MODELLING THE OIL PRODUCERS

Capturing Oil Industry Knowledge in a Behavioural Simulation Model

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ABSTRACT

A group of senior managers and planners from a major oil company met to discuss the changing structure of the oil industry stemming from the moves of traditional producers into refining and retailing. This broad ranging discussion led to a system dynamics simulation model of the oil producers.The model produced new insights into the power and stability of OPEC (the major oil producers' organization), the dynamics of oil prices, and the investment opportunities of non-OPEC producers.

The paper traces the model development process, starting from group discussions, to flip chart drawings, to STELLA maps and finally to working simulation models. Particular attention is paid to the methods used to capture team knowledge and to ensure that the STELLA models reflected opinions and ideas from the meetings. The paper describes how diagrams of behavioural decision functions were used to collect ideas about the 'logic' of the principal producers' production decisions. The diagrams served as a record of the meetings and the basis for first-cut STELLA maps. A selection of diagrams is used to illustrate the content of the model.

A sub-group of the project team was involved in developing and testing an algebraic model. The paper shows partial model simulations similar to those used by the sub-group to build confidence and a sense of 'ownership' in the algebraic formulations. Further simulations show how the full model can stimulate thinking about producers' behaviour and oil prices.

INTRODUCTION

The dramatic movements of oil price over the past 20 years have led to economic depression, inflation, huge concentrations of wealth in the oil-rich nations and to booms and busts in the exploration and production industry. As many know well, the 1970s began with low and stable oil prices of around $6 to $7 per barrel (in 1985 $). The year 1973 saw price rocket to more than $20 per barrel as OPEC exercised its newly discovered power. The trajectory of oil price then stabilized for five years at around $19 per barrel, only to shoot upwards once more in 1978 to hit a peak of $36 per barrel during 1981. The mid 1980s witnessed a dramatic reversal of the trajectory, as prices tumbled to less than $10 per barrel in 1985 -- back to the low levels of the early 1970s. In recent years, the price has been low and erratic in the $10 to $20 per barrel range (Jennings 1988).

Why and how do such disruptive price movements occur? Is it possible for producing nations and firms to orchestrate a more stable price profile that ensures predictable revenue flows and that wreaks less havoc in economic, commercial and social conditions? What range of oil prices is likely during, say, the next 20 years? (Jennings 1988, Fossli and Wilkinson 1986, Wilkinson 1988)

The Oil Producers' model arose from a desire by the oil company's managers to explore these questions in depth for themselves. The approach taken was to assemble an experienced team of ten of these managers and to use their knowledge of the oil industry as the basis for a model. (The experienced-team approach was chosen as a deliberate alternative to the usual option of seeking the opinion of an internationally recognized authority on oil markets). The team met three times for working sessions lasting two to three hours each. The meetings were facilitated by an experienced system dynamics modeller. Extracts from the brief used to organize the meetings are quoted below to indicate how the facilitator intended to capture the knowledge of the team. (A review of methods for eliciting group knowledge as a basis for model building is provided in Andersen et al 1989).

> "To examine the issue of 'industry structure and price dynamics', the planning department should convene a 'forum' to discuss the main 'players' in the industry, their decisionmaking processes, motivations, resources, internal needs, external needs, culture etc.
>
> The forum will consist of a series of meetings of a project team comprising experienced managers invited by the planning department
>
> The forum should aim to produce a 'map' showing the main players and connections which make-up the industry structure. The map will be accompanied by explanatory text and possibly, though not definitely, some small simulation models based on 'fragments' of the map.
>
> The project team should prepare for the forum by reading selected papers that indicate the desired 'flexible and participative' style of modelling (de Geus 1988, Morecroft 1988a, Richmond 1987). (other articles that convey a similar message about modelling are Kalff 1989, Morecroft 1990, Vennix et al 1987, Management Brief 1989)
>
> In addition the team should participate in a preliminary meeting to 'set the ground rules' for future working meetings and to clarify the modelling/problem structuring framework by reviewing the mapping symbols and in particular the behavioural decision function (Morecroft 1988a and 1988b) as a graphical aid to capturing team knowledge."

The working meetings were intended to concentrate on qualitative mapping and modelling. No computers were present in the meeting room, and the maps that were used to guide and capture team discussion were all drawn on flip-charts. By avoiding the early introduction into the meeting of very structured modelling (e.g. STELLA or detailed system dynamics diagramming) it was possible to sustain the involvement and input of the project team. (note that qualitative graphical mapping software or magnetics (Communikit Systems 1989 and Creativity Software 1989) might be used in place of flip-charts).

PRODUCERS AND THE MARKET -- CONCEPTUALIZATION

Figure 1 is the team's own framework (devised in the first working meeting) for organizing its discussion of the oil market. The oil producers are divided into three categories: swing producer, opportunists and independents. The swing producer together with the opportunists make up the oil producers' organization OPEC, while the independents represent all other producers. OPEC coordinates its production through quota setting shown in the middle of the figure. The market adjusts price according to the supply-demand imbalance, and adjusts demand according to short and long-term influences from price, GDP and other non-economic demand determinants.

Figure 1 was used by the facilitator to prompt in-depth discussion by the team of the upstream oil industry. The four circular symbols represent 'behavioural decision functions' of the producers. Each of the symbols was sketched in turn on a flip-chart in the meeting room and used as the basis of a 30 to 60 minute team discussion of 'producer logic'. Using the symbols (together with background knowledge of behavioral decision theory, Morecroft 1983, Sterman 1988 & 1987), an experienced modeller can pose many 'leading questions' such as: how do producers decide how much to produce; what information do they use; how does OPEC decide on a production quota; how is the quota allocated; what motivates the independents to change production; how does the 'production logic' of the swing producer differ from the opportunist or the independent. A similar process of facilitated team discussion took place with the box representing the market, in order to probe the team's opinions on price and demand changes (what information does the market use to 'measure' supply-demand imbalances, how rapidly does price adjust to a supply shortage of say 1 million barrels per day, which anchors and cues shape the consumers' demand decisions?).

The working meetings yielded about 20 flip chart pages showing graphically the information flows entering the producers' and consumers' behavioural decision functions, with text notation to indicate the team's opinions on how the information is processed. Additional text pages captured the team's judgements on factual information such as production rates, operating capacity, surplus capacity, producers' market share, current price, price profiles, and demand. Illustrative examples of this 'conceptual raw material' for modelling are shown later for the cases of the swing producer and the independents.

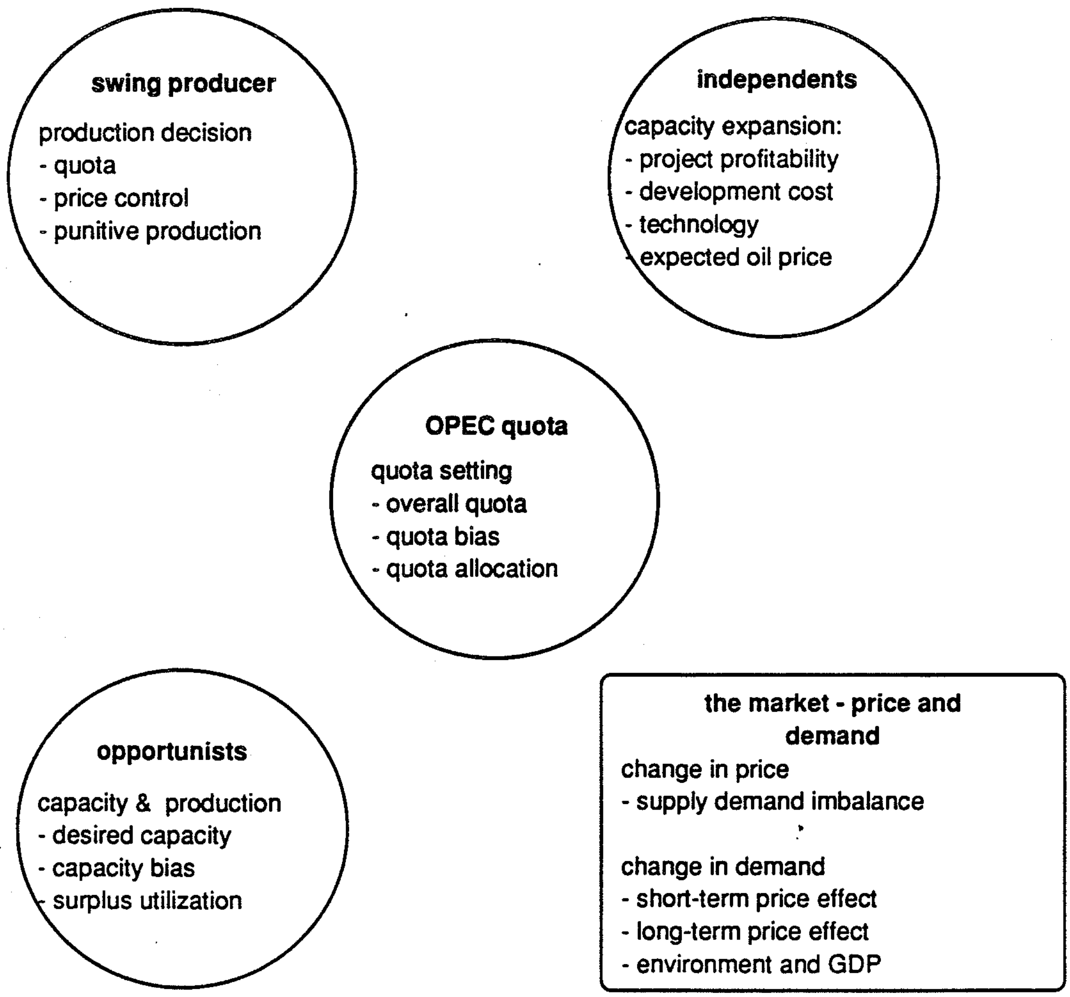

Figure 1: Producers and the Market -- Components of a Conceptual Model

MAPPING AND MODELLING THE SWING PRODUCER

The next two sections show sample 'maps' based on flip-chart drawings from the team meetings. The diagrams use symbols for policy maps (Morecroft 1982). A large circle with horizontal bars represents a behavioural decisionmaking process. Labelled, curved lines with an arrow head represent a flow of information -- information that is used in the decisionmaking process in question. Straight lines in **bold** represent the output of a decisionmaking process such as the swing producer's production. Labels in **bold** represent important policy levers or simulator controls. The diagrams are best understood by putting yourself in the position of the decisionmakers -- imagine being a swing producer, or sitting-in on a Capex meeting of an independent producer.

The role of the swing producer is to produce just enough to defend the intended price, known in the industry as the marker price. A producer taking on this role must have both the physical and economic capacity to increase or decrease production quickly, by as much as 2 million barrels per day or more, in order to absorb unexpected variations in demand (due say to an unusually mild winter) or to compensate for cuts in the output of other producers. (Few producers are capable of handling such variability of output and revenue) . But how does the swing producer decide how much to produce? Figure 2 shows the range of factors entering the decision making process.

The swing producer operates in two modes -- 'normal swing mode' and 'punitive mode'. In swing mode, the swing producer sets a production rate that is equal to the swing quota, unless the oil price deviates from the intended marker price. When a price deviation is detected, he quickly turns-up or turns-down the 'taps on production' in order to regulate the price. In swing mode, the swing producer can influence market price by making production adjustments, the size of which depend on the price he is trying to defend. In the model, price control is exercised through the policy lever **'oil price bias'**, shown in the bottom left of the diagram.

In 'punitive mode' the swing producer feels that his production is inadequate -- he is not getting a fair share of the market or is receiving too little revenue -- and so decides to re-establish his position by punishing the other producers. In the model, the swing producer has a 'threshold' below which he is unwilling to allow market share to fall. In the diagram the threshold is shown graphically with a slide bar. When market share falls below the threshold, the swing producer sets a new and higher volume of production that floods the market and quickly lowers the price. The switch to punitive mode can send a powerful price signal to discipline the other producers, but it is an act of last resort, because in this mode the swing producer has abandoned the role of price regulator -- essentially the market is no longer managed.

STELLA Map and Algebra for the Swing Producer

Figure 3 shows a partial STELLA map (Richmond et al 1987) of the swing producer (excluding the determinants of swing mode). The map was constructed by a 4-person modelling team which was a sub-group of the full project team, starting from the flip-chart drawings and meeting notes. (The modelling team included two experienced managers, an external consultant acting as facilitator and model designer, and a model builder).

The figure traces how the swing producer's production responds to quota and to market oil price. The principal logic of changes in production is shown in the left-hand branch of the figure. Indicated swing production (towards which production adjusts) depends on the swing quota and production pressure from the marker price. In the absence of price pressure, the swing producer produces at quota. But when the market oil price falls below the intended marker price (the price that OPEC is defending) the swing producer reduces production to compensate, and vice-versa. The intended marker price is shown as a function -- actually a two-year average -- of the market oil price, modified by the oil price bias (representing the swing producer's tendency to edge oil price up or down) and the 'OPEC quota bias' (which represents the degree to which OPEC intends to under-produce or over-produce). The right hand branch of the figure shows the 'logic' of punitive production. When the swing producer

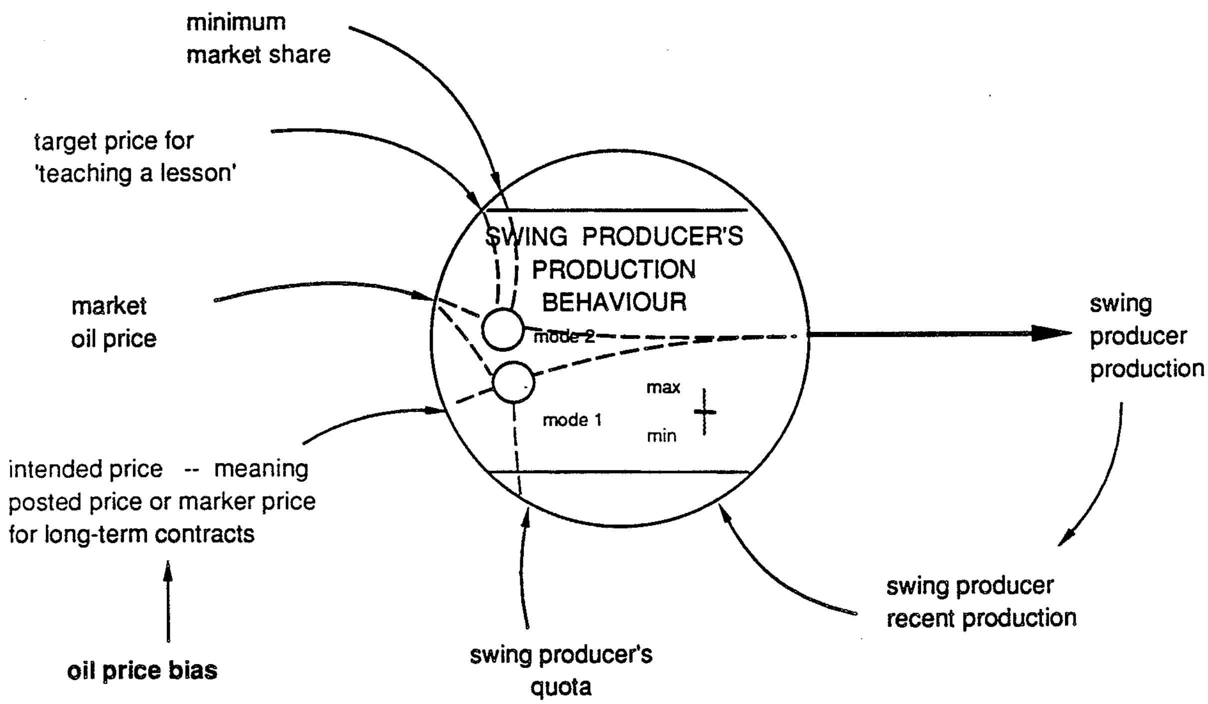

Figure 2: The Logic of the Swing Producer

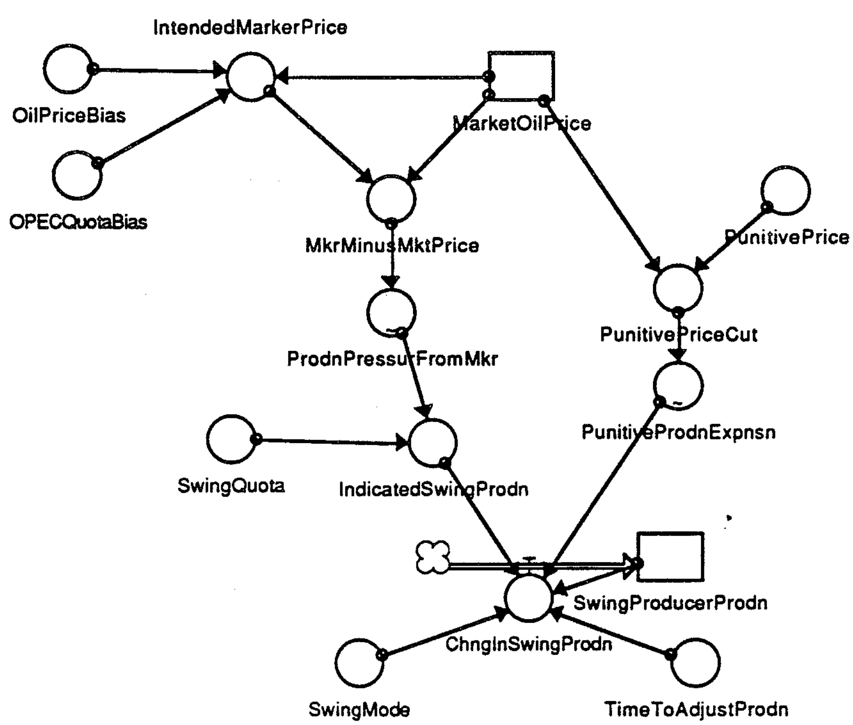

Figure 3: STELLA Map of the Swing Producer

switches into punitive mode, he ignores quota and price control and instead engages in punitive production expansion dictated by a punitive price cut. The size of the price cut depends on the difference between market oil price and a 'punitive price' representing the rockbottom price that the swing producer is prepared to tolerate.

```
MarketOilPrice = MarketOilPrice
INIT(MarketOilPrice) = 15  {$ per barrel}

SwingProducerProdn = SwingProducerProdn + dt * ( ChngInSwingProdn )
INIT(SwingProducerProdn) = 7
{Millions of barrels/day. To start, set CallOnOPEC-OpptCapcty = (50-26) - 17 = 7 }

OPECQuotaBias = 0

ChngInSwingProdn = IF (SwingMode=1)
THEN ((IndicatedSwingProdn-SwingProducerProdn)/TimeToAdjustProdn)  ELSE
(SwingProducerProdn*PunitiveProdnExpnsn*12)

IndicatedSwingProdn = SwingQuota*ProdnPressurFromMkr

IntendedMarkerPrice =  SMTH1(MarketOilPrice,2)*(1+OilPriceBias)/(1+OPECQuotaBias)
{The marker price the Swing Producer would like to see. Based on a 2 year average of
MarketOilPrice adjusted by the OilPriceBias and by the OPECQuotaBias}

MkrMinusMktPrice = (IntendedMarkerPrice-MarketOilPrice)
{Indicates the pressure on the Swing Producer's production from the need to keep market price
equal to the marker price}

OilPriceBias = 0
{A factor representing the amount by which the Swing Producer would like to increase market
oil price}

PunitivePrice = p  {dollars per barrel.  The minimum price that the Swing Producer will accept
when operating in punitive mode}

PunitivePriceCut = MarketOilPrice-PunitivePrice
{The  extent of price cut the Swing Producer can tolerate when operating in punitive mode}

SwingMode= 1
{Sets the Swing Producer's production behaviour.  SwingMode =1 represents normal swing
behaviour, and 0 represents punitive behaviour}

SwingQuota = q   {million barrels per day}
TimeToAdjustProdn = .25  {Years}

ProdnPressurFromMkr = graph(MkrMinusMktPrice)
(-10.00,1.80),(-8.00,1.50),(-6.00,1.30),(-4.00,1.20),(-2.00,1.10),(0.0,1.00),(2.00,0.900
),(4.00,0.800),(6.00,0.720),(8.00,0.670),(10.00,0.650)
 PunitiveProdnExpnsn = graph(PunitivePriceCut)
(0.0,0.0),(1.00,0.0500),(2.00,0.0800),(3.00,0.0950),(4.00,0.100),(5.00,0.100),(6.00,0.1
00),(7.00,0.100),(8.00,0.100),(9.00,0.100),(10.00,0.100)
```

Figure 4: Algebra for the Swing Producer

MAPPING AND MODELLING THE INDEPENDENTS

The independents are all those producers -- state-owned oil companies, the majors and other private producers -- that are not part of OPEC. The independents are assumed to produce at economic capacity all the time. So unlike the OPEC members, they do not operate with economic capacity surplus. Their production rate is therefore dictated by their capacity expansion decisions, and the speed at which they can change production is limited by the long time-lag in constructing new capacity and in depleting existing fields.

The rationale for capacity expansion is dominated by commercial factors as shown in figure 5. The independents will expand capacity (and therefore production) when they judge that it is profitable to do so. If the investment climate is unfavourable (say during a period of low oil prices) then no new upstream capacity is added, resulting in a net loss of output as the production of established fields peaks and then declines.

The model replicates the major inputs to upstream investment decisions in order to calculate the average profitability of potential projects. The independents obviously have to take a view of the development costs of new fields and the expected future oil price over the lifetime of the field. Knowing future cost, price, the likely size of a new field and the tax regime, one can calculate the future profit stream and apply a hurdle rate to identify 'acceptable projects'. In reality, each project undergoes a thorough and detailed screening, using well-tried upstream investment appraisal methods. The model treats project appraisal at the level of broad industry averages and computes a 'recommended fractional increase in capacity'. For example, if, at a specific hurdle rate, average industry project profitability is 24%, then the recommended fractional increase of capacity is 20% per year. Executive control over the recommended expansion is exercised through the policy lever **'investment optimism'**.

Development costs in the model are estimates of **industry average costs** starting in 1988. The independents start with a large pool of undeveloped reserves. (The estimation of fossil fuel reserves is a major topic in its own right that has received the attention of system dynamics modellers, Sterman 1988, Sterman and Richardson 1985). The development cost profile for these reserves (assuming no cost improvements from technology) is, broadly speaking, a curve that rises as reserves are depleted. There are assumed to be a small quantity, of low-cost reserves. Then the cost profile stays quite flat, rising gently until reserves are exhausted. (i.e. there is a finite supply of commercially viable oil).

Technology can undoubtedly be expected to lower costs as more efficient production and recovery methods are devised. The model's technology profile assumes a significant improvement over the next ten years. Thereafter the effect of technology is assumed to remain constant.

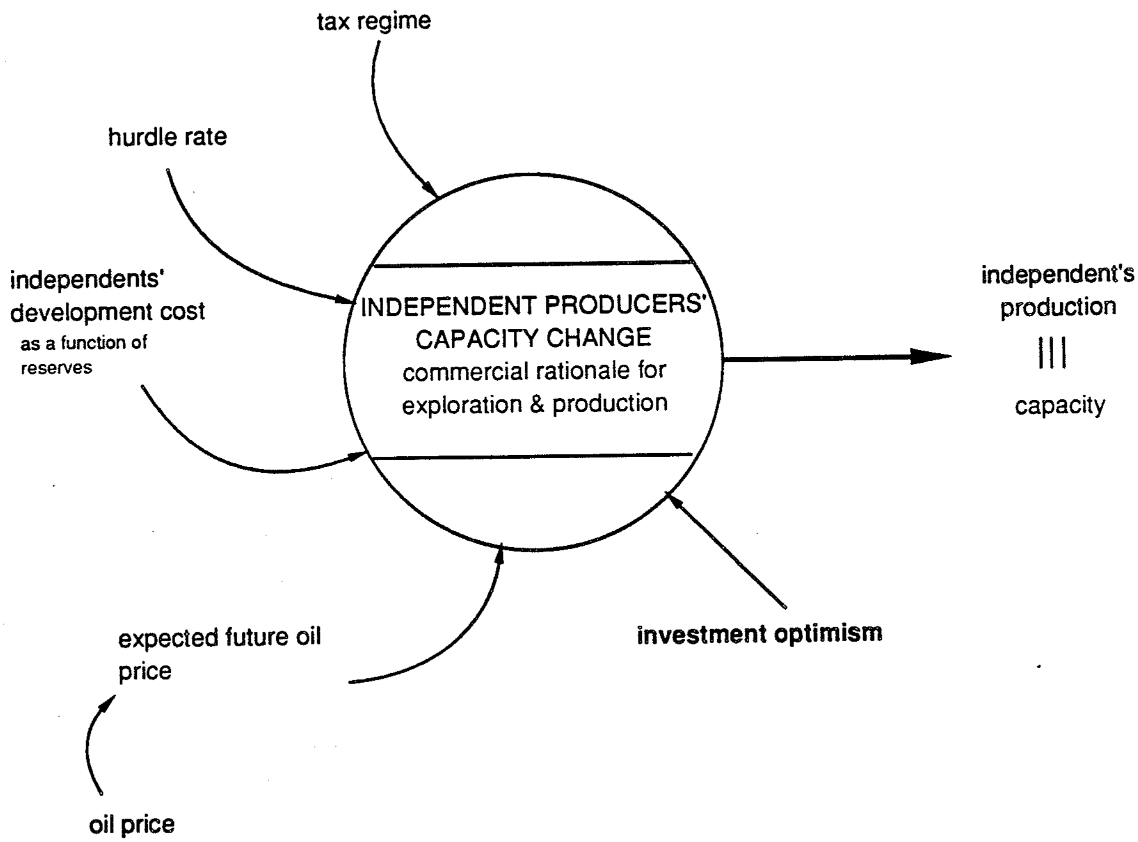

Figure 5: The Logic of the Independents

PARTIAL MODEL SIMULATIONS

To build confidence and a sense of ownership in the algebraic model, the facilitator designed a number of partial model simulations to demonstrate the 'algebra in action'. Two partial model simulations are shown below, similar to the ones used in the team meetings (though based on a more 'polished' version of the algebraic model). Needless to say, the following simulations are not predictions of oil supply, price and demand for the next 25 years. They are scenarios, initially used to raise questions about the model and later to stimulate thinking about alternative upstream oil futures.

Figure 6 is a simulation isolating the effect of the swing producer's price control. The simulation represents a 'thought experiment' in which the oil market starts in a supply-demand equilibrium of 50 million barrels per day in 1988, and is disturbed by a 5 percent exogenous decrease in oil demand in 1992, followed by a 5 percent increase in 1994. The experiment assumes that only the swing producer is able to change production (the output of the other producers is held constant at a value of 43 million barrels per day, a condition that implicitly assumes the independents have fixed development costs of just over $ 9 per barrel)). Price adjusts to the supply-demand imbalance, but has no feedback effect on demand in this run. The swing producer withholds production in an attempt to hold market price at the target value set by the marker price. The marker price itself adapts with a two year delay toward the market price. The experiment isolates the dynamic behaviour of the swing producer's price control loop which links the following variables in a goal-seeking feedback loop: market oil price --- market minus marker price --- indicated swing production --- swing producer production --- demand minus production --- change in oil price --- market oil price. In addition, the partial model contains a positive loop that contains a floating goal for intended marker price: market oil price --- intended marker price --- marker minus market price, linked to the remainder of the price control loop.

In this (artificial) situation, the simulation shows the oil market in equilibrium from 1988 to 1992. In 1992 the 5 percent step decrease in demand generates excess supply of 2.5 million barrels a day, which sends price plummeting from $15 per barrel to about $7 per barrel by 1994. In response the swing producer cuts back production from 7 million to 5 million barrels per day. The production cut-back stems the price decline, but does not reverse it. As a result of continuing oversupply, the intended marker price declines gradually to reach about $ 12 per barrel in 1994. Then, demand (not shown) steps back-up by 5 percent. Quickly, a new market equilibrium is established in which price settles at $10 per barrel, and the swing producer expands production back to 7 million barrels per day.

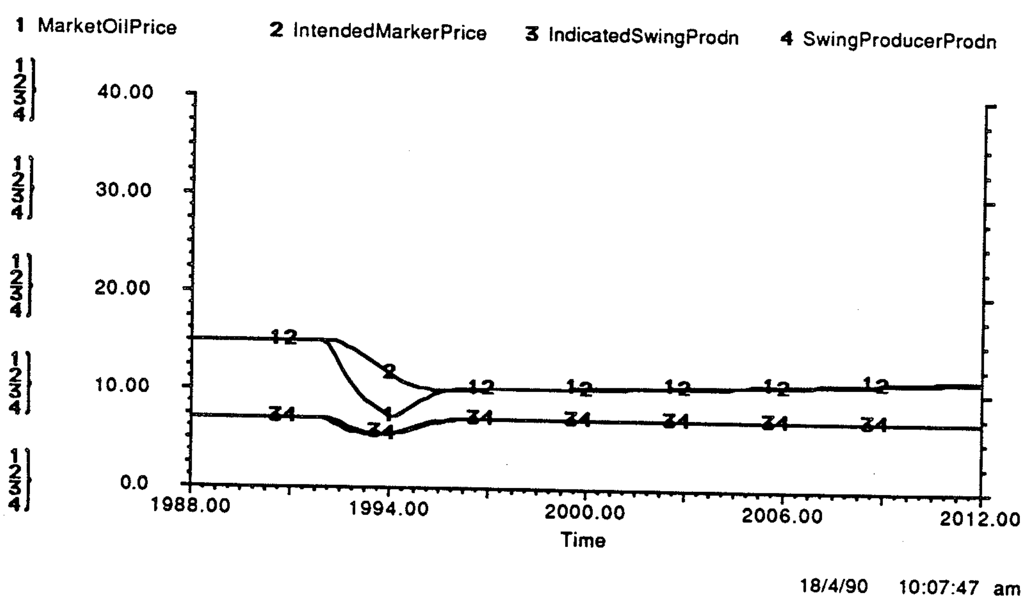

Figure 6: Swing Producer Price Control

Figure 7 is a simulation showing the change in dynamic behavior that occurs when realism is increased somewhat by activating an endogenous influence on demand from price. The conditions of the experiment are identical to those used in figure 6, with the exception that demand rises as price falls, and vice-versa. The market starts in equilibrium. The same profile of demand is used, a 5 percent decrease, sustained for four years. The difference is that the 5 percent demand shift is applied to a 'base demand' that is itself evolving. Only the swing producer can change production in this run. The experiment isolates the dynamic interaction of the swing producer's price control loop and the newly formed price-demand loop which links the following variables: demand for oil --- demand minus production --- fractional change in oil price --- change in oil price --- market oil price --- indicated demand --- demand for oil.

Demand and production start-out in balance at 50 million barrels per day, and price is steady at $ 15 per barrel. In 1992, demand for oil falls by 5 percent. Market oil price begins to fall. Unlike the previous run, falling price stimulates additional demand. As a result, base demand for oil (the volume of demand computed before taking-out the exogenous step decrease) actually begins to rise and peaks at about 53 million barrels per day. Demand for oil mirrors the upward trend in base demand, and returns to 50 million barrels per day by 1993. Price bottoms-out at $10 per barrel and begins to increase again during 1993. In 1994, demand steps back-up, causing a price spike that peaks at just over $ 20 per barrel during late 1995. Gradually a new equilibrium is reestablished (after mild price and production fluctuations). Market oil price settles at $ 16 per barrel, and swing producer's production returns to 7 million barrels per day.

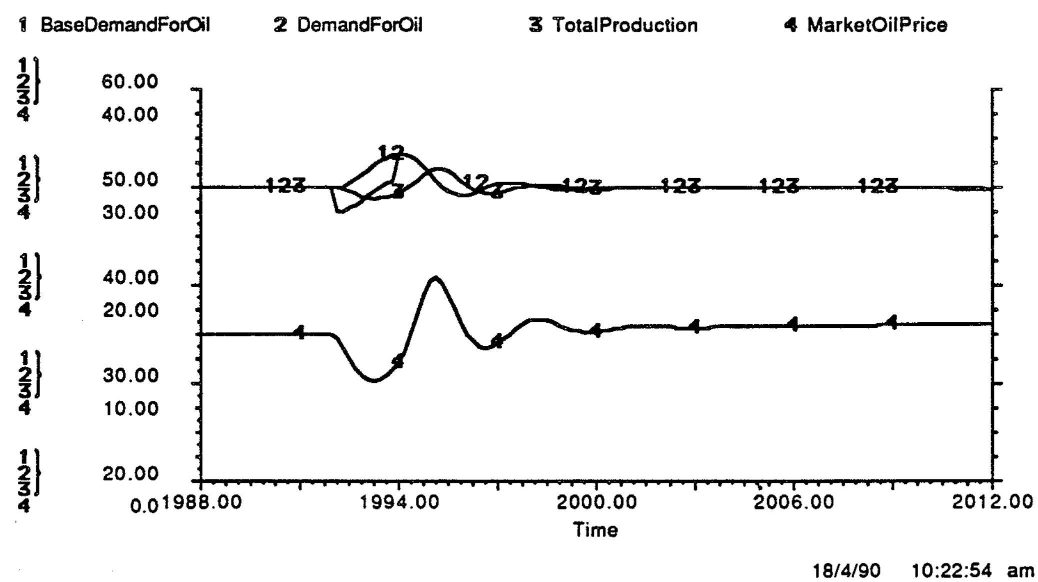

Figure 7: Interaction of the Price Control and Demand-Price Loops

SELECTED SIMULATIONS OF THE FULL MODEL

The full STELLA model contains 99 equations (including constants and graph functions). Separate pages of the STELLA map are devoted to the opportunists, the swing producer, OPEC quota setting, the independents, demand & price, and revenue calculations.

The model is capable of generating a very wide range of oil industry scenarios over periods of 20 years or more. To illustrate the model's output a selection of simulations is presented below taken from a 'base case scenario' for the period 1988 to 2012. In the base case, 'external' pressures on demand from GDP, technology and the environment are assumed to be neutral. In other words, in the absence of price changes, demand stays constant at 50 million barrels per day. OPEC is assumed to set quotas that exactly equal the call from the market (the estimated difference between total demand and independents' production), and the opportunists are assumed to produce at quota. The independents are assumed to adopt a neutral capex policy, meaning that they expand capacity at exactly the rate recommended by project appraisal methods, rather than being optimistic and so expanding capacity more than recommended, or being pessimistic and expanding less).

Figure 8 shows the base case demand profile. Demand begins at 50 million barrels per day in 1988 and rises gently to a peak of almost 52 million barrels per day (mbd) in 1993, before declining gradually to 47 mbd by the year 2005.

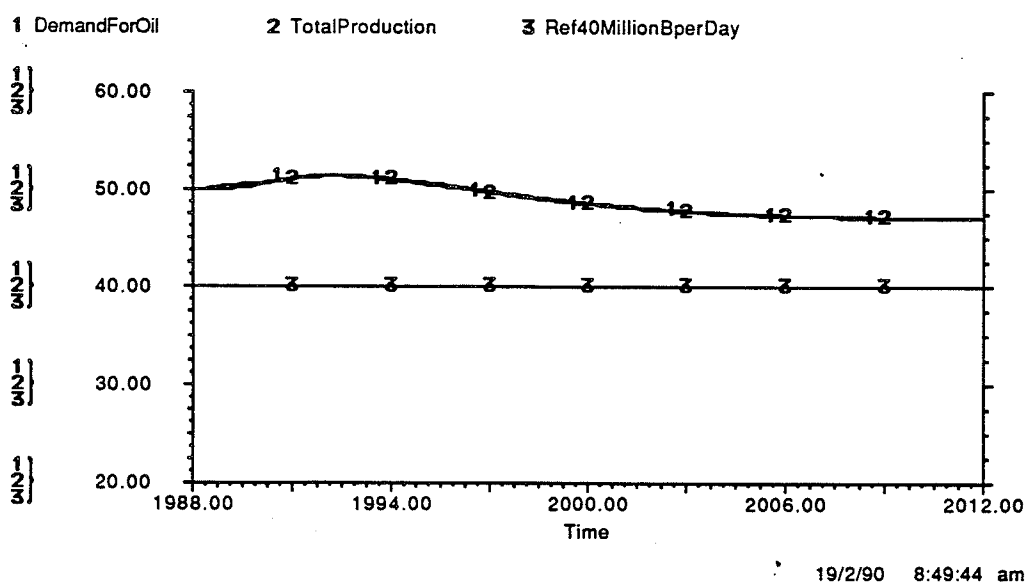

Figure 8: Demand Profile for Base Case Scenario

The behaviour of demand can best be understood by examining the trajectory of market oil price shown in figure 9. Price begins at $15 per barrel in 1988 and falls until 1991 due to a supply excess (shown in the figure by the slight difference between DemandMinusProduction and the reference zero, RefZero, line). The supply excess arises from a surge of independents' new production capacity, already in the construction pipeline in 1988, that comes onstream during the period 1988 to 1991. Supply and demand remain in almost perfect balance during the period 1991 to 1994 with the result that price remains static at $13 per barrel. In 1994 price begins a steady secular increase that continues to the end of the simulation in 2012, when oil price reaches a value of $22.5 per barrel in 1988 dollars. The price increase is the consequence of independents' escalating development costs. As reserves are depleted, new development costs rise and capex is curtailed. Although OPEC makes good some of the production shortfall, there is a slight but continuing supply shortage.

The production profile of the three producer groups is shown in figure 10. In 1988 the independents are the dominant producers with an output volume of 26 mbd. The opportunists' volume is 17 mbd and the swing producer's is 7 mbd. Up to 1994 production shares remain steady, with the independents showing a slight increase at the expense of the OPEC producers. In 1993, the independents' production peaks and begins a slow but steady decline as rising development costs (increasing more quickly than oil price) curtail capacity expansion. By the end of the scenario, the opportunists are the dominant producers with an output volume of 22 mbd, and the swing producer's and independents' volumes are equal at 12.5 mbd.

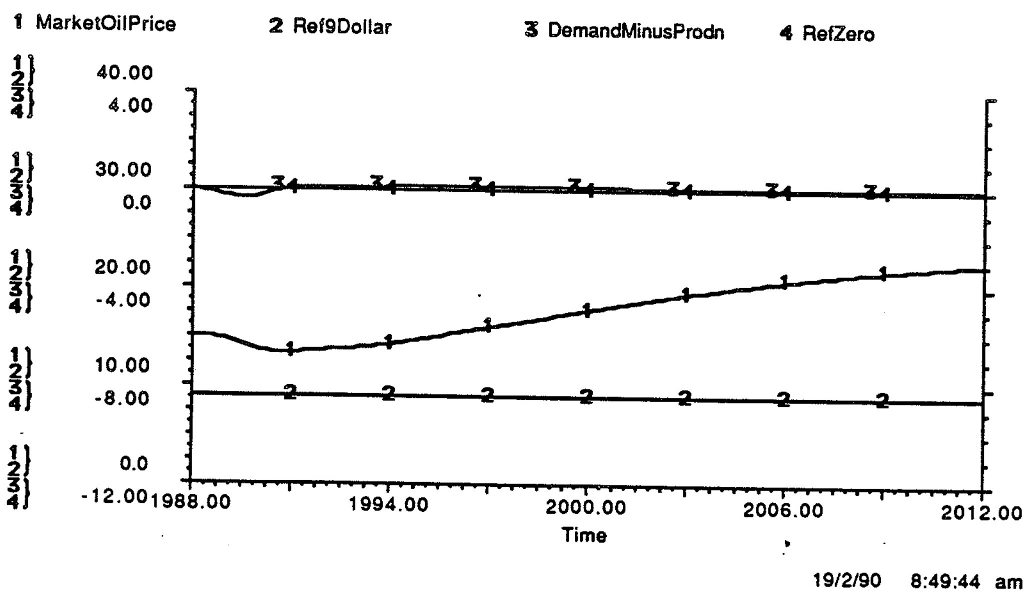

Figure 9: The Supply-Demand Balance and Price

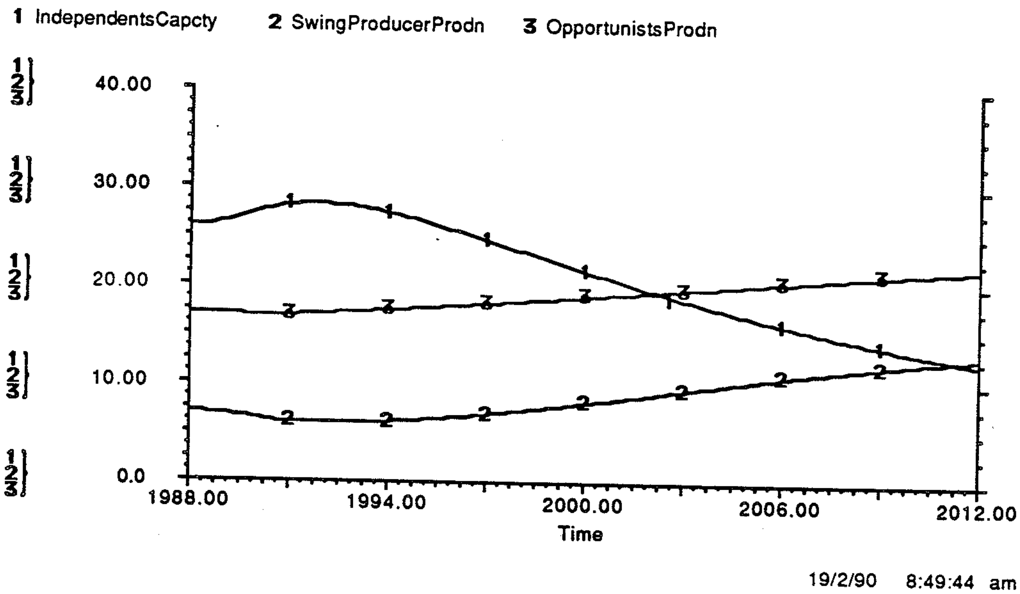

Figure 10: Production Profiles for the Three Producer Groups

USES OF THE MODEL

To date, the model's main use has been as an input to a scenario planning process (Wack, 1985a and 1985b). The model's characterisation of the swing producer and opportunists makes possible a wider range of industry scenarios than conventional models that incorporate just macroeconomic demand and price sensitivities. Repeated simulations of the model (under alternative assumptions for producer behaviour) reveal a 'geography' of future price profiles. The geography shows three distinct areas - Mountains, Plains and Plateaux - depending on whether oil price fluctuates, or is stable at a low or higher price level.

Recently the model has been converted into a gaming simulator and computer-based learning environment (Papert 1980) using the Microworlds software (Diehl, 1990). Game players (who need not be familiar with system dynamics or even with STELLA) can take the role of the oil producers and create their own scenarios. They can investigate whether OPEC should restrict quotas to force-up prices, or whether there is an advantage to be gained from producing over quota. They can explore the impact on oil price as the swing producer defends a higher price, or the independents expand capacity aggressively. They can replicate the conditions that led to the oil price shocks of the 1970s. They can discover the production strategies that stabilize oil price, and see the impact that declining reserves will have on production and oil price. They can find out the factors that determine the market power of the oil producers. In short, they can experience the difficulties of managing prices and production in the complex web of relationships that tie together the oil producers, the market and consumers.

The gaming simulator is currently being tested in management training programmes.

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