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Theory and evidence

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Abstract:
There is no consensus in the literature on how OPEC behaviour affects crude oil prices. Some studies treat the oil market as a standard competitive market where OPEC plays no important role, whereas others argue that OPEC is a dominant producer with a competitive fringe or a cartel that adjusts its production to influence crude oil prices in a way that benefits the member states. We analyse the behaviour of OPEC as a group for the period 1992 to 2015 by formulating a model that encompasses several of the alternatives discussed in the literature. Applying a system-based cointegration analysis, we find support for the imperfect competition hypothesis regarding the output decision of OPEC. We also find, using full information maximum likelihood and recursive methods, that a dynamic equilibrium correction model with imperfect competition is reasonably stable in-sample and has somewhat better fit than an alternative dynamic model with weaker theoretical underpinnings. However, a forecasting exercise reveals that the dynamic equilibrium correction model breaks down following the OPEC meeting in November 2014. At the end of 2015 the model underpredicts the production of OPEC by almost 2.5 million barrels per day. We therefore conclude that the OPEC behaviour has changed significantly, probably to limit the role of competitors like American producers of shale oil.

Keywords: OPEC behaviour; Economic and econometric modelling; Forecasting

JEL classification: C51; C52; D43

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Sammendrag

Det er ingen konsensus i litteraturen om hvordan adferden til OPEC påvirker oljepriser. Noen studier behandler oljemarkedet som et frikonkurransemarked hvor OPEC ikke spiller noen viktig rolle, mens andre argumenterer for at OPEC er en dominerende produsent eller et kartell som tilpasser sin produksjon for å påvirke oljeprisene på en måte som favoriserer medlemslandene. Vi analyserer adferden til OPEC som en gruppe over perioden 1992 til 2015 ved å formulere en modell som omslutter mange av alternativene diskutert i litteraturen. Basert på multivariat kointegrasjonsanalyse finner vi støtte for hypotesen om imperfekt konkurranse når det gjelder OPECs beslutninger om oljeproduksjon. Vi finner også ved hjelp av sannsynlighetsmakimeringsmetoden og rekursive tester at en dynamisk feiljusteringsmodell med imperfekt konkurranse er stabil i estimeringsperioden og har bedre forklaringskraft enn en alternativ dynamisk modell med svakere teoretisk utgangspunkt. En prognoseanalyse avslører imidlertid at den dynamiske feiljusteringsmodellen bryter sammen i kjølvannet av OPEC møte i november 2014. Mot slutten av 2015 underpredikerer modellen OPECs produksjon med nesten 2,5 millioner fat per dag. Vi konkluderer derfor med at adferden til OPEC har endret seg signifikant siden november 2014, trolig for å begrense rollen til konkurrenter som amerikanske produsenter av skiferolje.

1 Introduction

The growing importance of OPEC during the 1970s and the increased perception that the organisation could affect world oil prices initiated a large number of empirical work about the structure of the oil market, and in particular, about the behaviour of OPEC. Yet, there is no clear consensus in the literature about the exact nature of the behaviour of OPEC and its ability to influence world oil prices. Some studies rely on a competitive model while others specify models of imperfect competition often assuming that OPEC functions like a monopoly, an oligopoly or a cartel in some way, see for example Almoguera *et al.* (2011) and Alkhathlan *et al.* (2014) for reviews of the literature.

The study of Griffin (1985), which tests the various cartel models, the competitive model, the target revenue model and the property rights model for the period 1971 to 1983, is the starting point for much of the empirical work in this field of research. Among the various competing hypotheses of OPEC behaviour, Griffin (1985) finds some support for a cartel model where OPEC as a group is a dominant producer setting the oil price, while non-OPEC countries behave as a competitive fringe. A similar conclusion is also reached in Böckem (2004) relying on data for the 1990s. Other studies find that a core group within OPEC or even only Saudi Arabia fits the description of a dominant producer, see for example Dahl and Yücel (1991), Alhajji and Huettner (2000a,2000b) and Hansen and Lindholt (2008). Smith (2005) argues for a model of the OPEC countries as a "bureaucratic production syndicate" and finds strong evidence of collusion, but with significant transaction costs regarding redistribution of output between members of the cartel. Spilimbergo (2001), on the other hand, finds no support for the hypothesis that OPEC is a market sharing cartel and Ramcharran (2001) finds some evidence for a partial version of the target revenue model using annual data for the period 1973 to 2000. A more recent study by Almoguera *et al.* (2011) concludes that the behaviour of OPEC on average over the period from 1974 to 2004 is best described as a Cournot competition with a competitive fringe.

The empirical evidence about the OPEC behaviour is thus rather mixed. Kaufmann *et al.* (2008) argue that the failure to agree on a benchmark model is not a weakness, but rather a strength as OPEC behaviour does not fit easily into any single model. The disagreement and plethora of models may be due to changing OPEC behaviour over time, as stressed by Almoguera *et al.* (2011) and Alkhathlan *et al.* (2014) among others. According to Alkhathlan *et al.* (2014) OPEC set the oil price and allowed demand to determine output from 1973 to 1985. By the end of 1985 Saudi Arabia changed policy because the country itself no longer accepted to take most of the output adjustment within OPEC in order to defend the oil price. During 1986 OPEC switched to production quotas which was formally introduced in 1982. Kaufmann *et al.* (2008) also find that the quota system in OPEC is an important determinant of production and that Saudi Arabia closely adhered to its quota from 1986, supporting the view of a change in behaviour from that year. Some studies suggest that Saudi Arabia thereafter has been trying to stabilize the supply of OPEC, particularly in cases of supply disruptions due to conflicts and wars in the region, see for example Nakov and Nuño (2013). Recently, several economists have argued that OPEC on the meeting in November 2014 decided to keep its supply unchanged despite the huge oil price drop in advance, mainly to limit the role of competitors like American producers of shale oil. OPEC has then increased its supply alongside a continuing fall in the oil price relative to the production costs, which raises the question whether the organisation again has changed behaviour since the November meeting in 2014.

The empirical studies of OPEC behaviour are typically not based on models in the tradition of Hotelling (1931) and Pindyck (1978). One reason could be that many studies of oil prices based on the Hotelling set up have found little support for the theory relating world market oil prices to resource scarcity, marginal costs and discount rates, see for example Reynolds and Baek (2012) for a discussion. However, Pickering (2008) finds that the relationship between extraction and reserves of oil is quite well explained using the theory of resource extraction where the resource endowment is exogenous. Also, Holland (2008) argues that the Hotelling framework is useful when modelling "peak oil", although his analysis is not empirical. Pesaran (1990), on the other hand, offers an econometric analysis of exploration and extraction of oil based on a model in line with Pindyck (1978), but finds no supportive evidence of a forward-looking price expectation rule. An adaptive price expectation rule fits data better when economically sensible implications of the model, such as a negative impact of reserves on extraction costs, are added as a selection criterion.

In this paper, we analyse the behaviour of OPEC as a group for the period 1992 to 2015 with a special focus on the possibility of changes in actions taken by the organisation before and after the November meeting in 2014. Building on Berg *et al.* (1997), we set up a theoretical model of OPEC behaviour that encompasses several of the alternatives discussed in the literature, among them the competitive model and the imperfect competition model of various forms. Unlike related empirical studies, our model also includes a possible role for the resource stock to affect extraction or production costs of OPEC. However, we simplify matters by not considering exploration efforts and forward-looking behaviour, only backward-looking behaviour in the decision rule of OPEC. We contribute to the empirical literature by paying particular attention to time series properties, and possible existence of unit roots, of variables involved and searching for statistically well-specified underlying models as premises for valid inference about the OPEC behaviour. Applying a system-based cointegration analysis, we find support for the imperfect competition hypothesis regarding the output decision of OPEC. The implied average estimate of the price elasticity of demand for OPEC oil is significantly less than minus unity, consistent with the dominant producer model. Besides, the oil reserves of OPEC seem to affect costs of production positively, invalidating the Hotelling rule. We also find, using full information maximum likelihood and recursive methods, that a dynamic equilibrium correction model with imperfect competition is reasonably stable in-sample and has somewhat better fit than an alternative dynamic model with weaker theoretical underpinnings. However, a forecasting exercise reveals that the dynamic equilibrium correction model breaks down following the OPEC meeting in November 2014. At the end of 2015 the model underpredicts the production of OPEC by almost 2.5 million barrels per day. We therefore conclude that the behaviour of OPEC indeed has changed significantly since the November meeting in 2014.

The rest of the paper is organised as follows: Section 2 outlines the theoretical model of OPEC behaviour, Section 3 describes the data, Section 4 reports findings from the cointegration analysis and Section 5 evaluates the empirical performance of the two competing dynamic models of OPEC behaviour. Section 6 provides a conclusion.

2 A theoretical model

In the spirit of Berg *et al.* (1997), we build an intertemporal model of output decisions of OPEC as a cartel, assuming that the organisation being a large producer understands and exploits the fact that its own production affects the market price for crude oil. We thus start out by assuming a constant inverse price elasticity, ε, and a demand function that OPEC faces having the form

$$P_t = \varepsilon_0 X_t^{\varepsilon}, \tag{1}$$

where P_t is the nominal crude oil price per barrel in period t, X_t is the supply of OPEC measured in million barrels per day in period t, ε_0 are other factors than the oil price affecting demand and $-1 < \varepsilon < 0$. OPEC has oil reserves at the beginning of period t, R_t, that is exploited in every period by extraction or production, such that

$$R_{t+1} = R_t - X_t. \tag{2}$$

Note that we are not including additions to stocks due to discoveries. This could have been added to (2) without changing the model as long as explorations leading to new discoveries are not modelled as in Pesaran (1990). In line with Berg *et al.* (1997), we assume that the unit cost function of OPEC's production in period t, C_t, depends on the oil reserves, such that

$$C_t = c_0 e^{-\eta R_t}, \tag{3}$$

where c_0 incorporates factor prices, but not output, and $\eta \lesseqgtr 0$ depending on the hypothesis about how reserves affect production costs. There are constant returns to scale in crude production of OPEC if the exponential term is disregarded. This may not be the most obvious way to characterise a production function for natural resource extraction. Assuming decreasing returns to scale due to a resource factor may seem a more realistic alternative. However, the allocation of output quotas within OPEC does not take place according to a cost effective allocation between the member states that minimises production costs within OPEC for given total output, as a multi plant firm would do. When studying the oil supply of an individual country or a particular oil province a cost function like (3) may not be a reasonable choice. As argued by Livernois and Uhler (1987), there is no reason to assume that deposits with lower extraction costs tend to be found and explored first, and that other characteristics of deposits besides their state of depletion affect costs. Our choice of unit cost function is therefore related to the specific period of study where OPEC has been producing according to a quota system. We are not arguing that this choice would be the best if OPEC were allocating output differently.

One hypothesis about production costs and reserves is that costs of extraction are higher with fewer reserves ($\eta > 0$). Thus, higher extraction today increases costs tomorrow and in this sense there are increasing marginal costs in output. Another hypothesis is based on Arrow's (1962) learning by doing theory. Combining (2) and (3), the cost function can be expressed as depending on accumulated output ($R_0 - \sum X_{t-1-i}$). Letting the initial reserves, R_0, be included in the constant term, unit costs depend only on accumulated output. Learning by doing is a simple way of introducing endogenous technological change by assuming $\eta < 0$ so that unit costs fall as accumulated output increases. The way we model output decisions in this case is thus based on the assumption that OPEC is aware of the learning by doing effect.

OPEC is assumed to be acting as a cartel that maximises the present value of the net income, NI, from its crude reserves taking the supply from other producers (the "fringe") as given. NI is defined by

$$NI = \sum_{t=0}^{\infty} (P_t - C_t) X_t (1 + r_t)^{-t}, \tag{4}$$

where r_t is the discount rate. NI is maximised subject to (1), (2) and (3), and the restrictions of non-negative production and an exogenously given upper limit to the oil price (given by a back stop technology). Given our empirical focus, we do not need to go into detail here regarding other restrictions than those from (1), (2) and (3) because our data apply only to a period in time when OPEC output is positive.

The Lagrangeian of this intertemporal problem is

$$L = \sum_{t=0}^{\infty}[(P_t - C_t)X_t(1+r_t)^{-t} + \lambda_{t+1}(R_t - X_t - R_{t+1})], \tag{5}$$

where λ is the Lagrange-multiplier, which tells us how much the net present value of NI increases if the resource constraint is relaxed.

The first order condition with respect to X_t (for $t = 0, 1, ..., \infty$) can be written as

$$\lambda_{t+1} = [(1+\varepsilon)P_t - C_t](1+r_t)^{-t}. \tag{6}$$

Note the difference compared to the familiar and simpler static condition stating that the oil price is a mark-up over marginal costs, which would imply that the term inside the square brackets equals zero.[1] This would be the case if the resource constraint (2) was not binding. According to the model it is generally not optimal for OPEC to choose output so that the oil price equals marginal cost times a mark-up. For the model to be meaningful, we must have $-1 < \varepsilon < 0$, but also a non-negative λ restricts the value of ε.

The first order condition with respect to R_t is more complicated since R_t enters in two terms in the last part of the sum in (5). After rearranging, we have for $t = 1, ..., \infty$

$$\lambda_{t+1} - \lambda_t = -\eta C_t X_t (1+r_t)^{-t}, \tag{7}$$

which shows the time path of the Lagrangean or the shadow cost of the resource constraint. This condition does not apply for $t = 0$, as R_0 is exogenous (initial reserves are given by nature and thus not a choice variable). We see from (7) that λ is falling over time when $\eta > 0$ since the term on the right hand side is negative in this case. This implies that the scarcity rent of resources is increasing over time. We shall focus only on the interior solution to the maximization problem and thus disregard the non-negativity constraint on X_t and R_t. Notice that if reserves do not enter the unit cost function, the change in λ is zero according to (7). This constant will be zero as long as the resource constraint is not binding, which means that we have the standard mark-up pricing formula.

We eliminate λ using (6) and (7) and get

$$[(1+\varepsilon)P_t - C_t] - [(1+\varepsilon)P_{t-1} - C_{t-1}](1+r_t) = -\eta C_t X_t, \tag{8}$$

where the Hotelling rule follows when both $\varepsilon = 0$ and $\eta = 0$. In this special case the net price, $P_t - C_t$, grows with the interest rate and we have a typical Euler equation. Equation (8) also applies for a fringe supplier who takes the oil price as given and has no market power, so $\varepsilon = 0$. Hence, (8) can accommodate two special cases of a more general model that opens up for imperfect competition and a role for the resource stock affecting costs.[2] Note that since (8) also holds for $r_t = 0$, the mark up increases or decreases over time depending on the sign of η. This is easily seen when the producer is a fringe supplier. If the price is constant, unit costs will increase over time due to resource depletion and thus the mark-up falls if $\eta > 0$. By solving for X_t using (8) and letting $C_t = (1+c_t)C_{t-1}$ we get

$$X_t = \frac{1}{\eta} - \frac{(1+r_t)}{\eta(1+c_t)} - \frac{1+\varepsilon}{\eta}\left[\frac{P_t}{C_t} - \frac{(1+r_t)}{(1+c_t)}\frac{P_{t-1}}{C_{t-1}}\right]. \tag{9}$$

[1] In this case the mark-up is $(1+\varepsilon)^{-1}$ or $e/(1+e)^{-1}$ when e is the standard price elasticity of demand and $e = \varepsilon^{-1}$.

[2] See also Pickering (2008) for a detailed analysis of a similar model with alternative market structures.

We may get more insights from our theoretical model either through a number of computer experiments on a calibrated model version or through an empirical counterpart in which the parameters of interest, η and ε, are quantified by econometric methods. As mentioned in the introduction, we rely on the latter approach in this paper. Because all the variables in (9) are observable it is possible to estimate and test the significance of η and ε. We shall return to issues of estimation and testing in Section 4.

Meanwhile, let us modify the simple assumption regarding the demand function in (1) and consider the dominant producer model in which OPEC as a cartel collectively sets the oil price when marginal revenues equal marginal costs. Non-OPEC producers or the competitive fringe will then supply oil when marginal costs equal the oil price. The demand for OPEC oil or "call on OPEC" is given by the residual demand, which is total demand for oil in the world less supply of oil by the fringe. If we assume a standard world demand function depending on the real consumer price of oil, while the supply of non-OPEC producers depends positively on the real producer price of oil, the price elasticity of demand for OPEC oil, e_{OPEC}, can be expressed as[3]

$$\varepsilon^{-1} = e_{OPEC} = e_W MSOPEC^{-1} - s(MSOPEC^{-1} - 1), \tag{10}$$

where $e_W < 0$ is the price elasticity of world oil demand, $s > 0$ is the supply elasticity of the fringe and *MSOPEC* is the market share of OPEC in the world oil market. The price elasticity in (1) is then simply the inverse of the elasticity in (10). In this sense ε is not a structural parameter, but rather a combination of such parameters. Because the market share of OPEC is changing over time, ε is also a time varying parameter in (10). As pointed out by Alhajji and Huettner (2000a) and Almoguera *et al.* (2011) among others, (10) is consistent with the dominant producer model if the profit maximising OPEC operates on the elastic part of its demand curve, that is when $e_{OPEC} < -1$. Otherwise, the profit maximisation condition, saying that the oil price equals marginal cost times a mark-up, is rejected because the oil price becomes negative.

Another possible model of OPEC behaviour is to assume that the cartel acts like a Cournot player that takes into account that its decision regarding oil production influences the price of oil, but that the cartel does not take into account possible reactions on output by the fringe. In this case the perceived supply response by the fringe is zero and

$$\varepsilon^{-1} = e_{OPEC} = e_W MSOPEC^{-1}, \tag{11}$$

or $\varepsilon = MSOPEC/e_W$.

To sum up, our model of OPEC behaviour encompasses several of the alternatives discussed in the literature, including the competitive model, the imperfect competition model of various forms and the Hotelling rule. We now proceed to confront our theoretical model with data.

3 Background and data

As mentioned in the introduction, we analyse the behaviour of OPEC as a group. OPEC was founded in Baghdad with the signing of an agreement in September 1960 by the five countries

[3] World demand for oil is $X_W = aP^{ew}$, where other factors than the oil price affecting demand are included in the parameter a. Non-OPEC supply of oil is $X_{NO} = bP^s$, where other factors than the oil price affecting supply are captured by the parameter b. The "call on OPEC" is $X = X_W - X_{NO} = aP^{ew} - bP^s$ and the market share of OPEC is $MSOPEC = X/X_W$. The expression in (10) is then found by differentiating $\log(X)$ with respect to $\log(P)$.

Islamic Republic of Iran, Iraq, Kuwait, Saudi Arabia and Venezuela. These countries were later joined by Qatar (1961), Indonesia (1962), Libya (1962), the United Arab Emirates (1967), Algeria (1969), Nigeria (1971), Ecuador (1973), Gabon (1975) and Angola (2007). From December 1992 until October 2007, Ecuador suspended its membership, whereas Gabon terminated its membership in 1995. Indonesia suspended its membership in January 2009, but this was reactivated from 1st January 2016. This means that, currently, OPEC has a total of thirteen member countries.

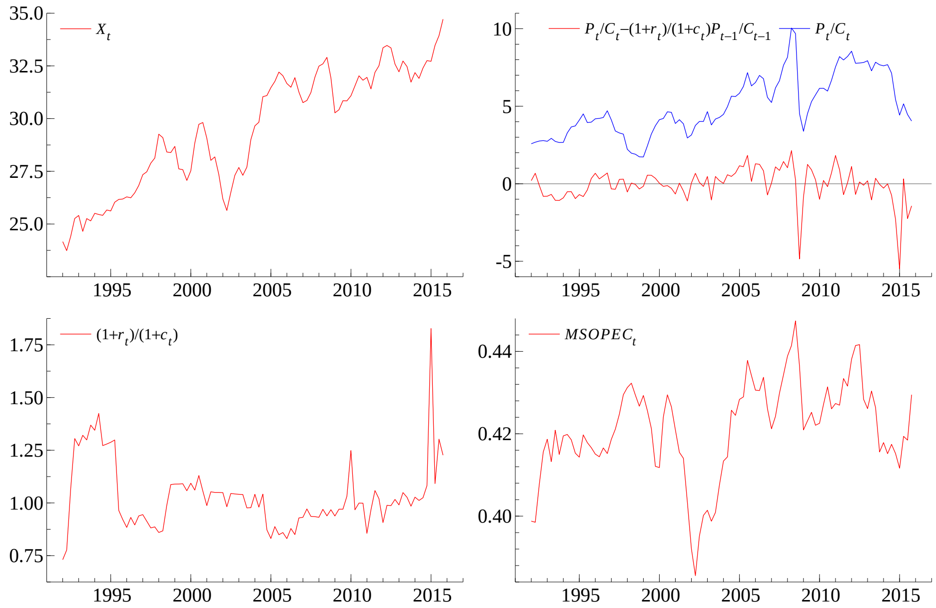
Our model is based on the assumption that OPEC members coordinate their production decisions in some way, although we are not explicit on the exact nature of this cooperation. There are clearly periods in the history of OPEC where coordination does not seem to be a reasonable assumption. In particular in periods of war between some member states, it is hard to justify that they are coordinated, even if it is possible to argue that they were coordinated within OPEC, but not otherwise. One obvious episode of some time duration is the war between Iraq and Iran. The Iraqi invasion of Kuwait in 1990 is another more recent example. The current system of production quotas was formally established in 1982, indicating that some element of coordination was at least intended by the countries involved at that time, see for example Smith (2005). However, Saudi Arabia stopped defending the price in 1985 so it is reasonable to argue that OPEC changed behaviour in 1986, as pointed out by Kaufmann *et al.* (2008) and Alkhathlan *et al.* (2014). Also, due to the Iraq-Kuwait war in 1990 and the following US invasion of Iraq, we argue that estimation should start after these conflicts. The empirical analysis is thus based on quarterly, seasonally unadjusted data that spans the period $1992Q1-2015Q4$, of which data from the period $1992Q1-2013Q4$ and $2014Q1-2015Q4$ are used for estimation and out-of-sample forecasting, respectively. Because OPEC members have not always been sticking to their quotas in absence of conflicts, we use recursive methods to investigate whether our estimated models are stable in-sample. We extend the estimation sample by eight quarters for forecasting to shed light on any change in the behaviour of OPEC before and after the meeting in late November 2014.

Figure 1 displays quarterly time series of the variables in (9), namely OPEC production (X_t) measured in million barrels per day, the nominal average OPEC export price on oil per barrel (P_t) measured in US dollars, OPEC total lifting costs per barrel (C_t) measured in US dollars and the US (annualised) ten year bond yield (r_t), together with the market share of OPEC ($MSOPEC_t$). Because the US ten year bond yield is annualised per definition, we annualise C_t/C_{t-1} to measure the variable $(1+r_t)(1+c_t)^{-1}$ on the same frequency both in the nominator and in the denominator. Data for OPEC production and the average OPEC export price on oil and the US ten year bond yield are acquired from the web site of OPEC and Macrobond, respectively.[4] Total lifting costs are based on the method of Hansen and Lindholt (2008) and are average supply costs and not marginal costs (ibid. p. 2944). As Hansen and Lindholt (2008) present cost estimates for several OPEC members including upper and lower bounds, we use a weighted average of the various cost estimates.

We clearly see that the production of OPEC, with some significant exceptions, has increased steadily from around 24 million barrels per day in 1992 to around 35 million barrels per day by the end of 2015. The supply of OPEC fell considerably through 2001 and 2002 alongside the international economic downturn before gradually picking up and reaching the very high historical 1980-level by 2004. Also, the crude production of OPEC fell significantly in the wake of the financial crisis in 2008. A similar picture is found when looking at the market share of OPEC during the sample period, although the market share has never reached

[4]See http://www.opec.org/opec_web/en/. Note that using the Saudi Arabian three month money market interest rate instead of the US ten year bond yield as the discount rate does not change any of the empirical findings qualitatively and hence any of the conclusions below.

Figure 1: Time series of variables in (9)



the level seen in the late 1970s.

The development in the crude production of OPEC coincides rather closely with the development in the ratio between the oil price and the lifting costs (P_t/C_t), one important explanatory variable in our theoretical model. For instance, OPEC reduced its production by around 2 million barrels per day following the huge drop in the oil price from around 145 dollars per barrel by July 2008 to below 40 dollars per barrel before the end of 2008, see Smith (2009). The market share of OPEC fell likewise by around 2 percentage points, down from 44 per cent.

Surprisingly enough, however, OPEC decided not to cut its production on the November meeting in 2014 despite the huge drop in the oil price from the early summer that year. OPEC has then increased its production and gained market shares alongside a continuing fall in the oil price to around 40 dollars per barrel at the end of 2015 and further to below 30 dollars per barrel in January 2016. As noted in the introduction, we may see this as evidence of OPEC having changed its behaviour to reduce supply of competitors like American producers of shale oil.

The US ten year bond yield used as the discount rate has fallen from around 7 per cent on average in 1992 to around 2 per cent on average in 2015. The lifting costs of OPEC has, however, increased from about USD 7 per barrel on average in 1992 to about USD 11.5 per barrel on average in 2015. The huge spike in the variable $(1 + r_t)(1 + c_t)^{-1}$ in the first quarter of 2015 is mainly attributed to the fact that OPEC reduced its lifting costs by around USD 2 per barrel or nearly 15 per cent during that quarter.

Turning to time series properties, we regard the crude production of OPEC as a non-stationary $I(1)$ variable because of its clear upward trend and no apparent mean reverting property. The variables $(1 + r_t)(1 + c_t)^{-1}$ and $[P_t/C_t - (1 + r_t)(1 + c_t)^{-1}P_{t-1}/C_{t-1}]$, on the other hand, are not so clear-cut with respect to time series properties and may be regarded as borderline cases of being either $I(0)$ or $I(1)$ variables. Therefore, we shall first assume that a reduced rank vector autoregressive (VAR) model in accordance with (9) is a candidate as an empirical model. Then, we shall relax the theoretical set up in (9) and postulate that the supply of OPEC is not equilibrium correcting and only is determined by the ratio between the oil price and the production costs. We note that this alternative model of OPEC behaviour is achieved by setting the variable $(1+r_t)(1+c_t)^{-1}$ equal to unity, and is one simple way of handling the potential stationarity property of the composite explanatory variables in (9). In so doing, we assume that both X_t and P_t/C_t are non-stationary $I(1)$ variables as an underlying premise for the econometric analysis of the alternative model.

4 Cointegration analysis

Because multiple long run relationships may exist among the variables included in the theoretical model of the OPEC behaviour, we employ the Johansen (1995, p. 167) trace test for cointegration rank determination. We thus start with an unrestricted p-dimensional VAR of order k having the form

$$(12) \qquad Y_t = \sum_{i=1}^{k} \Pi_i Y_{t-i} + \mu + \delta t + \epsilon_t, t = k+1, ..., T,$$

where Y_t is a (p x 1) vector of modelled variables at time t, μ represents constants and seasonals, δ is a (p x 1) coefficient vector of a linear deterministic trend t, $\Pi_1, ..., \Pi_k$ are (p x p) coefficient matrices of lagged level variables and $\epsilon_{k+1}, ..., \epsilon_T$ are independent Gaussian variables with expectation zero and (unrestricted) (p x p) covariance matrix Ω. The initial observations $Y_1, ..., Y_k$ are kept fixed.

The question now is how (12) can be reparameterised to a cointegrated VAR (henceforth CVAR) in which the OPEC behaviour can be formulated as a reduced rank restriction on the impact matrix $\Pi = -(I - \Pi_1 - ... - \Pi_k)$. The way the CVAR is formulated in our context depends on the exogeneity status of the $(1+r_t)(1+c_t)^{-1}$ series. First, we shall consider the case when the $(1+r_t)(1+c_t)^{-1}$ series is endogenous in the system, hence (12) is a three-dimensional VAR in $Y_t = (Y_{1,t}, Y_{2,t}, Y_{3,t})'$, where $Y_{1,t} = X_t, Y_{2,t} = [P_t/C_t - (1+r_t)(1+c_t)^{-1} P_{t-1}/C_{t-1}]$ and $Y_{3,t} = (1+r_t)(1+c_t)^{-1}$. If Y_t is $I(1)$, then the first difference ΔY_t is $I(0)$, implying either $\Pi = 0$ or Π has reduced rank such that $\Pi = \alpha\beta'$, where α and β are (3 x r) matrices and $0 < r < 3$. Here r denotes the rank order of Π. Assuming for notational simplicity that $k = 2$, the CVAR becomes

$$(13) \qquad \Delta Y_t = \Gamma_1 \Delta Y_{t-1} + \alpha\beta' Y_{t-1} + \mu + \delta t + \epsilon_t,$$

where $\beta' Y_{t-1}$ is an (r x 1) vector of stationary cointegration relations among $Y_{1,t}, Y_{2,t}$ and $Y_{3,t}$ and $\Gamma_1 = -\Pi_2$ is the (3 x 3) coefficient matrix of the lagged differenced variables. Next, we shall consider the case when $Y_{3,t}$ is weakly exogenous for the long run parameters such that valid inference on β can be obtained by considering the two-dimensional system of $Y_{1,t}$ and $Y_{2,t}$ conditional on $Y_{3,t}$ without loss of information, see Johansen (1992). Following Harbo *et al.* (1998), we may formulate the partial CVAR equivalent to (13) as (again assuming $k = 2$)

$$(14) \qquad \Delta \begin{pmatrix} Y_{1,t} \\ Y_{2,t} \end{pmatrix} = \omega \Delta Y_{3,t} + \gamma_1 \Delta Y_{t-1} + \begin{pmatrix} \alpha_{11} & \alpha_{1r} \\ \alpha_{21} & \alpha_{2r} \end{pmatrix} \beta' Y_{t-1} + \mu_1 + \delta_1 t + \epsilon_{1,t},$$

where ω and γ_1 are (2 x 1) and (2 x 3) matrices, respectively. The corresponding marginal model is $\Delta Y_{3,t} = \gamma_2 \Delta Y_{t-1} + \mu_2 + \delta_2 t + \epsilon_{2,t}$, where γ_2 is a (1 x 3) vector. It follows that $Y_{3,t}$ is included in the long-run part of (14) as a non-modelled variable. Because the number of relevant variables to be included in (12), and hence the number of parameters to be estimated, are potentially large relative to the number of observations in the sample period, it would be useful to impose weak exogeneity on $Y_{3,t}$. However, to know whether β can be estimated from

(14) we first estimate the full system in (13) and test formally rather than assume the weak exogeneity status of $Y_{3,t}$ in that system. We follow common practice and let inference about the rank of β from the full system be based on unrestricted intercepts and a restricted linear trend. Likewise, dummies capturing seasonality in the data enter the system unrestrictedly.

Strictly speaking, the cointegration rank does not have to be determined from the partial system once it has been determined from the full system. Nevertheless, we re-determine the cointegration rank from (14) for the sake of robustness check with the rank determination from (13). As noted by Harbo *et al.* (1998), the asymptotic distribution of the trace test statistic is influenced by conditioning on weakly exogenous variables and standard critical values are thus not valid. We therefore use the critical values in Table 2 in Harbo *et al.* (1998). Also, following the suggestions in Harbo *et al.* (1998) for partial systems, we restrict the linear trend to lie in the cointegration space for inference purposes only. Then, after having determined the cointegration rank, we test whether the linear trend can be dropped from the cointegration relation(s) by applying a conventional χ^2-test. As in the full system, both the constants and the seasonals enter the partial system unrestrictedly.

Irrespective of specifying a full three-dimensional VAR in $Y_t = (Y_{1,t}, Y_{2,t}, Y_{3,t})'$ or a partial two-dimensional VAR in $Y_{1,t}$ and $Y_{2,t}$ conditional on $Y_{3,t}$ being exogenous to the system, we find that $k = 3$ produces models with no serious misspecification according to standard diagnostic tests.[5] That said, the estimated residuals of the $Y_{3,t}$-equation in the full system, and thus also the estimated vector residuals, show some indication (at conventional significance levels) of autocorrelation. Such a problem may in itself be an argument for moving to a partial system to obtain more satisfying residual properties in our case, see Juselius (2006, p. 198). We note that no impulse dummies other than one in the fourth quarter of 2008 to mop up the recent financial crisis are needed to obtain Gaussian residuals in the $Y_{2,t}$-equation, and thus also in the partial system. Table 1 reports trace test statistics for the full and the partial CVAR assuming $k = 3$.

Table 1: Tests for cointegration rank

Full CVAR				Partial CVAR			
r	λ_i	λ_{trace}	p-value	r	λ_i	λ_{trace}	$5\%_{Harbo}$
$r = 0$	0.39	69.67	0.000	$r = 0$	0.38	50.39	30.5
$r \leq 1$	0.21	26.15	0.045	$r \leq 1$	0.09	7.88	15.2
$r \leq 2$	0.06	5.60	0.522				

Notes: Sample period: 1992*Q*1 – 2013*Q*4. The underlying VARs are of order 3. The full CVAR consists of $Y_t = (Y_{1,t}, Y_{2,t}, Y_{3,t})'$, whereas the partial CVAR consists of $Y_{1,t}$ and $Y_{2,t}$ with $Y_{3,t}$ as an exogenous variable. Both systems include unrestricted constants and seasonals and a restricted linear trend. r denotes the cointegration rank, λ_i are the eigenvalues from the reduced rank regressions, λ_{trace} are the trace test statistics, p-value are the significance probabilities from OxMetrics and $5\%_{Harbo}$ are the critical values (5 per cent significance level) from Table 2 in Harbo *et al.* (1998).

We note that the null hypothesis of no cointegration can be rejected, whereas the hypothesis of at most one cointegrating relationship between $Y_{1,t}$, $Y_{2,t}$ and $Y_{3,t}$ cannot be rejected at the 5 per cent significance level (albeit a borderline case) within the full CVAR. Testing a zero restriction on the equilibrium correction coefficient of $Y_{3,t}$ under the assumption of $r = 1$ gives $\chi^2(1)$=1.003 with a p-value of 0.32. Hence, $Y_{3,t}$ may be considered as weakly exogenous for the cointegrating parameters, whose estimates can then be efficiently obtained from the partial rather than the full system without loss of information. In so doing, we

[5] Whereas a VAR of order 2 provides similar diagnostics, a VAR of order 1 produces severe autocorrelation in both the vector residuals and in the residuals of the $Y_{1,t}$-equation and the $Y_{3,t}$-equation of the full system. Results from the diagnostic tests of the VARs are available from the authors upon request.

also save degrees of freedom. The formal tests in Table 1 support the hypothesis that $r = 1$ also in the case of the partial CVAR. Assuming the rank to be unity, a likelihood ratio test of model reduction [see Doornik and Hendry (2009, p. 51)] from a CVAR with the linear trend to a CVAR without the linear trend ($\delta_1 = 0$), yields $\chi^2(1)$=1.58 with a p-value of 0.21. The linear trend is thus *in*significant and excluded from the reduced rank partial VAR when testing the OPEC behaviour further based on the economic model in (9). Table 2 reports likelihood ratio tests about $\alpha = (\alpha_1, \alpha_2)'$ and $\beta = (\beta_1, \beta_2, \beta_3)'$ in (14) for $r = 1$.

Table 2: Likelihood ratio tests of the OPEC behaviour

Hypothesis	LR tests	p-values
$\alpha_1 = 0$	$\chi^2(1) = 7.25$	0.007
$\alpha_2 = 0$	$\chi^2(1) = 31.57$	0.000
$\beta_1 = 0$	$\chi^2(1) = 5.11$	0.024
$\beta_2 = 0$	$\chi^2(1) = 38.50$	0.000
$\beta_3 = 0$	$\chi^2(1) = 14.87$	0.000

Notes: Sample period: 1992Q1 − 2013Q4. All likelihood ratio (LR) tests with degrees of freedom in parentheses are based on the partial CVAR with $r = 1$ and and without a linear trend. $Y_{3,t}$ is weakly exogenous to the system. The exclusion test of $Y_{1,t}$ is based on normalizing on $Y_{3,t}$, whereas the exclusion tests of $Y_{2,t}$ and $Y_{3,t}$ are based on normalizing on $Y_{1,t}$.

First, we observe that weak exogeneity of both $Y_{1,t}$ and $Y_{2,t}$ for the long run parameters, in contrast to $Y_{3,t}$ is rejected. Also, the likelihood ratio tests reject the hypothesis that the modelled variables $Y_{1,t}$ and $Y_{2,t}$ as well as the conditional variable $Y_{3,t}$ are excluded from β. Hence, we obtain the following unrestricted cointegrating vector (normalized on OPEC production measured in million barrels per day)

$$Y_{1,t} = \mathit{const.} + \underset{(2.400)}{16.173} Y_{2,t} + \underset{(11.152)}{43.632} Y_{3,t}, \tag{15}$$

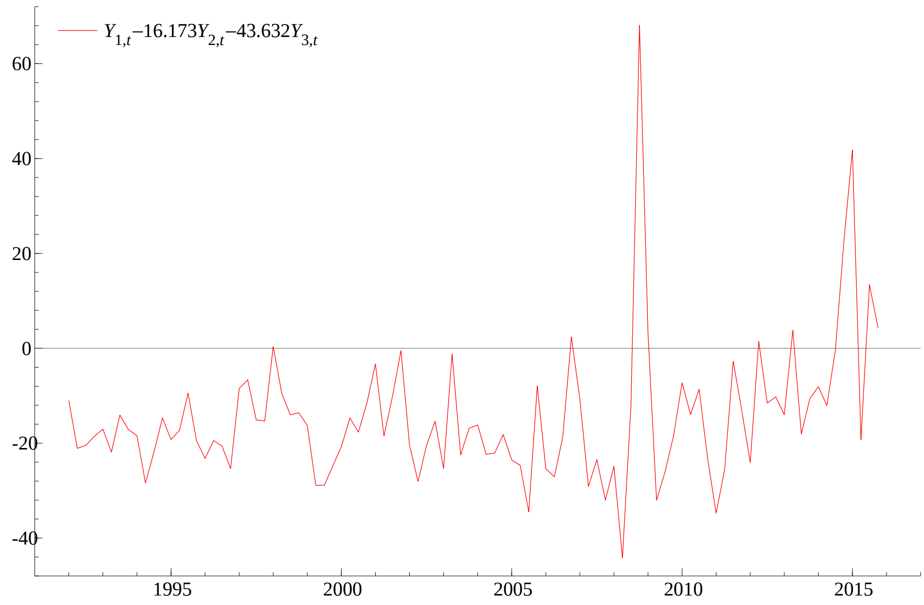
with standard errors in parentheses. The associated vector of equilibrium correction coefficients is estimated to $\alpha = (-0.019, 0.052)'$ with corresponding t-values equal to -2.58 and 5.83, respectively. Because any deviations from (15), due to say a shock in $Y_{3,t}$, are also significantly corrected through the adjustment of OPEC production, we regard the estimated cointegrating vector as a long run relationship of OPEC behaviour consistent with the economic model in (9). Besides, it is evident from Figure 2 that $\widehat{eqcm}_t = Y_{1,t} - 16.173Y_{2,t} - 43.632Y_{3,t}$ has a mean reversion property, indicating a stationary $I(0)$ variable over the sample period. The two big spikes in $\widehat{eqcm}_t$ in the fourth quarter of 2008 and in the first quarter of 2015 are related to the huge drop in the oil price, which reduces $Y_{2,t}$ significantly in these two quarters, cf. Figure 1.

To compute the implied estimates of the parameters of interest, η and ε, we normalize on $Y_{3,t}$, such that $Y_{3,t} = \mathit{const.} - \eta Y_{1,t} - (1 + \varepsilon)Y_{2,t}$, to get

$$Y_{3,t} = \mathit{const.} + \underset{(0.010)}{0.023} Y_{1,t} - \underset{(0.048)}{0.371} Y_{2,t}, \tag{16}$$

with standard errors in parentheses. We observe that $\widehat{\eta} = -0.023$ and $\widehat{\varepsilon} = -0.629$ are significantly estimated with t-values equal to -2.27 and -13.10, respectively. Both estimates are consistent with the OPEC behaviour inherent in (9). In particular, the fact that the estimates are non-zero implies that the Hotelling rule is rejected by the data. The negative estimates of η, although relatively small in magnitude, implies that OPEC production costs depend positively on oil reserves, such that accumulated production decreases the costs. Hence, we find support for Arrow's (1962) learning by doing hypothesis. Finally, the estimate

Figure 2: Time series of deviations of (15)



of the inverse price elasticity ε is well within its interval of having a plausible economic interpretation.

Given our estimate of $\widehat{\varepsilon} = -0.629$ it follows from the discussion in Section 2 that $\widehat{e}_{OPEC} = -1.589$ on average over the sample period. The magnitude of the price elasticity of demand for OPEC oil is thus consistent with the dominant producer model. Using (10) as the relevant formula for calculating the implied price elasticity of oil in the world market and assuming that $s = 0.2$ and $MSOPEC = 0.42$, cf. Figure 1, we calibrate e_W to be -0.55.[6] However, using (11) the estimate of e_W becomes -0.67. As pointed out by Nakov and Nuño (2013), who calibrate their model using -0.25 and -0.05 as values of the price elasticity of oil demand, there is some disagreement in the literature about the magnitude of this elasticity. Our estimates fall well within the range used by Gately (2007), but are fairly high in absolute value compared to for example Alhajji and Huettner (2000a) and Krichene (2002) who find the long run estimate of e_W to be -0.12 and close to zero, respectively.

5 Dynamic models

Having established an empirical counterpart to (9), we now compare and contrast the empirical performance of two competing dynamic models of OPEC behaviour, both in-sample and out-of-sample. To this end, we first estimate a partial CVAR utilizing the findings from the cointegration analysis above. We then estimate, as discussed in Section 3, an alternative single equation dynamic model by relaxing the theoretical set up in (9) such that the supply of OPEC only is determined by the ratio between the oil price and the production costs.

Since we found support for weak exogeneity of $Y_{3,t}$, we can without loss of information abstract from modelling the marginal model for this variable and focus on a CVAR for $Y_{1,t}$ and $Y_{2,t}$, which is fully in accordance with the reduced rank VAR in Section 4. Our point of

[6] Assuming that $s = 0.1$ and $s = 0.3$, the estimates of e_W become -0.61 and -0.49, respectively.

departure is therefore the general partial model written as

$$(17) \qquad \Delta \begin{pmatrix} Y_{1,t} \\ Y_{2,t} \end{pmatrix} = \theta_1 \Delta Y_{3,t} + \theta_2 \Delta Y_{t-1} + \theta_3 \Delta Y_{t-2} + \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} \widehat{eqcm}_{t-1} + \theta_0 + \varepsilon_t,$$

where θ_0 represents constants, seasonals (SD_{1t}, SD_{2t} and SD_{3t}) and the impulse dummy for the financial crisis ($d08q4$). Note that (17) is balanced in the terminology of Banerjee *et al.* (1993, p. 166) when $Y_{1,t}, Y_{2,t}$ and $Y_{3,t}$ all are non-stationary $I(1)$ variables and when $\widehat{eqcm}_t$ is a stationary $I(0)$ variable. We estimate (17) by full information maximum likelihood (FIML) and find that the resulting model has well behaved residuals according to standard diagnostic tests. The general estimated model thus serves as a starting point for the reduction process to obtain a parsimonious representation of (17). A parsimonious model is found by stepwise exclusion of insignificant variables in the system one by one, relying on the Sargan test for overidentifying restrictions and making sure that the well-behaved residuals are retained.

Based on this general-to-specific modelling strategy, we obtain the following parsimonious model together with diagnostics[7], standards errors of coefficients (in parenthesis), standard errors of equations ($\hat{\sigma}$) and the outcome of the Sargan test:

$$(18) \qquad \Delta\widehat{Y}_{1,t} = \underset{(0.104)}{0.409}\Delta Y_{1,t-1} - \underset{(0.098)}{0.226}\Delta Y_{1,t-2} - \underset{(0.055)}{0.125}\Delta Y_{2,t-2} - \underset{(0.004)}{0.0177}\widehat{eqcm}_{t-1} - \underset{(0.104)}{0.437} + \underset{(0.133)}{0.353}SD_{1t} + \underset{(0.130)}{0.520}SD_{3t}$$

$\hat{\sigma} = 0.467$

AR_{1-5}: $F(5, 76) = 0.24$ [0.94], $ARCH_{1-4}$: $F(4, 80) = 1.63$ [0.18]

$NORM$: $\chi^2(2) = 0.16$ [0.92], HET: $F(10, 77) = 1.11$ [0.37]

$$\Delta\widehat{Y}_{2,t} = -\underset{(0.703)}{3.114}\Delta Y_{3,t} + \underset{(0.0047)}{0.0486}\widehat{eqcm}_{t-1} + \underset{(0.097)}{0.859} - \underset{(0.559)}{5.202}d08q4$$

$\hat{\sigma} = 0.558$

AR_{1-5}: $F(5, 79) = 2.16$ [0.07], $ARCH_{1-4}$: $F(4, 80) = 2.33$ [0.06]

$NORM$: $\chi^2(2) = 2.01$ [0.37], HET: $F(4, 83) = 0.31$ [0.87]

$FIML, T = 88$ $(1992Q1 - 2013Q4)$

$Vector\ AR_{1-5}$: $F(20, 144) = 1.09$ [0.37]

$Vector\ NORM$: $\chi^2(4) = 1.99$ [0.74]

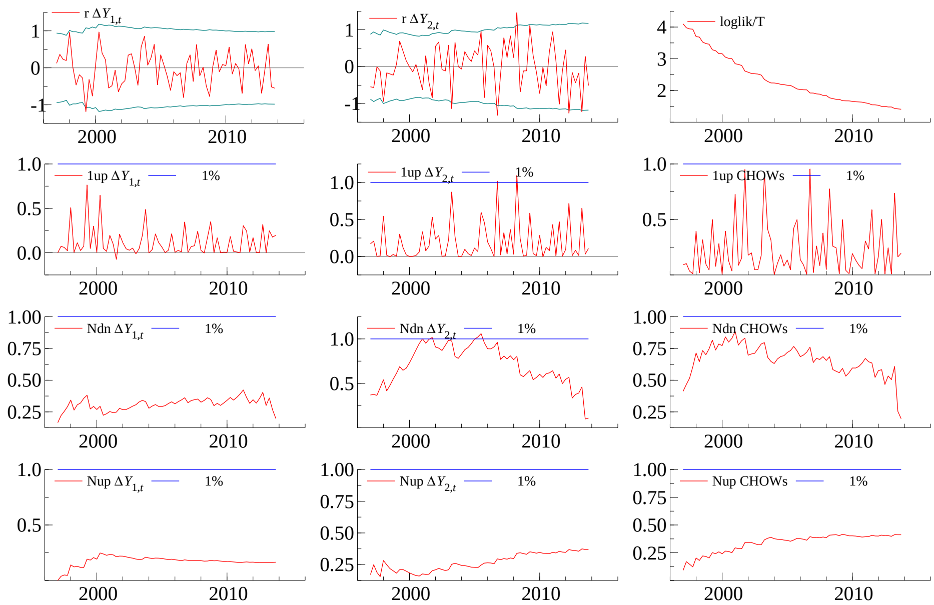
$Vector\ HET$: $F(72, 183) = 0.87$ [0.75]

$Sargan\ test$: $\chi^2(15) = 10.64$ [0.78]

The diagnostics, both single equation test statistics and vector test statistics, indicate that (18) is well specified and the Sargan test supports the restrictions imposed on the model. All the economic variables entering the model are highly significant. The production of OPEC seems to be rather persistent as represented by the significant autoregressive coefficients of $\Delta Y_{1,t-1}$ and $\Delta Y_{1,t-2}$. The $\widehat{eqcm}_{t-1}$ appears with a t-value of -4.4 in the specification for

[7] AR_{1-5} is a test for until 5th order residual autocorrelation; $ARCH_{1-4}$ is a test for until 4th order autoregressive conditional heteroskedasticity in the residuals; $NORM$ is a joint test for residual normality (no skewness and excess kurtosis) and HET is a test for residual heteroskedasticity. $Vector\ AR_{1-5}$, $Vector\ NORM$ and $Vector\ HET$ are the corresponding test statistics for the system as a whole, see Doornik and Hendry (2009, p. 168). The numbers in square brackets are p-values.

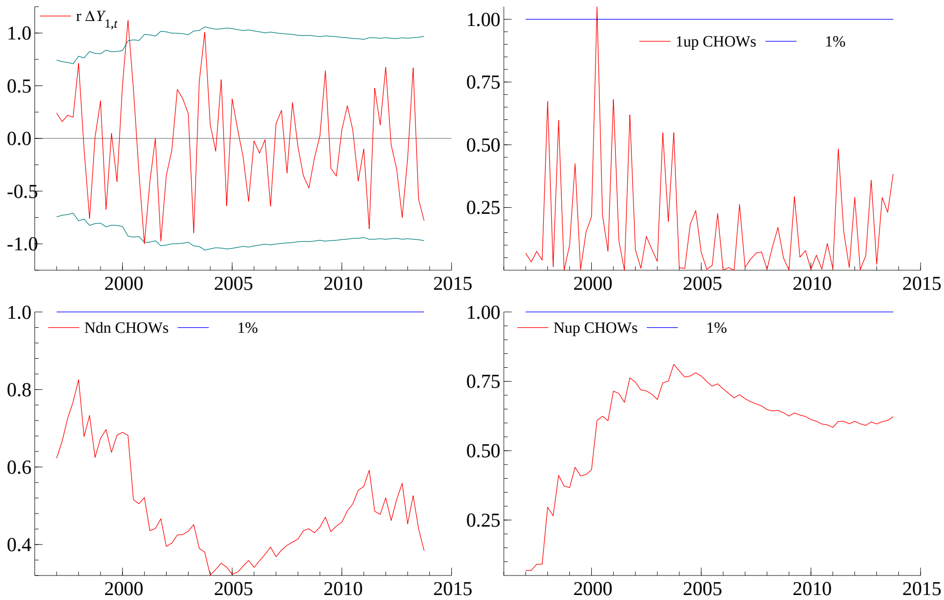
Figure 3: Recursive statistics of (18)



$Y_{1,t}$, hence adding force to the results obtained from the cointegration analysis. We do not find any short run effects on $Y_{1,t}$ from $Y_{3,t}$, only lagged, but relatively small short run effects from $Y_{2,t}$. No contemporaneous short run effects and the small magnitude of the estimated adjustment coefficient of -0.018 together imply rather slow adjustment in the production of OPEC in the face of shocks in the oil price, the costs of production or the interest rate. Turning to the specification for $Y_{2,t}$, we find that this variable also error corrects when departing from the long run equilibrium. A positive shock in say OPEC production will thus be transmitted to increased $Y_{2,t}$ through the highly significant $\widehat{eqcm}_{t-1}$ term, possibly reflecting that reduced extraction costs due to learning by doing effects in OPEC production dominate negative effects on the oil price. Normalising the cointegrating vector on $Y_{2,t}$, we find that the estimated adjustment coefficient is -0.79, indicating a much faster adjustment towards equilibrium than what production of OPEC does. This may not be very surprising as $Y_{2,t}$ consists of oil prices and production costs, which are more easily changed in the short run. Finally, we find some contemporaneous effects of $Y_{3,t}$ on $Y_{2,t}$ and large negative effects from the impulse dummy $d08q4$ due to the huge drop in the oil price of around 110 dollars per barrel from the third to the fourth quarter of 2008.

As mentioned in the introduction, we use recursive methods to investigate whether (18) exhibits empirical constancy in-sample. Figure 3 depicts the recursive residuals with $\pm 2\hat{\sigma}_t$ and the scaled log-likelihood function as T increases (i.e., the recursively computed Sargan test) in the first row, the sequence of one step Chow tests in the second row, the sequence of break point Chow tests in the third row and the sequence of forecast Chow tests in the fourth row, all of which are scaled by their 1 per cent critical values, see Doornik and Hendry (2009, p. 75). We see from the recursive residuals and the one step Chow tests that there are some minor instabilities in the specification for $Y_{2,t}$ in 2008/2009 during the financial crisis. That said, there is no evidence of instabilities in the specification for $Y_{1,t}$ and the system as a whole and the hypothesis that (18) parsimoniously encompasses the general system is not rejected for any sample sizes. Unlike Almoguera *et al.* (2011) and Alkhathlan *et al.* (2014), we therefore argue that the OPEC behaviour has not changed significantly in-sample.

Figure 4: Recursive statistics of (19)



To investigate whether there may be any improvement in the empirical performance of the model in-sample, we ignore the findings from the cointegration analysis and estimate an alternative dynamic model for $\Delta Y_{1,t}$ based on $\Delta Y_{1,t-1}$, $\Delta Y_{1,t-2}$, $\Delta Y_{4,t}$, $\Delta Y_{4,t-1}$, $\Delta Y_{4,t-2}$, 1, SD_{1t}, SD_{2t} and SD_{3t} as regressors, where $Y_{4,t} = P_t/C_t$. In so doing, we follow the alternative hypothesis in Section 3 about the time series properties of the variables involved and assume that both $Y_{1,t}$ and $Y_{4,t}$ are non-stationary $I(1)$ variables and that $Y_{2,t}$ and $Y_{3,t}$ both are stationary $I(0)$ variables. Under these assumptions, and the fact that $Y_{3,t}$ is set equal to unity such that $Y_{2,t}$ becomes equal to $\Delta Y_{4,t}$, the alternative dynamic model is balanced. For comparison reasons, the alternative general model includes the same lag length of the variables as in the general CVAR. We rely on the general-to-specific modelling strategy available in the autometrics procedure in OxMetrics when estimating the alternative dynamic model, see Doornik and Hendry (2009). Using OLS, autometrics picks the following specific alternative dynamic model:[8]

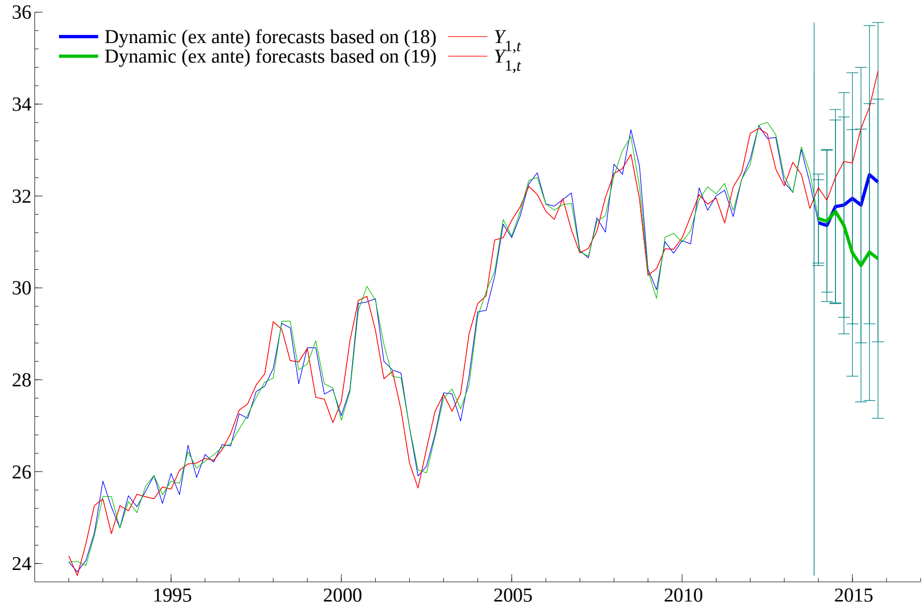
$$(19) \quad \Delta\widehat{Y}_{1,t} = \underset{(0.094)}{0.239}\Delta Y_{1,t-1} + \underset{(0.069)}{0.135}\Delta Y_{4,t} + \underset{(0.072)}{0.229}\Delta Y_{4,t-1} + \underset{(0.106)}{0.284}SD_{3,t}$$

$$OLS, T = 88\ (1992Q1 - 2013Q4), \hat{\sigma} = 0.485$$
$$AR_{1-5}\colon\ F(5,79) = 0.98\ [0.44],\ ARCH_{1-4}\colon\ F(4,80) = 2.42\ [0.055],$$
$$NORM\colon\ \chi^2(2) = 0.54\ [0.76],\ HET\colon\ F(7,80) = 0.56\ [0.79].$$

We see that the alternative model, just like (18), is well specified, albeit the test for autoregressive conditional heteroscedasticity now is a borderline case at the 5 per cent significance level. The two estimated models are quite different with respect to the effects on OPEC production from the autoregressive terms and the seasonal dummies. We note

[8]The target size of the reduction process matters for the outcome of the specific model. We present the model based on 0.10 as the target size. Using a target size of 0.05 autometrics picks a specific model which has poorer fit in-sample.

Figure 5: Actual values and dynamic (ex ante) forecasts of $Y_{1,t} \pm 2\hat{\sigma}_t$



that no constant term is significantly estimated in (19) in accordance with (9) when $Y_{3,t}$ is set equal to unity. Also, the alternative model includes contemporaneous as well as lagged effects from $Y_{4,t}$, effects which only come about through lags of $Y_{2,t}$ in (18). The estimated standard error, $\hat{\sigma}$, increases somewhat and indicates that (19) has slightly poorer fit than (18) in-sample. Figure 4 shows that (19) is reasonable stable within sample except for one significant instability around 2000, as revealed by the one step Chow tests.

To assess the forecasting performance of the two competing dynamic models of OPEC behaviour, we employ eight quarters ($2014Q1 - 2015Q4$) of out-of-sample observations, including the OPEC meeting in November 2014. Figure 5 depicts actual values of $Y_{1,t}$ together with dynamic (ex ante) forecasts based on (18) and (19), adding bands of 95 per cent confidence intervals to each forecast. Generally, the out-of-sample forecasting ability is quite poor for both models. Although the actual values of $Y_{1,t}$ all stay within their corresponding confidence intervals, we see that (18) systematically underpredicts the production of OPEC during the entire forecasting period. At the end of 2015 the model underpredicts the production of OPEC by almost 2.5 million barrels per day or by around 7 per cent. The forecasting properties of the alternative model are even worse. The actual values for the last three quarters of 2015 are either on or outside the confidence intervals and (19) underpredicts the production of OPEC by as much as 4 million barrels per day or nearly 12 per cent at the end of 2015. As a result, the RMSE (root mean square errors) statistics of the forecasts based on (19) is 2.3 compared to 1.3 based on (18).

Using a sequence of parameter constancy forecast Chow tests, we can detect whether there are any significant structural breaks in the forecasting period, see Doornik and Hendry (2009, p. 36). We find that these test statistics based on (18) are far from being significant for the first three quarters of 2014. However, from the fourth quarter of 2014 and to the end of the forecasting period, these test statistics are highly significant with p-values of close to zero in all cases. Since a significant structural break is occurring in the fourth quarter of 2014, we conclude that OPEC indeed changed its behaviour following the meeting in November 2014.

6 Conclusions

In this paper, we have formulated a theoretical model of OPEC behaviour that encompasses a number of hypotheses discussed in the literature, among them price taking behaviour, imperfect competition in various forms and the Hotelling rule. Confronting the model with quarterly data for the period 1992 to 2015, we found support for the imperfect market hypothesis regarding the output decisions of OPEC. Our average estimate of the price elasticity of demand for OPEC oil is significantly less than minus unity, consistent with the dominant producer model. Besides, we found that costs of extraction are significantly affected by the resource stock through learning by doing effects in OPEC production, invalidating the Hotelling rule.

We have also shown that a dynamic equilibrium correction model exhibits reasonable empirical constancy in-sample and has somewhat better fit than an alternative dynamic model with weaker theoretical underpinnings. The alternative dynamic model lacks the underlying theory of OPEC behaviour as the findings from the cointegration analysis are ignored, a major disadvantage because the parameters of interest, the price elasticity of oil demand in particular, are impossible to infer from that model. We therefore argue that there is value added of having a cointegration relationship in the dynamic model of OPEC behaviour once it is supported by the data, as is the case in our context.

A forecasting exercise revealed, however, that the dynamic equilibrium correction model systematically underpredicts OPEC production over the last two years. At the end of 2015 the model underpredicts OPEC production by almost 2.5 million barrels per day. We also found evidence of a significant structural break in the fourth quarter of 2014, coinciding with the OPEC meeting in November 2014. Our findings suggest that the OPEC behaviour regarding output decisions indeed has changed significantly out-of-sample, probably to protect its market share by limiting the role of competitors like American producers of shale oil.

An interesting question that arises is to what extent the change in the behaviour of OPEC has affected world oil prices after the meeting in November 2014. While beyond the scope of this paper, a more comprehensive model of world demand and supply for crude oil seems to be needed to describe the behaviour of OPEC in recent years. We leave this for future work.

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