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A Model for the Global Crude Oil Market Using a Multi-Pool MCP Approach*

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Abstract

This paper proposes a partial equilibrium model to describe the global crude oil market. Pricing on the global crude oil market is strongly influenced by price indices such as WTI (USA) and Brent (Northwest Europe). Adapting an approach for pool-based electricity markets, the model captures the particularities of these benchmark price indices and their influence on the market of physical oil. This approach is compared to a model with bilateral trade relations as is traditionally used in models of energy markets.

With these two model approaches, we compute the equilibrium solutions for several market power scenarios to investigate whether the multi-pool approach may be better suited than the bilateral trade model to describe the crude oil market. The pool-based approach yields, in general, results closer to observed quantities and prices, with the best fit obtained by the scenario of an OPEC oligopoly. We conclude that the price indices indeed are important on the global crude market in determining the prices and flows, and that OPEC effectively exerts market power, but in a non-cooperative way.

Keywords: crude oil, market structure, cartel, pool market, simulation model

JEL Codes: L13, L71, Q41

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1 Introduction

No commodity or resource has as big an impact on the global economy as oil. At the same time, no market is as opaque and unpredictable as the crude oil market, as the price spike and its subsequent decrease in 2008 demonstrated. While other fossil fuels like natural gas or coal have traditionally been traded bilaterally and mostly by long-term contracts, crude oil is to a large extent traded in highly liquid spot markets. In addition, the role of OPEC is still unclear to economists: OPEC is frequently cited as an example for a cartel and a number of possible ways of its functioning have been proposed to describe its behaviour, as summarized by Dahl (2004). In general, a cartel is characterized by joint optimization of its participants, i.e. collusion among OPEC producers, and a Stackelberg leader-follower market. However, this does not adequately describe reality, as the literature and our results indicate.

Models of natural resource markets often use a bilateral trade approach: market clearing prices are determined in each node and producers decide to which node to sell, taking into account the price at that node. When producers exert market power, price differentials between nodes may exceed transport costs between these nodes; this is referred to as price discrimination. Models that describe the European natural gas market in such a way were proposed by Egging et al. (2008), Holz et al. (2008) and Boots et al. (2004). These models are formulated as mixed complementarity problems (MCP). The MCP approach allows to include strategic non-cooperative behaviour by several players, such as competition à la Cournot. Aune et al. (2004) develop an equilibrium model in the MCP format for the entire energy sector in Western Europe, including crude oil, natural gas, coal and electricity. Since they focus on consumer markets, world crude oil trade is assumed to be competitive, while domestic extraction levels of fossil fuels are set exogenously.

A comprehensive review of the literature on oil market modeling and OPEC behaviour is provided in Al-Qahtani et al. (2008a). They compare a number of analyses of the global oil market, distinguishing between econometric simulations and optimization modeling approaches. Several types of market structure can be assumed, such as a dominant firm-competitive fringe market, a cartel, and the perfectly competitive market. Observing the actual behaviour of oil producing countries, one notices that some of them might not be able to reasonably absorb more than a certain amount of revenue. This led to the proposition of "target revenue models". The players in the oil market can be of a very different nature: one can distinguish international oil companies and national oil companies (NOCs), with the latter being the prevailing company type in most OPEC countries. NOCs can be expected to perform a number of activities that are not directly related to oil production, such as providing fuel subsidies or social welfare programs (Hartley and Medlock, 2008). In general, the literature is inconclusive on which economic theory best describes reality; the prevailing conclusion is that OPEC does push prices above marginal cost but is not a classical cartel.

Al-Qahtani et al. (2008b) propose a sophisticated simulation model that distinguishes between different types of crude oil, depicting the complete flow of oil from well to city gate, allowing for several refinery setups and using a large data set. There is, in our opinion, only one shortcoming: since it is formulated as a non-linear program with profit maximization either for Saudi-Arabia or OPEC, it does not allow to model strategic, non-cooperative interaction between several producers exerting Nash-Cournot market power.[1]

Another particularity of the global crude oil market largely ignored in previous optimization and equilibrium models is the existence of several highly liquid spot markets. The price indices of these markets exert an influence on crude oil prices in other countries. The observation of these "benchmark" prices and their integrated movements led to the proposition of the "one great pool" theory, in which the "law of one price" holds. Bentzen (2007) shows that there is a bi-directional causality between the OPEC price basket and different price indices in the USA (West Texas Intermediate, WTI) and in Northwest Europe (Brent).

This paper extends the bilateral trade equilibrium model following the approach proposed by Hobbs (2001) to describe a pool electricity market. Considering the global nature of oil trade compared to regional electricity markets, we introduce more than one pool for a global data set.[2] This representation aims at capturing the influence of benchmark indices and liquid spot markets on the crude oil market. The structure of this paper is as follows: in the next section, we propose an equilibrium model formulated as a mixed complementarity problem to investigate non-cooperative behaviour and the influence of price indices. In section 3, we present a numerical application comparing the market power theories usually proposed for the crude oil market, namely the perfectly competitive market, a Nash-Cournot market, an OPEC oligopoly with a competitive fringe (without joint profit maximization by the OPEC members) and an OPEC cartel (with joint profit maximization). Section 4 concludes.

[1] They formulate one scenario as a mixed complementarity problem, but there they assume that all producers behave perfectly competitively.

[2] The introduction of several pools does not conflict with the theory of "one great pool"; it is necessary to overcome the problem of where to locate the pool.

2 The Model

2.1 Mixed Complimentarity Problems

The mixed complimentarity (MCP) formulation is commonly used for equilibrium modeling. This approach defines the optimization problem and derives its first-order conditions (optimality conditions). The first order Karush-Kuhn-Tucker (KKT) conditions of the optimization problem $\max F(x,y)$ under constraints $G(x,y) = 0,\ H(x,y) \leq 0,\ x \geq 0$ are:

$$\begin{aligned}
\frac{\partial F}{\partial x} - \lambda \frac{\partial G}{\partial x} - \mu \frac{\partial H}{\partial x} \leq 0 \quad &\perp \quad x \geq 0 \\
\frac{\partial F}{\partial y} - \lambda \frac{\partial G}{\partial y} - \mu \frac{\partial H}{\partial x} \leq 0 \quad &\perp \quad y \quad (free) \\
G(x,y) = 0 \quad &\perp \quad \lambda \quad (free) \\
H(x,y) \leq 0 \quad &\perp \quad \mu \geq 0
\end{aligned}$$

where λ and μ are the dual variables (or Lagrange multipliers) of the constraints $G(x,y)$ and $H(x,y)$. The perpendicular operator ($\perp$) indicates that an equation $f(x,y) \leq 0$ is complimentary to the variable x, meaning that $f(\bar{x},\bar{y}) \cdot \bar{x} = 0$ must hold in the optimum $(\bar{x},\bar{y})$. A MCP consists in finding a vector (x,y,λ,μ) satisfying the KKT conditions. Most importantly to our aim, MCPs allow to include game-theoretic aspects and non-cooperative behaviour such as competition à la Cournot. Assuming convexity of $G(x,y)$ and $H(x,y)$ and strict quasiconcavity of $F(x,y)$, we know that the problem is tractable and that there exists a unique solution. The model we propose in this paper satisfies these conditions; we derive the KKT conditions of all optimization problems and market clearing constraints and use them to compute a numerical application using the PATH solver in GAMS. We refer to Facchinei and Pang (2003) and Ferris and Munson (2000) for an overview on KKT conditions and MCPs.

2.2 The Bilateral Trade Model

In a model setup with bilateral trade relations between each pair of players, prices are determined in each receiving node independently. Hence, price discrimination between different buyers may occur: the price differentials between two nodes may differ from the transport costs between these nodes, depending on the market power of the suppliers and the demand elasticity at the buying node. The approach of bilateral trading is extensively used in modeling of natural resource markets such as natural gas (e.g., in Holz et al., 2008) or coal (e.g., in Haftendorn and Holz, 2008).

2.2.1 The supplier

Oil companies own wells to produce (extract) crude oil and sell it downstream, usually to refineries. We separate these two activities of the oil company in our model formulation in a production entity P and a trading entity T. The production entity at node n carries out the production of crude oil (denoted by $Prod_n^P$). The trading entity then arranges the transportation and sales of the crude oil to the downstream market. The split of the two activities allows to model either a market where each player optimizes independently, or a joint profit maximization by an OPEC cartel by modeling a single cartel trading entity which buys the total OPEC production and sells it downstream.

The production entity The production entity P of the supplier operates at node n and can sell to its trading entity T for an intra-company price of ϕ_n^T equal to marginal cost. It aims at maximizing its profit:

$$\max_{Prod^P} Prod_n^P \cdot \phi_n^T - Cost_n^P(Prod_n^P) \tag{1}$$

where $Cost_n^P(\cdot)$ is the production cost function at node n, as used by Aune et al. (2001) for fossil fuel supply costs.

The production entity is subject to a production capacity constraint. Since we only investigate one period, we do not consider reserves. α_n^{Prod} is the dual variable of the capacity constraint, which can be interpreted as the shadow price of capacity.

$$\text{s.t.} \quad Prod_n^P \leq \overline{Cap}_n^P \quad \perp \quad \alpha_n^{Prod} \geq 0 \tag{2}$$

The trading arm The trading arm forms the link between the oil well and consumers. It receives the crude oil from its respective production entity, transports it either by pipeline ($Flow^T$) or tanker ship ($Ship^T$) to a consumption node and sells the oil to final demand R ($Sales^{T \to R}$). The trading arm aims at maximizing its profits in the downstream market. The model allows for imperfect competition à la Cournot. If the trader is a Cournot player, he knows the inverse demand function $\Pi_n^R(\cdot)$ at node n; he can therefore exert market power to influence the market price by deliberately withholding supplies. A value of $\delta^T = 1$ makes the trader a Cournot player, while a value of 0 means that he is acting competitively, taking into account only the market-clearing price $\pi_{y,n}^R$ at node n.

$$\max_{\substack{Sales^{T\to R}\\ Flow,Ship}} \sum_{n\in N} \Big[Sales_n^{T\to R} \cdot [\delta^T \cdot \Pi_n^R(\cdot) + (1-\delta^T)\cdot \pi_n^R] - \sum_{m\in A(n)} Flow_{n\to m}^T \cdot \tau_{n\to m}^{Reg} - \sum_{k\in P} Ship_{n\to k}^T \cdot TC_{n\to k}^{Ship} - Prod_n^P \cdot \phi_n^T \Big] \tag{3}$$

Here, $A(n)$ specifies all countries which can be reached from country n by pipeline, while P is the set of all ports. The transport costs τ^{Reg} and TC^{Ship} are accounted for at the exporting node.[3]

$$\text{s.t.} \quad - Sales^{T\to R} - \sum Flow^{T,out} - \sum Ship^{T,out} + Prod^P + \sum Flow^{T,in} + \sum Ship^{T,in} \le 0 \quad \perp \quad \phi_n^T \ge 0 \quad \forall\, n\in N \tag{4}$$

2.2.2 Crude Oil Final Demand

Aiming to model the international crude oil trade and the influence of price indices, we do not include the market for oil products. Demand for crude oil in country n is modelled via an inverse demand function. The market clearing condition therefore is:

$$DemInt_n^R - DemSlp_n^R \cdot \sum_T Sales_n^{T\to R} - \pi_n^R \le 0 \quad \perp \quad \pi_n^R \ge 0 \quad \forall\, n\in N \tag{5}$$

We collect the KKT conditions of all optimization problems above. Together with the market clearing condition from final demand, this gives an MCP model that is given in full detail in Appendix A.1.

2.3 The Pool Model - Introducing Arbitrageurs

We now extend the bilateral model by introducing several pools $i \in I$ where arbitrageurs are located. They exploit price differentials between consumption nodes in excess of transport costs.[4] It is important to stress that trading entities still sell to final demand directly, so crude oil is not necessarily directed via the pool node; only the amounts bought or sold by the arbitrageur $Arbit_{i,n}^{Pool}$ pass through the pool.[5]

Metzler et al. (2003) show that the following market setups yield identical results:

[3] The superscripts *in* and *out* with the variables *Flow* and *Ship* do not actually specify distinct variables, but are intended to improve readability of the equations.

[4] Since all arbitrageurs are identical apart from the pool node from which they operate, we assume that there is one arbitrageur per pool node.

[5] Note that this value can be positive or negative depending on whether the arbitrageur is a net buyer or net seller at this node.

- The arbitrageurs solve a profit maximization problem parallel to the suppliers,
- The suppliers are Stackelberg leaders and anticipate the arbitrageurs' actions,
- A pool Cournot market of suppliers.

Consequently, we do not need to introduce a distinct profit maximization problem for the arbitrageur, but can include the arbitrageur's problem directly in the optimization program of the trading entities and in the inverse demand function. See Hobbs (2001) for a thorough investigation of this approach.

We simplify the problem by assuming that final demand at node n can only buy and sell from and to one pool i, namely the one with the lowest transport costs to the country. The parameter $\vartheta_{n,i}$ of node n equals 1 for this pool and 0 otherwise. The equilibrium condition of final demand therefore changes such that prices in the node must equal the price in the nearest pool hub plus transport costs to the importing country. Dual variables of the arbitrageur are denoted by β.

$$DemInt_n^R - DemSlp_n^R \cdot \left[\sum_T Sales_n^{T \to R} + \sum_{i \in I} \vartheta_{n,i} \cdot Arbit_{i,n}^{Pool} \right] - \sum_{i \in I} \vartheta_{n,i} \cdot (\pi_i^{Pool} - TC_{i \to n}) = 0 \quad \perp \quad \beta_n^{Price}(free) \tag{6}$$

The arbitrageur can be neither a net producer nor net consumer; the sum of its purchases must equal its sales.

$$\sum_{n \in N} Arbit_n^{Pool} = 0 \quad \perp \quad \beta_i^{Pool}(free) \quad \forall\, i \in I \tag{7}$$

The new inverse demand function (6) is used to close the model instead of (5). The production entity's problem does not change; the trading arm considers not only the amounts sold by other traders, but also the arbitrageur's action. The price of crude oil in the pool π_i^{Pool} is determined as the dual to the constraint $\sum \beta_n^{Price} = 0$. See Appendix A.2 for the complete mathematical formulation of the pool model.

3 A Numerical Application

The two model setups are now used to compute equilibria for a data set comprising of more than 85% of global crude oil production and consumption, including all OPEC and OECD members and other countries with considerable production or consumption. A list of countries can be found in Appendix B.1. The pool nodes used in the pool model are USA (WTI), UK (Brent) and United Arab Emirates (Dubai). We use 2006 as the base year. Consumption and production quantities and reference prices are gathered from IEA (2008) and BP (2008). An overview of demand elasticity estimates is given in Fattouh (2007), ranging from 0.001 to -0.11 in the short run and 0.038 to -0.64 in the long run; we choose -0.10 in this paper. Production cost are taken from Aguilera et al. (2009).[6] Lacking coherent data on maximum production capacity by country, we assume that all countries are producing at 95% of capacity in the base year reference values. While this may underestimate the true potential production capacity, it allows to identify those countries which could gain from raising production without distorting results too much.[7] Transport cost are distinguished between pipeline and tanker shipping cost and are derived from BGR (2003).

In line with the prevailing literature and the theories generally brought forward to describe the crude oil market, the following market power scenarios are compared:

- No producer has market power, the market is perfectly competitive *(No MP)*
- All producers exert market power à la Cournot *(All MP)*
- OPEC producers form an oligopoly and exert market power, but optimize independently, while other producers form a competitive fringe *(Oligopoly)*
- OPEC jointly maximizes profits and exerts market power while other producers form a competitive fringe *(Cartel)*

We find that in a perfectly competitive market, prices would be only about half as high as was actually observed in 2006, while a perfect cartel would see a threefold price increase. A complete Nash-Cournot market would result in prices about 50% higher than observed values. Quantities consumed and final demand prices are best depicted by the OPEC oligopoly assumption in the pool market setup as shown in Tables 1 and 2 (squared deviations are listed in Appendix B.2).

Several results of the bilateral trade model seem unrealistic and call for the pool model setup. In particular, in the bilateral model, we find that prices in countries which are exclusively supplied by pipeline from Russia (namely Czech Republic and Slovakia) in the bilateral trade Cournot market scenario are about 50% higher than the price in other countries. These price differentials cannot be found in reality and are unlikely to occur in a liquid market. A similar observation is the price differential

[6] The estimates provided are average total production costs; we assume that marginal production costs plus transport to the export hub are three times average production costs and use this estimate to derive a quadratic cost function.

[7] In none of our scenario results is total output higher than the reference output.

Country	Scenario results				Reference
	No MP	All MP	Oligopoly	Cartel	(2006)
Germany	131.3	120.4	126.6	102.7	
	(131.2)	*(121.9)*	*(126.6)*	*(103.5)*	125.0
Russia	134.6	123.1	129.7	104.3	
	(134.7)	*(115.5)*	*(129.9)*	*(103.1)*	128.5
Spain	64.9	59.3	62.5	50.2	
	(64.9)	*(60.0)*	*(62.5)*	*(50.4)*	61.9
The Netherlands	85.6	78.3	82.5	66.4	
	(85.5)	*(79.1)*	*(82.5)*	*(66.5)*	81.6
Czech Republic	8.6	7.9	8.3	6.7	
	(8.6)	*(7.3)*	*(8.3)*	*(6.6)*	8.2
China	367.1	337.0	353.7	287.6	
	(367.5)	*(341.0)*	*(354.5)*	*(290.0)*	349.8
Japan	212.4	195.0	204.6	166.4	
	(212.6)	*(196.7)*	*(204.6)*	*(166.1)*	202.5
Brazil	96.1	88.1	92.4	73.6	
	(96.3)	*(89.3)*	*(92.8)*	*(75.0)*	92.1
USA	869.3	797.1	836.0	666.1	
	(867.5)	*(804.8)*	*(835.0)*	*(677.1)*	829.9
World	3236.0	2967.1	3116.2	2510.5	
	(3235.7)	*(2956.1)*	*(3116.2)*	*(2510.5)*	3085.8

Table 1: Consumption of selected countries and world total consumption, mio tons, Pool setup (including Arbitrageurs)/*Bilateral setup (without Arbitrageurs)* in brackets

between Japan and China: while the reference prices are virtually identical, the bilateral model yields price differences of more than 15 \$/ton in all scenarios in which some producers exert market power; the price differential is only 2 \$/ton in the pool setup which is roughly equal to the transport costs between the two countries. These findings indicate that the bilateral trade modeling approach can yield unrealistic results as soon as market power comes into play, and that the pool setup is better suited to examine the crude oil market.

The picture is, however, not clear on the production side: most producers are operating at or close to full capacity in all scenarios, in the bilateral and the pool approach. Table 3 shows some of the producers which have spare capacity in some scenarios: independent of whether we assume a bilateral trade or a pool setup, China, Russia and the USA are not producing as much as they could in the competitive scenario, since they have comparatively high production costs. When all players exert market power, Russia produces even less than in the competitive scenario, while China and the USA produce more to make up for reduced supplies from other countries, most notably Saudi Arabia. An interesting observation is the fact that other OPEC countries do not reduce their production significantly in both the Nash-Cournot and the oligopoly market. Only when a common OPEC trader

Country	Scenario results				Reference
	No MP	All MP	Oligopoly	Cartel	(2006)
Germany	231.00	636.48	404.17	1,294.64	
	(232.88)	*(581.20)*	*(403.18)*	*(1,294.00)*	465.81
Russia	233.58	639.06	406.75	1,297.22	
	(230.09)	*(904.79)*	*(400.39)*	*(1,291.22)*	450.58
Spain	232.87	638.35	406.04	1,296.51	
	(232.05)	*(585.65)*	*(405.37)*	*(1,296.21)*	448.89
The Netherlands	230.95	636.43	404.11	1,294.59	
	(232.88)	*(588.52)*	*(403.18)*	*(1,294.02)*	452.42
Czech Republic	234.70	640.18	407.87	1,298.35	
	(248.22)	*(928.37)*	*(418.52)*	*(1,309.35)*	456.69
China	237.68	643.02	418.02	1,309.06	
	(232.05)	*(589.64)*	*(407.10)*	*(1,297.94)*	471.11
Japan	240.17	645.51	420.52	1,311.55	
	(234.54)	*(606.33)*	*(422.16)*	*(1,312.99)*	471.26
Brazil	243.57	621.99	418.33	1,309.36	
	(233.63)	*(567.46)*	*(402.26)*	*(1,294.14)*	435.34
USA	228.53	606.94	403.29	1,294.32	
	(237.92)	*(566.68)*	*(408.22)*	*(1,299.06)*	435.34

Table 2: Crude oil prices in selected countries, \$/ton, Pool setup (including Arbitrageurs)/*Bilateral setup (without Arbitrageurs)* in brackets

maximizes joint profits, which corresponds to a perfectly enforceable cartel, are other (higher cost) OPEC members forced to reduce production, and Saudi Arabia produces slightly more than in the oligopoly scenario.

Country	Scenario results				Reference
	No MP	All MP	Oligopoly	Cartel	(2006)
China	153.8	160.5	192.8	192.8	
	(150.1)	*(173.0)*	*(192.8)*	*(192.8)*	183.7
Iran	220.2	220.2	218.4	184.3	
	(220.2)	*(220.2)*	*(218.4)*	*(184.4)*	209.8
Russia	391.6	272.3	504.5	504.5	
	(385.6)	*(260.2)*	*(504.5)*	*(504.5)*	480.5
Saudi Arabia	514.6	344.5	222.0	231.3	
	(514.6)	*(326.3)*	*(222.0)*	*(231.3)*	514.6
USA	243.3	257.2	266.0	266.0	
	(253.4)	*(263.9)*	*(266.0)*	*(266.0)*	253.3

Table 3: Quantities produced in selected countries, mio tons, Pool setup (including Arbitrageurs)/*Bilateral setup (without Arbitrageurs)* in brackets

Comparing model results to reference values, we find that most producers behave according to an OPEC oligopoly or a Nash-Cournot market; Saudi Arabia, however, does not fit the picture. This might be due to the fact that Saudi Arabia can, within OPEC, press others to keep their output below individual optimum by producing more than would be ideal from a Saudi profit maximization point of view. The Saudi motivation might be either to increase the joint profits of OPEC producers or domestic and international political issues. We conclude that, consistent with the prevailing literature, neither cartel, oligopoly nor perfect competition can perfectly capture and explain the behaviour of OPEC and other producers in this framework; our results support the proposition by Hartley and Medlock (2008) that the assumption of profit maximization ignores important aspects of the NOCs' behaviour.

One disadvantage of the pool setup is the fact that trade flows cannot be directly observed, as all quantities passing through the pool cannot be attributed to one specific producer. However, since all consumers can be attributed to one of the three pools, it is possible to make observations by region, which is especially interesting for swing producers in the Middle East. Table 4 shows exports and consumption from own production of Middle East producers. As is to be expected, trade is directed to regions close to the point of production to minimize transport costs if all producers behave competitively. If some producers exert market power and thereby push up prices, it becomes profitable to export to regions further away. It must be pointed out that consumption in the Middle East is roughly equal in all scenarios. In the bilateral trade setup under the oligopoly assumption, the Middle East imports more than 100 million tons of crude oil. This is difficult to reconcile with observed trade flows (no imports) and economic rationale of transport cost minimization. This phenomenon does not occur in the pool setup; we therefore, again, conclude that the pool setup is better suited to capture the peculiarities of the oil market.

Country	Scenario results		
	No MP	All MP	Oligopoly
Asia & Pacific	527.0	268.2	166.3
	(778.8)	*(335.3)*	*(305.9)*
Europe	250.4	282.6	236.8
	(216.8)	*(270.5)*	*(235.9)*
America	218.1	336.6	312.0
	(0.0)	*(329.8)*	*(315.7)*
Domestic Consumption$^{(*)}$	180.6	118.7	166.7
	(180.4)	*(52.3)*	*(24.2)*
Total production	1176.1	1006.0	881.8
	(1176.1)	*(987.9)*	*(881.8)*

Table 4: Middle East exports and domestic consumption$^{(*)}$(from domestic production only), mio tons, Pool setup (including Arbitrageurs)/*Bilateral setup (without Arbitrageurs)* in brackets

4 Conclusion and Future Directions

This paper proposes an extension to the partial equilibrium trade model typically used in the modeling of natural resource markets with bilateral trade relations. We include the characteristic of the global crude oil market where prices are influenced by indices of liquid spot markets. We adopt the pool approach used in modeling of electricity markets: prices are determined at a pool node where arbitrageurs are located and not in each consumption node separately. Due to the global scale of the crude oil trade, we introduce more than one pool. Using the pool setup, we force prices in each consumption node to equal the price at the closest pool node plus transport costs.

We use both model approaches, with the bilateral trade (without arbitrageurs) and the pool trade setup (which includes arbitrageurs), to compute numerical solutions for a data set of the global crude oil market. Comparing the model results to the reference values of the base year 2006, we find that the pool-based setup generally yields results closer to observed values than the bilateral approach in the consumption market. The best fit is obtained by the scenario in which all OPEC producers exert market power (but do not jointly maximize profits as in a cartel) while all other producers form a competitive fringe. We therefore assume that OPEC exerts market power vis-à-vis the downstream market, albeit not in a cooperative way.

However, our results do not lend themselves to easy interpretation: we know that the assumption of profit maximization does not do justice to the complex behaviour of NOCs that have to perform more activities than only oil production and sales. The model could be changed in such a way that NOCs are optimizing a social welfare function including the factors brought forward by Hartley and Medlock (2008), where employment, spending on social infrastructure and remaining reserves are also included, in addition to profits.

Our multi-pool setup can be extended to cover multiple periods, including endogenouos investment in production capacity. The investment decision could either be implemented via Lagrangian relaxation or recursively, applying real option theory as described by Pindyck and Dixit (1994) in each iteration. The latter approach would make sense especially due to the high volatility of oil prices, where an investment decision depends to a large extent on the assumptions regarding future prices. The producers would consider inter-temporal optimization as proposed by Hotelling (1931); the model projections regarding investment could provide insight into issues such as security of supply and future price developments.

A The Mathematical Formulation

A.1 The bilateral trade model

The maximization problems specified above lead to the following Karush-Kuhn-Tucker (KKT) conditions for each player. Each agent (P, T, R) faces the following equations in each node n where it is present.

- The production entity P of the supplier

$$\phi_n^T - LC_n^P - QC_n^P \cdot Prod_n^P - \alpha_n^{Prod} \leq 0 \quad \perp \quad Prod_n^P \geq 0 \tag{8}$$

$$Prod_n^P - \overline{Cap}_n^P \leq 0 \quad \perp \quad \alpha_n^{Prod} \geq 0 \tag{9}$$

- The trading arm T of the supplier

$$\pi_n^R - \delta^T \cdot DemSlp_n^R \cdot Sales_n^{T \to R} - \phi_n^T \leq 0 \quad \perp \quad Sales_n^{T \to R} \geq 0 \tag{10}$$

$$\phi_n^T - \tau_{m \to n}^R - \phi_{y,m}^T \leq 0 \quad \perp \quad Flow_{m \to n}^T \geq 0 \quad \forall\, m \in A(n) \tag{11}$$

$$\phi_n^T - TC_{k \to n}^{Ship} - \phi_k^T \leq 0 \quad \perp \quad Ship_{k \to n}^T \geq 0 \quad \forall\, k \in Sea \tag{12}$$

$$\begin{aligned} -Sales_n^{T \to R} - \sum_{m \in A(n)} Flow_{n \to m}^{out} - \sum_{k \in Sea} Ship_{n \to k}^{out} & \\ +Prod_n^P + \sum_{l \in A(n)} Flow_{l \to n}^{in} + \sum_{h \in P} Ship_{h \to n}^{in} \leq 0 \quad \perp \quad \phi_n^T \geq 0 & \end{aligned} \tag{13}$$

- Final Demand R

$$DemInt_n^R - DemSlp_n^R \cdot \sum_T Sales_n^{T \to R} - \pi_n^R \leq 0 \quad \perp \quad \pi_n^R \geq 0 \tag{14}$$

A.2 The pool model

The KKT conditions of the production entity and the trading arm are the same as in the bilateral model.

- Arbitrageur

$$DemSlp_n^R \cdot \left[\beta_n^{Price} - \sum_{t \in T} Sales_n^{T \to R} \right] - \beta^{Pool} = 0 \quad \perp \quad Arbit_n^{Pool}(free) \tag{15}$$

$$\sum_{n \in N} Arbit_n^{Pool} = 0 \quad \perp \quad \beta^{Pool}(free) \tag{16}$$

$$\sum_{n \in N} \beta_n^{Price} = 0 \quad \perp \quad \pi_i^{Pool}(free) \tag{17}$$

- Final Demand

$$DemInt_n^R - DemSlp_n^R \cdot \left[\sum_T Sales_n^{T\to R} + Arbit_n^{Pool} \right]$$
$$-\pi_i^{Pool} - TC_{i\to n} = 0 \quad \perp \quad \beta_n^{Price}(free) \quad (18)$$

B The Numerical Application

B.1 Countries included in the Model

Region	Countries		
America	Brazil *(P&C)*	Canada *(P&C)*	Ecuador *(P)*
	Mexico *(P&C)*	USA *(P&C)*	Venezuela *(P)*
Asia & Pacific	Australia *(C)*	China *(P & C)*	India *(C)*
	Indonesia *(P&C)*	Japan *(C)*	Korea *(C)*
	New Zealand *(C)*	Taiwan *(C)*	
Africa	Algeria *(P)*	Angola *(P)*	Libya *(P)*
	Nigeria *(P)*		
Middle East	Iran *(P&C)*	Iraq *(P)*	Kuwait *(P)*
	Qatar *(P)*	Saudi Arabia *(P&C)*	United Arab Emirates *(P)*
Europe	Austria *(C)*	Belgium *(C)*	Czech Republic *(C)*
	Denmark *(C)*	Finland *(C)*	France *(C)*
	Germany *(C)*	Greece *(C)*	Hungary *(C)*
	Ireland *(C)*	Italy *(C)*	The Netherlands *(C)*
	Norway *(P&C)*	Slovakia *(C)*	Turkey *(C)*
United Kingdom *(P&C)*			
Russia & Caspian	Kazakhstan *(P)*	Russia *(P&C)*	

(P) ... Producer
(C) ... Consumer

B.2 Deviation Measure

	Sum of squared deviation of results from base year			
	No MP	All MP	Oligopoly	Cartel
Production	9.43E+09	7.34E+10	8.69E+10	1.18E+11
	(1.07E+10)	*(8.47E+10)*	*(8.69E+10)*	*(1.18E+11)*
Consumption	2.30E+09	1.51E+09	7.49E+07	3.69E+10
	(2.19E+09)	*(1.38E+09)*	*(7.14E+07)*	*(3.36E+10)*
Prices	1.90E+06	1.09E+06	1.15E+05	2.52E+07
	(1.92E+06)	*(2.66E+06)*	*(1.17E+05)*	*(2.52E+07)*

Pool setup (including Arbitrageurs)
(Bilateral setup (without Arbitrageurs))

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