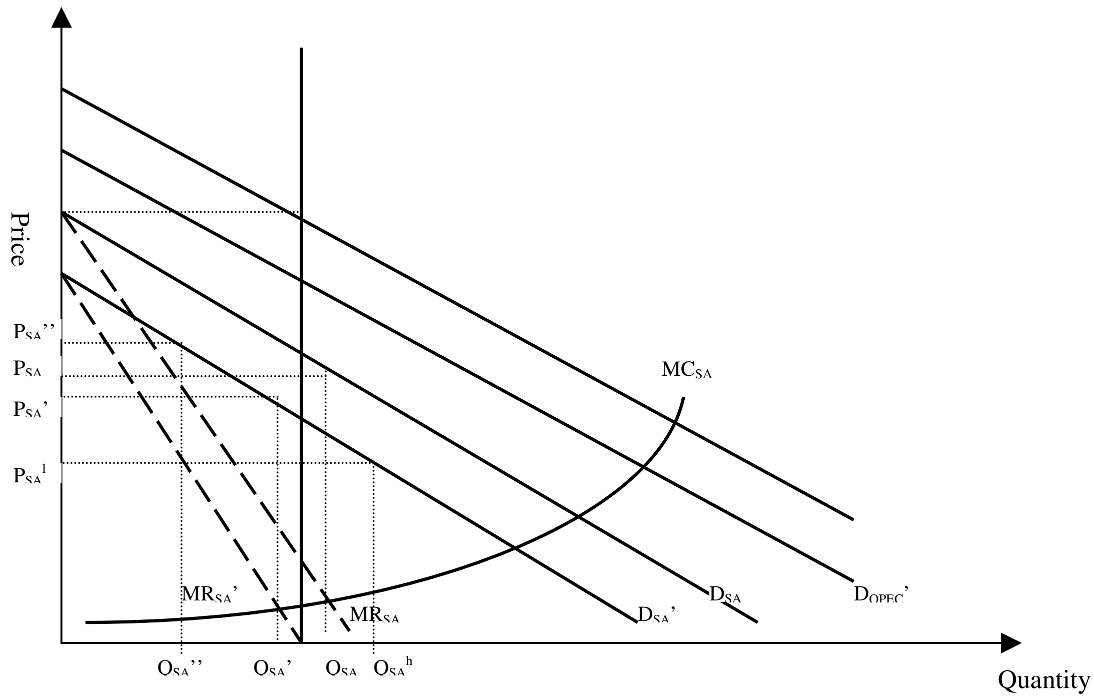

Figure 2.4 Reduced Demand Schedule for OPEC Production

Figure 2.5 depicts Saudi Arabia's response to other OPEC producers' weak compliance with their market share under the dominant firm model assumption. Under many circumstances, other OPEC producers do not strictly comply with their market share and deviate from the perpendicular supply curve S_{00} to a tilted supply curve S_{00}', which enables them to grasp more profit according to price changes. Note that S_{00}' is not necessarily the real marginal cost curve of the other OPEC producers. It could be any deviation from its predetermined market share. Similar to the case for reduced total demand for OPEC supply, the tilted supply curve of other OPEC producers would make the demand for Saudi shift left from D_{SA} to D_{SA}'. Again, under the framework of the dominant firm model, we see that Saudi Arabia's production would decrease from Q_{SA} to Q_{SA}' and the market price would decrease from P_{SA} to P_{SA}'. A positive relationship between Saudi Arabia's production and market price is shown in this case.

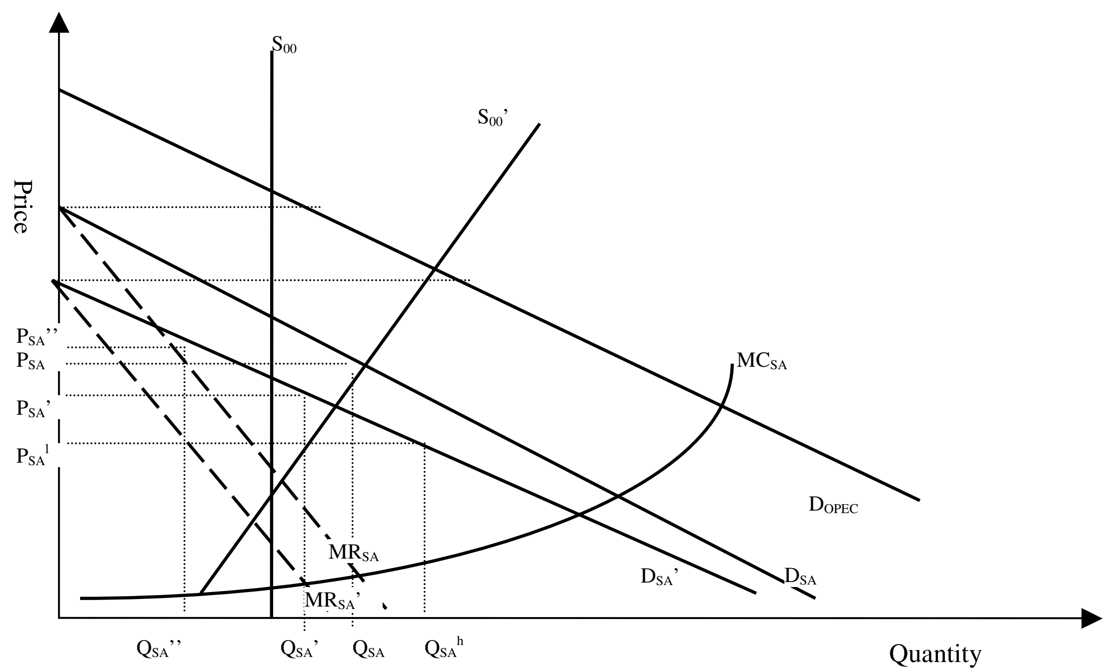

Figure 2.5 Other OPEC Producers' Weak Compliance with Quota

What does this paradox tell us? It says that Saudi Arabia may not behave as the dominant producer--in other words, Saudi Arabia may not maximize its own short-term profit when it makes a production decision. To exhibit a negative relationship between market price and its production level, Saudi Arabia would either reduce its production more than required to maximize its profit to increase the price, or increase its production level to reduce market price. This is shown in Figures 2.4 and 2.5. Both figures reveal that Saudi Arabia can reduce its production from Q_{SA} (I still assume the original point is determined by the dominant firm model for simplicity) to Q_{SA}'' rather than Q_{SA}' and hence the price can be increased from P_{SA} to P_{SA}''. In the other case, Saudi Arabia can increase its production from Q_{SA} to Q_{SA}^{h} and the price would correspondingly decrease from P_{SA} to P_{SA}^{l}. Then we will read a negative relationship between Saudi Arabia's production and the market price. The econometric tests have told us that Saudi Arabia behaves like this from a statistical perspective.

The next question is, why does Saudi Arabia reduce its production more than required to maximize its profits to increase the price, or increase its production to reduce the price? One plausible explanation is that Saudi Arabia, as the swing producer, would like to sacrifice its profits, to some extent, to keep the cartel stable when the entire market is weak and to punish the cheating behavior of other OPEC producers when their production significantly deviates from their committed level. The dynamics are illustrated in Figures 2.6 and 2.7.

Figure 2.6 depicts the Saudis' response to weak market conditions. Here I assume that both Saudi Arabia and other OPEC members have inelastic supply curves (see curve S_{SA} and S_{00}), an assumption consistent with the market-sharing model. Note that Saudi Arabia's beginning production level is lower than its optimal production (Q_{SA}^{M}), which is determined by equating marginal revenue to marginal cost. As discussed above, the committed market share may not perfectly suit any individual member; rather, it should be a compromise determined largely by each member's historical production level. Therefore, both Saudi Arabia and other producers may produce at a level deviating from their individual optimal level, and it is reasonable to assume the committed market-share production level is lower than the optimal one. Because of restricted production from Saudi Arabia, the beginning market price (P_{SA}) is higher than the one (P_{SA}^{M}) determined by Saudi Arabia's optimal production. Actually, P_{SA}^{M} should be higher than a competitive level since other OPEC producers reduce their production against their individual optimal level.

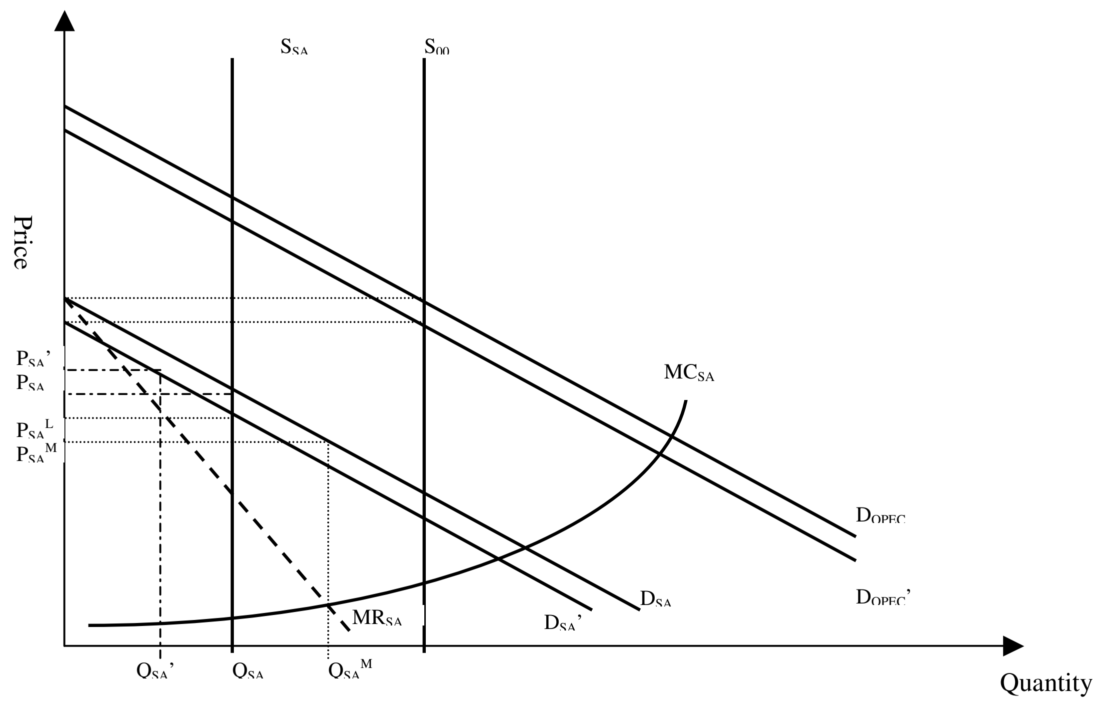

Figure 2.6 Saudi Arabia's Response to Weak Market

When the market is weak in situations such as increased non-OPEC production, sluggish economic growth, or seasonal declines in world oil demand, the demand for OPEC supply will shift left from D_{OPEC} to D_{OPEC}', and the demand for Saudi supply will shift left from D_{SA} to D_{SA}', assuming that other OPEC producers maintain their production level. If Saudi Arabia keeps its production level at Q_{SA}, the oil price will decrease from P_{SA} to P_{SA}^{L}. This implies that all OPEC members will lose profit by sticking with their previous production levels. If Saudi Arabia increases its production to its dominant optimal level so as to improve its financial situation, the market price will further decrease and hence worsen the other OPEC producers' oil revenue situation. Thus, the other OPEC producers are very likely to increase their production to a larger extent so as to maintain their market share and improve their decreasing oil revenue, causing the price to go down even more. The situation will tend to worsen for both Saudi Arabia and other OPEC producers and may result in the collapse of the cartel if the production increase goes on. Therefore, to sustain the stability of the cartel, Saudi Arabia is likely to choose to reduce its production level from Q_{SA} to Q_{SA}' such that the price will increase from P_{SA} to P_{SA}'. A collaborative production reduction from other OPEC producers will alleviate the burden of Saudi Arabia and keep the market share stable.

When the market is strong, the dynamics are opposite those described in the weak market situation. When demand for OPEC and for the Saudi supply increases, Saudi Arabia and other OPEC producers will split the increased demand and increase their production correspondingly, and finally the market price is likely to decrease. Following this strategy, OPEC will achieve a cooperative outcome by the market share scheme with Saudi Arabia working as a swing producer.

Figure 2.7 depicts Saudi Arabia's response to the cheating behavior of other OPEC producers. It is alleged that some of the OPEC members always disrespect their quota and make the production decision totally in their own interest. Although my statistical tests do not entirely support this argument, eight out of eleven members, namely Algeria, Indonesia, Iran, Iraq, Libya, Nigeria, Qatar and Venezuela, do show positive price elasticity in spite of insignificance.

One major argument against the hypothesis of OPEC as a cartel is that there is no effective punishment mechanism for enforcing the quota scheme. Figure 2.7 shows that Saudi Arabia may act as the enforcer in the situation of other OPEC producers' heavy deviation from their market share. When other OPEC producers cheat on their production quota, its supply curve will tilt right as shown in Figure 2.7, the curve S_{00}'. Because of the increase in other OPEC producers' production, the residual demand schedule for Saudi oil will shift left from D_{SA} to D_{SA}'. If the deviation is not too intimidating and is tolerable for Saudi Arabia, it may take the same strategy as depicted in Figure 2.6. It could reduce its production in order to keep or increase the price level so that the other producers' target revenue can be met.

However, this strategy requires sacrifice of its own benefits and hence would not be sustainable for a long time or to a large extent. To punish the cheating behavior, Saudi Arabia can use the tit-for-tat strategy by increasing its production to the optimal level (Q_{SA}'), which is determined by equaling the marginal revenue, associated with the new residual demand schedule, to marginal cost, as a dominant producer would do. Then, the price level would dramatically drop from P_{SA} to P_{SA}'. The oil revenue situation would then worsen for the other OPEC producers. This may either force them to go back on the right track, or trigger their further deviation from their current production level to maintain market share, causing the price to go down further. If this cycle goes on, collusion in OPEC is unsustainable and OPEC will end up with the Nash-Cournot outcome where every producer just maximizes its production assuming that others' production is constant. Since Saudi Arabia can meet any price, once it makes the others believe its threats will come true, all members realize that the Nash-Cournot outcome does nothing for their long-term benefit. They will negotiate to set the new collaborative market share scheme to accommodate the changing demand and supply situation.

The reality of the 1986 oil market testified to this. One occasion in which the market was misaligned with OPEC was during 1985-1986 when OPEC production was unrestricted for all members and Saudi Arabia produced at close to full capacity. Prices dropped to less than $10/barrel when Saudi Arabia chose to introduce netback pricing[5], a pricing mechanism that does not impose any restrictions on its output. Doing so allowed Saudi Arabia to easily recapture its market share. A few months later, when OPEC, under the leadership of Saudi Arabia, decided to cut back its production and reinstate the quota system, prices went back to $17/barrel.

[5] Crude oil is priced at the spot product value of the barrel less refining and transportation cost as well as a certain refining margin.

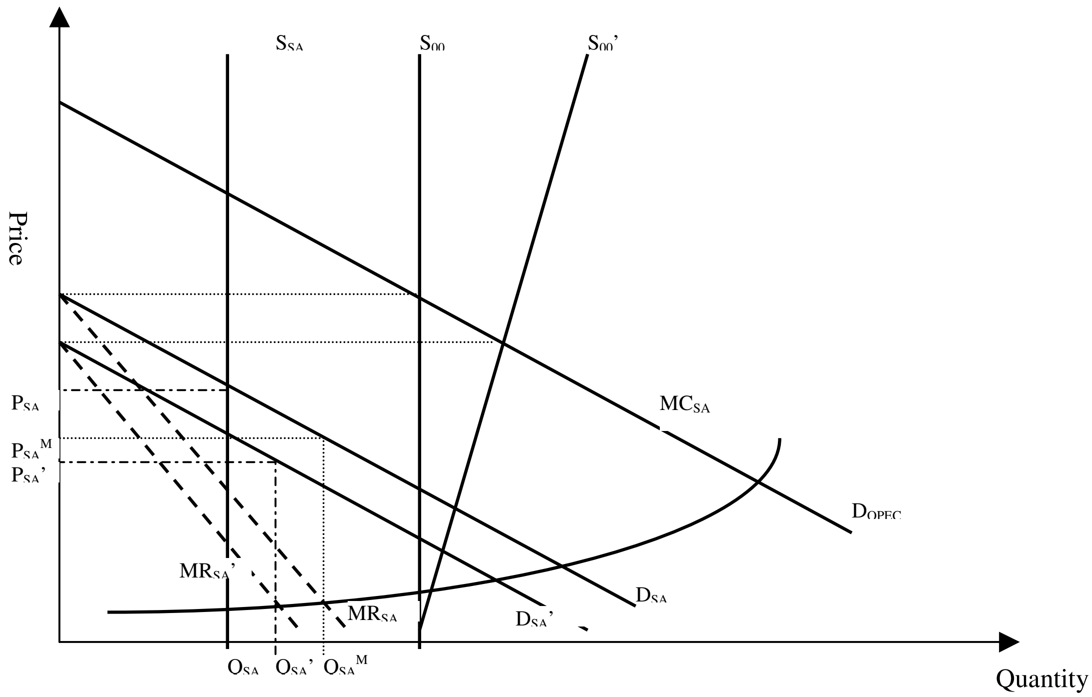

Figure 2.7 Saudi Arabia's Response to the Cheating Behavior of Other OPEC Producers

Previous studies of OPEC behavior always made the profit maximization assumption a prerequisite when analyzing a cartel or dominant firm's behavior. However, the above analysis enables us to ask: "Should a cartel have to maximize the organization's profit for it to be a cartel?" I believe that the criteria for a cartel are whether collusion occurs among the members and whether the market price is higher than the competitive level. But whether the cartel can really manage to maximize the organizational profit is questionable because it depends on many other factors, such as knowledge of the demand schedule facing it, the difficulty of side payment arrangement, and other political, historical, and accidental factors.

OPEC is never good at predicting the market responses to its production decisions. One prominent example occurred in 1997 and 1998. OPEC seriously misjudged the oil market and decided to increase its ceiling output from 25 million barrels per day to 27.5 based on the assumption that oil demand growth in 1998 would be 2.5%. However, combining the dramatic decline in Asian oil demand due to currency and banking crises in fall 1997, OPEC's decision to increase output contributed to oversupply in the oil market in 1998 and a collapse in oil prices that caused serious damage to OPEC economies. Because the oil market is a difficult market to manage, and OPEC still works with imperfect data and uses only one instrument, supply adjustment, to influence the market, it is almost impossible for OPEC to maximize its short-run profit even if it wanted to.

Moreover, the current quota scheme was largely determined according to the historical production level of each member. The production level may have never been the one that could maximize the profit of OPEC as a whole. It would be too costly and infeasible to adjust the quota to restrict the members' production to achieve the optimal profit, providing there is no feasible side payment scheme.

In addition, to maintain the stability of the cartel and to gain long-term profit, members may sacrifice their current profit by sticking with the market-sharing scheme, which cannot ensure that they will maximize their current profit. Therefore, current term profit maximization should not be a necessary condition for considering OPEC a cartel.

The dynamics of OPEC behavior must be much more complicated than have been depicted above. Nonetheless, the analysis provides us with a plausible mechanism for understanding puzzling market fluctuations, a mechanism virtually consistent with Adelman's long-standing argument:

> The cartel (OPEC) oscillates between two models: (1) the largest firm sets output, and all others produce ad lib. (2) All firms participate in setting an output total, and dividing it…. Both are unstable: in (1), the dominant firm will try to make others share the burden; in (2), cheating may force the dominant firm willy-nilly into (1). (Adelman, 1993, p. 287)

In conclusion, I would like to describe the cartel's behavior as follows: OPEC members collude to achieve a higher than competitive-level price, which may not necessarily suit each member perfectly nor maximize the current profit of the cartel as a whole. The collusion is facilitated by a market-sharing strategy and is well maintained most of the time. Like other cartels, OPEC faces problem in keeping the cartel stable, and Saudi Arabia takes the role of enforcing the collusion. The conduct of Saudi Arabia varies over time in response to the cooperation of other producers, its willingness to allow others to cheat, and other market conditions.

2.5 Conclusion

The estimation results in this study strongly support the hypothesis that OPEC has operated as a market-sharing cartel since the early 1980s. The comparison between Griffin's study and this one indicates that OPEC did improve coordination on production control in response to changing market conditions. The majority of OPEC producers demonstrate substantially coordinated behavior in making their production decisions and Saudi Arabia takes the leadership in the cartel, a crucial factor for its success and stability.

This conclusion is in opposition to those from statistical tests on the profit-maximizing cartel model (see Dahl, 1989; Alhajji, 2000). One mistake in those studies could be the profit maximization assumption. OPEC works with limited data and limited power, and is almost unable to predict precisely the market response to its production decisions. Assuming some ideal cohesion in OPEC, those studies, using historic statistical data, retrospectively test the profit maximization behavior of OPEC and reject the hypothesis that OPEC is a cartel when the profit maximization conditions are not met.

However, was OPEC able to make its production decision with respect to those theoretical conditions, knowing and predicting precisely all of the data used in those fancy econometric models? Using the profit-maximizing condition with historical data to test the behavior of a losing stock-broker would reject the hypothesis of the loser as a profit maximizer. Supported by the results of this study, OPEC goes with the strategy of coordinated production restraints, led by Saudi Arabia, and oil prices have been always higher than competitive levels, a fact no one doubts. These two observations are enough to enable us to say confidently that OPEC is indeed a cartel.

On the other hand, admitting that the cartel failed to maximize its short-run profit does not help us explain how OPEC countries decide their production levels and understand the impact of their behavior on the market. The study of OPEC's behavior is not to testify as a final objective whether OPEC is a cartel; rather, people are interested in the interaction of OPEC's behavior with the market. The statistical tests only provide a general trend of each member's conduct. Although statistically the majority of OPEC members adhere to market-share strategies, deviations from committed coordination do exist. One can observe that the conduct of OPEC producers varied over time and the market responded accordingly. Therefore, the more intriguing question is: under what circumstances are the deviations triggered to occur? Specifically, to what extent can Saudi Arabia tolerate cheating behavior from others, and what punishment can drag the cheaters back to the track? Furthermore, what direction will the market develop given the variations in OPEC's behavior? All of these questions require further study.

Chapter 3

OPEC BEHAVIOR: VIEW FROM A MARKOV REGIME-SWITCHING MODEL

3.1 New Model of OPEC's Behavior Under the Concept of Non-Cooperative Collusion with Imperfect Market Information

The development of oligopoly theories enables me to draw a more realistic picture of the interactions among OPEC producers, and specifically about their production behavior. The conceptual analysis of the game in OPEC closely follows Green and Porter's (1984) theory with moderate modifications.

I assume that there are two discrete strategies, the Cournot strategy and collusive strategy, that can be employed by each OPEC producer.[6] In Green and Porter's model, it is assumed that firms agree on a "trigger price" to which firms compare the market price while they select from these two strategies. Initially, firms produce at the collusive level and continue to do so until the market price dips below the trigger price, after which time firms will revert to Cournot production for some periods of time. Since price signal alone does not suffice to indicate the extent of collusion compliance among OPEC members due to the complexity of oil market, producers of OPEC may condition their strategies on a bunch of market information, such as price changes and reported quota violations. In

[6] It may be more realistic to assume a producer has a continuous production strategy set. But for the purpose of illustration, two discrete strategies should suffice.

addition, as suggested by Geroski, Ulph and Ulph (1987), internal financial constraints as well as some other country-specific factors may also cause producers to vary its production conducts.[7]

Therefore, I assume that each producer's production strategy is governed by a country-specific trigger index A_i, where A_i is a function of a set of variables including some market information and country-specific attributes. This assumption has important implications for the producer's behavior switches as they differ from predictions by Green and Porter. The identical trigger price suggested by Green and Porter implies that producers have simultaneous conduct shifts; once price dips below the trigger price, all producers will simultaneously revert to Cournot behavior. The country-specific trigger index will allow for different timing of production behavior switches on individual producers' own rhythms.

While the assumption about triggers is more general, the underlying mechanism of deterring cheating behavior should still apply. A producer in OPEC will continue to produce its restricted output until the market information in the trigger index makes it believe that the market is turning to a "reversionary" period (whether caused by demand shock or cheating behavior from others). Once that "reversionary" inference is triggered, the producer will enter the punishment periods, producing the Cournot output for a certain amount of time. Therefore, although each producer would have its own rhythm in

[7] It should be noted that the country-specific factors affecting behavior shifts do not play a role in the collusion enforcement mechanism; rather, they indeed add extra uncertainties on deviation from collusion behavior.

switching its production behavior, joint reversionary episodes should still be observed given commonly recognized depressing market information.

In collusive periods, a producer produces at its restricted output level with respect to allocated quota. It could increase its current payoff by producing more than the committed output. However, the cheating behavior would increase the probability of triggering other producers switching to competitive behavior, which would lead to a reduced profit level in some periods of time. Therefore, the producer should set its production level at a point where its marginal expected loss in future profits from possibly triggering punishment from its peers must be equal to (in terms of present discounted value) the marginal gain from over-producing in the current period.

Each producer can be modeled as facing a two-state (collusion and Cournot-competition) dynamic programming problem. As denoted below,

$\pi(Q_{it})$, the expected discounted present profit of producer *i* if it sets output level at Q_{it} in collusive period *t*,

$\kappa_i(Q_{it})$, the expected current period profit of producing Q_{it},

κ_{cnti}, the expected Cournot profit of producer *i* at one punishment period,

τ_i, the discount rate adopted by producer *i,*

T, the expected duration of the punishment period,

$Pr(S_{t+1} = \text{CC})$, the probability that the market falls into Cournot-Competition state at period $t+1$,

then the output level of producer *i* in collusive periods should be determined by maximizing the following objective function:

$$\pi_i(Q_{it}) = \kappa_i(Q_{it}) + \tau_i\left\{[1 - Pr(S_{t+1} = CC)]\pi_i(Q_{it}) + Pr(S_{t+1} = CC)\left[\sum_{t=0}^{T-1}\tau_i^t\kappa_{cnti} + \tau_i^T\pi_i(Q_{it})\right]\right\}$$

The above equation can be rearranged in an explicit form as follow:

$$\pi_i(Q_{it}) = \frac{\kappa_i(Q_{it}) + Pr(S_{t+1} = CC)\dfrac{\tau_i - \tau_i^{T+1}}{1-\tau_i}\kappa_{cnti}}{1 - \tau_i[1 - Pr(S_{t+1} = CC)] - Pr(S_{t+1} = CC)\tau_i^{T+1}}$$

$$= \frac{\kappa_{cnti}}{1-\tau_i} + \frac{\kappa_i(Q_{it}) - \kappa_{cnti}}{1 - \tau_i + (\tau_i - \tau_i^{T+1})Pr(S_{t+1} = CC)} \qquad (3.1)$$

This equation says that the expected discounted present value of producer *i* equals the expected return of a perpetuity profit of Cournot outcome plus the single-period gain in returns to collusion, appropriately discounted. The producer needs to set its collusive output at a level such that the second term of equation (3.1) is maximized. There are tradeoffs in increasing its collusive output level. A higher output level would increase the expected current period profit $\kappa_i(Q_{it})$. On the other hand, higher output would increase the probability of facing punishment from other producers as represented by $Pr(S_{t+1} =$ CC) because higher output would drag down the market price and increase the aggregate quota deviation. Both would trigger other producers to revert to Cournot behavior.

When this maximization problem holds for all OPEC producers, the *n* equations generate a set of output levels for the *n* producers in equilibrium. As shown in Porter (1983), this output profile for collusive periods should be different from the one that would maximize the static joint profit to OPEC because producers would forgo some profits in collusive periods in order to reduce the frequency and duration of reversionary periods. Therefore, it is rationalized that most OPEC producers' output is constantly above allocated quota but still at a restricted level.

Because oil is a special good in terms of exhaustibility and is important to OPEC producers' entire economy and well-being, OPEC producers' production decisions should also be subject to some constraints, such as revenue requirements, needs for hard currency, reserve endowment, etc.

According to the model presented above, production behavior switches should be observed for each producer over time. But unlike the prediction of Green and Porter, the timing of the switches of individual producers is expected to be divergent because each producer has its own interpretation of market situation and its production strategy is also affected by some internal attributes. That being said, joint reversionary episodes with sharp price depression should also be observed. In contrast to indicating the demise of the cartel, the reversionary episodes play an essential role in maintaining the long-run collusion of OPEC.

3.2 The Econometric Model

As it is impossible to explicitly test for the applicability of the enforcement mechanism, Porter (1983) constructed a simultaneous equation-switching regression model to detect the behavioral switches and identify the periods in which they took place, and then analyze whether the pattern of the behavioral switches is consistent with an equilibrium predicted in Green and Porter's enforcement mechanism. The empirical work of this study follows Porter's thought as providing indirect evidence for the predictions of the conceptual model described above. Tests will be made for the occurrence and timing of production behavioral switches of each OPEC producer and for the possible triggers of the behavioral shifts from collusion to competition.

Several assumptions underlying Porter's econometric model are unrealistic to OPEC. First, Porter specifies an aggregate supply function with the feature of regime-switching. This specification is based on two assumptions that are not applicable to OPEC. One is simultaneous regime-switching. According to Green and Porter's theoretical model, cartel members would simultaneously proceed into the punishment period and simultaneously revert to collusion. As noted above, OPEC does not have an explicit enforcement mechanism and producers are likely to employ the competitive strategy on their own rhythm according to different interpretations of market evolvement and some internal constraints. Therefore, different timing in regime switches should be captured in the econometric model. In addition, the aggregate supply function assumes an identical elasticity of variable costs with respect to output across all firms, based on which individual supply equations can be added up and whether an identical price elasticity in the aggregated supply function is viable. But the elasticity of variable costs should differ vastly across OPEC producers as their reserve endowment, spare capacity, and quality of wells are disparate.

Second, parameters in supply function are constant and the regime-switching feature is captured only by a stand-alone state indicator variable. This assumption says the supply curve will take a parallel shift with the regime switch. The assumption is quite restrictive and may mis-describe the real behavior change, such as a price elasticity shift in the two regimes.

Third, Porter assumes that the transitions of the two production regimes are governed by the Bernoulli distribution. According to this assumption, the transition probabilities of the two regimes are constant over time, i.e., no matter how market and internal constraints evolve, the industry will have the identical probability of reverting to a price war. Consequently, the assumption disables Porter's model to provide inferences on potential triggers of regime switches. In order to detect the causes of price wars, Ellison (1994) imposed a Markov structure on the transitions so that the transition probabilities would vary across time according to a set of predetermined variables.

The econometric model for this study makes some important innovations on the approach of Porter and thus more inferences can be drawn from estimates of the model.

The model assumes two production regimes--collusive and competitive--from which each OPEC producer may choose. However, researchers do not have a *priori* information about which regime each producer is taking at each time point. The transitions between the two regimes are assumed to be governed by a Markov structure according to a set of market information and internal attributes.

There are two parts to the econometric model: supply function and the regime transition probability functions[8].

Supply Function

Quantity produced by producer *i* at period t (Q_{it}) is a function of a vector of variables, represented by

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[8] Ideally, a simultaneous system with demand function included should be constructed and estimated to address the endogenous bias problem. However, simultaneous estimation on this complicated system is infeasible. (More details will be discussed in the section on estimation issues.)

$$Q_{it} = f(P_t, Q_{nit}, R_{it}, I_{it}, DM_t), \tag{3.2}$$

Where P_t is price, Q_{nit} is production from all OPEC producers except producer *i,* R_{it} is the crude oil reserve of producer *i,* I_{it} is the investment needs of producer *i,* *DMt* is the war indicator variables for Iraq and Kuwait. This specification can be deemed an extension of Griffin's simplistic market-sharing model as two more important variables (crude oil reserve and investments) are included in the supply function.

In contrast to Porter's empirical model (1983), which uses a stand-alone dummy indicator to capture the switches of the supply function between two regimes, I propose that the supply function have varying parameters between two regimes. Among the explanatory variables in the empirical model, $(P_t, Q_{nit}, R_{it}, I_{it}, DM_t)$, the model will allow switches of the coefficients on P_t and Q_{nit} between the two regimes. The coefficient for reserve, investment needs, and war indicators are assumed to be constant across time. Therefore, the supply function of the empirical model will take the following form:

$$\ln Q_{it} = (1 - S_{it})(\alpha_{i1}^0 + \alpha_{i2}^0 \ln P_t + \alpha_{i3}^0 \ln Q_{nit}) + S_{it}(\alpha_{i1}^1 + \alpha_{i2}^1 \ln P_t + \alpha_{i3}^1 \ln Q_{nit}) + \beta_i X_{it} + e_{it} \tag{3.3}$$

$S_{it} = 0$ or 1,

where S_{it} is the state of production regime of producer *i* at time *t*, which is unknown to researchers; P_t is price; Q_{nit} is production from all OPEC producers except producer *i*; X_{it} is a vector of explanatory variables (R_{it}, I_{it}, DM_t), of which coefficients do not switch; R_{it} is the crude oil reserve of producer *i;* I_{it} is the investment needs of producer *i;* and *DMt* is war indicator variables for Iraq and Kuwait.

In addition, I assume that the error term e_t evolves as an autoregressive model of order 1:

$$e_{it} = \rho_i e_{it-1} + \varepsilon_{it}\, ,\ \varepsilon_{it} \sim N(\,0, \sigma_i^2\,)$$

Regime Transition Probability Function

If the states of production regime were observable, the supply function was just a dummy variable model and was easy to estimate with traditional estimation techniques such as MLE or others. However, researchers do not have this *priori* information and this becomes the major difficulty in the estimation of the model. To estimate the model, assumption about the stochastic behavior of the regime variable S_t variable has to be made. Porter (1984) assumes that S_t evolves independently of its own past values with constant transition probabilities. And because of that assumption, there is no way to examine what factors trigger the switches in one step. In this study, I follow Ellison's (1994) approach that imposes a first order Markov structure on the transitions of the two regimes, assuming the evolution of S_t is dependent on the regime and other information at last period of time. By making this assumption, I can evaluate the factors affecting the switches.

The transition probability matrix of the first order Markov process is:

$$\begin{bmatrix} Pr_{it}^{00} & 1-Pr_{it}^{00} \\ 1-Pr_{it}^{10} & Pr_{it}^{11} \end{bmatrix}$$

The transition probability functions are:

$$Pr_{it}^{00} = Pr\left[S_{it} = 0 \,/\, S_{it-1} = 0, h_{it}\right] = \phi(\gamma_i h_{it}) \qquad (3.4)$$

$$Pr_{it}^{11} = Pr\left[S_{it} = 1 \,/\, S_{it-1} = 1, h_{it}\right] = \phi(\delta_i h_{it}) \qquad (3.5)$$

where h_{it} represent factors probably affecting the transition probabilities and $\phi(.)$ takes the logic form to assure that transition probabilities fall in the range of [0, 1]:

$$\phi(\gamma_i h_{it}) = \frac{exp[\gamma_i h_{it}]}{1 + exp[\gamma_i h_{it}]} \tag{3.6}$$

$$\phi(\delta_i h_{it-1}) = \frac{exp[\delta_i h_{it}]}{1 + exp[\delta_i h_{it}]} \tag{3.7}$$

Pr_{it}^{00} represents the probability that the regime at current period t remains in collusion ($S_{it} = 0$), given that the regime at last period $t - 1$ was in collusion ($S_{it-1} = 0$)and given the factors probably affecting the transition probabilities. Obviously, $Pr_{it}^{01} = 1 - Pr_{it}^{00}$, which represents the probability of regime switch from collusion at last period $t\text{-}1(S_{it-1} = 0)$ to competition at current period t ($S_{it} = 1$), i.e., the probability that the regime at period t is competition given that the regime at period $t\text{-}1$ was collusive and given the affecting factors.

Pr_{it}^{11} represents the probability that the regime at period t is in competition ($S_{it} = 1$) given that the regime at period $t\text{-}1$ was also in competition ($S_{it-1} = 1$) and given the affecting factors.

Also, $Pr_{it}^{10} = 1 - Pr_{it}^{11}$.

Vector h_{it} includes the following variables as affecting factors relating to transition probability, $h_{it} = [1 \quad DP_{t-1} \quad Ogdp_t \quad DVquota_{it-1} \quad ER_{it} \quad G_{it}]$

Where DP_{t-1}, the percentage of price change in the last period,

$Ogdp_t$, the GDP of OECD countries at period t ,

$DVquota_{it-1}$, quota violation change of producers other than i in the last period,

ER_{it} the currency exchange rate of country *i* at period *t,* and

G_{it}, the production share of the host country *i,* which is the government or national oil company's gross share of crude oil production.

Price change and quota violation change are market information that a producer monitors as indicators of the collusive status of its rivals as suggested in Porter (1984) and Ellison (1994).

The GDP of OECD countries as a demand shifter is a factor from the demand side that can possibly affect the regime transition decision. Green and Porter's theory and Rotemberg and Saloner's theory have contradicted predictions about triggers of competitive behavior of firms in a cartel. Green and Porter's theory predicts that with uncertainty about other firms' compliance with the cartel agreement, a price drop caused by demand noise would trigger a firm's production strategy to move from collusion to competition. On the other hand, Rotemberg and Saloner's theory predicts that firms are likely to behave more competitively in demand booms, in that benefits from cheating in booms would be greater and pending punishment would be less affected by the state of demand.

The currency exchange rate acts as an indicator of a producer's internal financial constraint. Because oil export is the major source of hard currency for all OPEC countries, the needs for hard currency will possibly affect their oil production strategy.

The coefficient for host government production share can be seen as an indicator of production strategy selection regarding a private company vs. a national oil company.

Therefore, the parameters I am going to estimate for producer *i* are:

$\alpha_i^0 = (\alpha_{i1}^0, \alpha_{i2}^0, \alpha_{i3}^0)$, the intercept and coefficients for price and market share of the supply function in the collusion regime;

$\alpha_i^1 = (\alpha_{i1}^1, \alpha_{i2}^1, \alpha_{i3}^1)$, the intercept and coefficients on price and market share of the supply function in the competition regime;

$\beta_i = (\beta_{i1}, \beta_{i2}, \beta_{i3}, \beta_{i4}, \beta_{i5})$, the coefficients for variables in the supply function--coefficients do not vary between two regimes.

$\gamma_i = (\gamma_{i0}, \gamma_{i1}, \gamma_{i2}, \gamma_{i3}, \gamma_{i4}, \gamma_{i5})$, the coefficients of the transition probability function in the collusion regime; and

$\delta_i = (\delta_{i0}, \delta_{i1}, \delta_{i2}, \delta_{i3}, \delta_{i4}, \delta_{i5})$, the coefficients of the transition probability function in the competition regime.

Hypothesis to Test

Three questions may be asked to derive inferences from the model. First, I want to know whether two different production regimes exist for each producer; second, whether the two different regimes entail different production strategies corresponding to collusive and competitive conducts; and third, whether the factors raised above affect the regime transition probabilities and trigger the switches.

Estimations for three different forms of the model assist in answering these questions. The benchmark model is the constant transition Markov regime-switching model, assuming $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \gamma_{i5} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = \delta_{i5} = 0$, i.e., the transition probability evolves constantly without varying across time with those proposed affecting factors in transition probability functions such that

$Pr_{it}^{00} = Pr[\,S_{it} = 0 / S_{it-1} = 0\,] = \phi(\gamma_{i0})$ and $Pr_{it}^{11} = Pr[\,S_{it} = 1 / S_{it-1} = 1\,] = \phi(\delta_{i0})$. The other two empirical models to be estimated are a single regime market share model, assuming $\alpha_i^0 = \alpha_i^1$, and the time-varying transition Markov regime-switching models specified above.

To answer these questions, the following hypotheses are raised and tested:

1. Do two different production regimes exist?

The null hypothesis I wish to test for this question is this: two different production regimes do not exist and OPEC members produce in a constant manner, i.e., the producers do not switch their production strategy between two regimes; rather, they constantly follow a single regime supply function. The null hypothesis is that all parameters in the supply function of the two regimes are equal, i.e., a single regime supply function can sufficiently describe a producer's conduct. In a mathematical form, the null hypothesis can be expressed as:

$$H_0:\ \alpha_{i1}^0 = \alpha_{i1}^1,\ \alpha_{i2}^0 = \alpha_{i2}^1 \text{ and } \alpha_{i3}^0 = \alpha_{i3}^1$$

A likelihood ratio test can be used to verify or reject the null hypothesis. If the restrictions in the null hypothesis are valid, imposing them should not lead to a large reduction in the log-likelihood function. The likelihood ratio test is based on the difference between the log-likelihood value of the benchmark model and the single regime market-sharing model. The null hypothesis is rejected if the difference in the log-likelihood value exceeds the appropriate critical value of Chi-squared distribution. (In the definition of the likelihood ratio test, the large sample of distribution for the likelihood ratio test statistic is *Chi*-squared, with degrees of freedom equal to the number of restrictions imposed.) Compared to the constant transition Markov switching model (the benchmark model), besides the three parameters restricted in the hypothesis, the single regime model has two fewer free parameters, which are the ones in the transition probability function (γ_0 and δ_0). To be conservative in rejecting the null hypothesis[9], I employ the degrees of freedom at five, of which the critical value of *Chi*-squared distribution is 11.07.

2. **Do the two different regimes entail different production strategies that correspond to collusive and competitive conduct?**

I expect that the signs and values of the coefficients for price and market share should be consistent with the predicted pattern under corresponding regimes. The benchmark test of $\alpha_{i2}^{S_{it}} = 0$ (coefficient for price) and $\alpha_{i3}^{S_{it}} = 1$ (coefficient for market share), where $S_{it} = 0$ or 1 represents the state of the regime, is going to be carried out for each member under each regime. The hypothesis of $\alpha_{i2}^{S_{it}} = 0$, and $\alpha_{i3}^{S_{it}} = 1$ refers to the constant market-sharing behavior specified in Griffin's paper, meaning that a producer's production does not vary with price change and only coordinates with other producers' production. A significantly positive coefficient for price is likely to indicate a competitive conduct. The value of the coefficient for market share will provide implications for coordination among the cartel members. The coefficient for market share

[9] If the three restrictions in the hypothesis are valid, no matter what the value of the two parameters in transition probability functions (γ_0 and δ_0), the production behavior still follows a single regime as the parameters in the supply function of the two regimes have the same value.

is expected to be positive and closer to one, implying better coordination with cartel-wide production adjustments.

3. **Do the factors raised above, namely price change, demand shifter, quota violation, currency exchange rate and host government production share, affect regime transition probabilities?**

The null hypothesis to be tested is that these factors do not affect the transition probabilities, in mathematical form:

H_0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \gamma_{i5} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = \delta_{i5} = 0$.

As for the first question, the likelihood ratio test is going to be carried out to test the hypothesis. The difference between the log-likelihood value of the benchmark model and the time-varying transition model will be calculated and tested against the critical value the of corresponding Chi-squared distribution at the 95% significant level.

Only Indonesia has experienced significant change in the host government production share during the study period so it is the only country including this variable in the transition probability function.

For all producers except Indonesia, there are eight restrictions in the hypothesis, i.e, $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$, and thus the degrees of freedom are eight, with critical value at 15.51. For Indonesia, an extra variable (host government production share) is included in the two transition probability functions so there will be ten restrictions in the hypothesis and the degrees of freedom are ten with a critical value of 18.31.

In addition, the individual *t*-statistics for each parameter in the transition probability function can be also examined to infer implications for what factors determine the producer's regime selection.

The expectation for the signs of the parameters is as follows:

First, the coefficient sign for the same variable in the transition probability functions of the two regimes is expected to be opposite because the two regimes are mutually exclusive and the rise of a variable that increases the probability of staying in one regime should decrease the probability of staying in the other. For example, the increase in price, as a sign of good collusion in the cartel, is expected to increase the probability of staying in the collusion regime and to decrease the probability of staying in the competition regime according to Green and Porter's theory.

For the collusion regime, I have the following expectations for parameters in the transition probability function:

The sign of the coefficient for GDP in OECD can be either positive or negative according to different theories. Green and Porter (1984) predict that favorable demand evolvement would signal rising prices and thereby sustain the collusion of the cartel. Therefore, the coefficient for GDP in OECD, the demand shifter, should be positive in the collusion regime. In contrast, Rotemberg and Saloner (1986) argue that cheating in booms can generate more profit for producers and thus producers should behave in a countercyclical manner. Accordingly, the coefficient for GDP in OECD should be negative in a collusion regime.

The sign of the coefficient for the quota violation change is expected to be negative in the collusion regime in that the worsening quota compliance of other producers should increase the probability of switching to the competition regime.

The sign of the coefficient for the exchange rate (local currency/hard currency) is expected to be negative in the collusion regime in that depreciation of the national currency provides an incentive for the producer to cheat in acquiring more hard currency from oil production to ease a deteriorating international financial situation.

The sign of the coefficient for host government production share is expected to be positive in that production controlled by a national oil company is more likely to comply with the quota agreement.

3.3 Issues in Estimation

3.3.1 Estimation Algorithm

The parameters of the model can be estimated by following Hamilton (1989) and Kim and Nelson's (1998) MLE filter algorithm. An important by-product of the estimation procedure is the predicted regime probabilities that allow an inference to be drawn about the unobserved regime for each time period. Based on the predicted regime probabilities at each period for each producer, the pattern of individual's regime switching timing can be examined.

Note the regime probabilities are not transition probabilities described above. The regime probabilities $Pr(S_{it}=0)$ and $Pr(S_{it}=1)$ are the probabilities that production regime falls into a specific state, for example, $Pr(S_{it}=0)$ = 0.9 means there is a 90% chance the production regime will fall into state 0 at time t. Since only two regimes are specified, given $Pr(S_{it}=0) = 0.9$, the chance that the production regime will fall into state 1 at time t is 0.1 because $Pr(S_{it}=1) = 1 - Pr(S_{it}=0) = 0.1$. Transition probabilities are the ones denoted as:

$$Pr_{it}^{00} = Pr[S_{it} = 0 / S_{it-1} = 0, h_{it}] = \phi(\gamma_i h_{it})$$

$$Pr_{it}^{11} = Pr[S_{it} = 1 / S_{it-1} = 1, h_{it}] = \phi(\delta_i h_{it})$$

For the sake of simplicity, I drop the country subscript i in describing the algorithm, just keeping in mind that parameters and unknown regime indicators (S_t) are country-specific.

Given the empirical model:

$$ln\,Q_t = (1 - S_t)(\alpha_1^0 + \alpha_2^0\, ln\,P_t + \alpha_3^0\, ln\,Q_{othert}) + S_t(\alpha_1^1 + \alpha_2^1\, ln\,P_t + \alpha_3^1\, ln\,Q_{othert}) + \beta\, X_t + e_t \qquad (3.8)$$

$S_t = 0$ or 1,

$$e_t = \rho e_{t-1} + \varepsilon_t,\ \varepsilon_t \sim N(0, \sigma^2)$$

maximum likelihood estimation can be used to estimate the parameters, and the log likelihood function is given by:

$$ln\,L = \sum_{t=1}^{T} ln(f(Q_t \mid S_t, S_{t-1})),\ \text{where}$$

$$f(Q_t \mid S_t, S_{t-1}) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left\{ - \frac{\left[(Q_t - x_t\alpha^{S_t}) - \rho(Q_{t-1} - x_{t-1}\alpha^{S_{t-1}})\right]^2}{2\sigma^2} \right\} \qquad (3.9)$$

If the regime variable S_t and S_{t-1}, $t = 1, 2, \ldots, T$ were known as *priori* information, the above model could be simply solved as a dummy variable model. To deal with the unobservable regime problem, a filter algorithm has been developed (Hamilton, 1989 and Kim and Nelson, 1998) to endogenously identify the probabilities for the regime at each time period and then determine the log likelihood function. The procedure proceeds as follows:

Since the regime variables S_t and S_{t-1} are unknown to us, the density function of Q_t has to be given as a function of past information (θ_{t-1}) known to us:

$$f(Q_t \mid \theta_{t-1}) = \sum_{S_t=0}^{1} \sum_{S_{t-1}=0}^{1} f(Q_t, S_t, S_{t-1} \mid \theta_{t-1}) \tag{3.10}$$

i.e., the density function of Q_t is equal to the sum of the joint density over all possible values of S_t and S_{t-1} given past information (θ_{t-1}). There are two regimes in my case so there are four combinations of S_t and S_{t-1}, namely, (S_t =0, S_{t-1}=0), (S_t =1, S_{t-1}=0), (S_t =0, S_{t-1}=1), (S_t =1, S_{t-1}=1). Since it is not known which is the real combination, it is necessary to derive the probability for each combination, namely $Pr(S_t, S_{t-1} \mid \theta_{t-1})$, so I can integrate a weighted average of the four conditional densities to obtain the density function of Q_t as follows, weights being $Pr(S_t, S_{t-1} \mid \theta_{t-1})$:

$$\begin{aligned} f(Q_t \mid \theta_{t-1}) &= \sum_{S_t=0}^{1} \sum_{S_{t-1}=0}^{1} f(Q_t, S_t, S_{t-1} \mid \theta_{t-1}) \\ &= \sum_{S_t=0}^{1} \sum_{S_{t-1}=0}^{1} f(Q_t \mid S_t, S_{t-1}) Pr(S_t, S_{t-1} \mid \theta_{t-1}) \end{aligned} \tag{3.11}$$

where $f(Q_t \mid S_t, S_{t-1})$ is given by equation (*3.9*).

Then, the log likelihood function is given by:

$$ln\,L = \sum_{t=1}^{T} ln(f(Q_t \mid \theta_{t-1}))$$

Therefore, in order to calculate the density function of Q_t, it is necessary to derive the probabilities for the unobserved regime at each time period from the previous market information known to researchers. The filter algorithm has the following two steps to calculate $Pr(S_t , S_{t-1} | \theta_{t-1})$:

STEP 1. Given $Pr(S_{t-1} = i | \theta_{t-1})$, $i = 0,1$, at the beginning of time *t,* each weighting term $Pr(S_t , S_{t-1} | \theta_{t-1})$ is calculated as

$$Pr(S_t = j, S_{t-1} = i | \theta_{t-1}) = Pr_t^{ij} \times Pr(S_{t-1} = i | \theta_{t-1}),\ i = 0,1,\ j = 0,1. \qquad (3.12)$$

Recall the transition probabilities Pr_t^{ij} are defined as:

$$Pr_t^{01} = Pr[S_t = 1 / S_{t-1} = 0, h_t] = \phi(\gamma h_t)$$

$$Pr_t^{00} = 1 - Pr_t^{01}$$

$$Pr_t^{11} = Pr[S_t = 1 / S_{t-1} = 1, h_t] = \phi(\delta h_t)$$

$$Pr_t^{10} = 1 - Pr_t^{11}$$

STEP 2. Once Q_t is observed at the end of time *t*, the probability terms can be updated with the Bayesian rule as follows:

$$Pr(S_t = j, S_{t-1} = i | \theta_t) = Pr(S_t = j, S_{t-1} = i | \theta_{t-1}, Q_t)$$

$$= \frac{f(S_t = j, S_{t-1} = i, Q_t | \theta_{t-1})}{f(Q_t | \theta_{t-1})}$$

$$= \frac{f(Q_t | S_t = j, S_{t-1} = i) Pr(S_t = j, S_{t-1} = i | \theta_{t-1})}{\sum_{S_t=0}^{1} \sum_{S_{t-1}=0}^{1} f(Q_t | S_t = j, S_{t-1} = i) Pr(S_t = j, S_{t-1} = i | \theta_{t-1})} \qquad (3.13)$$

and then, $Pr(S_t = j | \theta_t) = \sum_{S_{t-1}=0}^{1} Pr(S_t = j, S_{t-1} = i | \theta_t)$

Iterating the above two steps for t=1, 2,….., T provides the appropriate weighting terms $Pr(S_t, S_{t-1} \mid \theta_{t-1})$ in (*3.11*), and a filtered probability for regime $Pr(S_t = j \mid \theta_t)$ at each time period, which is the predicted regime probability.

To start the above filter at time t = 1, $Pr\ (S_0 \mid \theta_0)$ is needed. Hamilton suggests employing the following steady-state probabilities of S_t:

$$Pr\left(S_0 = 0 \mid \theta_0\right) = \frac{1 - Pr^{11}}{2 - Pr^{00} - Pr^{11}}$$

$$Pr\left(S_0 = 1 \mid \theta_0\right) = 1 - Pr\left(S_0 = 0 \mid \theta_0\right) = \frac{1 - Pr^{00}}{2 - Pr^{00} - Pr^{11}}$$

3.1.2 Simultaneous Bias Problem

In the algorithm described above, all explanatory variables are assumed to be exogenous. Certainly, the assumption is somewhat restrictive because at least price and production from other producers should be endogenously generated. Porter (1983) constructed a simultaneous system of equations that includes a demand function to address the endogeniety problem. However, addressing the problem in my model will not be feasible as I model the supply function for each producer rather than an aggregated function as in Porter's model. The specification exponentially increases the complexity of the problem and consequently will run out of degrees of freedom if the filter MLE algorithm is applied on a simultaneous system.

To construct a simultaneous system of equations, a demand function of OPEC crude oil comes in the form:

$$ln\,Q_t = \phi_0 + \phi_1\, ln\,P_t + \phi_2\, ln\,G_t + \varepsilon_{1t} \qquad (3.14)$$

The demand function includes the endogenous price and a vector of exogenous factors (*G*) as explanatory variables.

Together with the demand function, the system has nine supply functions for individual OPEC producers, taking the form:

$$ln\,Q_{it} = (1 - S_{it})(\alpha_{i1}^{0} + \alpha_{i2}^{0}\, ln\,P_t + \alpha_{i3}^{0}\, ln\,Q_{nit}) + S_{it}(\alpha_{i1}^{1} + \alpha_{i2}^{1}\, ln\,P_t + \alpha_{i3}^{1}\, ln\,Q_{nit}) + \beta_i X_{it} + e_{it}$$
$$S_{it} = 0 \text{ or } 1,$$

and each producer's regime state variable (S_{it}) evolves according to a first-order Markov process with country-specific regime transition probability functions:

$$Pr_{it}^{00} = Pr[S_{it} = 0 / S_{it-1} = 0, h_{it}] = \phi(\gamma_i h_{it})$$

$$Pr_{it}^{11} = Pr[S_{it} = 0 / S_{it-1} = 1, h_{it}] = \phi(\delta_i h_{it})$$

What makes the problem much more complicated is that each producer is assumed to have its own timing for regime-switching, and thus the whole system of equations will have 2^9 possible combinations of regimes at each time point (there are nine OPEC producers on which I plan to build individual supply functions). As endogenous variables, market price and output from other producers should be correlated with the state of the regime for all producers. Therefore, I need to evaluate the marginal density function and thus the log likelihood on a set of 2^9 scenarios[10]. The lack of degree of freedom and computational difficulties will make Maximum Likelihood Estimation (MLE) impractical. More formally, I can demonstrate the problem as follows:

To apply MLE to address the simultaneous bias problem, I need to construct a reduced form for the system of equations.

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[10] If auto-regression effects are taken into consideration, there are indeed 2^{18} scenarios for regime combinations.

Take as an example estimating producer *i's* supply function. For simplicity, I omit the *ln* symbol in front of each variable.

Denote:

$Y_{it} = [P_t\ ,\ Q_{nit}]$, representing vector of endogenous variables other than Q_{it}.

$X^*_{it} = [Q_{nopect},\ Q_{nit-1},\ G]$, representing the vector of instrument variables excluded from supply function of producer *i*, where Q_{nopect} represents production from non-OPEC producers at time *t* and Q_{nit-1} represents the production from all other OPEC producers except producer *i*, both of which can be reasonably assumed to be uncorrelated with the error term; *G* represents the vector of exogenous variables in the demand function.

$X_{it} = [1, R_{it}, I_{it}, DM_{it}]$, representing the vector of instrumental variables included in the supply function of producer *i*,

The general reduced form is as follows:

$$[Q_i\ \ Y_i] = [X_i\ \ X^*_i] \begin{bmatrix} \pi_i & \tilde{\Pi}_i \\ \pi^*_i & \Pi^*_i \end{bmatrix} + [v_i\ \ V_i]$$

or

$$Y^0_i = X \prod\nolimits^0_i + V^0_i$$

The estimates for $\alpha^{S_{it}}_i$ and β_i need to be calculated with the constraints that relate to the reduced form parameters to the structure form parameters:

$$\pi_i - \overline{\prod}_i \alpha^{S_{it}}_i = \beta_i$$

$$\pi^*_i - \prod\nolimits^*_i \alpha^{S_{it}}_i = 0$$

To estimate the reduced form parameters $\prod_i^0$, I need to construct the joint density function. The difficulties arising here are that the joint distribution of the endogenous variables, Q_{it} and (P_t, Q_{nit}), depends on the regime evolvement of each individual producer. Because the model allows for different regime-switching timing for each producer, there will be 2^9 possible combinations of regimes at each time point. Therefore, the joint density

$$f(Y_{it}^0) = \sum_{S_{1t}=0}^{1} \cdots \sum_{S_{it}=0}^{1} \cdots \sum_{S_{10t}=0}^{1} f(Y_{it}^0 \mid S_{1t}, \ldots S_{it} \ldots, S_{9t})$$

where

$$f(Y_{it}^0 \mid S_{1t}, \ldots S_{it} \ldots, S_{9t})$$
$$= (2\pi)^{\frac{-3}{2}} \mid \Omega_i^0 \mid^{-\frac{1}{2}} exp(-\frac{\{[Y_{it}^0 - X_{it}^{'} \prod_i^0]^{'} (\Omega_i^0)^{-1} [Y_{it}^0 - X_{it}^{'} \prod_i^0]\}}{2}) \mid (S_{1t}, \ldots S_{it} \ldots, S_{9t})$$

where the reduced form covariance matrix is

$$\Omega_i^0 = \begin{bmatrix} \omega_{ii} & \overline{\omega}_j \\ \overline{\omega}_i & \Omega_{ii} \end{bmatrix}$$

Therefore, to evaluate the above joint density at each observation, I need to calculate 2^9 regime probabilities, 2^9 log likelihood and evaluate 2^9 sets of $\prod_i^0 = \begin{bmatrix} \pi_i & \tilde{\Pi}_i \\ \pi_i^* & \Pi_i^* \end{bmatrix}$, which is not practical due to a lack of degrees of freedom and computational difficulties.

A preliminary thought may promote researchers' use of the GMM estimation technique to solve the simultaneous bias problem. However, a close examination rules out the applicability of GMM to my model. The fundamental problem comes from the unknown state of the regime at each time point. While the filter MLE algorithm utilizes

Bayesian rule to calculate the regime probabilities with information updated at each point of time as shown in the second step of the algorithm, GMM estimation cannot successfully predict the regime-switching point based on the time series data. Without accurate prediction on the state of the regime at each time point, estimation of the parameters of two contrary production regimes will certainly be biased. In the course of this study, I have experimented with two versions of GMM estimations and both have failed to provide meaningful estimates.

There are tradeoffs between an aggregated supply function model as used by Porter, in which the simultaneous bias problem can be solved, and the separate supply function for each individual producer as proposed in my model. As noted previously, the assumptions needed to make an aggregate supply function sound are overly restrictive in the case of OPEC and will lead to more serious problems than the simultaneous bias problem.

Further, the simultaneous bias problem may not be that serious in this study. As far as I know, all of the studies modeling individual OPEC producer's supply function in the literature do not address the simultaneous bias problem. The most widely cited papers by Griffin (1985), Jones (1990), Dahl (1991), Watkins and Streifel (1998) and Ramcharran (2001,2002) only use OLS estimation, assuming market price and other explanatory variables are exogenous. The production of each OPEC member only constitutes a very small portion of world oil demand (Saudi Arabia constitutes barely more than 10%; all others less than 5%). Yang (2003) has applied the 2SLS technique to estimate the market-sharing model, and the results have shown that most estimates from 2SLS are not significantly different from those from OLS.

Therefore, estimation on the model in this study will not address the simultaneous bias problem.

3.1.3 Data

The empirical model is estimated on a monthly basis. This is done to meet the large sample requirement of the Maximum Likelihood Estimation. Since only for a small portion of time, producers' production would fall into the competition regime, it would not be consistent to estimate whether MLE is used on a quarterly or annual data basis. In addition, the regime switches could occur within a quarter, so that using quarterly data would cause an aggregation bias problem. Unfortunately, data for some variables are only available on an annual (quarterly) basis. These variables are kept constant in a single year (quarter) and vary annually (quarterly).

Monthly crude oil output data for each OPEC producer and price data are available from EIA's online petroleum database. Annual data for crude oil reserve may also be obtained from EIA's online database. Investment needs are proxied by gross capital formation, annual data for which are obtained from the *International Financial Yearbook* of the IMF. Monthly data for currency exchange rates may be obtained from IMF's online database. Quarterly data on the OECD real gross domestic product (GDP) at 1995 constant value may be obtained from the OECD's *Quarterly National Accounts.* Host government production share is government or national oil company's gross share of crude oil production in each OPEC producer, annual data of which may be obtained from *OPEC statistical bulletin*. Data for quota allocation may also be obtained from *OPEC statistical bulletin*.

The price series is a weighted average of free on board (f.o.b.) costs of U.S. crude oil imports from OPEC members. The real price of oil is then derived by deflating the nominal price by the inflation index published by Bureau of Economic Analysis on its website.

The investment needs data for Qatar, U.A.E. and Libya are only available through 1997, 1998 and 1999, respectively, so the study periods for these three countries are limited accordingly.

Only Indonesia has experienced significant change in host government production share during the study period so it is the only country for which this variable was included in the transition probability function.

3.4 Results and Interpretation

Estimations and tests for the three variant forms of model have been run for each of the OPEC producers (except Kuwait and Iraq). In this section, I present first a summary of results and interpretations and then a detailed description for each producer. A list of parameters and expected signs is contained in Table 3.S1.

3.4.1 Summary

For all producers, the single production regime model is rejected at a high confidence level, indicating that the production behavior of all OPEC producers does appear to vary over time. The constant transition Markov regime-switching model is also rejected for seven out of nine producers and coefficients obtained for proposed affecting factors provide some inferences on the causes of production conduct shifts.

Econometric estimates for the time-varying transition Markov regime-switching model of each producer are displayed in Table 3.S2 and a summary of inferences on the production behavior of each producer is displayed in Table 3.S3. Complete sets of estimates, test statistics and interpretation of each country are presented in the country analysis subsection. Robust and sensible estimates are obtained for Iran, Nigeria, Libya, Saudi Arabia, U.A.E., Qatar and Venezuela on the two production regimes with remarkably different characteristics, consistent with different conducts under collusion and competition regimes. To a lesser extent, estimates for Algeria and Indonesia are also plausible.

Persian Gulf producers (Saudi Arabia, U.A.E. and Qatar), usually considered core producers in OPEC, show some common characteristics in their production behavior. Most of the time, their production conduct falls into the constant market-sharing regime as they appear to adjust their output level proportionally with other producers (market share coefficient equal to one) and do not vary their output level with market price (price coefficient equal to zero). But unlike U.A.E. and Qatar as well as the other producers, which take a more competitive-like strategy from time to time, Saudi Arabia shows a unique altruism strategy at times. In the altruism regime, Saudi Arabia’s market-share coefficient is significantly greater than one. Further examination implies that Saudi Arabia sacrificed its market share in that regime likely in order to counter the drop in price and keep the cartel stable.

The periodic altruism behavior of Saudi Arabia may still be rationalized by the theory of collusion with imperfect information. Although occasionally switching from collusive conduct to Cournot competition plays a key role in the collusion enforcement mechanism, frequent shifts of this sort could be very costly to all producers as the payoff during the reversionary periods would be vastly less than the collusive payoff.

The volatility of the oil market is likely to often trigger the competitive behavior if the enforcement mechanism is employed without flexibility. If a cartel leader that is willing and able to accommodate intermediate market deterioration voluntarily cuts its own production to counter the down-market trend so that the Cournot behavior of other producers will not be triggered, all producers, including the leader, may obtain better payoff than would occur by jointly switching to Cournot production. The leader will be better off by exhibiting altruism behavior when the loss from cutting its production to keep prices in a favorable range is less than the loss from a jointly Cournot behavior of all producers for a certain amount of time.

The willingness to follow an altruism strategy should be conditioned on the collusion compliance of other producers and overall market situation, including demand profile and competition from rivals outside of the cartel. If other producers behave competitively or the burden to sustain collusion of the cartel is too high due to unfavorable market development, the incentive for the leader to exhibit altruistic behavior will diminish and Cournot behavior will be then preferable for the leader.

As is widely recognized, Saudi Arabia takes the lead role in OPEC due to its output level (the largest), enormous reserve endowment, and the bulk of OPEC’s spare capacity. In particular, Saudi Arabia was explicitly cast in the a role of “swing producer,” balancing demand and supply to stabilize market price when OPEC instituted its quota allocation system first in early 1982. The econometric results of my model are consistent with the anecdotal evidence. Saudi Arabia did act as a swing producer at times and likely intended to reduce the frequency of competition war among OPEC producers. But as in the period 1985-1986, Saudi Arabia abandoned the role of swing producer and turned to a market share matching strategy when it was facing rampant cheating by its peers in OPEC and a deteriorating market situation.

Iran, Libya, Venezuela, and Indonesia are other active participators to the cartel as most of time their production behavior can be identified as non-competitive. The market share coefficients of these countries are generally smaller than those of the Persian Gulf countries, indicating that these countries coordinate cartel-wide production adjustment in a less close manner.

Algeria and Nigeria seem to behave as the competitive fringe in OPEC as their production conduct is more competitive-like in vastly most of the time.

The timing of production conduct shifts is roughly consistent with the predictions of the conceptual model. While OPEC producers appear to switch between production regimes according to their own rhythm, the occurrence of joint competition wars was indeed evident in the results of the econometric model. The most prominent reversionary period of OPEC is the price plunge of 1986. The predicted regime probabilities of each producer show that all producers were likely exhibiting a competitive or punishment behavior during that period.

While all other producers showed competitive characteristics in their production during the price plunge in 1986, the three Persian Gulf producers undertook a constant market-sharing strategy. This could be deemed as a “tit-for-tat” strategy to punish other producers’ competitive conduct since all other producers were likely following a competitive strategy during that period. The vast oil reserves and extremely low marginal production cost in Persian Gulf oil fields enabled these countries to match any price level that other producers could possibly take. Rather than signaling the end of OPEC, the price collapse of 1986 was likely just a temporary switch to non-contingent strategies by OPEC producers and has taught them a good lesson and indeed helped to maintain collusion in the organization.

Reassuringly, the timing of the regime switching of Saudi Arabia as predicted by the econometric model matches very well with Griffin and Neilson’s artificial split of the two periods in which Saudi Arabia employed two contrast strategies. In Griffin and Neilson’s study, August 1985 is artificially set as the watershed before which Saudi Arabia acted as swing producer and thereafter employed a tit-for-tat strategy. According to the regime probabilities predicted by the econometric model, it is in August 1985 that Saudi Arabia switched to a constant market-sharing strategy after running an altruism strategy for about one year.

Green and Porter’s theory and Rotemberg and Saloner’s theory have contrary predictions on triggers of competitive behavior of firms in a cartel. The tests on a variety of triggers of regime switching in this study provide some support for Green and Porter’s theory. Green and Porter’s theory predicts that with uncertainty about compliance on cartel agreement by other firms, a price drop caused by demand noise would switch a firm's production strategy from collusion to competition. On the other hand, Rotemberg and Saloner's theory predicts that firms are likely to behave more competitively in demand booms in that benefits from cheating in booms would be larger and pending punishment would be less affected by the state of demand.

The estimates on the transition probability function in the collusion regime for Indonesia, Iran, Nigeria, Qatar, U.A.E. and Venezuela have a significantly positive coefficient for either price change or demand shifter, indicating that a decrease in price or demand would decrease the probability of staying with a collusive regime and thus increase the probability of switching to a competitive regime. The estimates for price change and demand shifter for Algeria and Libya are not significant, and thereby do not provide supportive evidence for either of the theories. Saudi Arabia again shows some unique features on triggers, which seem consistent with its leader role. The results indicate that the dip price and demand would likely cause Saudi Arabia to take on the altruism strategy to counter the down market and thereby deter the other producers from switching from collusive production to competitive production. But the "altruism" role is not unconditional. The significantly positive coefficient for quota violation change implies that if the quota compliance of the other producers gets worse, Saudi Arabia will be reluctant to switch to an "altruism" regime; rather, it will be more likely to stay with the constant market-sharing model and maintain its market-share in the organization.

Table 3.S1 List of Parameters

Parameters	Meaning	Expected Sign
Transition Probability Function:		
Regime 0 (Collusive): $Pr_{it}^{00} = Pr[S_{it} = 0 / S_{it-1} = 0, h_{it}] = \phi(\gamma_i h_{it})$		
γ_0	Constant	+/-
γ_1	Price Change Coefficient	+
γ_2	GDP of OECD Coefficient	+/-
γ_3	Quota Violation Coefficient	-
γ_4	Currency Exchange Rate Coefficient	-
γ_5	Host Government Production Share Coefficient	+
Regime 1 (Competitive): $Pr_{it}^{11} = Pr[S_{it} = 0 / S_{it-1} = 1, h_{it}] = \phi(\delta_i h_{it})$		
δ_0	Constant	+/-
δ_1	Price Change Coefficient	-
δ_2	GDP of OECD Coefficient	-/+
δ_3	Quota Violation Coefficient	+
δ_4	Currency Exchange Rate Coefficient	+
δ_5	Host Government Production Share Coefficient	-
Supply Function:		
$ln Q_{it} = (1 - S_{it})(\alpha_{i1}^0 + \alpha_{i2}^0 ln P_t + \alpha_{i3}^0 ln Q_{nit}) + S_{it}(\alpha_{i1}^1 + \alpha_{i2}^1 ln P_t + \alpha_{i3}^1 ln Q_{nit}) + \beta_i X_{it} + e_{it}$		
$S_{it} = 0$ or 1		
Regime 0 (Collusive)		
α_1^0	Intercept	+/-
α_2^0	Price Coefficient	insignificant or -
α_3^0	Other Producers' Output Coefficient	+
Regime 1 (Competitive)		
α_1^1	Intercept	+/-
α_2^1	Price Coefficient	+
α_3^1	Other Producers' Output Coefficient	+
Unvarying Parameters in Supply Function		
β_1	Reserve Coefficient	+
β_2	Investment Needs Coefficient	+
β_3	War Indicator for Iraq	+
β_4	War Indicator for Kuwait	+

Table 3.S2 Estimation Results Summary for Time-varying Transition Model

	Algeria		Indonesia		Iran		Libya		Nigeria		Qatar		Saudi Arabia		U.A.E.		Venezuela	
Parameter	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Transition Probability Function																		
γ_0	-49.619	107.065	8.478	25.620	-26.291*	10.332	-5.839	4.520	17.393	19.986	-22.281*	7.774	-10.147*	4.402	-18.509	13.804	-24.19**	14.553
γ_1	0.480	0.450	0.219**	0.122	-0.122	0.094	0.029	0.075	0.893**	0.489	0.112**	0.062	0.198*	0.091	-0.033	0.070	0.664*	0.290
γ_2	-4.478	9.048	-6.833	6.582	5.139*	1.959	1.093	1.575	-2.783	4.080	5.720*	2.172	4.253*	1.681	5.363**	3.014	4.731	3.226
γ_3	-0.185	0.206	-0.127	0.104	-0.125	0.095	0.033	0.078	-0.190	0.135	0.096	0.080	0.206*	0.073	0.098	0.071	0.072	0.092
γ_4	13.840	27.546	13.856**	7.962	1.112	7.698	8.912	18.597	-209.99	143.542	-1.059	2.004	-2.446**	1.334	-1.876	3.239	1.096	1.258
γ_5			21.540**	13.242														
δ_0	-33.576	30.995	31.804	34.608	16.993	16.336	-1.848	8.340	1.316	5.492	131.631	151.636	3.207	4.623	45.728*	21.277	0.395	3.939
δ_1	0.086	0.081	-0.172	0.219	-0.067	0.114	0.067	0.098	-0.406*	0.201	-1.071	1.282	-0.017	0.043	0.098	0.103	0.108	0.097
δ_2	3.252	2.976	-9.506	10.272	-1.790	1.777	-0.681	2.161	-0.126	1.136	-9.152	15.855	-2.000	1.812	-14.319*	6.555	8.666**	4.687
δ_3	-0.115	0.102	0.016	0.203	-0.187**	0.105	0.018	0.078	-0.037	0.106	0.424	0.424	-0.021	0.056	0.001	0.268	0.234*	0.112
δ_4	3.856	6.958	7.788	13.080	-59.839	94.309	19.708	18.949	63.768**	35.007	-23.569	20.566	1.826	1.465	7.331**	4.140	-8.283**	4.476
δ_5			11.851	19.523														
Supply Function																		
α_1^0	-0.211	1.323	3.875*	0.718	1.709**	1.004	-0.384	1.099	-4.232*	1.587	-5.433*	2.138	-1.155	1.175	-2.422*	0.999	6.415*	0.685
α_2^0	0.052*	0.024	-0.021	0.021	0.027	0.023	0.017	0.028	-0.153*	0.049	0.094	0.082	-0.033	0.030	-0.022	0.030	-0.020	0.021
α_3^0	0.529*	0.072	0.368*	0.049	0.353*	0.095	0.631*	0.066	1.162*	0.123	0.794*	0.146	1.111*	0.096	0.967*	0.081	0.285*	0.051
α_1^1	2.714*	1.370	-0.267	0.747	0.240	0.948	-4.350*	1.163	-0.543	1.280	-9.890*	3.397	-7.561*	1.365	3.385*	1.395	5.822*	1.064
α_2^1	0.056*	0.016	0.043**	0.023	0.119*	0.028	0.067*	0.033	0.063*	0.031	0.550*	0.108	0.033	0.035	0.043	0.033	0.198*	0.032
α_3^1	0.237*	0.036	0.734*	0.056	0.451*	0.076	1.017*	0.083	0.618*	0.093	0.852*	0.312	1.715***	0.112	0.299*	0.113	0.171*	0.086
Unvarying Parameters of Supply Function																		
β_1	0.285**	0.150	0.001	0.003	0.223*	0.038	0.007	0.065	0.141	0.097	0.188	0.189	-0.506*	0.084	0.104*	0.029	-0.152*	0.029
β_2	-0.110*	0.044	-0.025	0.034	-0.022	0.023	0.109*	0.044	-0.004	0.059	0.167	0.087	0.189*	0.051	-0.073	0.066	0.041*	0.016
β_3	0.046**	0.025	0.124*	0.038	0.422*	0.031	0.140*	0.033	0.145*	0.054	0.062	0.080	0.441*	0.044	0.072*	0.035	0.119*	0.036
β_4	0.008	0.019	0.017	0.024	-0.044*	0.022	0.118*	0.034	0.016	0.041	0.030	0.070	0.166*	0.038	0.141*	0.029	-0.019	0.024
Log Likelihood	587.512		544.404		390.439		393.319		359.313		180.927		414.185		340.422		554.437	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from zero at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

Table 3.S3 Summary of Production Behavior for Each Country

Country	Production Strategies	Triggers of Regime Switching	Pattern of Regime Switching
Cartel Leader: Taking constant market sharing strategy most of time and sacrificing own market share under intermediate reversionary conditions.			
Saudi Arabia	Constant Market Sharing Strategy: proportionally matching output from others without varying with price Altruism Strategy: cutting output more than proportionally with others and voluntarily decreasing market share.	Price change, demand shifter and quota violation have expected significant effects on regime switching.	Most time taking constant market sharing strategy with average probability of 85%. Regime shifts mostly took place in 80s. Switching to constant market sharing strategy in August 1985 after running about one-year altruism strategy.
Market Share Matching Producer: Taking constant market sharing strategy most of time, showing competitive conducts occasionally			
Qatar	Constant Market Sharing Strategy: proportionally matching output from others without varying with price Competitive Strategy: having significant positive price coefficient.	Price change and demand shifter have expected significant effects on regime switching	Regime switches occurred mostly in first half of 80s and stabilized its production strategy as a constant market sharing producer thereafter. Taking constant market sharing strategy during the price plunge in 1986.
U.A.E.	Constant Market Sharing Strategy: proportionally matching output from others without varying with price Competitive Strategy: having positive price coefficient and a significantly lower market share coefficient	Demand shifter and currency exchange rate have expected significant effects on regime switching	Being in competitive regime mostly in 80s and stabilizing as a constant market sharing producer after 90s. Taking constant market sharing strategy during the price plunge in 1986.
Market Sharing Participator: Taking non-competitive strategy most of time with significant but relatively low market share coefficient, showing competitive conducts occasionally			
Indonesia	Non-competitive strategy: insignificant negative price coefficient Competitive strategy: significant positive price coefficient	Price change, currency exchange rate and host government production share have expected significant effects on regime switching	Most time taking non-competitive strategy with average probability of 88%. Taking competitive strategy during the price plunge of 1986.
Iran	Non-competitive strategy: insignificant positive price coefficient Competitive strategy: significant positive price coefficient	Demand shifter has expected significant effects on regime switching	Taking competitive strategy for most of 80s and non-competitive behavior prevailed from early 90s. Taking competitive strategy during the price plunge of 1986.
Libya	Non-competitive strategy: insignificant positive price coefficient Competitive strategy: significant positive price coefficient	No significant triggers.	Most time taking non-competitive strategy with average probability of 86%. Taking competitive strategy in the period of price plunge of 1986
Venezuela	Non-competitive strategy: insignificant negative price coefficient Competitive strategy: significant positive price coefficient and very low market share coefficient	Price change and quota violation have expected significant effects on regime switching	Taking competitive strategy during the slump price period in the middle of 80s and non-competitive behavior prevailed for the rest of time.
Competitive Fringe: Taking competitive strategy most of time			
Algeria	Distinction between two regimes is vague, both have significant price coefficient in the time-varying transition model.	No significant triggers	Virtually taking competitive strategy.
Nigeria	Non-competitive strategy: significantly negative price coefficient Competitive strategy: significantly positive price coefficient	Price change and currency exchange rate have expected significant effects on regime switching	Most time taking competitive strategy with average probability of 89%. Production behavior shifts occurred mostly in 80s and it was in competitive regime during the price plunge of 1986.

3.4.1 Country Analysis

Algeria

The estimation results for Algeria are presented in Table 3.C1.

Highlights:

- Regime switching exists in Algeria's oil supply function but estimates on the constant transition model and time-varying transition model provide mixed inferences on the characteristics of the two regimes.
- The likelihood ratio test fails to reject at a high confidence level the hypothesis that transition probabilities do not vary with those factors and none of the proposed affecting factors on transition probabilities has a significant coefficient.
- According to estimates on the constant transition model, Algeria has a significantly positive coefficient for price in one regime, indicating competitive behavior, while an insignificantly positive coefficient for price is seen in the other.
- Algeria's oil supply function falls into a more competition-like regime most of the time.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Algeria. The test statistic is 168.3, enormously greater than the critical value of the Chi-squared distribution at the 95%

confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Algeria's oil supply function.

The likelihood ratio test for the time-varying transition model fails to reject the hypothesis that the transition probabilities do not vary across time with price change, demand shifter, quota violation changes and currency exchange rate, i.e., the null hypothesis H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ cannot be rejected at a high confidence level. The test statistic is 13.61, less than 15.51--the critical value of the 95% confidence level. An individual *t*-test to the estimate of each factor also does not support any significant effects on the transition probability of these factors. Therefore, the estimates on the transition probability functions of Algeria do not provide supportive evidence for either Green and Porter's theory or Rotemberg and Saloner's theory.

The estimates for the constant transition model and time-varying transition model provide mixed inferences on the characteristics of the two regimes. According to the constant transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. In regime 0, the hypothesis of $\alpha_2^0 = 0$ (coefficient for price equal to zero) cannot be rejected at the 95% confidence level ($\hat{\alpha}_2^0 = 0.024$, *Sd* = 0.019) while the coefficient for price is significantly positive in regime 1 ($\hat{\alpha}_2^1 = 0.055$, *Sd* = 0.017). The coefficients on the market share variable in the two regimes indicate that Algeria is more coordinated with other OPEC producers in regime 0 than in regime 1($\hat{\alpha}_3^0 = 0.484$ *Sd* = 0.046 and $\hat{\alpha}_3^1 = 0.239$ *Sd* = 0.040). By the contrary, the time-varying transition model has significant coefficients on price in both regimes while regime 0 also has a significantly higher market share coefficient than regime 1.

The estimation of the constant transition model also gives the constant transition probability matrix as follows:

$$\begin{bmatrix} 0.404 & 0.066 \\ 0.596 & 0.934 \end{bmatrix}$$

which indicates that the probability of staying with regime 1, which is more competitive, is much higher than the probability of staying with regime 0. The constant transition probability of regime 1 is $Pr^{11} = Pr(S_t = 1 | S_{t-1} = 1) = 0.934$, indicating when the state of regime at time *t*-1 is regime 1, the probability that the regime staying with regime 1 is 0.934, while the constant transition probability of regime 0 is $Pr^{00} = Pr(S_t = 0 | S_{t-1} = 0) = 0.404$, indicating that when the regime at time *t*-1 is regime 0, the probability of its staying with regime 0 is 0.404. And the steady probability of regime 0 and regime 1 is 0.095 and 0.905, respectively, indicating that about 90% of the time Algerian oil production falls into a more competitive-like regime. The regime probabilities evolvement pattern indicates that Algeria took the more collusive-like strategy for short periods of time only in the early stage of the quota system and behaved like a competitive producer the rest of the time. The predicted probabilities of falling in regime 0 can be seen in Figure 3.C1.

The estimated coefficient for the oil reserve in the supply function is significantly positive at the 90% confidence level in the time-varying transition model while insignificant in the constant transition model. Surprisingly, the coefficient for investment needs in the supply function is significantly negative in both cases, which is against our expectation.

Table 3.C1 Algeria ML Estimates for the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.404*	0.141	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in Non-competitive Regime	-	-		-	-49.619	107.065
γ_1 (Price Change Coeff.)		-	-	-	-	0.480	0.450
γ_2 (GDP of OCED Coeff.)		-	-	-	-	-4.478	9.048
γ_3 (Quota Violation Coeff.)				-	-	-0.185	0.206
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	13.840	27.546
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.934*	0.026	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Competitive Regime	-	-	-	-	-33.576	30.995
δ_1 (Price Change Coeff.)		-	-	-	-	0.086	0.081
δ_2 (GDP of OCED Coeff.)		-	-	-	-	3.252	2.976
δ_3 (Quota Violation Coeff.)		-	-	-	-	-0.115	0.102
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	3.856	6.958
α_1^0 (Intercept)	Parameters in Supply function in the Collusion Regime	1.141	1.848	4.401*	1.916	-0.211	1.323
α_2^0 (Price Coeff.)		0.024	0.019	0.045*	0.019	0.052*	0.024
α_3^0 (Market Share Coeff.)		0.484*	0.046	0.288*	0.054	0.529*	0.072
α_1^1 (Intercept)	Parameters in Supply function in the Competition Regime	3.379**	1.892	-	-	2.714*	1.370
α_2^1 (Price Coeff.)		0.055*	0.017	-	-	0.056*	0.016
α_3^1 (Market Share Coeff.)		0.239*	0.040	-	-	0.237*	0.036
β_1 (Reserve Coeff.)	Non-switching coefficients	0.191	0.197	-0.024	0.203	0.285**	0.150
β_2 (Investment Needs Coeff.)		-0.091*	0.045	-0.042	0.062	-0.110*	0.044
β_3 (War Indicator - Iraq)		0.047**	0.027	0.093*	0.022	0.046**	0.025
β_4 (War Indicator - Kuwait)		0.008	0.019	0.009	0.020	0.008	0.019
Log Likelihood		580.708		496.58		587.512	
Likelihood Ratio Statistic				168.256		13.608	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

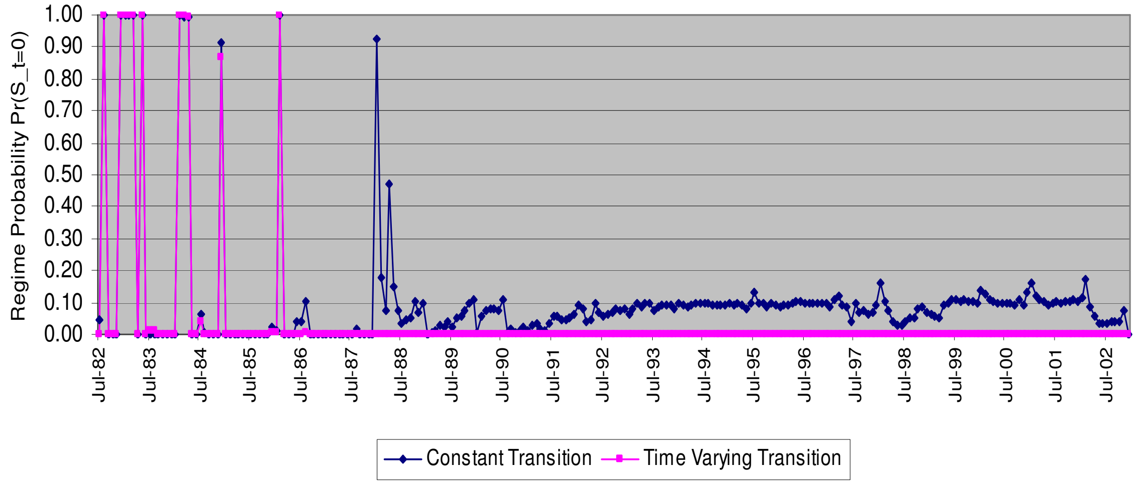

Figure 3.C1 Algeria's Predicted Probabilities of Being in Non-competitive Regime

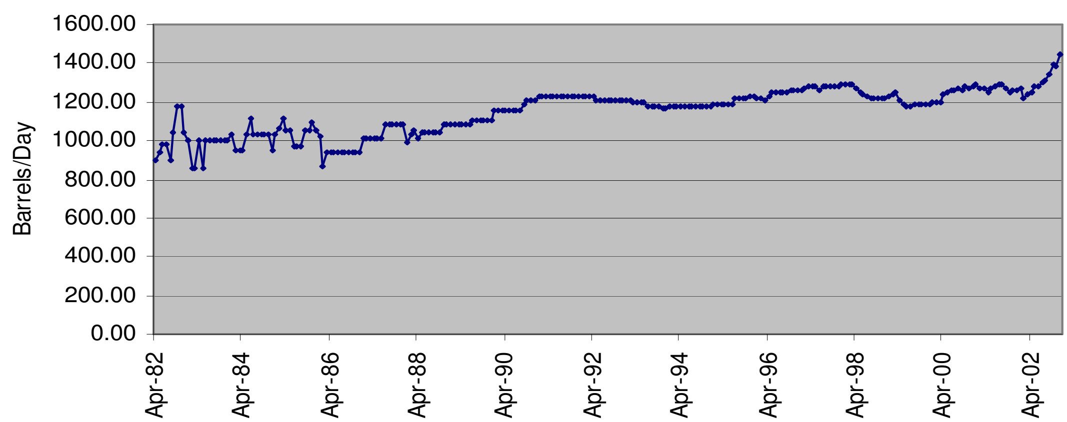

Figure 3.C2 Algeria's Crude Oil Production, April 1982- December 2002

Indonesia

The estimation results for Indonesia are presented in Table 3.C2.

Highlights:

- Regime switching exists in Indonesia's oil supply function but the distinction between the two regimes is a little vague and the predicted regime probabilities of Indonesia do not seem to provide as robust implications about regime switches as those of other producers.
- According to estimates for the time-varying transition model, Indonesia has a significantly positive coefficient for price in one regime, indicating competitive behavior, while an insignificantly negative coefficient for price is seen in the other.
- The likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with the proposed affecting factors and price change, while currency exchange rate and host government production share seem to have significant effects on determining the transition probabilities.

During the study period, Indonesia experienced a drastic change in the government's share of crude oil production, which dropped from 52.4% in 1982 to 5.7% in 1988 and then to 3.6% in 2002. To examine the effects of private *vs.* government ownership of Indonesia's oil production strategy selection, I include this factor in the transition probability function.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market sharing model prevailing for Indonesia. The test statistic is 113.822, enormously greater than the critical value of Chi-squared distribution at the 95% confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Indonesia's oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities does not vary across time with price change, demand shifter, quota violation changes, currency exchange rate and property right, i.e., the null hypothesis H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \gamma_{i5} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = \delta_{i5} = 0$ is rejected. The test statistic is 19.64, higher than 18.31--the critical value of the 95% confidence level. Therefore, the time-varying transition model prevails in explaining Indonesia's oil production behavior. According to the estimates on time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. The coefficient for price is insignificantly negative in regime 0 ($\hat{\alpha}_2^0 = -0.021$, Sd = 0.021) while it is positive at the 90% confidence level in regime 1 ($\hat{\alpha}_2^1 = 0.043$, Sd = 0.023). Therefore, I infer that regime 1 is a more competitive regime and regime 0 is non-competitive.

The coefficients on price change and host government production share have an expected sign and are significant at a high confidence level in the transition probability function of a non-competitive regime. The coefficient for the price change in the transition probability function is significantly positive at the 90% confidence level in non-competitive regime and it is negative in the competitive regime, indicating that when price increases, Indonesia is more likely to stay with a non-competitive production strategy and a dip of price would lead to a competitive strategy as predicted by Green and Porter's theory. The coefficients on demand shifter are insignificantly negative in both regimes and thus do not provide any inference on the applicability of either of the collusive theories. The coefficient for host government production share is significantly positive in non-competitive regime, implying that the increase in the government's share of production may lead to a higher probability of staying with a non-competitive regime, and thereby implying that the government is more willing to take a non-competitive production strategy than private companies. However, the sign of the host government production share coefficient in a competitive regime is not the opposite of that in a non-competitive regime, weakening the implication to some extent. The coefficient for the currency exchange rate is significant at the 90% confidence level in a non-competitive regime but the sign is against our expectation, being positive.

The average probability that Indonesia is in a non-competitive regime is about 88.0%. The regime probabilities evolvement pattern shows that the distinction between the two regimes is vague and it is difficult to identify the two regimes from the regime probabilities in the 1980s as they bounce up and down quite frequently and many of them fall in the middle of the probability range. The predicted probabilities of falling into a non-competitive regime can be seen in Figure 3.C3.

The estimated coefficients on reserve and investment needs are at a very low significant level, indicating that these two variables do not play an important role in determining the output level of Indonesia’s oil production.

Table 3.C2 Indonesia ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.834*	0.051	-	-	-	-
γ_0		-	-		-	8.478	25.620
γ_1 (Price Change Coeff.)	Parameters in Trans. Prob. Function in the Regime 0	-	-	-	-	0.219**	0.122
γ_2 (GDP of OCED Coeff.)		-	-	-	-	-6.833	6.582
γ_3 (Quota Violation Coeff.)				-	-	-0.127	0.104
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	13.856**	7.962
γ_5 (Property Right Coeff.)						21.540**	13.242
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.416*	0.133	-	-	-	-
δ_0		-	-	-	-	31.804	34.608
δ_1 (Price Change Coeff.)	Parameters in Trans. Prob. Function in the Regime 1	-	-	-	-	-0.172	0.219
δ_2 (GDP of OCED Coeff.)		-	-	-	-	-9.506	10.272
δ_3 (Quota Violation Coeff.)		-	-	-	-	0.016	0.203
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	7.788	13.080
δ_5 (Property Right Coeff.)						11.851	19.523
α_1^0 (Intercept)	Parameters in Supply function in the Regime 0	3.996*	0.685	3.812*	0.706	3.875*	0.718
α_2^0 (Price Coeff.)		-0.014	0.020	0.017	0.024	-0.021	0.021
α_3^0 (Market Share Coeff.)		0.358*	0.046	0.327*	0.059	0.368*	0.049
α_1^1 (Intercept)	Parameters in Supply function in the Regime 1	1.346**	0.734	-	-	-0.267	0.747
α_2^1 (Price Coeff.)		0.009	0.021	-	-	0.043**	0.023
α_3^1 (Market Share Coeff.)		0.604*	0.052	-	-	0.734*	0.056
β_1 (Reserve Coeff.)	Non-switching coefficients	0.002	0.003	0.007	0.005	0.001	0.003
β_2 (Investment Needs Coeff.)		-0.030	0.035	0.001	0.041	-0.025	0.034
β_3 (War Indicator - Iraq)		0.115*	0.039	-0.009	0.031	0.124*	0.038
β_4 (War Indicator - Kuwait)		0.019	0.026	0.085*	0.027	0.017	0.024
Log Likelihood		534.583		477.672		544.404	
Likelihood Ratio Statistic				113.822		19.642	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

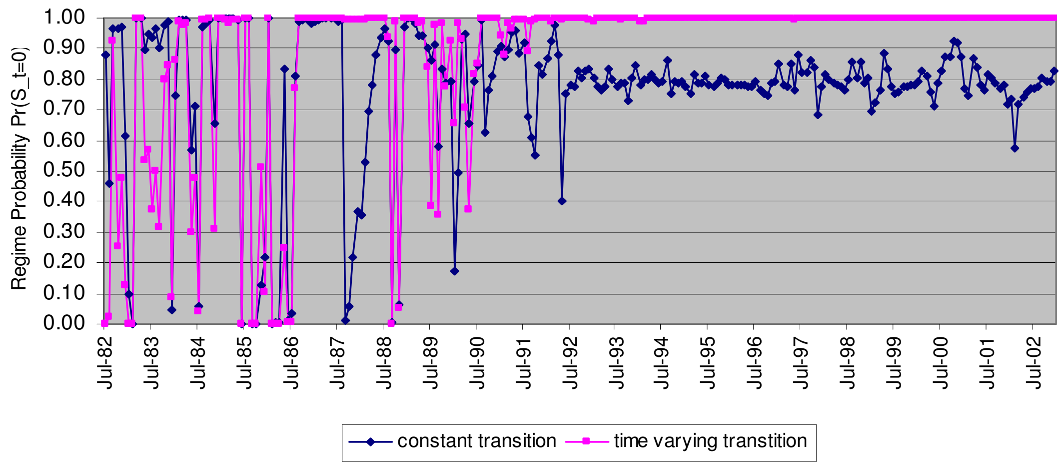

Figure 3.C3 Indonesia's Predicted Probabilities of Being in a Non-competitive Regime

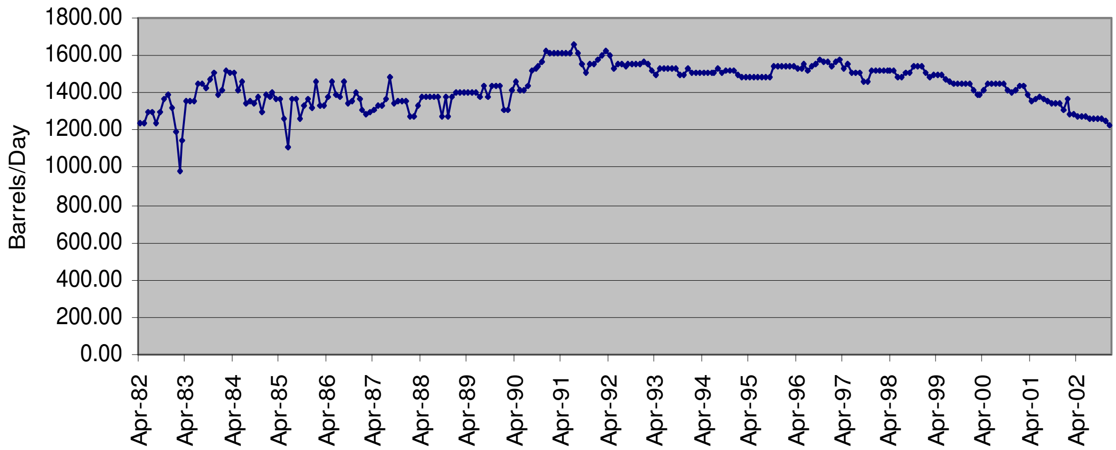

Figure 3.C4 Indonesia's Crude Oil Production, April 1982- December 2002

Iran

The estimation results for Iran are presented in Table 3.C3.

Highlights:

- Regime switching exists in Iran's oil supply function and two regimes have significantly different characteristics.
- According to the estimates, Iran has a significantly positive coefficient for price in one regime, indicating competitive behavior, while an insignificantly positive coefficient for price is seen in the other.
- The predicted regime probabilities indicate that Iran undertook a competitive strategy for most of the 1980s and non-competitive behavior prevailed from the early 1990s.
- A likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with the proposed affecting factors, and demand shifter and quota violation seem to have significant effects on determining the transition probabilities.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Iran. The test statistic is 59.152, enormously greater than the critical value of Chi-squared distribution at the 95% confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Iran's oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities do not vary across time with those proposed affecting factors, i.e., the null hypothesis

H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ is rejected. The test statistic is 29.154, higher than 15.51--the critical value of the 95% confidence level. Therefore, the time-varying transition model prevails in explaining Iran's oil production behavior. According to the estimates for the time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. The coefficient for price is insignificantly positive in regime 0 ($\hat{\alpha}_2^0 = 0.027$, *Sd* = 0.023) while it is positive at the 95% confidence level in regime 1 ($\hat{\alpha}_2^1 = 0.119$, *Sd* = 0.028). Therefore, I infer that regime 1 is a more competitive-like regime and regime 0 is non-competitive.

The coefficients for demand shifter (GDP of OECD countries) and quota violation changes are significant at a high confidence level in the transition probability function. Supporting Green and Porter's theory, the coefficient for demand shifter is significantly positive at the 95% confidence level in the non-competitive regime ($\hat{\gamma}_2$ = 5.139, *Sd* = 1.959) indicating that higher demand may increase Iran's probability of staying with a non-competitive strategy. As expected, the sign of the demand shifter coefficient in the competitive regime is opposite to that in the non-competitive regime ($\hat{\delta}_2$ = -1.790, *Sd* = 1.777). The price change coefficients are insignificantly negative in both regimes and do not provide any inference in support of either collusive theory. Against our expectation, the significantly negative coefficient for quota violation change in Iran's competitive regime, meaning that worsening quota compliance from other producers would increase the probability of switching from the competitive regime to the non-competitive regime. But the identical sign of the coefficient in the non-competitive regime lessens the counter-intuitive implication.

The regime probabilities evolvement pattern shows that Iran was in the competitive regime for most of the 1980s, including the price plunge in 1986. It may be that the 1980-88 Iran-Iraq war dictated Iran's oil production strategy as one that maximized its profit in order to sustain the war. Starting from the early 1990s, a non-competitive production strategy prevailed in Iran's oil production. The predicted probabilities of falling into a non-competitive regime can be seen in Figure 3.C5.

The estimated coefficient for reserve is as expected--significantly positive. The coefficient for investment needs is insignificant.

Table 3.C3 Iran ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.972*	0.013	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Non-competitive Regime	-	-		-	-26.291*	10.332
γ_1 (Price Change Coeff.)		-	-	-	-	-0.122	0.094
γ_2 (GDP of OCED Coeff.)		-	-	-	-	5.139*	1.959
γ_3 (Quota Violation Coeff.)				-	-	-0.125	0.095
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	1.112	7.698
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.938*	0.029	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Competitive Regime	-	-	-	-	16.993	16.336
δ_1 (Price Change Coeff.)		-	-	-	-	-0.067	0.114
δ_2 (GDP of OCED Coeff.)		-	-	-	-	-1.790	1.777
δ_3 (Quota Violation Coeff.)		-	-	-	-	-0.187**	0.105
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-59.839	94.309
α_1^0 (Intercept)	Parameters in Supply function in the Non-competitive Regime	1.279	1.074	0.779	1.135	1.709**	1.004
α_2^0 (Price Coeff.)		0.021	0.023	0.083*	0.033	0.027	0.023
α_3^0 (Market Share Coeff.)		0.391*	0.101	0.415*	0.089	0.353*	0.095
α_1^1 (Intercept)	Parameters in Supply function in the Competitive Regime	-0.019	0.326	-	-	0.240	0.948
α_2^1 (Price Coeff.)		0.123*	0.020	-	-	0.119*	0.028
α_3^1 (Market Share Coeff.)		0.465*	0.054	-	-	0.451*	0.076
β_1 (Reserve Coeff.)	Non-switching coefficients	0.228*	0.035	0.196*	0.061	0.223*	0.038
β_2 (Investment Needs Coeff.)		-0.018	0.022	0.016	0.037	-0.022	0.023
β_3 (War Indicator - Iraq)		0.424*	0.031	0.264*	0.035	0.422*	0.031
β_4 (War Indicator - Kuwait)		-0.039**	0.022	-0.044	0.034	-0.044*	0.022
Log Likelihood		375.862		346.286		390.439	
Likelihood Ratio Statistic				59.152		29.154	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

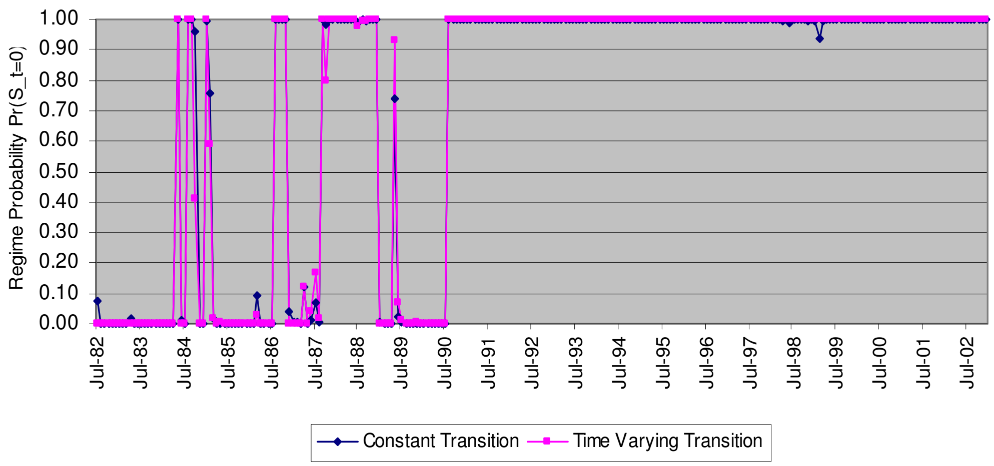

Figure 3.C5 Iran's Predicted Probabilities of Being in Non-competitive Regime

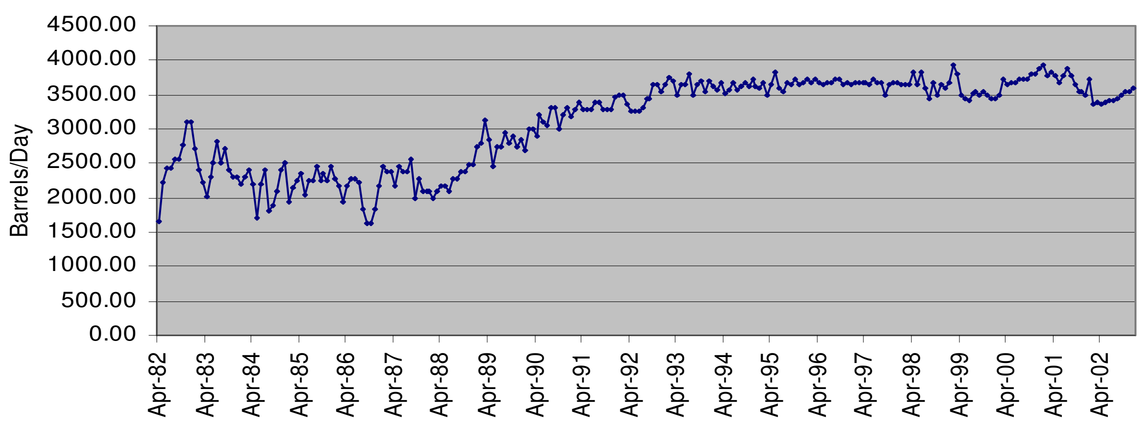

Figure 3.C6 Iran's Crude Oil Production, April 1982 – December 2002

Libya

The estimation results for Libya are presented in Table 3.C4.

Highlights:

- Regime switching exists in Libya’s oil supply function and the two regimes have significantly different production characteristics.
- The likelihood ratio test fails to reject at a high confidence level the hypothesis that transition probabilities do not vary with those factors. None of the proposed affecting factors on transition probabilities is significant.
- According to estimates, Libya has a significantly positive coefficient for price in one regime, indicating competitive behavior, while an insignificantly positive coefficient for price is seen in the other.
- Libya’s oil supply function falls into a non-competitive regime in most of time.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Libya. The test statistic is 88.76, enormously greater than the critical value of Chi-squared distribution at the 95% confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Libya’s oil supply function.

The likelihood ratio test for the time-varying transition model fails to reject the hypothesis that the transition probabilities do not vary across time with price change, demand shifter, quota violation changes and currency exchange rate, i.e., the null hypothesis H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ cannot be rejected at a high confidence level. The test statistic is 14.49, less than 15.51--the critical value of the 95% confidence level. An individual *t*-test to the estimate of each factor also does not verify any significant effects on transition probability of these factors. Therefore, the estimates on transition probability functions for Libya do not provide supportive evidence for either Green and Porter's theory or Rotemberg and Saloner's theory.

According to the estimates for the time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. In regime 0, the hypothesis of $\alpha_2^0 = 0$ (coefficient for price equal to zero) cannot be rejected at a high confidence level ($\hat{\alpha}_2^0 = 0.017$, *Sd* = 0.028) while the coefficient for price is significantly positive in regime 1 ($\hat{\alpha}_2^1 = 0.067$, *Sd* = 0.033), indicating competitive-like behavior.

The estimation of the constant transition model also results in a the constant transition probability matrix as follows:

$$\begin{bmatrix} 0.973 & 0.172 \\ 0.027 & 0.828 \end{bmatrix}$$

This indicates that the probability of staying in regime 0, which is more non-competitive, is higher than that of regime 1. The steady probability of regime 0 and regime1 is 0.864 and 0.136, respectively, indicating that about 86% of the time Libya oil production falls into a more non-competitive-like regime.

Interestingly, the regime probabilities evolvement pattern indicates that Libya most likely undertook a competition strategy during the price plunge of 1986 and 1988. Entering into the 1990s, Libya seemed to stabilize its production strategy as a non-competitive producer. The predicted probabilities of falling into a non-competitive regime can be seen in Figure C7.

The estimated coefficient for reserve in the supply function is insignificant in all variant models. As expected, the coefficient for investment needs in the supply function is significantly positive in all specifications, indicating that needs for revenue from oil is a significant determinant in Libya's oil production decision.

Table 3.C4 Libya ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.973*	0.012	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Non-competitive Regime	-	-		-	-5.839	4.520
γ_1 (Price Change Coeff.)		-	-	-	-	0.029	0.075
γ_2 (GDP of OCED Coeff.)		-	-	-	-	1.093	1.575
γ_3 (Quota Violation Coeff.)				-	-	0.033	0.078
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	8.912	18.597
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.828*	0.070	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Competitive Regime	-	-	-	-	-1.848	8.340
δ_1 (Price Change Coeff.)		-	-	-	-	0.067	0.098
δ_2 (GDP of OCED Coeff.)		-	-	-	-	-0.681	2.161
δ_3 (Quota Violation Coeff.)		-	-	-	-	0.018	0.078
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	19.708	18.949
α_1^0 (Intercept)	Parameters in Supply function in the Non-competitive Regime	-0.609	0.999	-1.690	1.182	-0.384	1.099
α_2^0 (Price Coeff.)		0.022	0.029	0.044	0.030	0.017	0.028
α_3^0 (Market Share Coeff.)		0.631*	0.073	0.757*	0.073	0.631*	0.066
α_1^1 (Intercept)	Parameters in Supply function in the Competitive Regime	-4.554*	1.131	-	-	-4.350*	1.163
α_2^1 (Price Coeff.)		0.073*	0.037	-	-	0.067*	0.033
α_3^1 (Market Share Coeff.)		1.014*	0.088	-	-	1.017*	0.083
β_1 (Reserve Coeff.)	Non-switching coefficients	0.012	0.052	-0.039	0.101	0.007	0.065
β_2 (Investment Needs Coeff.)		0.127*	0.043	0.153*	0.039	0.109*	0.044
β_3 (War Indicator - Iraq)		0.134*	0.032	0.064*	0.031	0.140*	0.033
β_4 (War Indicator - Kuwait)		0.124*	0.034	0.175*	0.031	0.118*	0.034
Log Likelihood		386.074		341.696		393.319	
Likelihood Ratio Statistic				88.756		14.49	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

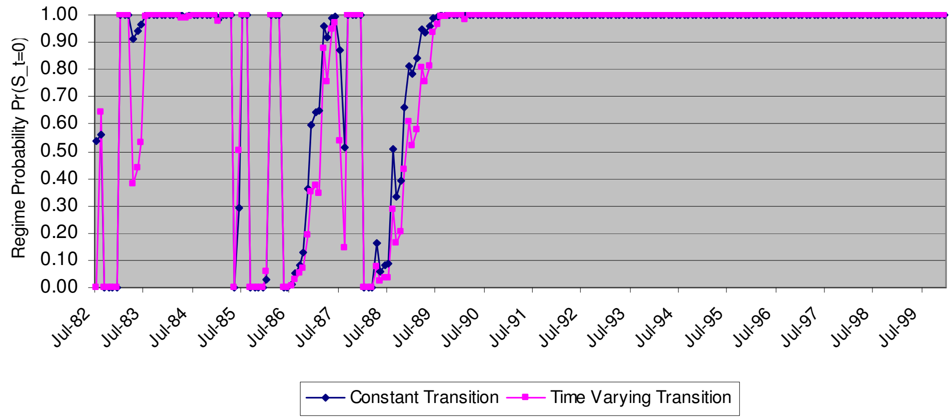

Figure 3.C7 Libya's Predicted Probabilities of Being in a Non-competitive Regime

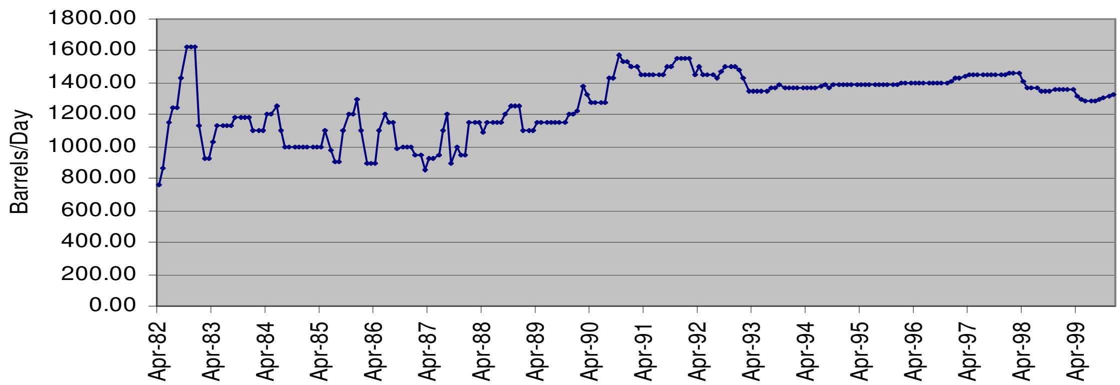

Figure 3.C8 Libya's Crude Oil Production, April 1982 – December 1999

Nigeria

The estimation results for Nigeria are presented in Table 3.C5.

Highlights:

- Regime switching exists in Nigeria's oil supply function and the two regimes have significantly different characteristics.
- According to the estimates, Nigeria has a significantly positive coefficient for price in one regime, indicating competitive behavior, while a significantly negative coefficient for price is seen in the other.
- The likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with the proposed affecting factors. Price change and currency exchange rate seem to have significant effects on determining the transition probabilities.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Nigeria. The test statistic is 83.28, enormously greater than the critical value of Chi-squared distribution at the 95% confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Nigeria's oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities do not vary across time with those proposed affecting factors, i.e., the null hypothesis

H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ is rejected. The test statistic is 22.30, higher than 15.51--the critical value of the 95% confidence level.

According to the estimates for the time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. The coefficient for price is significantly negative in regime 0 ($\hat{\alpha}_2^0 = -0.153$, Sd = 0.049) while it is positive at the 95% confidence level in regime 1 ($\hat{\alpha}_2^1 = 0.063$, Sd = 0.031). In addition, Nigeria has better coordination with other producers as the hypothesis of market share coefficient equal to one cannot be rejected for regime 0 ($\hat{\alpha}_3^0 = 1.162$, Sd = 0.123) but the coefficient is significantly lower than one in regime 1 ($\hat{\alpha}_3^1 = 0.618$, Sd = 0.093). Therefore, regime 0 can be labeled as a non-competitive regime and regime 1 as a competitive regime.

In support of Green and Porter's theory, the coefficients for price change in transition probability functions in both non-competitive and competitive regimes are significant and have opposite signs (positive in non-competitive and negative in competitive), indicating that a price signal is a significant determinant in Nigeria's oil production strategy selection. When price drops, the probability of switching from a collusive to a competitive regime will increase. The other important determinant in Nigeria's oil production strategy selection is likely the currency exchange rate. The coefficients for currency exchange rate for the transition probability functions have opposite signs in the two regimes and is significantly positive at 90% in the competitive regime, indicating that the depreciation of its national currency may increase Nigeria's probability of staying with a competition regime in order to get more hard currency in the short term.

The regime probabilities evolvement pattern shows that Nigeria's production regime switches occurred mostly in the 1980s and that it was in the competition regime during the price plunge period in 1986. Shortly after that, Nigeria stabilized its production strategy as a competition producer in the organization. The predicted probabilities of falling in a non-competitive regime can be seen in Figure 3.C9.

The estimated coefficient for reserve is as expected--positive and significant at the 95% confidence level in the constant regime model. The coefficient for investment needs is insignificant in all variant models.

Table 3.C5 Nigeria ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.717*	0.088	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Non-competitive Regime	-	-		-	17.393	19.986
γ_1 (Price Change Coeff.)		-	-	-	-	0.893**	0.489
γ_2 (GDP of OCED Coeff.)		-	-	-	-	-2.783	4.080
γ_3 (Quota Violation Coeff.)		-	-	-	-	-0.190	0.135
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-209.994	143.542
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.866*	0.056	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Competitive Regime	-	-	-	-	1.316	5.492
δ_1 (Price Change Coeff.)		-	-	-	-	-0.406*	0.201
δ_2 (GDP of OCED Coeff.)		-	-	-	-	-0.126	1.136
δ_3 (Quota Violation Coeff.)		-	-	-	-	-0.037	0.106
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	63.768**	35.007
α_1^0 (Intercept)	Parameters in Supply function in the Non-competitive Regime	-3.331*	1.346	-2.631	1.640	-4.232*	1.587
α_2^0 (Price Coeff.)		-0.078*	0.039	0.021	0.040	-0.153*	0.049
α_3^0 (Market Share Coeff.)		0.977*	0.096	0.851*	0.115	1.162*	0.123
α_1^1 (Intercept)	Parameters in Supply function in the Competitive Regime	-1.213	1.279	-	-	-0.543	1.280
α_2^1 (Price Coeff.)		0.061**	0.033	-	-	0.063*	0.031
α_3^1 (Market Share Coeff.)		0.662*	0.092	-	-	0.618*	0.093
β_1 (Reserve Coeff.)	Non-switching coefficients	0.195*	0.097	0.174	0.123	0.141	0.097
β_2 (Investment Needs Coeff.)		-0.039	0.046	-0.036	0.064	-0.004	0.059
β_3 (War Indicator - Iraq)		0.145*	0.048	0.144*	0.064	0.145*	0.054
β_4 (War Indicator - Kuwait)		0.022	0.040	0.042	0.052	0.016	0.041
Log Likelihood		348.162		306.52		359.313	
Likelihood Ratio Statistic				83.284		22.302	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

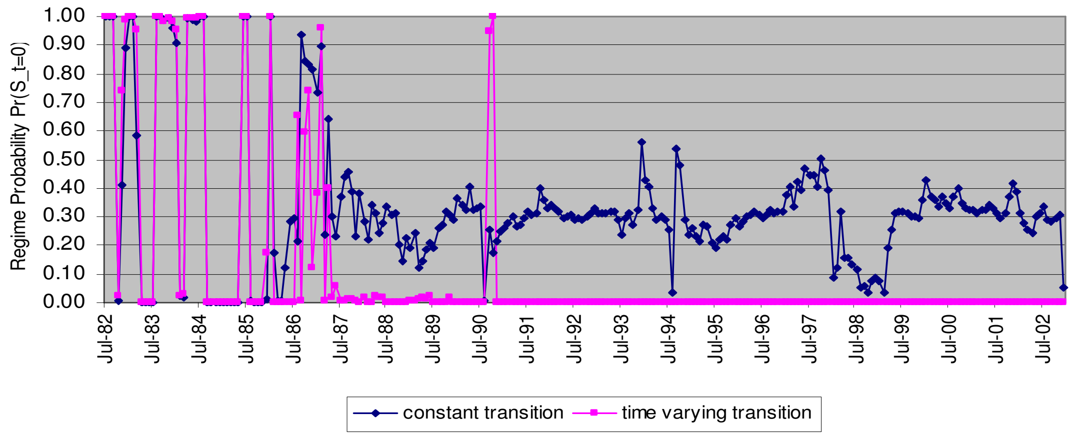

Figure 3.C9 Nigeria’s Predicted Probabilities of Being in a Non-competitive Regime

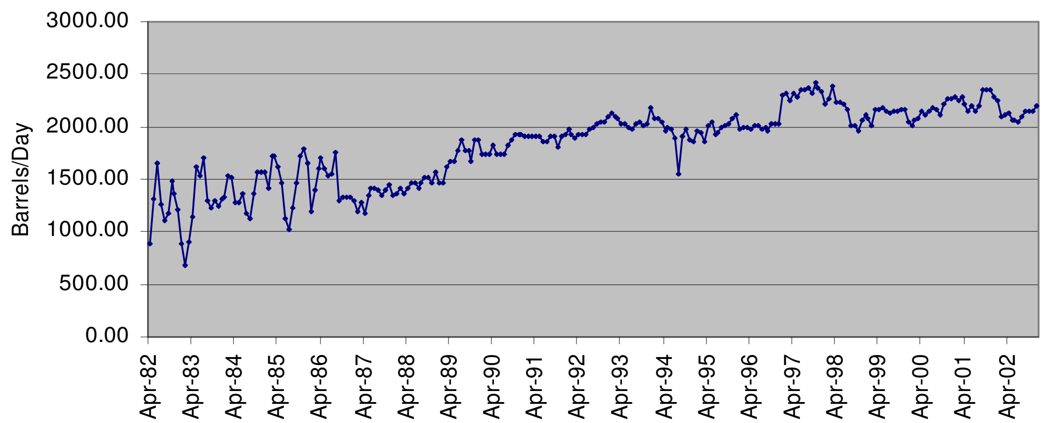

Figure 3.C10 Nigeria’s Crude Oil Production, April 1982 – December 2002

Qatar

The estimation results for Qatar are presented in Table 3.C6.

Highlights:

- Regime switching exists in Qatar's oil supply function and the two regimes have significantly different characteristics.
- According to the estimates, Qatar has a significantly positive coefficient for price in one regime, indicating competitive behavior, while an insignificantly positive coefficient for price is seen in the other. The collusive regime of Qatar appears to follow the constant market-sharing conduct.
- The likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with the proposed affecting factors. Price change and demand shifter seem to have significant effects on determining the transition probabilities.

The likelihood ratio test of the constant transition model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Qatar. The test statistic is 76.89, enormously greater than the critical value of Chi-squared distribution at the 95% confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Qatar's oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities do not vary across time with those proposed affecting factors, i.e., the null hypothesis

H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ is rejected. The test statistic is 42.48, higher than 15.51--the critical value of the 95% confidence level.

According to estimates for the time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. The coefficient for price is insignificantly positive in regime 0 ($\hat{\alpha}_2^0 = 0.094$, *Sd* = 0.082) while it is positive at the 95% confidence level in regime 1 ($\hat{\alpha}_2^1 = 0.550$, *Sd* = 0.108), indicating competitive behavior in regime 1. The market share coefficient equal to one cannot be rejected for both regimes ($\hat{\alpha}_3^0 = 0.794$, *Sd* = 0.146 and $\hat{\alpha}_3^1 = 0.852$, *Sd* = 0.312). Therefore, regime 0 can be characterized as a constant market-sharing regime and regime 1 as a competitive regime.

The coefficient for price change in transition probability functions in the constant market share regime is significantly positive at the 90% confidence level and is negative in the competitive regime, indicating that price signal is a significant determinant in Qatar's oil production strategy selection. When price drops, the probability of switching from a non-competitive regime to a competitive regime will increase. The other important determinant in Qatar's oil production strategy selection is the demand shifter, OECD GDP. The coefficients for OECD GDP in transition probability functions have opposite signs in the two regimes and are significantly positive at the 95% level in the constant market share regime, indicating higher demand would lead to higher probability of being in a non-competitive regime. Both the estimates on price change and demand shifter are supportive of Green and Porter's theory.

The regime probabilities evolvement pattern shows that Qatar's production regime switches occurred mostly in the first half of the 1980s and stabilized its production strategy as a constant market share producer thereafter. Qatar was in a constant market share strategy during the price plunge in 1986. As for Saudi Arabia and the U.A.E., constant market share behavior in the price plunge period could be deemed a form of the "tit-for-tat" strategy. The predicted probabilities of falling in a constant market-sharing regime can be seen in Figure 3.C11.

The estimated coefficient for reserve is as expected--positive but insignificant at a high confidence level. The coefficient for investment needs is significantly positive at the 90% confidence level, indicating that obtaining sufficient revenue from oil production is an important factor in determining Qatar's oil output.

Table 3.C6 Qatar ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.968*	0.014	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Non-competitive Regime	-	-		-	-22.281	7.774
γ_1 (Price Change Coeff.)		-	-	-	-	0.112**	0.062
γ_2 (GDP of OCED Coeff.)		-	-	-	-	5.720*	2.172
γ_3 (Quota Violation Coeff.)		-	-	-	-	0.096	0.080
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-1.059	2.004
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.000	0.001	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Competitive Regime	-	-	-	-	131.631	151.636
δ_1 (Price Change Coeff.)		-	-	-	-	-1.071	1.282
δ_2 (GDP of OCED Coeff.)		-	-	-	-	-9.152	15.855
δ_3 (Quota Violation Coeff.)		-	-	-	-	0.424	0.424
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-23.569	20.566
α_1^0 (Intercept)	Parameters in Supply function in the Non-competitive Regime	-4.134	2.618	-5.244*	2.454	-5.433*	2.138
α_2^0 (Price Coeff.)		-0.005	0.120	0.036	0.085	0.094	0.082
α_3^0 (Market Share Coeff.)		0.710*	0.187	0.806*	0.221	0.794*	0.146
α_1^1 (Intercept)	Parameters in Supply function in the Competitive Regime	-4.738	5.389	-	-	-9.890*	3.397
α_2^1 (Price Coeff.)		0.266*	0.129	-	-	0.550*	0.108
α_3^1 (Market Share Coeff.)		0.506	0.517	-	-	0.852*	0.312
β_1 (Reserve Coeff.)	Non-switching coefficients	0.225	0.194	0.217	0.218	0.188	0.189
β_2 (Investment Needs Coeff.)		0.159**	0.095	0.146	0.094	0.167*	0.087
β_3 (War Indicator - Iraq)		0.088	0.084	0.077	0.087	0.062	0.080
β_4 (War Indicator - Kuwait)		0.015	0.076	-0.012	0.080	0.030	0.070
Log Likelihood		159.686		121.239		180.927	
Likelihood Ratio Statistic				76.894		42.482	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

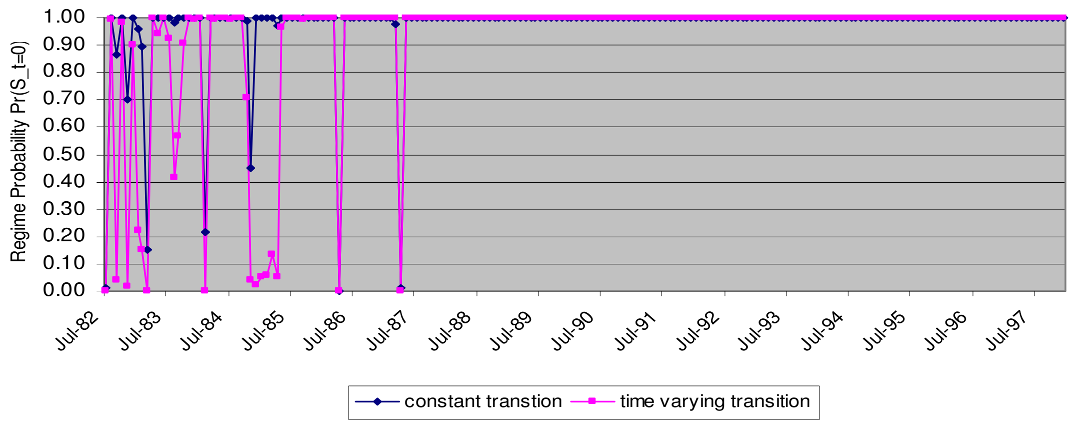

Figure 3.C11 Qatar's Predicted Probabilities of Being in a Non-competitive Regime

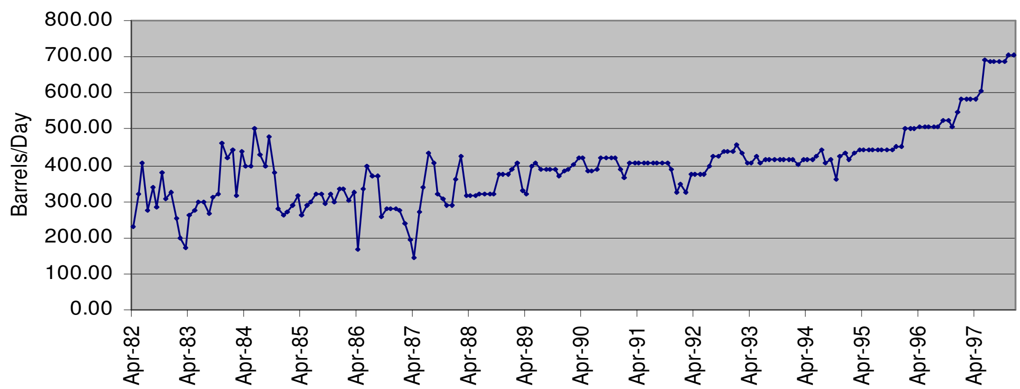

Figure 3.C12 Qatar's Crude Oil Production, April 1982 – December 1997

Saudi Arabia

The estimation results for Saudi Arabia are presented in Table 3.C7.

Highlights:

- Regime switching does exist in Saudi Arabia's oil supply function.
- Saudi Arabia behaves as a constant market-sharing player in regime 0. There is no evidence that Saudi Arabia behaves in a competitive manner in regime 1. Rather, regime 1 is better labeled as an "Altruism Regime" in that the greater than one market share coefficient indicates Saudi Arabia cuts its production more than proportionally with other producers in that regime.
- The likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with the proposed affecting factors. Price change, demand shifter and quota violation change seem to have significant effects on determining the transition probabilities.
- Saudi Arabia's oil supply function falls into a constant market-sharing regime most of the time.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Saudi Arabia. The test statistic is 103.256, enormously greater than the critical value of Chi-squared distribution at the 95% confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Saudi Arabia's oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities do not vary across time with those proposed affecting factors, i.e., the null hypothesis

H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ is rejected. The test statistic is 22.93, higher than 15.51--the critical value of the 95% confidence level.

According to the estimates for the time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. In regime 0, neither hypothesis $\alpha_2^0 = 0$ (coefficient for price equal to zero) nor the hypothesis of $\alpha_3^0 = 1$ (coefficient for market share equal to 1) can be rejected at the 95% confidence level ($\hat{\alpha}_2^0 = -0.033$, *Sd* = 0.030 and $\hat{\alpha}_3^0 = 1.111$, *Sd* = 0.096), indicating that the constant market-sharing behavior cannot be rejected for Saudi Arabia in the regime.

A unique feature of Saudi Arabia's production strategy is present in the other regime. While the coefficient for price is still insignificantly different from zero ($\hat{\alpha}_2^1 = 0.033$, *Sd* = 0.035), the market-share coefficient in the regime is significantly greater than one ($\hat{\alpha}_3^1 = 1.715$, *Sd* = 0.112). There are two possible explanations for the greater than one market share coefficient. One is that a producer's production increases more than proportionally when overall production increases. Thus, the producer will increase its market share. The other explanation is that a producer's production decreases more than proportionally when overall production decreases and thus the producer will decrease its market share.

A further examination of the timing of Saudi Arabia's production regime 1 reveals that the latter explanation prevails in the regime. The predicted regime probabilities (see Figure 3. C13) indicate that there are roughly five periods, including July 1982 to June 1983, January 1984 to March 1984, September 1984 to August 1985, January 1987 to March 1987, and January 1989 to March 1989, along with several other scattered time periods in which Saudi Arabia's oil production fell into regime 1, which has significantly greater than one coefficient for market share.

There is one common characteristic among these periods: OPEC was cutting production, and Saudi Arabia contributed the bulk of the cuts so that its market share dropped dramatically. In the meantime, the market price was rising or only dropping moderately. For example, from September 1984 to August 1985, OPEC's oil production dropped from 16,553 barrels/day to 14,798 barrels/day while Saudi Arabia cut its production from 4,520 barrels/day to 2,340 barrels/day, so that its market share in OPEC dropped from 27.3% to 15.8%; in the meantime, the market price was only moderately dropping from $27.45 per barrel in September 1984 to $25.36 per barrel in August 1985, in contrast to the drastic price plunge in the following months, when the price dropped more than 50% to $ 11.64 per barrel in February 1986. Without Saudi Arabia's sacrifice of its own output during September 1984 to August 1985, the oil price could have plunged earlier. (See Table 3.C8 for more details about market evolvements during the periods in which Saudi Arabia was likely in production regime 1.)

These facts indicate that Saudi Arabia sacrificed its market share in production regime 1 to keep the price at a favorable level and perhaps to maintain a stable cartel, in a regime I now call an “Altruism Regime.”

With regard to factors possibly affecting regime selection, price change, quota violation change, and OECD GDP have a significant coefficient with an expected sign in the transition probability function for the constant market-sharing regime. The coefficient for the currency exchange rate is significant at the 90% confidence level with an against-expected sign.

The coefficient for price change in the transition probability function for the constant market-sharing regime is significantly positive, indicating that when the oil price goes up, Saudi Arabia is more likely to stay with the constant market-sharing regime. When price dips down, Saudi Arabia is more likely to switch to altruism regime perhaps with an intent to deter price declines by cutting production more than proportionally with other producers.

OECD GDP as a demand shifter has a significantly positive coefficient in the transition probability function of the constant market-sharing regime, indicating that Saudi Arabia is more likely to stay in a constant market-sharing regime when market demand grows, while a slump market tends to increase the probability of switching to an altruism regime.

The estimates for price change and OECD GDP imply that Saudi Arabia acts as the residual supplier in OPEC, counters the down market, and stabilizes the cartel.

But the “altruism” role is not unconditional. The significantly positive coefficient for quota violation change implies that Saudi Arabia is reluctant to switch to an “altruism” regime if the quota compliance gets worse. Rather, they will more likely stay with the constant market-sharing model and maintain their market share in the organization. The regime probabilities evolvement pattern shows that Saudi Arabia was in a constant market-sharing regime during the price plunge of 1986 rather than the altruism regime. Because most other producers were following a competition strategy during the price plunge period, a constant market-sharing regime in Saudi Arabia during the same time may be deemed as a “tit-for-tat” strategy and could be the primary reason for the price war.

All parameters in the transition probability function for the altruism regime are not significant. This is plausible because Saudi Arabia was in that regime for only a short period of time. As expected, the signs for the parameters are opposite in the transition probability function of the two regimes.

The two explanatory variables, crude oil reserve and investment needs, added into the simple market-sharing model both have significant coefficients in the time-varying transition model. Surprisingly, the coefficient for crude oil reserve has a negative sign in all three estimations, against my expectation that increases in reserves would lower the user cost and thus increase the quantity of production. The significant positive coefficient for investment needs implies that obtaining sufficient revenue from oil production is an important factor in determining Saudi Arabia’s oil output.

Table 3.C7 Saudi Arabia ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.883*	0.042	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Constant Market-Sharing Regime	-	-		-	-10.147*	4.402
γ_1 (Price Change Coeff.)		-	-	-	-	0.198*	0.091
γ_2 (GDP of OCED Coeff.)		-	-	-	-	4.253*	1.681
γ_3 (Quota Violation Coeff.)		-	-	-	-	0.206*	0.073
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-2.446**	1.334
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.492	0.335	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Altruism Regime	-	-	-	-	3.207	4.623
δ_1 (Price Change Coeff.)		-	-	-	-	-0.017	0.043
δ_2 (GDP of OCED Coeff.)		-	-			-2.000	1.812
δ_3 (Quota Violation Coeff.)		-	-			-0.021	0.056
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	1.826	1.465
α_1^0 (Intercept)	Parameters in Supply function in the Constant Market-Sharing Regime	-0.954	1.287	-2.801	1.529	-1.155	1.175
α_2^0 (Price Coeff.)		-0.027	0.034	-0.028	0.042	-0.033	0.030
α_3^0 (Market Share Coeff.)		1.153*	0.103	1.280***	0.115	1.111*	0.096
α_1^1 (Intercept)	Parameters in Supply function in the Altruism Regime	-6.776*	1.635	-	-	-7.561*	1.365
α_2^1 (Price Coeff.)		0.014	0.047	-	-	0.033	0.035
α_3^1 (Market Share Coeff.)		1.716***	0.114	-	-	1.715*	0.112
β_1 (Reserve Coeff.)	Non-switching coefficients	-0.507*	0.093	-0.388*	0.120	-0.506*	0.084
β_2 (Investment Needs Coeff.)		0.124	0.093	0.124**	0.074	0.189*	0.051
β_3 (War Indicator - Iraq)		0.457*	0.050	0.389*	0.054	0.441*	0.044
β_4 (War Indicator - Kuwait)		0.157*	0.042	0.170*	0.052	0.166*	0.038
Log Likelihood		402.72		351.092		414.185	
Likelihood Ratio Statistic				103.256		22.93	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

Table 3.C8 Oil Market Evolvements When Saudi Arabia was in Production Regime 1

Date	Probability in Regime 0	Saudi Arabia Oil Production (Barrels)	Total OPEC Oil Production (Barrels)	Saudi Arabia's Production Share in OPEC (Percentage)	Oil Market Price ($/Barrel)
Jun-82		6,621	18,982	34.9%	33.60
Jul-82	0.000	6,316	18,635	33.9%	33.66
Aug-82	0.587	6,010	18,457	32.6%	33.00
Sep-82	0.307	5,603	18,356	30.5%	33.38
Oct-82	0.108	5,603	19,556	28.7%	34.18
Nov-82	0.109	5,603	19,857	28.2%	33.86
Dec-82	0.167	5,195	18,803	27.6%	33.98
Jan-83	1.000	4,950	16,914	29.3%	31.30
Feb-83	0.000	3,510	14,161	24.8%	29.13
Mar-83	0.000	3,910	15,117	25.9%	30.03
Apr-83	0.000	3,930	15,448	25.4%	27.62
May-83	0.538	4,725	17,183	27.5%	28.44
Jun-83	0.299	4,620	17,264	26.8%	27.89
Dec-83	1.000	5,825	18,557	31.4%	26.73
Jan-84	0.146	5,130	17,863	28.7%	27.71
Feb-84	0.143	5,040	17,994	28.0%	26.65
Mar-84	0.163	4,843	18,265	26.5%	27.70
Aug-84	0.998	4,520	16,553	27.3%	27.45
Sep-84	0.010	4,133	16,694	24.8%	27.99
Oct-84	0.014	4,129	16,756	24.6%	27.14
Nov-84	0.022	3,990	16,628	24.0%	27.05
Dec-84	0.005	3,590	16,519	21.7%	26.60
Jan-85	0.208	3,510	15,698	22.4%	26.15
Feb-85	0.476	4,025	16,866	23.9%	26.48
Mar-85	0.459	3,835	16,798	22.8%	26.47
Apr-85	0.222	3,470	16,364	21.2%	26.81
May-85	0.000	2,590	14,905	17.4%	26.29
Jun-85	0.000	2,420	14,209	17.0%	25.72
Jul-85	0.068	2,740	14,795	18.5%	25.71
Aug-85	0.000	2,340	14,798	15.8%	25.36
Dec-86	0.999	5,164	18,005	28.7%	15.15
Jan-87	0.000	4,004	17,316	23.1%	14.51
Feb-87	0.000	3,868	16,822	23.0%	15.84
Mar-87	0.000	3,300	16,287	20.3%	16.34
Dec-88	0.999	6,655	23,375	28.5%	13.85
Jan-89	0.000	4,918	20,583	23.9%	14.77
Feb-89	0.000	4,673	20,424	22.9%	15.98
Mar-89	0.000	4,515	20,747	21.8%	17.37

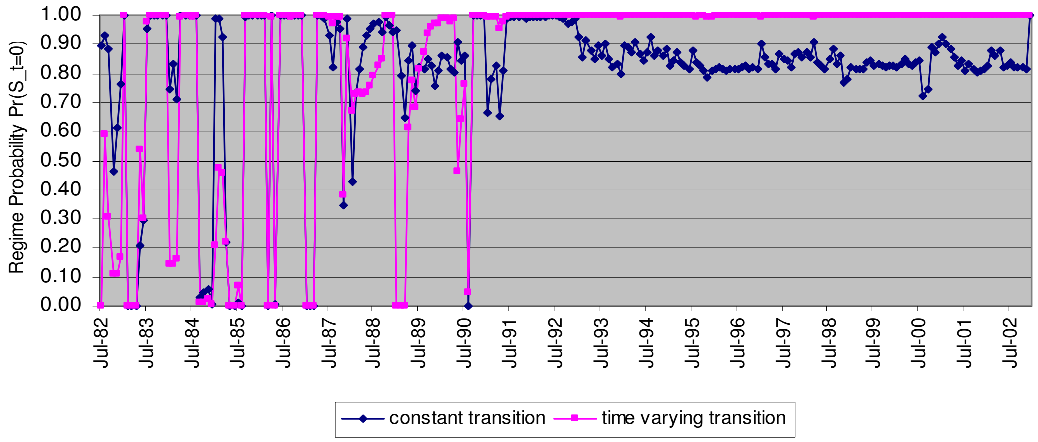

Figure 3.C13 Saudi Arabia's Predicted Probabilities of Being in a Constant Market-Sharing Regime

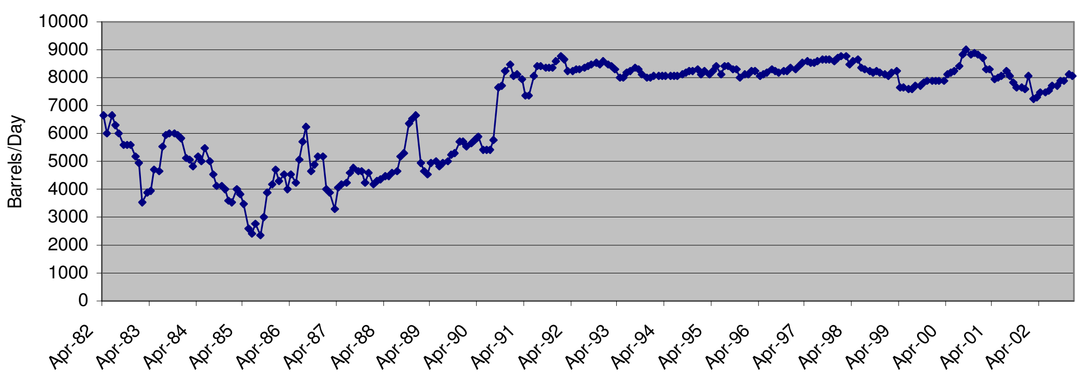

Figure 3.C14 Saudi's Crude Oil Production, April 1982 – December 2002

U.A.E.

The estimation results for U.A.E. are presented in Table 3.C9.

Highlights:

- Regime switching exists in U.A.E.'s oil supply function and two regimes have significantly different characteristics.
- According to the estimates, one of U.A.E.'s production regimes can be characterized as a constant market-sharing regime and the other is a more competitive-like regime with a positive sign for price and a significantly lower coefficient for market share.
- The predicted regime probabilities indicate that U.A.E. undertook a competitive-like strategy mostly in the 1980s and non-competitive behavior prevailed from the early 1990s.
- A likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with the proposed affecting factors, and demand shifter and currency exchange rate seem to have significant effects on determining the transition probabilities.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for U.A.E. The test statistic is 81.79, enormously greater than the critical value for Chi-squared distribution at the 95% confidence level

(11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to U.A.E.'s oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities do not vary across time with those proposed affecting factors, i.e., the null hypothesis

H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ is rejected. The test statistic is 19.18, higher than 15.51--the critical value of the 95% confidence level.

According to the estimates on time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. In regime 0, neither hypothesis $\alpha_2^0 = 0$ (coefficient for price equal to zero) nor hypothesis $\alpha_3^0 = 1$ (coefficient for market share equal to 1) can be rejected at a high confidence level ($\hat{\alpha}_2^0 = -0.022$, *Sd* = 0.030 and $\hat{\alpha}_3^0 = 0.967$, *Sd* = 0.081), indicating that the constant market-sharing behavior cannot be rejected for U.A.E. in the regime.

In regime 1, the supply function has a positive coefficient for price and a significantly smaller coefficient for market share ($\hat{\alpha}_2^1 = 0.043$, *Sd* = 0.033 and $\hat{\alpha}_3^0 = 0.299$, *Sd* = 0.113), indicating less coordination with other producers in the regime. Although U.A.E. does not show a significantly positive price coefficient in regime 1, considering the significantly smaller market share coefficient, it may be plausible to characterize regime 1 as a competitive regime.

The coefficients for demand shifter (GDP of OECD countries) and currency exchange rate are significant at a high confidence level in the transition probability function. The coefficient for demand shifter in the transition probability function is significantly positive at the 90% confidence level in constant market share regime ($\hat{\gamma}_2$=5.363, *Sd* = 3.014) and is significantly negative at the 95% confidence level in a competitive regime ($\hat{\delta}_2$= -14.319, *Sd* = 6.555), indicating that a favorable market demand situation may increase U.A.E.'s probability of coordinating with other producers. This result is consistent with predictions in Green and Porter's theory. The coefficients for price change are insignificant in both regimes and therefore do not provide supportive evidence for either of the collusive theories. The coefficient for the currency exchange rate is significantly positive at the 90% confidence level in a competitive regime and is negative in a constant market-sharing regime, indicating that depreciation of the national currency may increase U.A.E.'s probability of being in a less collusive regime.

The regime probabilities evolvement pattern shows that U.A.E. was in a competitive regime mostly in the 1980s and stabilized its production strategy as a constant market share producer after the 1990s. U.A.E. followed a constant market share strategy during the price plunge of 1986. As for Saudi Arabia and Qatar, constant market-sharing behavior during the price plunge period could be deemed a form of the "tit-for-tat" strategy. The predicted probabilities of following a constant market-sharing regime can be seen in Figure 3.C15.

The estimated coefficient for reserve is as expected--significantly positive. The coefficient for investment needs is insignificant.

Table 3.C9 U.A.E. ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.968*	0.014	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Regime 0	-	-		-	-18.509	13.804
γ_1 (Price Change Coeff.)		-	-	-	-	-0.033	0.070
γ_2 (GDP of OCED Coeff.)		-	-	-	-	5.363**	3.014
γ_3 (Quota Violation Coeff.)		-	-	-	-	0.098	0.071
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-1.876	3.239
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.884*	0.050	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Regime 1	-	-	-	-	45.728*	21.277
δ_1 (Price Change Coeff.)		-	-	-	-	0.098	0.103
δ_2 (GDP of OCED Coeff.)		-	-			-14.319*	6.555
δ_3 (Quota Violation Coeff.)		-	-			0.001	0.268
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	7.331**	4.140
α_1^0 (Intercept)	Parameters in Supply function in the Regime 0	-1.905*	0.990	-2.729	1.501	-2.422*	0.999
α_2^0 (Price Coeff.)		-0.038	0.028	-0.083*	0.043	-0.022	0.030
α_3^0 (Market Share Coeff.)		0.916*	0.080	0.888*	0.108	0.967*	0.081
α_1^1 (Intercept)	Parameters in Supply function in the Regime 1	3.953*	1.391	-	-	3.385*	1.395
α_2^1 (Price Coeff.)		0.032	0.033	-	-	0.043	0.033
α_3^1 (Market Share Coeff.)		0.239*	0.114	-	-	0.299*	0.113
β_1 (Reserve Coeff.)	Non-switching coefficients	0.107*	0.030	0.152*	0.047	0.104*	0.029
β_2 (Investment Needs Coeff.)		-0.066	0.066	0.035	0.114	-0.073	0.066
β_3 (War Indicator - Iraq)		0.079*	0.036	0.040	0.064	0.072*	0.035
β_4 (War Indicator - Kuwait)		0.133*	0.030	0.102*	0.050	0.141*	0.029
Log Likelihood		330.834		289.938		340.422	
Likelihood Ratio Statistic				81.792		19.176	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

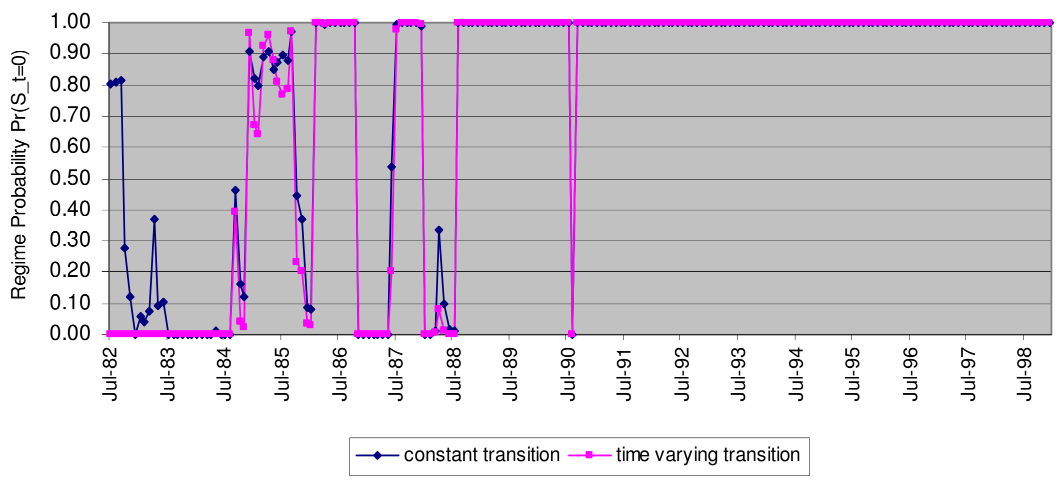

Figure 3.C15 U.A.E.'s Predicted Probabilities of Being in Regime 0

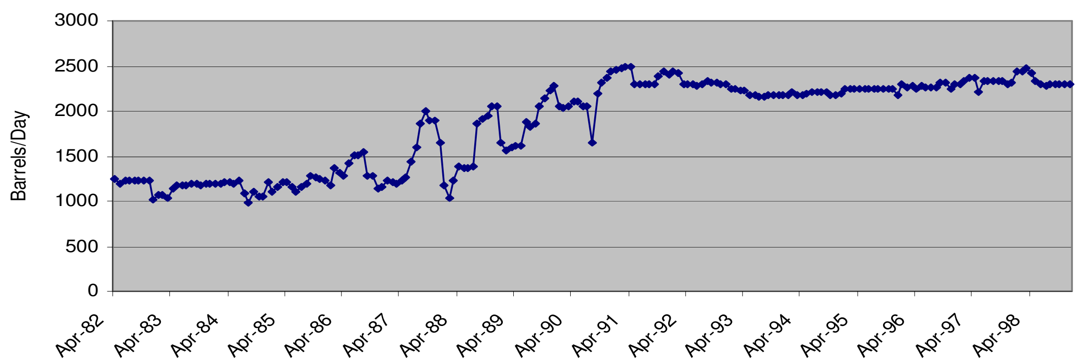

Figure 3.C16 U.A.E.'s Crude Oil Production, April 1982 – December 1998

Venezuela

The estimation results for Venezuela are presented in Table 3.C10.

Highlights:

- Regime switching exists in Venezuela's oil supply function and the two regimes have significantly different characteristics.
- According to estimates, Venezuela has a significantly positive coefficient for price in one regime, indicating competitive behavior, while an insignificantly negative coefficient for price is seen in the other. The coefficient for market share is virtually small, indicating that Venezuela does not coordinate with other OPEC producers closely.
- The predicted regime probabilities indicate that Venezuela undertook a competitive strategy during the slump price period in the mid-1980s and non-competitive behavior prevailed for the rest of the time.
- The likelihood ratio test rejects at the 95% confidence level the hypothesis that transition probabilities do not vary with proposed affecting factors, and price change and quota violation seem to have significant effects on determining transition probabilities.

The likelihood ratio test over the constant Markov regime-switching model and single regime market-sharing model overwhelmingly rejects the hypothesis of a single regime market-sharing model prevailing for Venezuela. The test statistic is 129.20, enormously greater than the critical value of Chi-squared distribution at the 95%

confidence level (11.07), indicating that the feature of Markov regime-switching significantly increases the fitness of the ML estimation to Venezuela's oil supply function.

The likelihood ratio test for the time-varying transition model rejects the hypothesis that the transition probabilities do not vary across time with those proposed affecting factors, i.e., the null hypothesis H0: $\gamma_{i1} = \gamma_{i2} = \gamma_{i3} = \gamma_{i4} = \delta_{i1} = \delta_{i2} = \delta_{i3} = \delta_{i4} = 0$ is rejected. The test statistic is 21.28, higher than 15.51--the critical value of the 95% confidence level.

According to the estimates for the time-varying transition model, there are significant differences between the two sets of coefficient estimates for the two production regimes. The price coefficient is significantly positive at the 95% confidence level in regime 1 while it is negative in regime 0. In addition, the coefficient for market share is not significantly different from 0 in regime 1 of the constant transition model while it is also quite small in regime 0 in comparison with other producers, indicating that Venezuela does not coordinate with other OPEC producers closely.

Price change and quota violation change seem to have significant effects on Venezuela's selection of a production regime. The coefficient for price change in regime 0 is significantly positive at the 95% confidence level ($\hat{\gamma}_1$=0.664, *Sd* = 0.290), indicating that a price increase may increase Venezuela's probability of undertaking a non-competitive strategy. This result complies with the prediction in Green and Porter's theory. The coefficient for a quota violation change is significantly positive at the 95% confidence level ($\hat{\delta}_3$=0.234, *Sd* = 0.112) in a competitive regime, indicating that worse quota compliance from other producers may increase Venezuela's probability of staying with a competitive regime.

The regime probabilities evolvement pattern shows that Venezuela was in a competitive regime during the slump price period and a non-competitive regime the rest of the time. The predicted probabilities of falling into a non-competitive regime can be seen in Figure 3.C17.

The estimated coefficient for investment needs is as expected, significantly positive, indicating desires for revenue from oil are an important determinant in Venezuela's oil output. Like that of Saudi Arabia, the reserve coefficient in Venezuela's supply function is significantly negative, against expectation.

Table 3.C10 Venezuela ML Estimates of the Markov Regime-switching Models

Parameter	Meaning of the Parameter	Constant Transition Model		Single Regime Model		Time-varying Transition Model	
		Estimate	SD	Estimate	SD	Estimate	SD
Pr^{00}	Trans. Prob. $Pr(S_t=0/S_{t-1}=0)$	0.977*	0.011	-	-	-	-
γ_0	Parameters in Trans. Prob. Function in the Non-competitive Regime	-	-		-	-24.186**	14.553
γ_1 (Price Change Coeff.)		-	-	-	-	0.664*	0.290
γ_2 (GDP of OCED Coeff.)		-	-	-	-	4.731	3.226
γ_3 (Quota Violation Coeff.)		-	-	-	-	0.072	0.092
γ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	1.096	1.258
Pr^{11}	Trans. Prob. $Pr(S_t=1/S_{t-1}=1)$	0.809*	0.077	-	-	-	-
δ_0	Parameters in Trans. Prob. Function in the Competitive Regime	-	-	-	-	0.395	3.939
δ_1 (Price Change Coeff.)		-	-	-	-	0.108	0.097
δ_2 (GDP of OCED Coeff.)		-	-			8.666**	4.687
δ_3 (Quota Violation Coeff.)		-	-			0.234*	0.112
δ_4 (Currency Exchange Rate Coeff.)		-	-	-	-	-8.283**	4.476
α_1^0 (Intercept)	Parameters in Supply function in the Non-Competitive Regime	7.433*	0.664	3.679	1.072	6.415*	0.685
α_2^0 (Price Coeff.)		-0.027	0.021	-0.008	0.031	-0.020	0.021
α_3^0 (Market Share Coeff.)		0.187*	0.048	0.441*	0.068	0.285*	0.051
α_1^1 (Intercept)	Parameters in Supply function in the Competitive Regime	6.483*	0.781	-	-	5.822*	1.064
α_2^1 (Price Coeff.)		0.212*	0.025	-	-	0.198*	0.032
α_3^1 (Market Share Coeff.)		0.092	0.063	-	-	0.171*	0.086
β_1 (Reserve Coeff.)	Non-switching coefficients	-0.154*	0.028	-0.079**	0.044	-0.152*	0.029
β_2 (Investment Needs Coeff.)		0.051*	0.015	0.054*	0.024	0.041*	0.016
β_3 (War Indicator - Iraq)		0.105*	0.035	0.248*	0.070	0.119*	0.036
β_4 (War Indicator - Kuwait)		-0.027	0.024	-0.070	0.047	-0.019	0.024
Log Likelihood		543.796		479.197		554.437	
Likelihood Ratio Statistic				129.198		21.282	

* Coefficient significant different from zero at the 95% confidence level
** Coefficient significant different from one at the 90% confidence level
*** Coefficient significant greater than one at the 95% confidence level

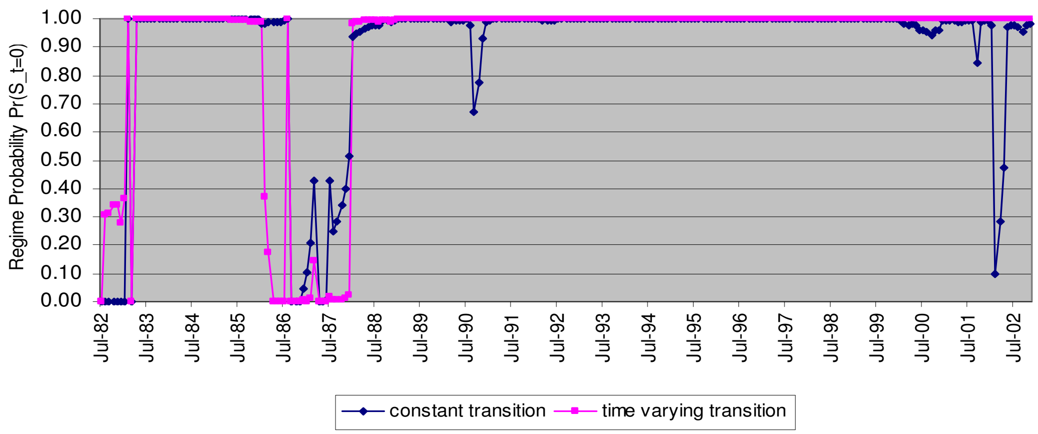

Figure 3.C17 Venezuela's Predicted Probabilities of Being in a Non-competitive Regime

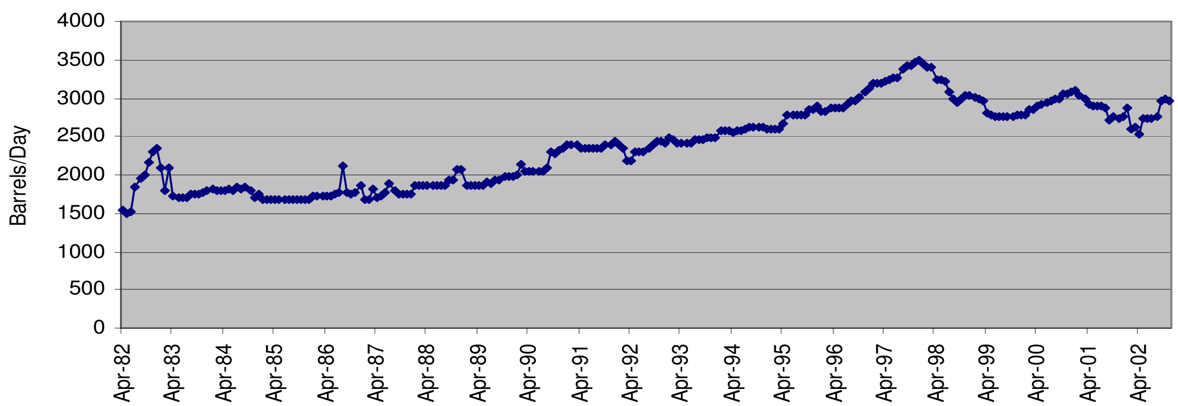

Figure 3.C18. Venezuela's Crude Oil Production, April 1982 – December 2002

3.5 Conclusion

Forty years after its foundation, OPEC's behavior is still in a source of controversy among economists. Many economics textbooks use OPEC as an example of a cartel. However, previous studies show that OPEC does not fit neatly any classic forms of cartel, such as joint profit-maximizing organization, dominant firm, market-sharing cartel, etc.

A literature review of empirical studies of OPEC reveals a major deficiency in previous works--the monolithic conduct assumption that OPEC producers behave consistently no matter what form of cartel is assumed. Some researchers have realized that OPEC's conduct varies over time and thus are motivated to use econometric tools to analyze the performance of OPEC under the concept of varying conduct. However, studies in this direction are still very limited and many important questions still have not been answered, such as, what market development and interactions among the members trigger their conducts switching, what the conduct switches mean to OPEC's stability and whether the conduct switches can be rationalized from the economic payoff perspective.

Using the concept of collusion under imperfect information theory proposed by Green and Porter, this study presents an innovative explanation for OPEC's intriguing conduct during the period after the quota allocation system was first instituted in early 1982. The conceptual analysis posits that each OPEC producer varies its production between collusive and Cournot-competitive strategy from time to time, subject to a set of variables that include internal financial constraints and market information. The conduct switches play a key role in sustaining the collusion of the organization as a cheating behavior would trigger punishment from others and the loss induced from the punishment lasting a certain amount of time would outweigh the gain from cheating during the current period. Since a cheating behavior cannot be directly observed, producers monitor some market indicators, such as market price and reported quota violation, etc., to decide when to switch to a competitive strategy. Because the monitored market indicators are imperfectly correlated with producers' conduct, the stochastic properties of those indicators would trigger a competition war among producers at times in the absence of real cheating. A consequence of employing such an enforcement mechanism is that a competition war among OPEC producers would occur from time to time and different production behaviors of each producer could be observed and empirically distinguished. In addition, producers would forgo some profits in collusive periods in order to reduce the frequency and duration of reversionary periods. Therefore, it is rationalized that most OPEC producers' output is constantly above allocated quota but still at a restricted level.

An econometric model is then developed to verify the applicability of the conceptual model in explaining OPEC's behavior. With some innovative features incorporated, such as individual supply function for each producer and varying parameters between the two production regimes, the econometric model provides answers to four important and relevant questions: (i) do production conducts shift at times for each producer; (ii) can the contradictory conducts consistent with competitive strategy and collusive strategy be distinguished in the two production regimes; (iii) what factors trigger the conduct shifts; and (iv) are the pattern of the conduct shifts consistent with the prediction of the theory?

The estimation results of the econometric model provide evidence supportive of the theory and deeper insights into the dynamics of OPEC's behavior, especially the unique role of Saudi Arabia in the organization.

First, the hypothesis of production conduct switching over time is strongly supported by statistical tests. Behaviors consistent with competitive conduct and collusive conduct are observed in the two production regimes for most producers.

Second, tests on a variety of triggers indicate that competition strategy is likely to be triggered by a dip in price and market demand as supportive of the enforcement mechanism under imperfect information.

Third, while producers appear to switch their production strategy according to their own rhythm, periods of joint competition/punishment conducts do exist according to the regime probabilities predicted from the estimation. The results indicate that the price collapse of 1985-86 was a predictable consequence of OPEC producers' temporary joint switching to a competition/punishment strategy.

Finally, the special role of Saudi Arabia is also verified by the results of the study. A unique altruism behavior is found at times in Saudi Arabia's production. The altruism behavior not only benefits other producers but indeed is rational for Saudi Arabia as it could help to deter triggering a competition war in OPEC under intermediate market deterioration.

The conceptual analysis and empirical test lead me to conclude that OPEC members collude under normal circumstances and behave competitively at times in response to imperfect market signals of cartel compliance and some internal attributes.

Periodic joint competition conduct plays an important role in sustaining collusion in the long run. Saudi Arabia acts as the leader of the cartel, accommodating intermediate unfavorable market development and punishing others with a tit-for-tat strategy under extreme circumstances.

According to predictions of the model of this study, price depressions engendered by OPEC members' periodic joint competitive-like conduct are still expected to occur at times in the future; however, these episodes should not indicate the demise of OPEC and reestablishment of collusion would likely come back.

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Appendix A. TSP Program Code for the Market-Sharing Model

```
Options  memory = 10 crt signif =4;
read (file = 'c:\opec1.xls');
Genr QLa=Qw(-1);
genr SnopLa= snop(-1);
Param q0 q1 q2 q3;
param nop0 nop1 nop2 nop3 nop4;
param al0 al1 al2 al3 al4 al5;
param lib0 lib1 lib2 lib3 lib4 lib5;
param qa0 qa1 qa2 qa3 qa4 qa5;
param sd0 sd1 sd2 sd3 sd4 sd5;
param uae0 uae1 uae2 uae3 uae4 uae5;
param ind0 ind1 ind2 ind3 ind4 ind5;
param ir0 ir1 ir2 ir3 ir4 ir5;
param nig0 nig1 nig2 nig3 nig4 nig5;
param ven0 ven1 ven2 ven3 ven4 ven5;
param iraq0 iraq1 iraq2 iraq3 iraq4 iraq5;
param kuw0 kuw1 kuw2 kuw3 kuw4 kuw5;
frml eq1 Qw = q0 + q1*P + q2*Gdp + q3*Qw(-1);
frml eq2 Snop = nop0 + nop1*P +  nop2 * Snop(-1);
frml eq3 Salg = al0 + al1*P + al2*Snalg  ;
frml eq4 Slib = lib0 + lib1*P +lib2*Snlib  ;
frml eq5 Sqa = qa0 + qa1*P + Qa2*Snqa ;
frml eq6 Ssd = sd0 +sd1*P + sd2*Snsd  ;
frml eq7 Suae = uae0 + uae1*P + uae2*Snuae ;
frml eq8 Sindo = ind0 +ind1*P + ind2*Snindo  ;
frml eq9 Sir = ir0 + ir1*P + ir2*Snir ;
frml eq10 Snig = nig0 + nig1*P + nig2*Snnig  ;
frml eq11 Sven = ven0 + ven1*P + ven2*Snven ;
frml eq12 Siraq = iraq0 + iraq1*P  + iraq2 * Sniraq + iraq3 * diraq;
frml eq13 Skuw = kuw0 + kuw1*P  + kuw2 * Snkuw + kuw3 * dkuw;
LSQ (Inst= (GDP,Qw(-1),Snop(-1), Salg(-1),Slib(-1), Sqa(-1),
  Ssd(-1),Suae(-1),
  Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
  dkuw,diraq)) eq1;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1), Salg(-1),Slib(-1),
  Sqa(-1), Suae(-1),
  Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
  dkuw,diraq)) eq2;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1),Slib(-1), Sqa(-1), Suae(-1),
  Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
  dkuw,diraq)) eq3;
frml talg al2-1;
analyz talg;

LSQ (Inst= (GDP,Qw(-1),Snop(-1), Ssd(-1),Salg(-1),Sqa(-1), Suae(-1),
  Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
  dkuw,diraq)) eq4;
frml tlib lib2-1;
analyz tlib;
```

```
LSQ (Inst= (GDP,Qw(-1),Snop(-1), Ssd(-1),Salg(-1),Slib(-1),
Suae(-1),
Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
dkuw,diraq)) eq5;
frml tqa qa2-1;
analyz tqa;
LSQ (Inst= (GDP,Qw(-1),Snop(-1), Salg(-1),Slib(-1), Sqa(-1),
Suae(-1),
Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
dkuw,diraq)) eq6;
frml tSd sd2-1;
analyz tsd;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1), Salg(-1),Slib(-1), Sqa(-1),
Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1),
dkuw,diraq)) eq7;
frml tuae uae2-1;
analyz tuae;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1), Salg(-1),Slib(-1),
Sqa(-1), Suae(-1),
Sir(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1), dkuw,diraq)) eq8;
frml tindo ind2-1;
analyz tindo;
LSQ (Inst= (GDP,Qw(-1),Snop(-1), Ssd(-1),Salg(-1),Slib(-1),
Sqa(-1), Suae(-1),
Sindo(-1),Snig(-1),Sven(-1), Siraq(-1), Skuw(-1), dkuw,diraq)) eq9;
frml tir ir2-1;
analyz tir;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1), Salg(-1),Slib(-1),
Sqa(-1), Suae(-1),
Sindo(-1),Sir(-1),Sven(-1), Siraq(-1), Skuw(-1), dkuw,diraq)) eq10;
frml tnig nig2-1;
analyz tnig;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1), Salg(-1),Slib(-1),
Sqa(-1), Suae(-1),
Sindo(-1),Sir(-1),Snig(-1), Siraq(-1), Skuw(-1), dkuw,diraq)) eq11;
frml tven ven2-1;
analyz tven;
LSQ (Inst= (GDP,Qw(-1),Snop(-1),Ssd(-1), Salg(-1),Slib(-1),
Sqa(-1), Suae(-1),
Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Skuw(-1), dkuw,diraq)) eq12;
frml tiraq iraq2-1;
analyz tiraq;
LSQ (Inst= (GDP,Qw(-1),Snop(-1), Ssd(-1),Salg(-1),Slib(-1),
Sqa(-1), Suae(-1),
Sindo(-1),Sir(-1),Snig(-1),Sven(-1), Siraq(-1),  dkuw,diraq)) eq13;
frml tkuw kuw2-1;
analyz tkuw;
```

APPENDIX B: GAUSS Computer Code for Markov Regime-Switching Model (Algeria as an Example)[a]

```
new;
library optmum,PGRAPH;

format /m1 /rd 9,5;
load data[247,17]=d:algeriaextend.prn;

 QI_d=ln(data[1:247,1]); @log producer i's production@
t0=rows(QI_d);
RP=ln(data[1:247,17]);@price adjusted by US inflation index@
NQI=ln(data[1:247,5]);@log production from all producers except i@
R=ln(data[1:247,6]); @log reserve@;
IN=ln(data[1:247,8]); @log investment needs@;
intercept=ones(t0,1);
x_d=(intercept~RP~NQI); @vector of variables@

DI_d=data[1:247,3];@Dummy variable of Iraq@
DM_d=data[1:247,4];@Dummy variable of Kuwait@
Dumm_d=(R~IN~DI_d~DM_d);

deltaP=data[1:247,9]; @price change@
er=data[1:247,12]; @ exchange rate@
Ogdp= data[1:247,13]; @ OECD gdp@
deltaQ= data[1:247,14]; @quota violation@

LAG_AR=1;
NO_ST=lag_ar+1; @ NUMBER OF STATES TO BE CONSIDERED@
DMNSION=2^NO_ST;

st_mat=zeros(DMNSION,NO_ST);
     j=1;
          st1=0; do until st1>1;
     st=0; do until st>1;
    st_mat[j,.]=st1~st; @2^2 probable arrangments on state, 0 or 1 @

   j=j+1;
   st=st+1;endo;
   st1=st1+1;endo;

QI=QI_d[lag_ar+1:t0,1];
QI_lag=QI_d[Lag_ar:T0-1,1];
X=X_d[lag_ar+1:t0,1:3];
X_lag=x_d[Lag_ar:T0-1,1:3];
Dumm=Dumm_d[lag_ar+1:t0,1:4];
Dumm_lag=Dumm_d[lag_ar:t0-1,1:4];
```

---

[a] The author acknowledges that the composition of this GAUSS program is based on the computer routines described in Kim and Nelson (1998) with necessary modifications made for this application.

```
Dumm_trans=Dumm_d[.,1];
transp=(intercept~deltaP~Ogdp~deltaQ~er);
T=rows(QI);


@================ Initialize Global Variables======1982.4-2002.12======@

        START=1;

PRMTR_IN={ -49.61876   0.47961  -4.47831  -0.18545  13.84045
-33.57602   0.08596   3.25244  -0.11534   3.85568
 0.89224   0.02022
-0.21057   0.05190   0.52884
  2.71361   0.05581   0.23693
 0.28534  -0.11041   0.04637   0.00833
};

PRMTR_IN=PRMTR_IN';
@ Maximum Likelihood Estimation @
@==================================================@

{xout,fout,gout,cout}=optmum(&lik_fcn,PRMTR_in);

PRM_FNL=TRANS(xout);            @ Estimated  coefficients, constrained@
output file=d:Algeriaparatv.out reset;   prm_fnl;  OUTPUT OFF;

"==FINAL OUTPUT========================================================";

"initial values of prmtr is";
             trans(prmtr_in)';
"============================================================";
"code is--------";;cout;
"likelihood value is ";; -1*fout;
"Estimated parameters are:";
prm_fnl'; " ";
xout';
output off;

"Calculating Hessian";
             hout0=hessp(&lik_fcn,xout);
             hout=inv(hout0);

grdn_fnl=gradfd(&TRANS,xout);
Hsn_fnl=grdn_fnl*hout*grdn_fnl';
SD_fnl =sqrt(diag(Hsn_fnl)); @Standard errors of the estimated coefficients@

output file=d:algeriasdtv.out reset;   sd_fnl;  OUTPUT OFF;
"Standard errors of parameters are:"; sd_fnl';
"=============================================================";
output off;

{pr_tt0,pr_tl0}=FILTER(XOUT);  @Pr[S_t=0|Y_t] and Pr[S_t=0|Y_{t-1}]@
```

```
FLTR=pr_tt0;

format /m1 /rd 8,4;

output file=d:algerialag1.out reset; FLTR; output off;
end;

@ END OF MAIN PROGRAM @


@==========================================================================@
@==========================================================================@
PROC LIK_FCN(PRMTR1);
local prmtr, ppr,qpr,gemma,thi,Rho,var0,var1,Alpha1,
Alpha0,Alpha_mat,du,PR_STT0,PR_STL0,PR_TR,var,
     prob__0,prob__1,QQ, lik, j_iter,  pr_tr,pr_trf1,pr_trf, pr__0_l,pr__1_l,prob__t,prob__,pro_,
     F_cast, f_cast1,pr_trf0,var_L,pr_vl, pr_val,likv,phi,PSIC,PSIX,prob_dd,VAR,TMP,OUT_MAT,A,EN;
     ;

PRMTR=TRANS(PRMTR1);
LOCATE 15,1; PRMTR';

/* DEFINE PARAMETERS  */

         Gemma = PRMTR[1:5,1];    @ Pr[St=0/St-1=0] @
          Thi=PRMTR[6:10,1];    @ Pr[St=1/St-1=1] @

          Rho=PRMTR[11,1];
          VAR=PRMTR[12,1]^2;
          Alpha0=PRMTR[13:15,1];  @ cooperative parameter @
          Alpha0=Alpha0';
          Alpha1=PRMTR[16:18,1];  @ competitive parameter @
          Alpha1=Alpha1';
          DU=PRMTR[19:22,1];
          DU=DU';

          Alpha_MAT=ST_MAT.*.Alpha1 + (ONES(DMNSION,NO_ST)-ST_MAT).*.Alpha0;

/* INITIALIZING THE FILTER                          */
@-----------------------------------------------------@
@(1)--------------------------------------@
     QPR=EXP(transp[1,1:5]*gemma)/
           (1+EXP(transp[1,1:5]*gemma));

          PPR=EXP(transp[1,1:5]*thi)/
             (1+EXP(transp[1,1:5]*thi));

            PR_TR=(QPR~    (1-PPR))|
               ((1-QPR)~  PPR);

          A = (eye(2)-pr_tr)|ones(1,2);
          EN=(0|0|1);
          PROB__T = INV(A'A)*A'EN;  @PR[S_t=0]|PR[S_t=1],
```

```
                    2x1 steady-state PROBABILITIES@
 PROB__ =VECR(PROB__T~PROB__T);

@====================================================================@
/* START ITERATION............................................... */

  LIKV=0.0;
  J_ITER=2;
  do until J_ITER>T;

        QPR=EXP(transp[J_iter,1:5]*gemma)/
          (1+EXP(transp[J_iter,1:5]*gemma));

        PPR=EXP(transp[J_iter,1:5]*thi)/
          (1+EXP(transp[J_iter,1:5]*thi));

        PR_TR=(QPR~    (1-PPR))|
            ((1-QPR)~  PPR);

        PR_TRF0=VEC(PR_TR);

 F_CAST1=(QI[J_ITER,1]-du*(Dumm[J_iter,1:4])'-QI_lag[J_ITER,1]*rho +
du*(Dumm_lag[J_iter,1:4])'*rho)
*ONES(DMNSION,1)-(Alpha_MAT[.,4:6]*(x[J_iter,1:3])'  - Alpha_MAT[.,1:3]*(X_lag[J_iter,1:3])'*rho);

   VAR_L=VAR*ONES(DMNSION,1);

   PROB_DD=PR_TRF0 .* PROB__;
              /* Pr[S_t,S_{t-1} | I(t-1)]*/

   PR_VL=(1./SQRT(2.*PI.*VAR_L)).*EXP(-0.5*F_CAST1.*F_CAST1./VAR_L).*PROB_DD;
                                                   /* 2^2x1 */
                      /* Joint density of qi_t,S_t,,S_{t-1} given past information : */

   PR_VAL=SUMC(PR_VL);         /* f(qi_t|I(t-1)), density of qi_t given past information:  This is weighted
average of  2^2 conditional densities   */

   LIK=-1*LN(PR_VAL);

   PRO_=PR_VL/PR_VAL; /* Pr[S_t,S_{t-1} | I(t-1),qi_t]*/
                /* Updating of prob. with new information, y_t   */


   PROB__T=PRO_[1:DMNSION/2,1]+PRO_[DMNSION/2+1:DMNSION,1];
                /* Integrate out S_{t-1}: then you get Pr[S_t, S_{t-1}| qi_t]  */
                /*   2x1*/

   PROB__=VECR(PROB__T~PROB__T);
                /*  2^2x1  */

LIKV = LIKV+LIK;
J_ITER = J_ITER+1;
ENDO;
```

```
            LOCATE 2,35;"LIKV=";;LIKV;
RETP(LIKV);
ENDP;
@++++++++++++++++++++++++++++++++++++++++++++++++++++++++@

@++++++++++++++++++++++++++++++++++++++++++++++++++++++++@


PROC (2) = FILTER(PRMTR1);
local prmtr, ppr,qpr,gemma,thi,Rho,var0,var1,Alpha1,
Alpha0,Alpha_mat,du,PR_STT0,PR_STL0,PR_TR,var,
     prob__0,prob__1,QQ, lik, j_iter,  pr_tr,pr_trf1,pr_trf, pr__0_l,pr__1_l,prob__t,prob__,pro_,
     F_cast, f_cast1,pr_trf0,var_L,pr_vl, pr_val,likv,phi,PSIC,PSIX,prob_dd,VAR,TMP,OUT_MAT,A,EN;
     ;

PRMTR=TRANS(PRMTR1);
LOCATE 15,1; PRMTR';

         Gemma = PRMTR[1:5,1];    @ Pr[St=0/St-1=0] @
         Thi=PRMTR[6:10,1];    @ Pr[St=1/St-1=1] @

         Rho=PRMTR[11,1];
         VAR=PRMTR[12,1]^2;
         Alpha0=PRMTR[13:15,1];  @ cooperative parameter @
         Alpha0=Alpha0';
         Alpha1=PRMTR[16:18,1];  @ competitive parameter @
         Alpha1=Alpha1';
         DU=PRMTR[19:22,1];
         DU=DU';

         Alpha_MAT=ST_MAT.*.Alpha1 + (ONES(DMNSION,NO_ST)-ST_MAT).*.Alpha0;

/* INITIALIZING THE FILTER                          */
@-------------------------------------------------------@
@(1)----------------------------------------@
     QPR=EXP(transp[1,1:5]*gemma)/
            (1+EXP(transp[1,1:5]*gemma));

         PPR=EXP(transp[1,1:5]*thi)/
            (1+exp(transp[1,1:5]*thi));

           PR_TR=(QPR~    (1-PPR))|
              ((1-QPR)~  PPR);

         A = (eye(2)-pr_tr)|ones(1,2);
         EN=(0|0|1);
         PROB__T = INV(A'A)*A'EN;  @PR[S_t=0]|PR[S_t=1],
                             2x1 steady-state PROBABILITIES@
 PROB__ =VECR(PROB__T~PROB__T);

@=====================================================================@
/* START ITERATION................................................ */
```

```
 PR_STT0=ZEROS(T,1);  @WILL SAVE Pr[S_t=0|Y_{t}@
 PR_STL0=ZEROS(T,1);  @WILL SAVE Pr[S_t=0|Y_{t-1}@

 LIKV=0.0;
 J_ITER=2;
 DO UNTIL J_ITER>T;

        QPR=EXP(transp[J_iter,1:5]*gemma)/
           (1+EXP(transp[J_iter,1:5]*gemma));

        PPR=EXP(transp[J_iter,1:5]*thi)/
           (1+exp(transp[J_iter,1:5]*thi));

        PR_TR=(QPR~    (1-PPR))|
             ((1-QPR)~  PPR);

        PR_TRF0=VEC(PR_TR);


   F_CAST1=(QI[J_ITER,1]-du*(Dumm[J_iter,1:4])'-QI_lag[J_ITER,1]*rho +
du*(Dumm_lag[J_iter,1:4])'*rho)
*ONES(DMNSION,1)-(Alpha_MAT[.,4:6]*(x[J_iter,1:3])'  - Alpha_MAT[.,1:3]*(X_lag[J_iter,1:3])'*rho);

   VAR_L=VAR*ONES(DMNSION,1);

   PROB_DD=PR_TRF0 .* PROB__;

@----------------------------------------------------@
      TMP=PROB_DD;

      TMP=TMP[1:2]+TMP[3:4];

  PR_STL0[J_ITER,1]=TMP[1,1];        @Pr[S_t=0|Y_t-1]@
@-----------------------------------------------------@

   PR_VL=(1./SQRT(2.*PI.*VAR_L)).*EXP(-0.5*F_CAST1.*F_CAST1./VAR_L).*PROB_DD;

                @PR[S_t,S_{T-1},qi_t|I_{t-1}]@

   PR_VAL=SUMC(PR_VL);   @f(qi_t| I_{t-1})@
   LIK=-1*LN(PR_VAL);

   PRO_=PR_VL/PR_VAL;    @Pr[S_t, S_{t-1} | I_t]@

@------------------------------------------------------@
      TMP=PRO_;

      TMP=TMP[1:2]+TMP[3:4];

  PR_STT0[J_ITER,1]=TMP[1,1];         @Pr[S_t=0|I_t]@
@------------------------------------------------------@
```

```
  PROB__T=PRO_[1:DMNSION/2,1]+PRO_[DMNSION/2+1:DMNSION,1];
                    @Pr[S_t, S_{t-1}| I_t]@

  PROB__=VECR(PROB__T~PROB__T);

J_ITER = J_ITER+1;
ENDO;

RETP(PR_STT0,PR_STL0);
ENDP;
@==========================================================================@

PROC TRANS(c0); @ constraining values of reg. coeff.@
        local c1,m,u,d1,d2,d3,d4,d5,d6;

        c1=c0;

retp(c1);
endp;
```

VITA

Bo Yang was born in Tian Jin and grew up in the oil city, Ren Qiu, China, the son of Qi Wan Yang and Cheng Lan Zhou, and the brother of Fan Yang.

He obtained his bachelor degree in Petroleum Chemical Engineering with a double major in International Business Management at East China University of Science and Technology in 1995. After that, he worked for five years at China Petro-Chemical Consulting Co., SINOPEC, a Chinese national oil company, where he was engaged in oil market research and corporate strategy planning.

In 2000, he came to the Energy, Environmental and Mineral Economics Department at Pennsylvania State University for the doctoral studies. In 2003, he obtained a dual title Master degree in Energy, Energy, Environmental and Mineral Economics and Operations Research.

He is married to Cai Mei Feng, and is the father of Summer Yuxi Yang.