

World Oil Depletion Models: Price Effects Compared with Strategic or Technological Interventions

Modelli per l'Esaurimento Mondiale del Petrolio: Effetto Comparato dei Prezzi in Presenza di Interventi Strategici o Tecnologici

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Riassunto: L'esaurimento del *crude oil* mondiale, comprensivo degli NGL (*Natural Gas Liquids*), è stato modellato di recente in Guseo and Dalla Valle (2004) e in Guidolin (2004) mediante processi di diffusione a ciclo di vita limitato. Qui si introducono separatamente e congiuntamente interventi regolatori di natura strategico–tecnologica e di natura economica. Le modellazioni confermano il ruolo centrale degli shock storici osservati, 1973 e 1979, mentre le variazioni del prezzo del greggio, in dollari costanti, sembrano avere un ruolo subordinato. Di grande rilievo risulta lo shock a memoria lunga, qui evidenziato, che ha origine nel primo dopoguerra, 1951, ed i cui effetti sono ancora presenti.

Keywords: oil peak, depletion times, price effects, Bass models, nonlinear models.

1. Introduction

One of the current main problems is the development of a coherent and feasible energy policy for economy and security. The powerful worldwide economic growth after the World War II has caused very high demographic growth rates, never experimented before. This extraordinary economic growth sustained by surplus capacity in hydrocarbon fuels, in particular by crude oil production, seems to be the foundational basis of a structural modification of global economy and correlated energy consumptions. Nowadays, the most expanded economies are facing the beginning of capacity limitations so that the assumption of an increasing oil production in the next decade does not seem realistic. Emerging technologies are not yet commercially or technologically viable to fill completely the shortage.

The first historical evaluation of crude oil depletion goes back to 1949 by Hubbert. In 1956 he correctly estimated that USA oil production would peak around 1970 and later in 1962 he recognized the explicit role of logistic equation in his previous model. Campbell and Laherrère (1998) in a key-paper, assert that a world oil peak is imminent and recent geological studies confirm this fact. From this date in advance many works were developed in this area to describe the decline of oil production and, sometimes, to identify depletion times. We skip here reviewing discussion. The common starting point is the Hubbert model: the final awareness is that this model is too simplistic for the declared purposes.

Almost all of the geological models produced till now, include, not always in a rigorous mathematical way, the influence of technology, but never systematic shocks or interventions which may heavily affect normal production evolution. For instance, the forced production of Prudhoe Bay in Alaska was a positive shock, and, on the contrary, the negative effect of accidents in pipelines (Piper Alpha disaster) in the North Sea depressed regular production.

In this paper we extend Guseo and Dalla Valle (2004) and Guidolin (2004) results by considering oil production as a diffusion model and we refer to special generalized Bass models (GBM) introduced by Bass *et al.* (1994). We use cumulative production data because the technical evaluation of reserves is not very reliable since the resources have been over estimated for financial reasons. To point out systematic shocks we include also intervention variables useful for separating stochastic disturbances from systematic changes in life-cycle behaviour possibly due to strategic effects, price effects, etc.. We use also the series of barrel prices to include economic theories of demand and supply.

In Section 2 we briefly introduce the Generalized Bass model, its properties and the description of the intervention variables which can be included in the model. The model with three exponential shocks is briefly discussed together with the result that variations in oil prices have a subordinate role.

2. World Oil Depletion Models: interventions and price effects

The diffusion of an innovation in a social system may depend upon two principal forces which describe the asymmetric information of the agents in a system or in an economy. At a first step, only two types of agents can be considered: innovators and imitators. The first ones give direct attention to advertising or communication of companies. The second ones adopt the innovation only in a second time by reinforcing a personal opinion on the basis of a word-of-mouth effect.

A Bass model describes the life-cycle of a generic product by the cumulative function $z = z(t)$. It is a function of time and potential market, m . Denoting with z' the instantaneous adoptions, the generalized Bass model, GBM, is therefore

$$z' = m \left(p + q \frac{z}{m} \right) \left(1 - \frac{z}{m} \right) x(t) = \left(p + q \frac{z}{m} \right) (m - z)x(t), \quad (1)$$

and the general closed form solution, for $z(0) = 0$, is

$$z(t) = m \frac{1 - e^{-(p+q) \int_0^t x(\tau) d\tau}}{1 + \frac{q}{p} e^{-(p+q) \int_0^t x(\tau) d\tau}} = mF(t), \quad 0 \leq t < +\infty. \quad (2)$$

The function $x(t)$ is an integrable function varying around 1 and representing political, economical and structural interventions. It modifies the perception of the residual market, $(m - z)x(t)$ but not the carrying capacity, m , and the intrinsic diffusion parameters p and q . For further details about this topic see Guseo (2004). A simple parametric description of the intervention function $x(t)$ in Equation (1) may be modeled by some exponential shocks, for example three,

$$x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{t \geq a_1} + c_2 e^{b_2(t-a_2)} I_{t \geq a_2} + c_3 e^{b_3(t-a_3)} I_{t \geq a_3}, \quad (3)$$

if we consider a non uniform distribution of memory effects on intervention.

The coefficients c_i , $i = 1, 2, 3$, control depth and sign of perturbation, while the coefficients b_i , $i = 1, 2, 3$, describe the nature of persistency of the effect. If the b_i are positive we obtain a strong acceleration in the saturation of the life-cycle. The coefficients a_i , $i = 1, 2, 3$ denote the starting times of exponential shocks.

A simple specification of a statistical version of a GBM model may be of nonlinear regressive nature, i.e., $y(t) = f(\beta, t) + \varepsilon(t)$, where $f(\beta, t) = z(t)$ is the deterministic part which is a nonlinear function of the unknown vector of parameters $\beta \in R^k$, and other time-dependent variables included in $x(t)$ (such as prices). The component $\varepsilon(t)$ is a stochastic process representing the i.i.d. residual error. The usual assumptions consider $\varepsilon(t)$ as a white noise process. Therefore, we estimate parameters β following a nonlinear least squares procedure. At a second step, we use the estimated function $f(\hat{\beta}, t)$ as a regressor, or a lagged multiplicity of regressors, in a ARMAX model in order to identify possibly autocorrelated error structures (see Guseo (2004)). The solution is clearly sub-optimal if compared with an estimation procedure which takes into account jointly all the parameters. The lack of fit is however quite limited.

We consider data provided by Industriedatenbank (2001) based on daily world oil production in thousands of barrels, from 1900 to 1986. The second part of the series going from 1987 to 2002 and based on BP (British Petroleum) data considers also new contribution of NGL (*Natural Gas Liquids*). The same source, BP, gives also the series of barrel prices $D(t)$, with $t \in [1900 - 2002]$ in USA dollars (fixed base: 2002).

As a first approach to the modeling, we have considered GBM models with pure price control. However, the obtained results suggest us that prices series alone may not control completely the series of world oil production. There is also a self-evident contradictory behaviour: the growth of prices corresponds to local increment in expressed demand. This is incoherent with standard economic theory of quantity-price relationship.

The second modeling approach is based on the hypothesis that the historical shocks must be modeled separately and/or jointly with prices data. Sometimes, the regressive implementation is improved with an ARMAX model based upon one regressor or more lagged regressors that depend upon the predicted values of the first regressive step.

The most interesting and surprising result is represented by a model in which we directly attempt to accommodate three shocks with a very high goodness-of-fit, $R^2 = 0.999994708$. We discover here, for the first time, the strong positive long memory effect starting with 1951. If we compare the nested model with two exponential shocks with the last one we find that squared partial multiple correlation coefficient is $\tilde{R}^2 = 0.56$, ($F \simeq 17.06$), so that the evidence of a third shock, starting with 1951, is very strong.

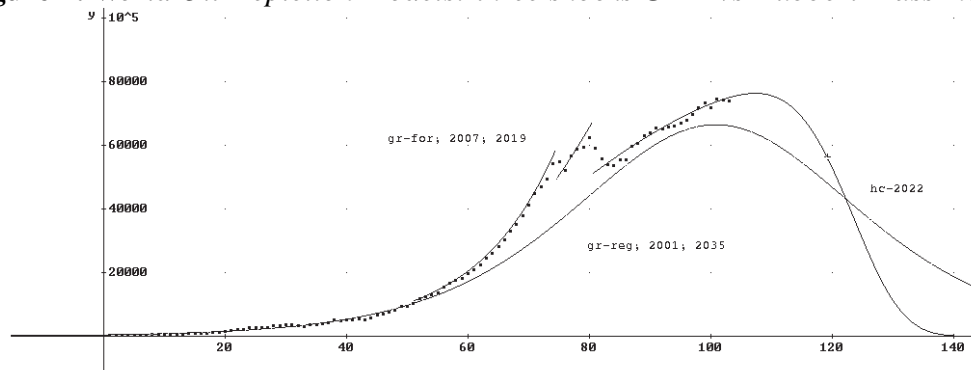
Table 1: World oil depletion: GBM model estimates with 3 exponential shocks.

$m = 4174561$	$p = 0.00010439$	$q = 0.063497$	$R^2 = 0.999994708$
$c_1 = -0.3021860$	$b_1 = 0.05674$	$a_1 = 80.50$	
$c_2 = 0.0717753$	$b_2 = 0.07187$	$a_2 = 51.07$	(annual m :)
$c_3 = -0.2272032$	$b_3 = 0.07098$	$a_3 = 74.60$	URR=1524 Gbo

All coefficients b_i , $i = 1, 2, 3$ (see Table 1) are positive so that the effects are persistent in time and interact significantly with the main stream of normal evolution controlled by

standard Bass structure. The beginning times of the shocks are correctly positioned and this allows clear interpretations as briefly developed in introduction.

Figure 1: World Oil Depletion Models: three shocks GBM vs Hubbert–Bass model.



The GBM with three exponential shocks predicts an URR (Ultimate Recoverable Resource) of 1524 Gbo. The peak time of maximum instantaneous production, 2007, is shifted of one year w.r. to the corresponding peak time based on a GBM with two exponential shocks. The effect of long memory perturbations is recognized in the identification depletion times, $t_{0.90} = 2019$ and $t_{0.95} = 2023$, which appear particularly imminent. Note that the peak–date, by 2007, and the estimated production during 2020, by about 55 mb/d, are exactly equivalent to those referred by Bakhtiari (2004) by the means of WOCAP model developed upon oil reserves estimates by C.J. Campbell. See for instance Figure 1 where x is time t with origin corresponding to 1900 and dots (ordinates) represent the daily oil production per year, y , the broken line depicts the proposed GBM model and the continuous line represents the evolution of the Bass process without interventions.

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