The Oil Producers' Model

Equation Description

Contents

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EQUATION DESCRIPTION

There are six sectors that make up the Oil Producers' Model: The Independents, Price and Demand, The Swing Producer, Quota Setting and Allocation, The Opportunists, and Revenue Calculations. The simulation equations for each sector are described in turn.

The Independents

Figure 1 shows the first sector of the Oil Producers' Model which represents the Independent oil producers. The equations underlying this flow-diagram are detailed below in table 1: Operating Capacity and Depletion of Fields.

The equations describe the independents' capacity and the depletion of their oil fields. The **Independents Capacity** is measured in millions of barrels per day. It is dependent on three terms: the initial value of **Independents Capacity**, the rate at which new capacity comes on line, **Onstream Rate**, and the **Capacity Loss from Depletion**. The initial value of **Independents Capacity** is set to 26 million barrels per day. This is the value of **Independents Capacity** at the start of a simulation run.

Independents Capacity = Independents Capacity + dt * (-Capacity Loss from Depletion + Onstream Rate)

INIT(Independents Capacity) = 26 {million barrels per day}

Onstream Rate = Capacity in Construction/4

Capacity Loss from Depletion = Independents Capacity/Average Lifetime of Field

Average Lifetime of Field = 10 {years}

Fractional Loss of Capacity = 1/Average Lifetime of Field

Independents Production = Independents Capacity {million barrels per day}

Table 1: Operating Capacity and Depletion of Fields

Onstream Rate is the rate at which new capacity comes on-line. It depends on how much capacity there is under construction, **Capacity in Construction**, and the construction time for the new capacity. The time-lag for new capacity to come on line is assumed to be 4 years.

Capacity Loss from Depletion is the amount by which the operating capacity of existing fields declines as the fields' oil reserves are used up. Generally speaking the output of oil fields is greatest early in their lifetime and then falls. The capacity loss effect is represented by taking the ratio of **Independents Capacity** to the **Average Lifetime of Field** which is set to 10 years.

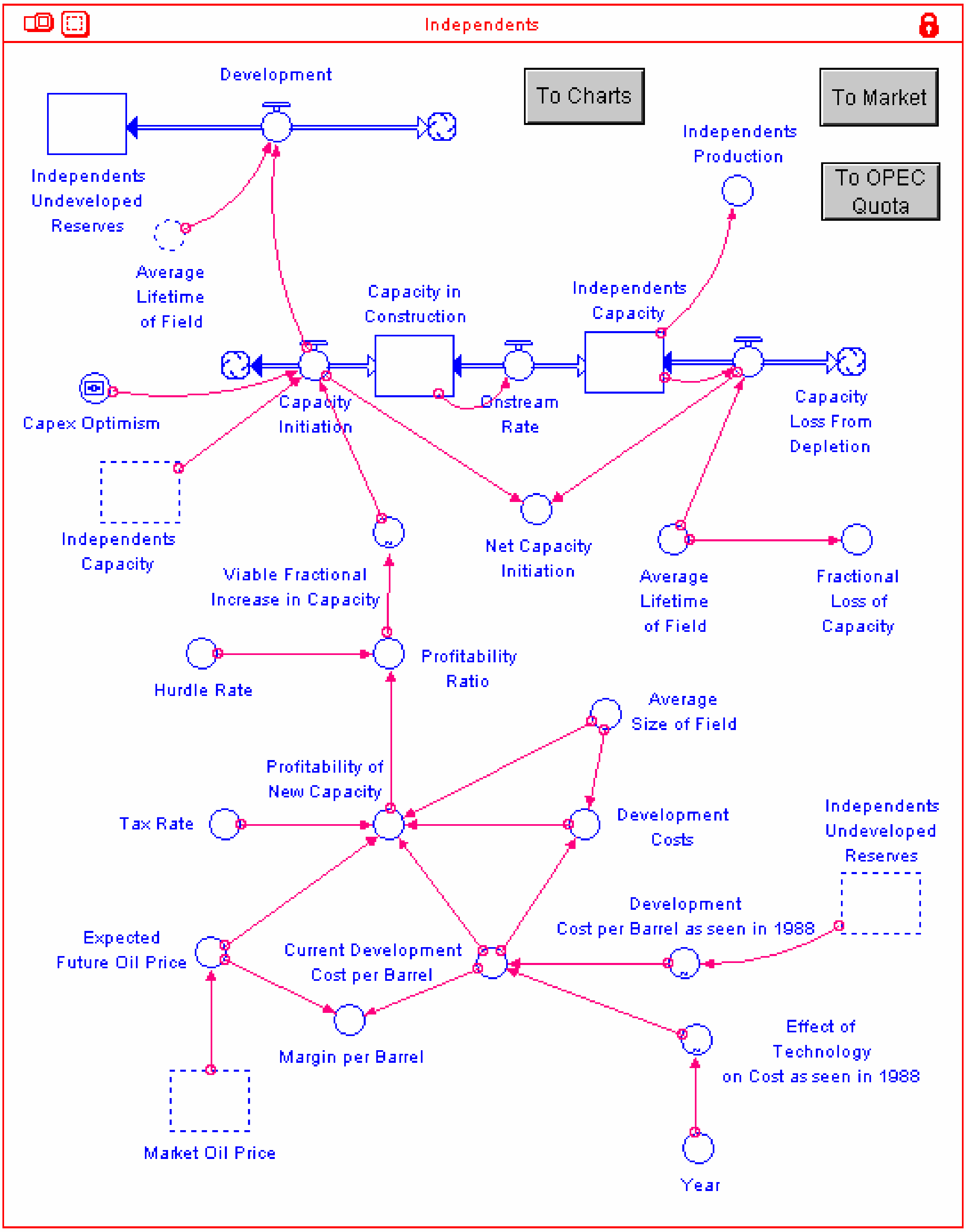

Figure 1: The Independents

Fractional Loss of Capacity is the fraction of capacity the independent producers are losing every year. It is just the reciprocal of the average lifetime of a field. In this case, the independent producers are losing a constant 10 percent of capacity each year.

Finally, **Independents Production** is equal to the **Independents Capacity**. This assumption means that the Independent producers always operate at full capacity. Therefore, the Independents cannot change their output rapidly. To expand output they must wait for new capacity to be constructed. To reduce output they must restrict new investment and deplete their existing fields.

Table 2 shows formulations for capacity expansion (capex) and capacity in construction. The amount of **Capacity in Construction** is a level that depends on the rate at which new development projects are started, **Capacity Initiation**, and the rate at which finished capacity comes on-line, the **Onstream Rate**. The initial value for **Capacity in Construction** is 10.4 million barrels per day.

Capacity in Construction = Capacity in Construction + dt * (Capacity Initiation - Onstream Rate)

INIT(Capacity in Construction) = 10.4 {millions of barrels per day}

Capacity Initiation = Independents Capacity*Viable Fractional Increase in Capacity*Capex Optimism {millions of barrels per day per year}

Capex Optimism = 1

Net Capacity Initiation = Capacity Initiation-Capacity Loss from Depletion

Table 2: Capex and Capacity in Construction

The amount of capacity initiated, **Capacity Initiation**, is a function of the Independents' existing capacity, **Independents Capacity**, and two variables: **Viable Fractional Increase in Capacity** and **Capex Optimism**. **Viable Fractional Increase in Capacity** represents the recommendation for capacity expansion from project appraisal. When profitability is high, there are many attractive investment opportunities. The model portrays these opportunities as a fraction of existing capacity. The fractional formulation captures an important and realistic bootstrapping property of the aggregate system: the smaller the independents (in terms of existing capacity), then the fewer new projects they can launch for any given profitability -- see table 4. **Capex Optimism** represents the climate of opinion amongst the independents' top managers about the desirability of capacity expansion. If **Capex Optimism** is smaller than 1, then managers are cautious about expansion, and will authorize a smaller amount of new capacity than project appraisal methods alone would suggest. Conversely, if **Capex Optimism** is greater than 1, then managers are optimistic about expansion, and will authorize more new capacity than the profitability calculations would suggest. If **Capex Optimism** is equal to 1, then managers will authorize new capacity exactly in line with recommendations from project appraisal.

Net Capacity Initiation is the net change of independents' capacity. It is equal to the amount of **Capacity Initiation** less the amount of **Capacity Loss from Depletion**. If this number is negative, then the Independents are losing capacity. If it is positive, then the Independents are adding new capacity.

Table 3 describes the Independents' reserves. It is assumed that the Independents start with a fixed and finite endowment of reserves, including both discovered and undiscovered reserves. The starting value is very large and though perhaps a matter of conjecture, is chosen to yield realistic development costs as the simulation proceeds.

Independents Undeveloped Reserves = Independents Undeveloped Reserves + dt * (-Development)

INIT(Independents Undeveloped Reserves) = 580000-Average Lifetime of Field* Capacity in Construction {millions of barrels of oil}

Development = Capacity Initiation*360*Average Lifetime of Field {millions of barrels per year}

Table 3: Reserves

The **Independents Undeveloped Reserves** represent the remaining volume of undeveloped reserves belonging to the independent producers. The initial reserves are assumed to be 580,000 million barrels of oil minus the capacity under development. The total number of barrels under development is the product of **Capacity in Construction** and **Average Lifetime of Field**. The Independents' undeveloped reserves will become smaller and smaller as time passes, depending on the rate of development. **Development** is an estimate of the rate at which officially recognized undeveloped reserves should be reduced to account for current capacity expansion. It is calculated as the product of **Capacity Initiation** (measured in millions of barrels per day per year), and the **Average Lifetime of Field** (expressed in years), which yields the daily development rate of reserves (in millions of barrels per day). The constant 360 is introduced to annualize the daily development rate.

Table 4 describes the Independents' investment appraisal; i.e. how much new capacity the Independents will approve during the next period. The extent of investment in new capacity is determined by the **Viable Fractional Increase in Capacity**. The fractional increase in capacity is a function of the **Profitability Ratio** as shown in figure 2. The corresponding numerical values can be found in table 4. The profitability ratio is defined as the **Profitability of New Capacity**, divided by the **Hurdle Rate**. The **Hurdle Rate** is the target rate of return for upstream investment. In this case the hurdle rate is set at 15 percent. If **Profitability Ratio** is less than 0.6 (i.e. the rate of return is less than 9 percent) the Independents will not invest in new capacity at all. As the profitability ratio rises, so the investment climate becomes more and more favourable. At a return of 15 percent, when **Profitability Ratio** equals 1, the independents add new capacity at the rate of 6 percent per year of their existing capacity. When **Profitability Ratio** equals 1.5, the capacity expansion rate is 20 percent per year. The upward trend continues until the profitability ratio reaches 1.9

at which point the capacity expansion rate reaches a plateau of 25 percent per year. The plateau represents a logistical limit to the growth rate of capacity. Note that because the Independents lose 10 percent of their capacity each year through depletion, net growth in capacity does not happen until the viable fractional increase in capacity exceeds 10 percent per year which calls for a profitability ratio greater than 1.2.

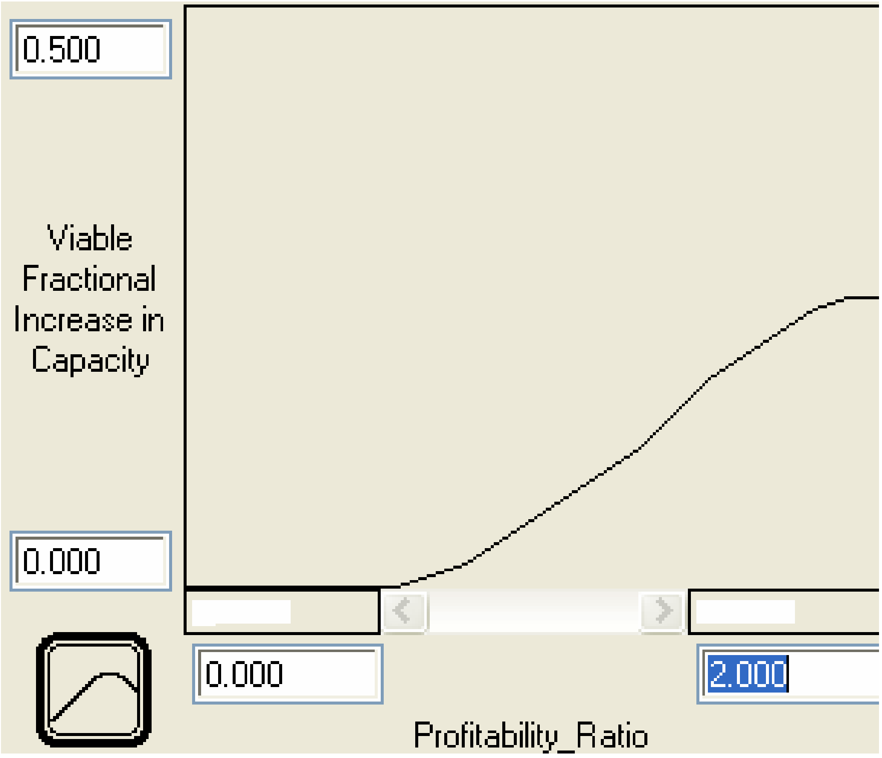

Figure 2: The Viable Fractional Increase in Capacity

The profitability of a new upstream investment is defined as the total profit over the lifetime of the investment, divided by its development cost (all computed in constant dollars). In the Independents' sector, **Profitability of New Capacity** depends on five factors: the tax rate, the expected future oil price, the current development cost per barrel, the average field size and the development costs. The **Tax Rate** is the average rate of tax levied on Independent producers. The value of (1-**Tax Rate**) is the fraction of profits retained after tax. The tax rate in the oil producers' model is set to 70 percent. The expected profit for one barrel of oil is the **Expected Future Oil Price**, minus the **Current Development Cost per Barrel**. The total profit for one oil field is the expected profit for one barrel multiplied by the **Average Size of Field**. The **Profitability of New Capacity** is the total profit for a field divided by the **Development Costs**.

Viable Fractional Increase in Capacity = graph(Profitability Ratio)
(0.0, 0.0),(0.100, 0.0),(0.200, 0.0),(0.300, 0.0),(0.400, 0.0),
(0.500,0.0),(0.600,0.0),(0.700,0.0100),(0.800,0.0200),(0.900,0.0400),
(1.00,0.0600),(1.10,0.0800),(1.20,0.100),(1.30,0.120),(1.40,0.150),
(1.50,0.180),(1.60,0.200),(1.70,0.220),(1.80,0.240),(1.90,0.250),
(2.00,0.250)

Profitability Ratio = Profitability of New Capacity/(Hurdle Rate)

Hurdle Rate = .15

Profitability of New Capacity = (1-Tax Rate)*(Expected Future Oil Price-Current Development Cost per Barrel)*Average Size of Field/Development Costs

Tax Rate = 0.7

Expected Future Oil Price = SMTH1(Market Oil Price, 1)

Current Development Cost per Barrel = Development Cost per Barrel as seen in 1988* Effect of Technology on Cost as seen in 1988

Development Costs = Average Size of Field*Current Development Cost per Barrel

Average Size of Field = 1000

Margin per Barrel= Expected Future Oil Price-Current Development Cost per Barrel

Table 4: Capex Investment Appraisal

The **Expected Future Oil Price** is an exponential average (SMTH1) of the **Market Oil Price** over the previous year. (**Market Oil Price** can be found in table 8.) The formulation makes **Expected Future Oil Price** less volatile than **Market Oil Price**, but still responsive to medium and long term trends in price.

The **Current Development Cost per Barrel** is the **Development Cost per Barrel as seen in 1988** (see table 5) multiplied by **Effect of Technology on Cost as seen in 1988** (see table 5).

The **Development Costs** for a new field are calculated by taking the product of the **Average Size of Field** and the **Current Development Cost per Barrel**. **Average Size of Field** is set to 1,000 million barrels. In order to calculate the profitability, it is not strictly necessary to know the average size of a field, as it cancels out in the calculation. However, the concept of field size helps clarify the steps of the calculation.

Finally, the profit or **Margin per Barrel**, measured in $ per barrel, is the difference between the **Expected Future Oil Price** and the **Current Development Cost per Barrel.**

Table 5 shows the numerical values used in the graph functions that affect development costs.

Development Cost per Barrel as seen in 1988= graph(Independents Undeveloped Reserves)
(10000.00,1000.00),(30000.00,48.00),(50000.00,43.50),(70000.00,42.50),
(90000.00,40.80),(110000.00,40.00),(130000.00,38.50),(150000.00,38.00),
(170000.00,37.50),(190000.00,36.30),(210000.00,35.80),(230000.00,34.8),
(250000.00,34.50),(270000.00,33.00),(290000.00,32.50),(310000.00,31.3),
(330000.00,30.50),(350000.00,30.00),(370000.00,29.30),(390000.00,28.5),
(410000.00,28.00),(430000.00,27.00),(450000.00,25.80),(470000.00,24.3),
(490000.00,21.50),(510000.00,17.50),(530000.00,12.00),(550000.00,8.75),
(570000.00,5.75),(590000.00,5.50),(610000.00,5.00)

Effect of Technology on Cost as seen in 1988 = graph(Years)
(1988.00,1.00),(1989.00,0.940),(1990.00,0.890),(1991.00,0.840),
(1992.00,0.800),(1993.00,0.750),(1994.00,0.720),(1995.00,0.690),
(1996.00,0.670),(1997.00,0.650),(1998.00,0.640),(1999.00,0.640),
(2000.00,0.640),(2001.00,0.640),(2002.00,0.640),(2003.00,0.640),
(2004.00,0.640),(2005.00,0.640),(2006.00,0.640)

Years = TIME

Table 5: Development Costs and Technology

Figure 3 shows graphically how development costs depend on the **Independents Undeveloped Reserves**. For convenience in scaling, figure 3 is truncated at the point when there are 10,000 million barrels of oil left and the development costs are $1,000 per barrel.

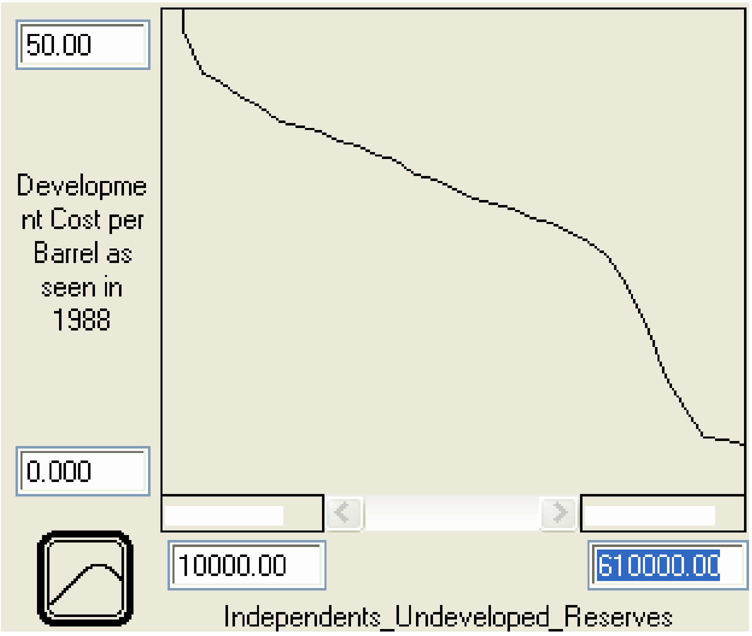

Figure 3: Development Costs as Seen in 1988

When reserves are high, between 550 and 580 thousand million barrels, then development costs are low at around $8 per barrel. Below 550 thousand million barrels, as the next 100 thousand million barrels of oil are used, development costs rise sharply, tripling to more than $24 per barrel. As reserves fall from 450 to 30 thousand million barrels, development costs increase gradually from $25 to $48 per barrel. Thereafter the development costs rise sharply from $48 to $1000 per barrel as reserves are exhausted.

It is assumed that over time technology will be improved, which will make it cheaper to develop new fields. The effect of advance in technology is shown in figure 4.

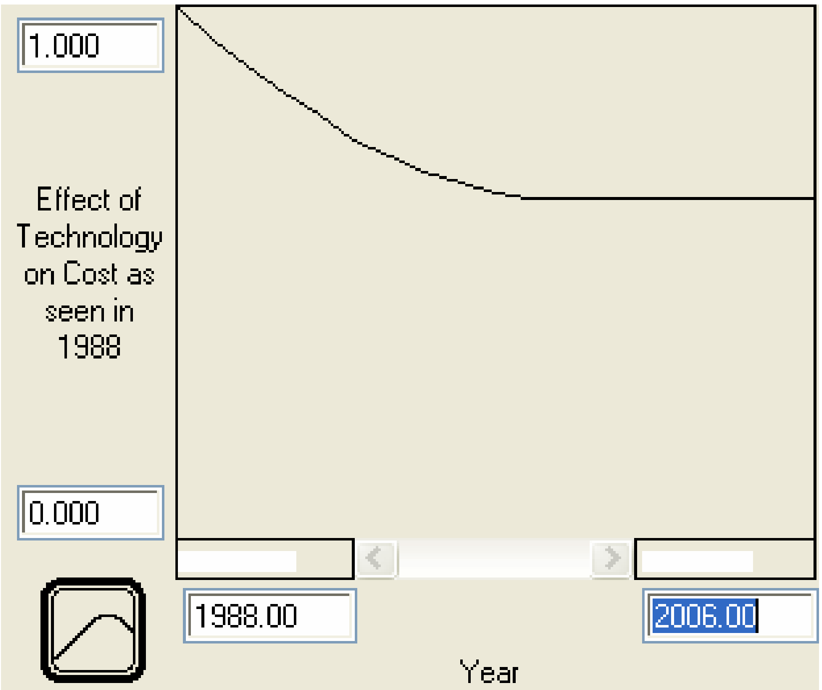

Figure 4: Effect of Technology on Cost as Seen in 1988

Technology is assumed to improve rapidly at the end of the eighties and most of the nineties. For example, if the estimated development costs for 1992 were $10 per barrel using 1988 technology, then advancing technology would cut the actual development costs in 1992 to $8 ($10*0.8). After 1998 it is assumed that there will be no further improvement in technology, so that development costs stabilize at 65 percent of the cost estimate assuming 1988 technology. (Editorial note: An assumption of static technology in the post-1998 era may seem unrealistic when looking back from the perspective of 2006. However, at the time the model was first conceptualised in 1988 the management team took a conservative view of technology improvement beyond a 10-year horizon. Figure 4 simply reflects this view).

Price and Demand

This section describes the pressures that influence demand and market price. Figure 5 shows the associated flow-diagram for demand and price setting. Table 6 shows the equations describing demand and adjustment of demand.

Base Demand for Oil = Base Demand for Oil + dt * (Change in Demand)

INIT(Base Demand for Oil) = 50 {million barrels per day}

Change in Demand = (Indicated Demand - Base Demand for Oil)/Time to Adjust Demand

Time to Adjust Demand = 2.5 {years}

Indicated Demand = Benchmark Demand * (1+Effect of Global Economy and Environment on Demand) * Effect of Price on Demand

Benchmark Demand = SMTH1(Base Demand for Oil,10)

Effect of Global Economy and Environment on Demand = 0

Demand for Oil = Base Demand for Oil

Table 6: Demand Adjustment

Base Demand for Oil, represents consumers' current level of oil consumption resulting from the interplay over time of price, economic and environmental pressures. The initial demand for oil at the start of the simulation in 1988, **INIT(Base Demand for Oil)**, is 50 million barrels per day. The **Change in Demand** represents consumers' efforts to close the gap between the **Indicated Demand** and **Base Demand for Oil**. It takes time for consumers to adjust. **Time to Adjust Demand** represents the average number of years it takes for consumers to fully-adjust their oil consumption to indicated demand through conservation and substitution. This consumer adjustment lag is assumed to be 2.5 years.

The **Indicated Demand** is a measure of the overall level of demand consumers would like to achieve at the current price and under current economic and environmental conditions. It depends on three factors: **Benchmark Demand**, **Effect of Global Economy and Environment on Demand** and **Effect of Price on Demand** (see table 7).

The **Benchmark Demand** is a 10 year average of **Base Demand for Oil**, and it shows the long-term underlying demand for oil that changes only gradually as energy consuming devices are replaced.

Effect of Global Economy and Environment on Demand is the net effect of GDP, technology improvements and environmental pressures on demand for crude oil. A value of '0' is neutral and represents no change in oil consumption, whereas a value of

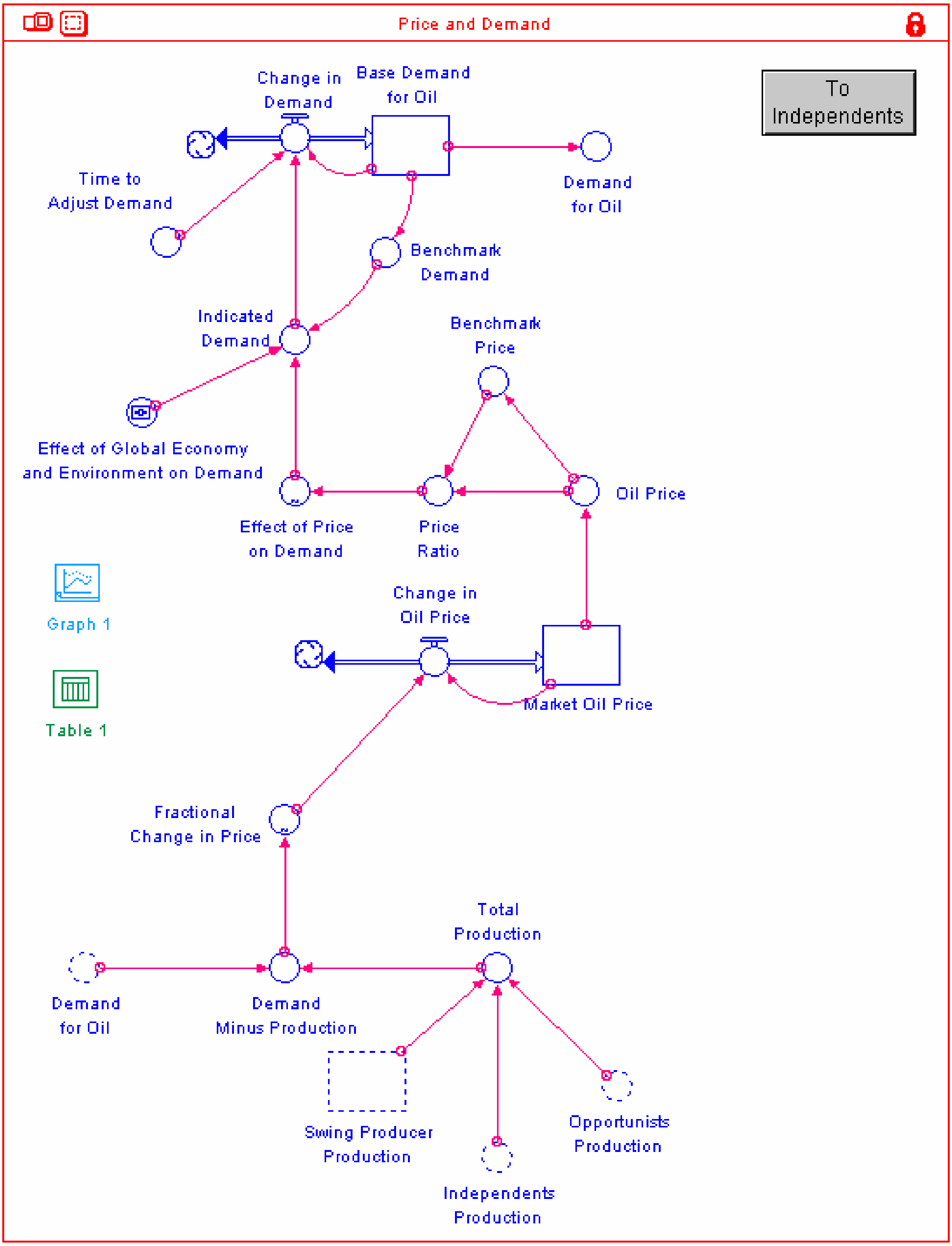

Figure 5: Price and Demand

'-.1' represents a continual pressure to reduce oil consumption by 10 percent below current usage.

The operating measure of demand used in the model is called **Demand for Oil** and is equal to **Base Demand for Oil**.

Table 7 shows the effect of price on the demand for oil.

Effect of Price on Demand = graph(Price Ratio)
(0.0,1.80),(0.500,1.30),(1.00,1.00),(1.50,0.800),(2.00,0.650),
(2.50,0.500),(3.00,0.450),(3.50,0.400),(4.00,0.400),(4.50,0.400),
(5.00,0.400)

Price Ratio = Oil Price/Benchmark Price

Benchmark Price = SMTH1(Oil Price,4)

Oil Price = Market Oil Price

Table 7: Effect of Price

The **Effect of Price on Demand** is a graph which depends on the price ratio. **Price Ratio** is defined as the **Oil Price** divided by the **Benchmark Price**, which represents the price consumers are used to. The relationship is shown in figure 6 and the corresponding numerical values in table 7. If the **Benchmark Price** and **Oil Price** are the same then the **Price Ratio** is equal to 1, so there will be no change in the demand for oil from price. However, if **Oil Price** is higher than the **Benchmark Price**, then indicated demand will fall as the value of **Effect of Price on Demand** becomes less than 1. Indicated demand continues to fall until the price ratio equals 3, in other words when oil price is three times the normal value. At this very high price ratio consumers intend to cut oil consumption to only .4 (or 40 percent) of normal. As the **Price Ratio** rises above 3 then the graph becomes flat. The **Effect of Price on Demand** remains at .4 to represent consumers' core and basic need for oil regardless of price. On the other hand, if **Oil Price** is lower than **Benchmark Price**, then the **Effect of Price on Demand** becomes greater than 1, causing indicated demand for oil to increase.

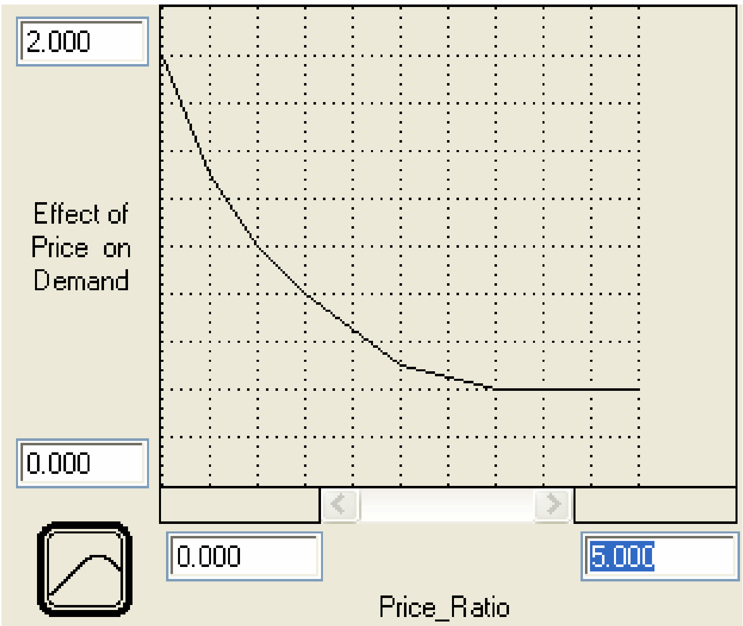

Figure 6: Effect of Price on Demand

The **Benchmark Price** is calculated as the average oil price over the last 4 years, and is used as a benchmark against which shocks in oil price are gauged. The **Benchmark Price** can also be viewed as the price that oil consumers regard as normal. Note that because benchmark price is an average of oil price, then over the course of time, consumers can become used to any price level, no matter how high or how low.

Oil Price is equal to the **Market Oil Price**.

Table 8 shows the price adjustment mechanism. The **Market Oil Price** is determined by the **Change in Oil Price**. The initial oil price, **INIT(Market Oil Price)**, is $15 per barrel. **Change in Oil Price** is based on the current price multiplied by **Fractional Change in Price**. Any changes are based on a fraction of the current price rather than an absolute change in price. The factor '12' converts the monthly fractional change in the graph function to an annual rate of price change.

Fractional Change in Price is a graph function based on **Demand Minus Production** which is the difference between **Demand for Oil** and **Total Production** (see table 6). **Total Production** is the sum of all the producers' production (Opportunists + Independents + Swing producers). Figure 7 shows how **Fractional Change in Price** depends on **Demand Minus Production**.

Market Oil Price = Market Oil Price + dt * (Change in Oil Price)
INIT(Market Oil Price) = 15 {$ per Barrel}

Change in Oil Price = Market Oil Price*Fractional Change in Price*12

Fractional Change in Price = graph(Demand Minus Production)
(-10.00,-0.110),(-8.00,-0.110),(-6.00,-0.100),(-4.00,-0.0750),
(-2.00,-0.0400),(0.0,0.0),(2.00,0.0400),(4.00,0.0750),
(6.00,0.100),(8.00,0.110),(10.00,0.110)

Demand Minus Production = SMTH1((Demand for Oil -Total Production),.25)
{millions of barrels per day}

Total Production = Swing Producer Production + Independents Production +
Opportunists Production

Table 8: Price Adjustment

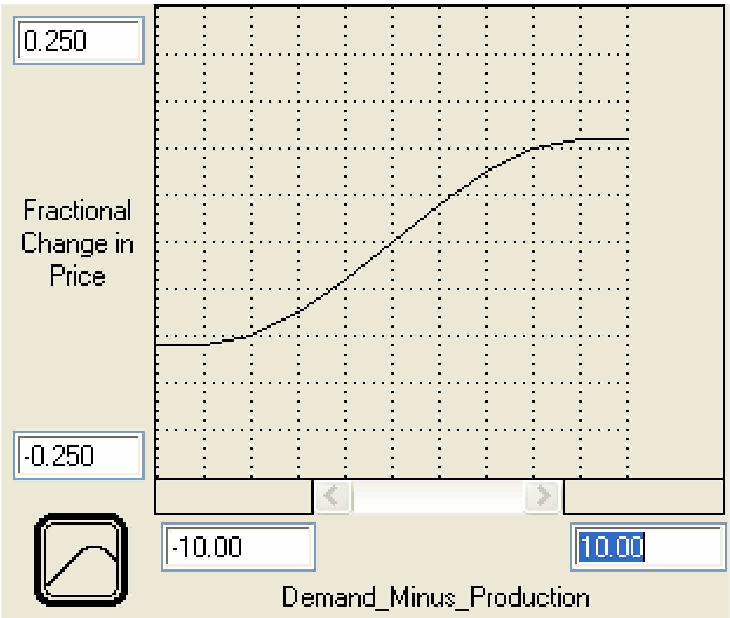

Figure 7: Fractional Change in Price

When **Demand Minus Production** is zero, then by definition the **Fractional Change in Price** is zero. The graph is symmetrical around the zero-zero point, and is almost linear for small differences between **Total Production** and **Demand for Oil**. The fractional change of price is limited to 6 per cent per month when the difference between production and demand exceeds 5 million barrels per day. This 6 percent monthly limit represents the effect of institutional constraints on price change.

The Swing Producer

This section describes the Swing Producer and the associated logic. Figure 8 illustrates the flow-diagram for the Swing Producer.

Table 9 shows the equations which decide mode switching and the adjustment of production.

Swing Producer Production = Swing Producer Production + dt * (Change in Swing Production)
INIT(Swing Producer Production) = 7 {Millions of barrels per day. For initial balance set to Call On Cartel-Opportunists Capacity = (50-26) - 17 = 7}

Change in Swing Production = IF (Swing Mode=1) THEN ((Indicated Swing Production-Swing Producer Production)/Time to Adjust Production) ELSE (Swing Producer Production*Punitive Production Expansion*12)

Time to Adjust Production = .25 {Years}

Swing Mode= IF (Swing Producer Call Share ≥ Minimum Quota Share) THEN 1 ELSE 0

Swing Producer Call Share = SMTH1((Swing Quota/Demand for Oil),.5)

Minimum Quota Share =.08+STEP(0,1993)

Table 9: Mode Switching and Adjustment of Production

Swing Producer Production is the Swing Producer's current volume of production. The initial volume of production is set to 7 million barrels a day, **INIT(Swing Producer Production)**. The change in the swing producers' production is represented by the variable **Change in Swing Production** which can be positive or negative. Here it is assumed that capacity is not a constraint, i.e. after a short time to adjust production, the Swing Producers can produce the required amount of oil no matter how large or small.

The **Change in Swing Production** can be in one of two different modes:

Swing Mode = 1 When **Swing Mode** is equal to 1, the Swing Producer adjusts production to keep market oil price equal to the price intended by OPEC. The amount of production adjustment is given by the difference between **Indicated Swing Production** and **Swing Producer Production**. The Swing Producer adjusts current production until it is equal to indicated swing production. The period of time required to make such production changes is called **Time to Adjust Production** and is set at 3 months (1/4 year).

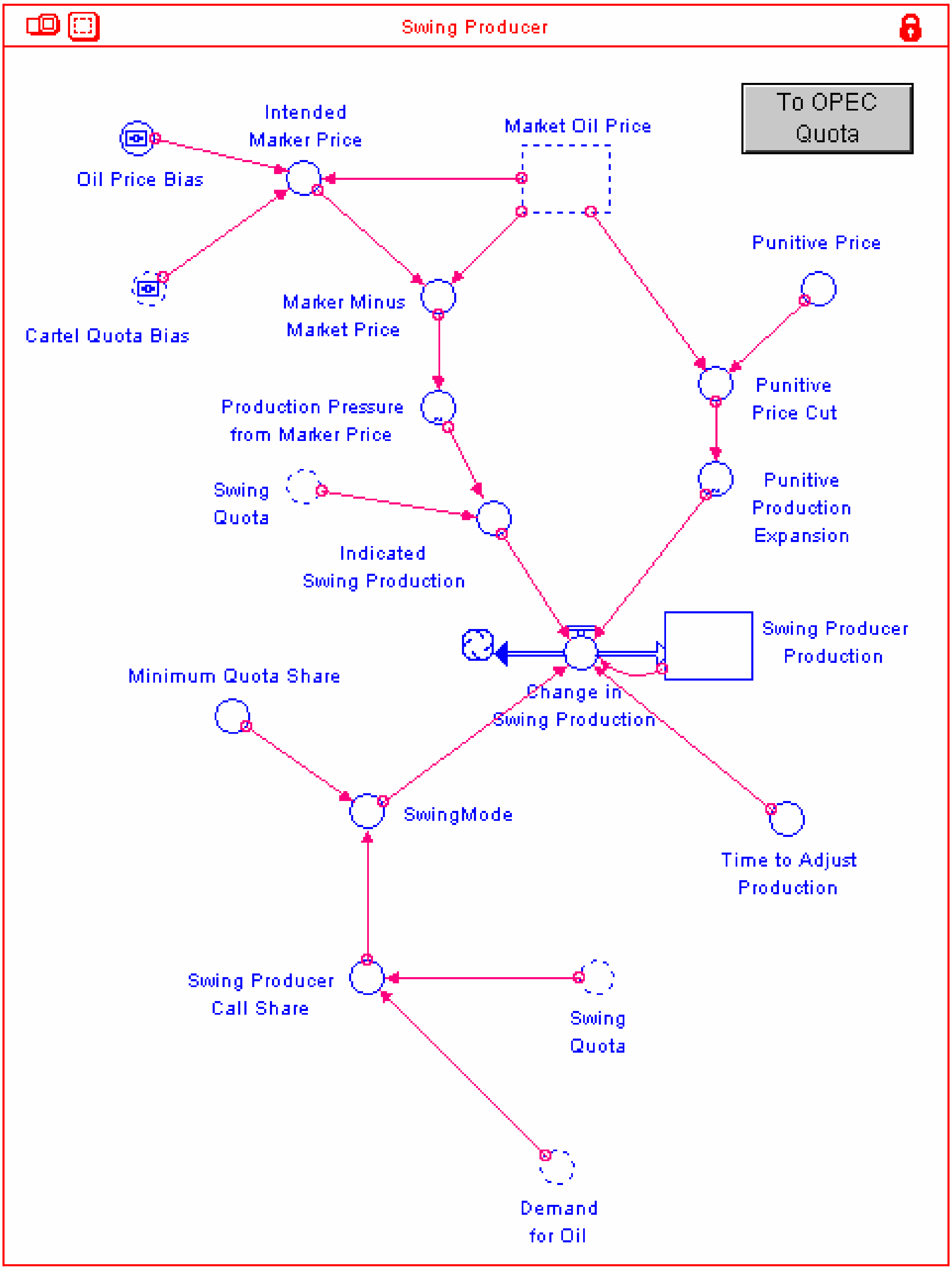

Figure 8: The Swing Producer

Swing Mode = 0 When **Swing Mode** is equal to 0, the Swing Producer is dissatisfied with its share of crude oil production and decides to increase production dramatically, both to regain share and to discipline the other producers. In this so-called punitive mode, the **Swing Producer Production** is multiplied by **Punitive Production Expansion** in order to increase output, expressed as a fractional increase per month. The factor '12' converts the monthly fractional increase to an annual fractional increase.

The **Swing Mode**, which determines the Swing Producers' production mode, is set by comparing the **Swing Producer Call Share** to the minimum market share the Swing Producers can accept, **Minimum Quota Share**. **Minimum Quota Share** is 8 percent of the market, with a possibility to change this using a STEP function. **Swing Mode** = 1 when **Swing Producer Call Share** is greater than or equal to **Minimum Quota Share**. In this case the Swing Producer will operate in swing mode. Otherwise, if **Swing Producer Call Share** is smaller than **Minimum Quota Share**, the Swing Producer will operate in punitive mode.

The **Swing Producer Call Share** is calculated as the ratio of **Swing Quota** (see table 13) to **Demand for Oil** (see table 6), averaged over the past half year. Call share is the signal the Swing Producer looks at when deciding whether to switch to punitive mode.

Indicated Swing Production = Swing Quota*Production Pressure from Market Price

Production Pressure from Market Price = graph(Marker Minus Market Price)
(-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)

Marker Minus Market Price = (Intended Marker Price-Market Oil Price)

Intended Marker Price = SMTH1(Market Oil Price,2)*(1+Oil Price Bias)/(1+Cartel Quota Bias)

Oil Price Bias = 0

Table 10: Swing Production and Price Management

The indicated production of the Swing Producer, **Indicated Swing Production**, is the amount that the Swing Producer intends to produce in swing mode. It depends on the **Swing Quota** (see table 13) and the **Production Pressure from Market Price**.

Production Pressure from Market Price is the adjustment to **Swing Quota** that the Swing Producer makes in an effort to keep market oil price in line with the intended marker price while in swing mode. **Production Pressure from Market Price** is shown in figure 9.

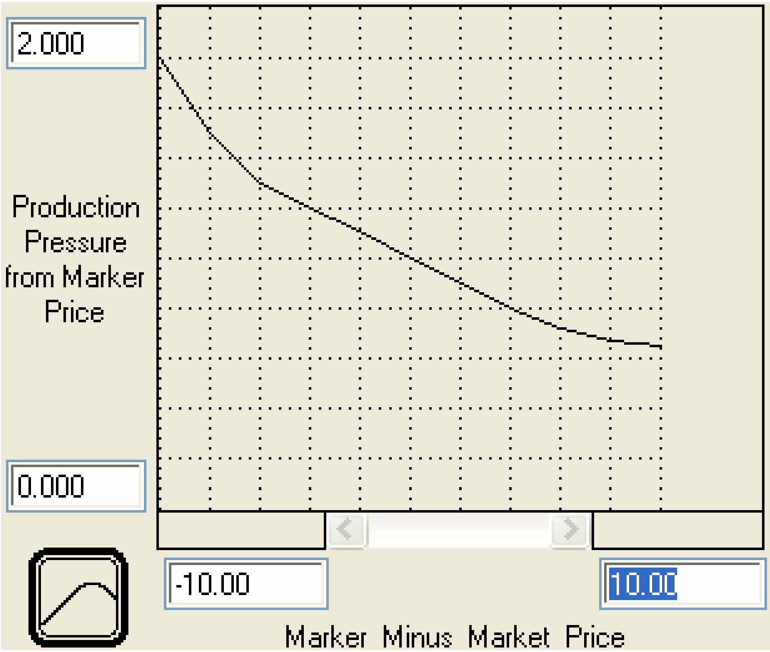

Figure 9: Production Pressure from the Marker Price

The **Marker Minus Market Price** is the difference between the **Intended Marker Price** and the **Market Oil Price**. If **Market Oil Price** (see table 8) is higher than **Intended Marker Price**, i.e. **Marker Minus Market Price** is negative, there will be pressure on the Swing Producer to increase production in order to reduce the price gap. The pressure is reversed if **Market Oil Price** is lower than **Intended Marker Price**.

The **Intended Marker Price** is the market price that OPEC has agreed and that the Swing Producer is trying to enforce. The marker price is based on a 2 year average of **Market Oil Price** adjusted by the **Oil Price Bias** and by the **Cartel Quota Bias** (see table 10) to represent OPEC's pricing levers. **Oil Price Bias** is a lever that allows the Swing Producer to exert upward or downward pressure on market oil price by setting a marker price that is consistently higher or consistently lower than average market oil price.

Punitive Production Expansion = graph(Punitive Price Cut)
(0.0,0.0),(1.00,0.0500),(2.00,0.0800),(3.00,0.0950),(4.00,0.100),
(5.00,0.100),(6.00,0.100),(7.00,0.100),(8.00,0.100),(9.00,0.100),
(10.00,0.100)

Punitive Price Cut = Market Oil Price-Punitive Price

Punitive Price = 8 {dollars per barrel}

Table 11: Punitive Production

Table 11 lists the equations governing the Swing Producer's output when operating in punitive mode. Figure 10 shows the graph function for punitive production. **Punitive Production Expansion** depends on the size of the **Punitive Price Cut**. **Punitive Price Cut** is the maximum price cut the Swing Producer can tolerate when operating in punitive mode. It is defined as the difference between the current market price, **Market Oil Price**, and the punitive price. **Punitive Price** is the lowest price the Swing Producer can accept when in punitive mode. Even at this price the Swing Producer will be profitable, as production costs are assumed to be very low. With reference to figure 10, you can see that the maximum rate for punitive expansion of production is 10 percent per month, whenever the **Punitive Price Cut** is higher than $4 per barrel (corresponding to a **Market Oil Price** of $12 or higher). For a market price of less than $12 per barrel, the Swing Producer will expand production less aggressively in punitive mode.

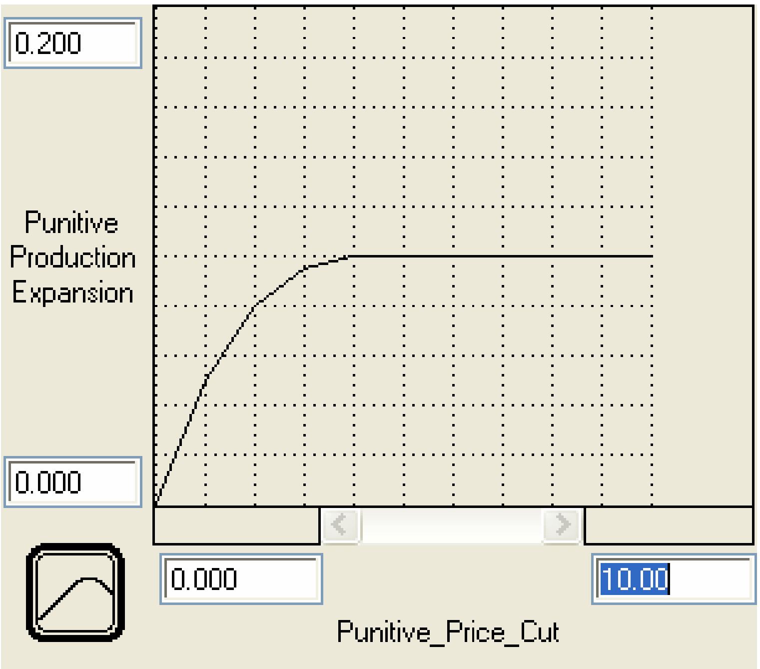

Figure 10: Punitive Production Expansion

Quota Setting and Allocation

This section describes how the OPEC cartel sets an overall quota and decides to allocate the quota between the Swing Producer and the Opportunists.

Figure 11 shows the associated flow-diagram.

Table 12 lists the equations that determine cartel quota in the model. The starting point is the current amount of oil the cartel have agreed to produce, **Cartel Agreed Quota**. The initial value is 24 million barrels per day, **INIT(Cartel Agreed Quota)**. Changes in the agreed quota are implemented through a variable describing the change in cartel quota. **Change in Cartel Quota** is an adjustment to quota whose size depends on the amount by which the call on the cartel differs from the agreed quota, **Cartel Quota Imbalance**, and the time to adjust the quota. **Time to Adjust Cartel Quota** is 0.5 years, representing the time between cartel meetings.

Cartel Agreed Quota = Cartel Agreed Quota + dt * (Change in Cartel Quota)
INIT(Cartel Agreed Quota) = 24 {millions of barrels per day}

Change in Cartel Quota = (Cartel Quota Imbalance/Time to Adjust Cartel Quota)

Time to Adjust Cartel Quota = 0.5 {half a year represents the interval of time between cartel meetings}

Cartel Quota Imbalance = Call on Cartel*(1+Cartel Quota Bias) - Cartel Agreed Quota

Call on Cartel = Demand for Oil - Independents Production
{Millions of barrels of oil per day}

Cartel Quota Bias = 0

Table 12: Quota Setting

Cartel Quota Imbalance depends on three terms: **Call on Cartel**, **Cartel Quota Bias**, and **Cartel Agreed Quota**. The cartel is aiming for total production equal to the **Call on Cartel**, modified by an adjustment factor **Cartel Quota Bias**. The difference between this adjusted call on the cartel and the **Cartel Agreed Quota** is the basis for changes in **Cartel Agreed Quota**.

The **Call on Cartel** is the difference between the **Demand for Oil** (see table 6) and the **Independents Production** (see table 1). This formulation assumes that the cartel's production is flexible in the short run because the Independent producers must always produce at capacity. In other words, any short to medium term change in total production required by a change in demand will have to come from the cartel itself.

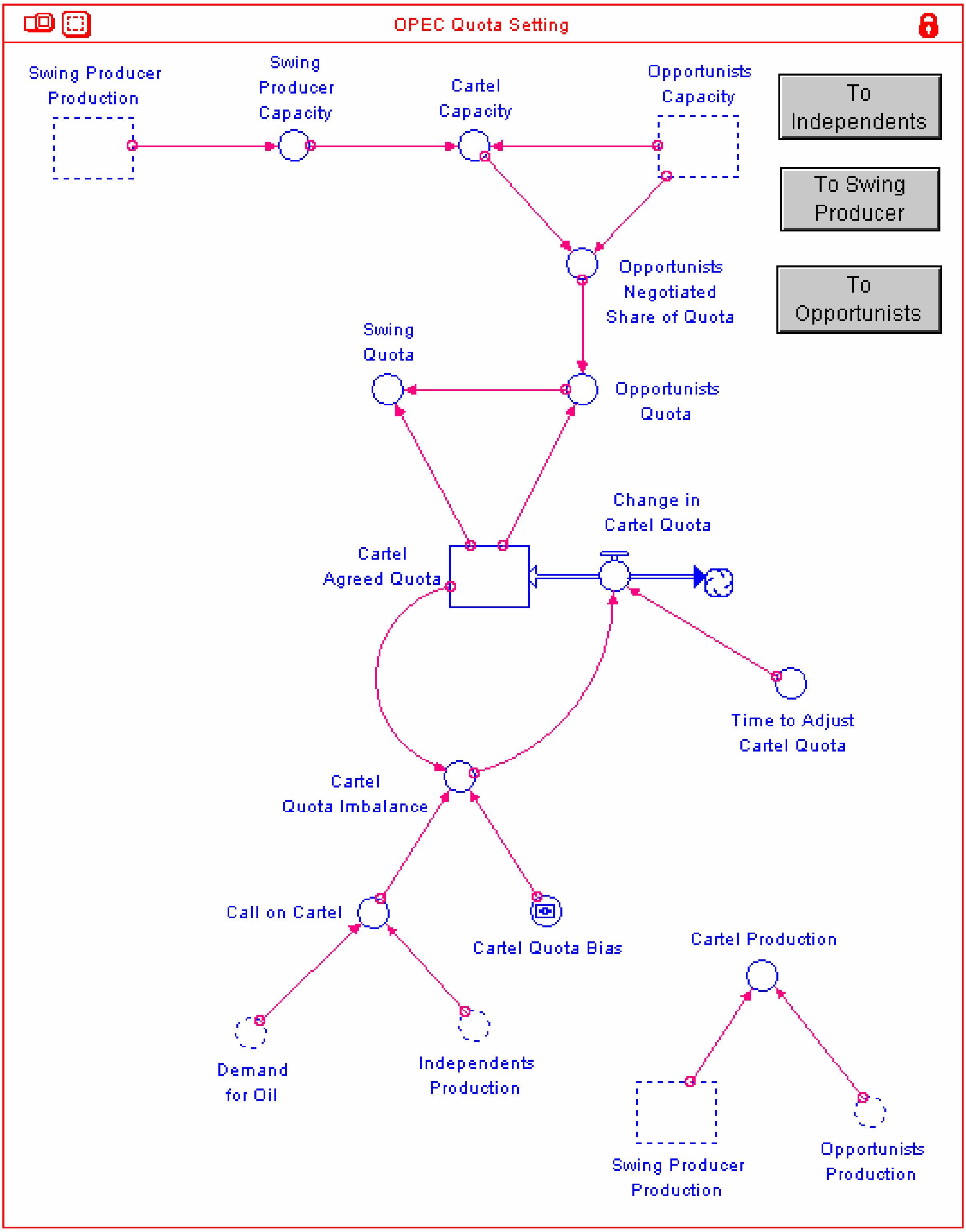

Figure 11: Quota Setting and Allocation

Cartel Quota Bias represents the cartel's tendency to withhold production. When the bias is -.05 the cartel sets a quota that withholds 5 percent of the call with the likely intention of increasing market oil price. The bias can also be used to represent a policy of excess production by the cartel. If the bias is .05, then the cartel sets a quota that exceeds the call by 5 percent, thereby flooding the market with crude oil.

Table 13 show the policy of quota allocation within the cartel.

Swing Quota =Cartel Agreed Quota -Opportunists Quota

Opportunists Quota = Cartel Agreed Quota * Opportunists Negotiated Share of Quota

Opportunists Negotiated Share of Quota = Opportunists Capacity/Cartel Capacity
{quota is allocated in proportion to capacity}

Cartel Capacity = Swing Producer Capacity +Opportunists Capacity
{Millions of barrels per day}

Swing Producer Capacity = SMTH1(Swing Producer Production,1)
{The swing producer's capacity for the purpose of bargaining in quota allocation. Based on average production over the past year}

Cartel Production = Swing Producer Production + Opportunists Production

Table 13: Quota Allocation

The Swing Producer's quota, **Swing Quota**, is the difference between the **Cartel Agreed Quota** and the Opportunists' quota. The **Opportunists Quota**, is the **Cartel Agreed Quota** multiplied by the fraction the Opportunists have negotiated during quota bargaining, **Opportunists Negotiated Share of Quota**. This fraction is based on the ratio **Opportunists Capacity** (see table 14) to the total **Cartel Capacity**, as a surrogate for bargaining power in a political bargaining process. The total capacity of the cartel is the sum of the **Swing Producer Capacity** and the **Opportunists Capacity** in millions of barrels per day. By assumption, the Swing Producers have plenty of surplus capacity, so for the purpose of quota bargaining, the Swing Producers' operating capacity is estimated as the average production over the previous year. The total **Cartel Production** is the sum of the Swing Producers' production and the Opportunists' production.

The Opportunists

This section describes the Opportunists and their behaviour.

Figure 12 shows the associated flow-diagram and Table 14 shows the Opportunists' capacity adjustments.

Opportunists Capacity = Opportunists Capacity + dt * (Change in Opportunists Capacity)

INIT(Opportunists Capacity) = 17 {millions of barrels per day}

Change in Opportunists Capacity = (Opportunists Desired Capacity-Opportunists Capacity) /Time to Adjust Capacity

Opportunists Desired Capacity = Opportunists Quota*(1+Opportunists Capacity Bias) {millions of barrels per day}

Opportunists Capacity Bias = graph(Opportunists Declared Capacity Bias)
(0.0,0.0),(0.0200,0.0200),(0.0400,0.0400),(0.0600,0.0600),
(0.0800,0.0800),(0.100,0.100),(0.120,0.120),(0.140,0.140),
(0.160,0.160),(0.180,0.180),(0.200,0.200)

Opportunists Declared Capacity Bias = 0.02

Time to Adjust Capacity = 2*Effect of Capacity Limit on Time to Adjust

Effect of Capacity Limit on Time to Adjust = graph(Opportunists Fraction of Maximum Capacity)
(0.900,1.00),(0.910,1.00),(0.920,2.00),(0.930,4.00),(0.940,6.00),
(0.950,8.00),(0.960,9.00),(0.970,10.00),(0.980,10.00),(0.990,10.00),
(1.00,10.00)

Opportunists Fraction of Maximum Capacity = Opportunists Capacity/Opportunists Maximum Feasible Capacity

Opportunists Maximum Feasible Capacity = 35

Table 14: Opportunists' Capacity Adjustments

The **Opportunists Capacity** begins from an initial value **INIT(Opportunists Capacity)** of 17 Millions of barrels per day and accumulates capacity changes. The **Change in Opportunists Capacity** is the difference between the **Opportunists Desired Capacity** and their current capacity, **Opportunists Capacity**, adjusted over a period of time, **Time to Adjust Capacity**. The Opportunists' desired capacity is based on the **Opportunists Quota** (see table 13) and the **Opportunists Capacity Bias**. The formulation assumes that the Opportunists want to expand their capacity above quota, and use the 'excess' capacity to improve their bargaining position in quota negotiations. **Opportunists Capacity Bias** is defined as a graph function in figure 13.

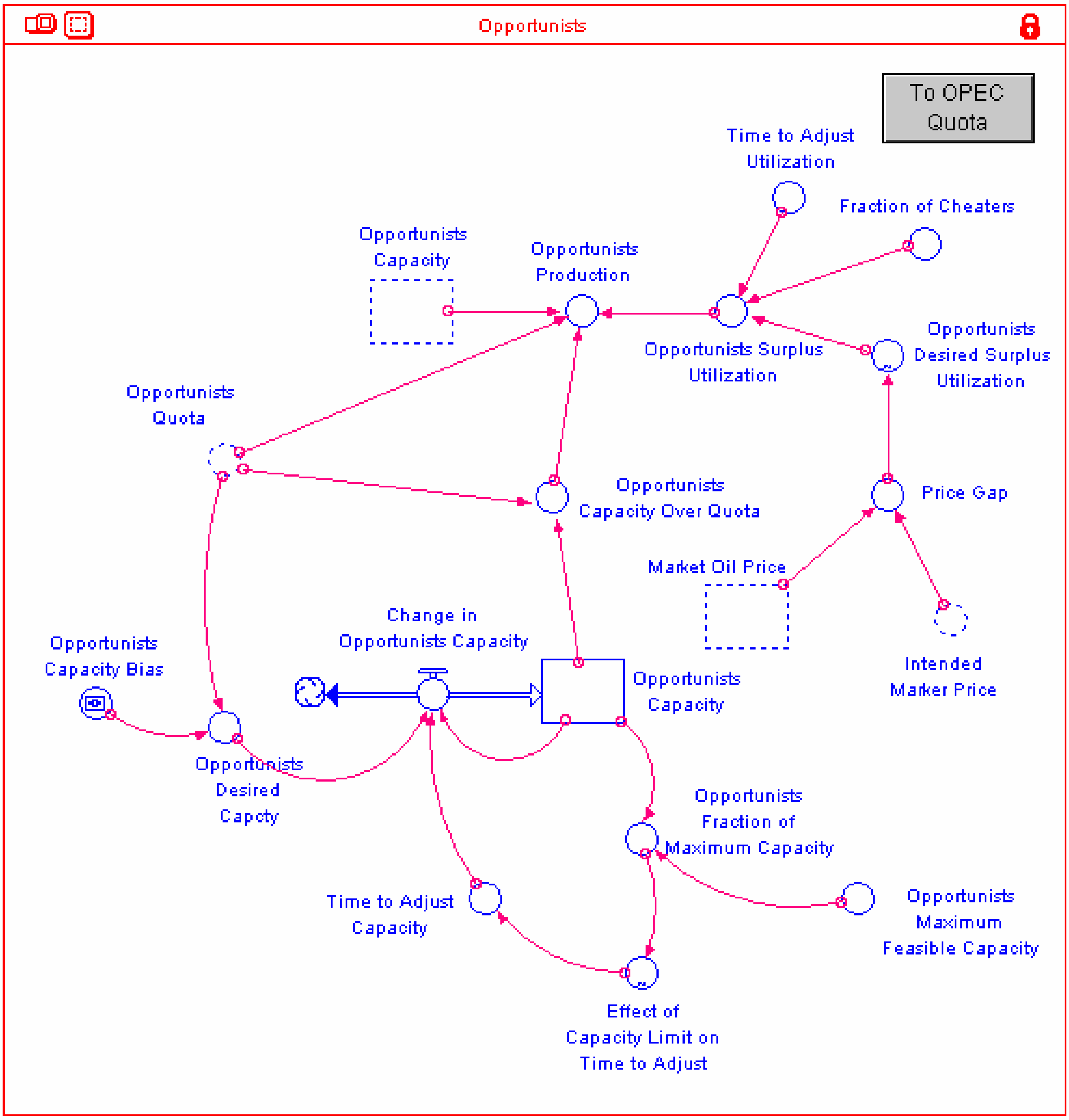

Figure 12: The Opportunists

Opportunists Capacity Bias represents the Opportunists' intended reserve capacity above quota. In the base run it is assumed that the Opportunists are aiming for capacity 2 percent higher than quota, so **Opportunists Capacity Bias** is set to 0.02.

The time for the Opportunists to add new capacity, **Time to Adjust Capacity**, is normally 2 years. However, as Opportunists' capacity approaches an assumed political limit (at which it is clear to other producers that the opportunists are being greedy), the time it takes to develop new capacity becomes much longer. The political limit is represented by **Opportunists Maximum Feasible Capacity** and is set at 35 million barrels per day.

The effect of this limit on time to add capacity is shown in figure 13. **Opportunists Fraction of Maximum Capacity** measures how close Opportunists' capacity is to the 35 million barrel per day limit. Providing the fraction stays below .9 (90 percent) then new capacity can be added in the normal time of 2 years. If the fraction exceeds .9, then political opposition grows to further capacity expansion by the Opportunists. The result is that the time to add new capacity increases sharply from 2 years to a maximum of 20 years, as the **Effect of Capacity Limit on Time to Adjust** rises from 1 to 10.

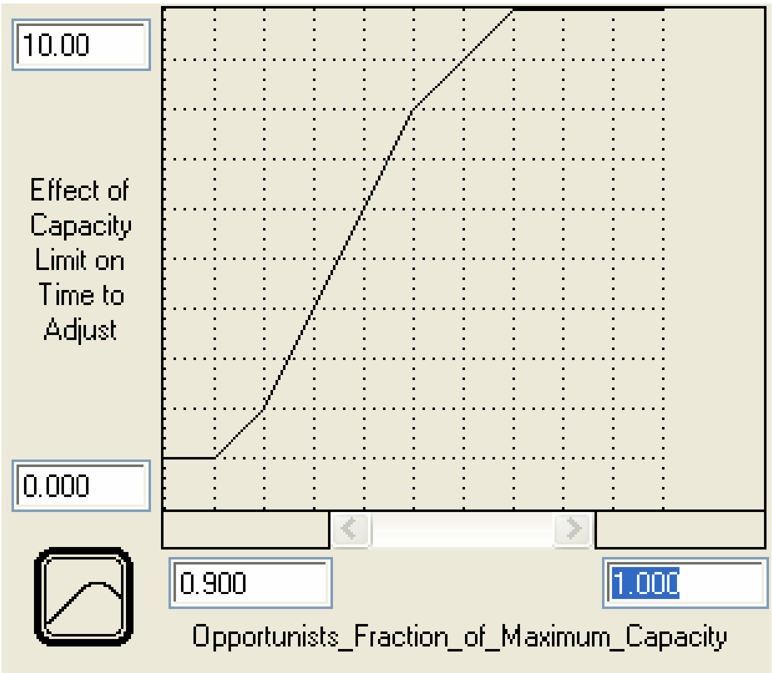

Figure 13: Effect of Capacity Limit

Table 15 shows the last part of the Opportunists' formulation, the equations representing production.

The actual **Opportunists Production** depends on four variables: **Opportunists Quota**, **Opportunists Capacity**, **Opportunists Capacity over Quota**, and **Opportunists Surplus Utilization**.

The Opportunists will always aim to produce an amount equal to at least their negotiated quota, **Opportunists Quota**, unless constrained by **Opportunists**

Capacity. So they choose whichever is the smaller, quota or capacity. In addition to quota, they gamble on using a portion of surplus capacity, if they have any. (Remember that in the base case, the Opportunists are aiming for a 2 percent surplus capacity (see table 14)). This portion of surplus capacity is expressed as the product of **Opportunists Capacity over Quota** and **Opportunists Surplus Utilization**.

Opportunists Capacity over Quota is the amount (in millions of barrels per day) by which the Opportunists' capacity exceeds quota. If this number is negative, i.e. capacity is smaller than the Opportunists' quota then **Opportunists Capacity over Quota** is set to '0'. This condition makes the formulation of the **Opportunists Production** equation consistent, so that the Opportunists are never in the position of using a portion of negative 'surplus' capacity, an outcome that clearly makes no sense.

The **Opportunists Surplus Utilization** is the average of the **Opportunists Desired Surplus Utilization** (averaged over a time period to adjust utilization, **Time to Adjust Utilization)** multiplied by the fraction of Opportunists that 'cheat' by using their excess capacity to produce over and above quota, **Fraction of Cheaters**.

Opportunists Production = MIN(Opportunists Quota, Opportunists Capacity) + (Opportunists Capacity over Quota* Opportunists Surplus Utilization)

Opportunists Capacity over Quota = MAX((Opportunists Capacity-Opportunists Quota),0)

Opportunists Surplus Utilization = SMTH1(Opportunists Desired Surplus Utilization, Time to Adjust Utilizationn)*Fraction of Cheaters

Opportunists Desired Surplus Utilization = graph(Price Gap)
(-5.00, 0.0),(-4.50, 0.0),(-4.00, 0.0),(-3.50,0.0150),(-3.00,0.0400),
(-2.50,0.0700),(-2.00,0.145),(-1.50,0.275),(-1.00,0.540),(-0.500,0.920),
(0.0,1.00)

Time to Adjust Utilization= .5

Fraction of Cheaters = .5

Price Gap = Market Oil Price-Intended Marker Price

Table 15: Opportunists Production

The **Opportunists Desired Surplus Utilization** is a graph depending on **Price Gap**. The graph is shown in figure 14. **Price Gap** is the difference between **Market Oil Price** (see table 8) and **Intended Marker Price** (see table 10). If **Price Gap** is negative, the **Market Oil Price** is lower than the **Intended Marker Price**. Therefore, the Opportunists will be cautious in producing more than their quota because such quota busting will be visible to the swing producer as a depressed price. However, as the gap between **Market Oil Price** and **Intended Marker Price** closes the Opportunists will be more tempted to cheat because the effects of cheating will be invisible. Figure 15 shows that if there is more than $4 per barrel difference between the intended and actual price the Opportunists will not cheat at all. When the gap disappears (i.e. **Price Gap** = 0) the Opportunists will cheat as much as possible.

Time to Adjust Utilization is the time it takes the Opportunists to adjust their utilization of surplus capacity. This is assumed to be half a year. Finally, the fraction of the Opportunists that 'cheat', **Fraction of Cheaters**, by using their excess capacity to produce over quota, is assumed to be 50 percent of the Opportunists.

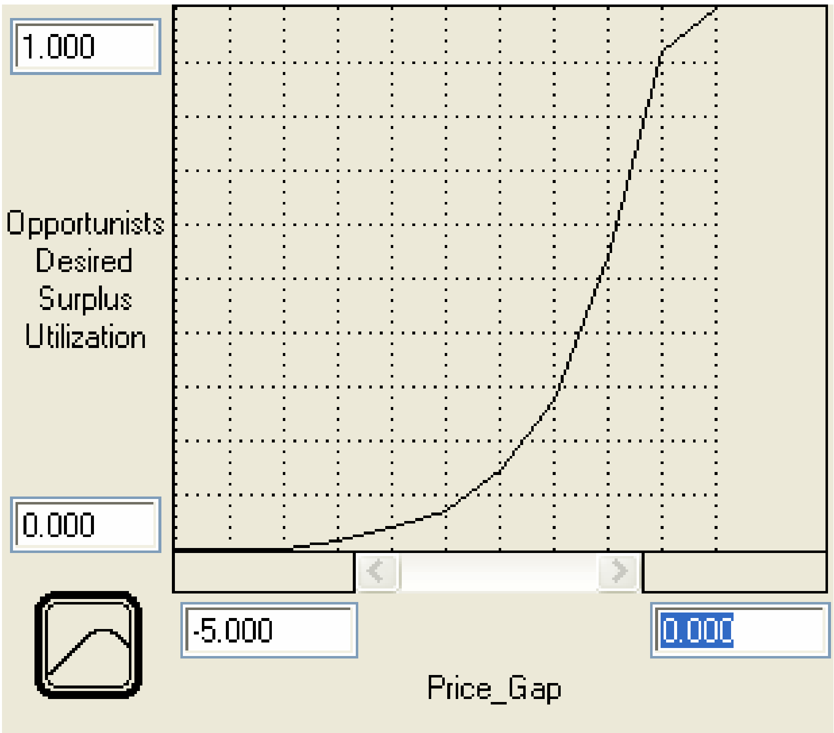

Figure 14: The Opportunists' Desired Surplus Utilization

Revenue Calculations

This section describes how revenue is calculated for the three groups of producers: Independents, Swing Producers and Opportunists.

Figure 15 shows the associated flow diagram.

The equations are shown in table 16. A number of the equations shown are defined and used elsewhere in the model. These equations are marked by a '**' and will not be described again.

Daily revenue is calculated for each producer based on the product of current production: **Swing Producer Production** (see table 9), **Opportunists Production** (see table 15), and **Independents Production** (see table 1), and the current market price, **Market Oil Price** (see table 8). Daily revenue is multiplied by 360 to convert it into yearly revenue. Yearly revenue accumulates for each type of producer into a cumulative revenue: **Independents Cumulative Revenue**, **Opportunists Cumulative Revenue**, **Swing Producer Cumulative Revenue**. All these cumulative revenues are set at a starting value of zero when the simulation begins in 1988.

The **Industry Revenue** is the sum of the three yearly revenues. Similarly, the **Industry Cumulative Revenue** is the sum of the three cumulative revenues.

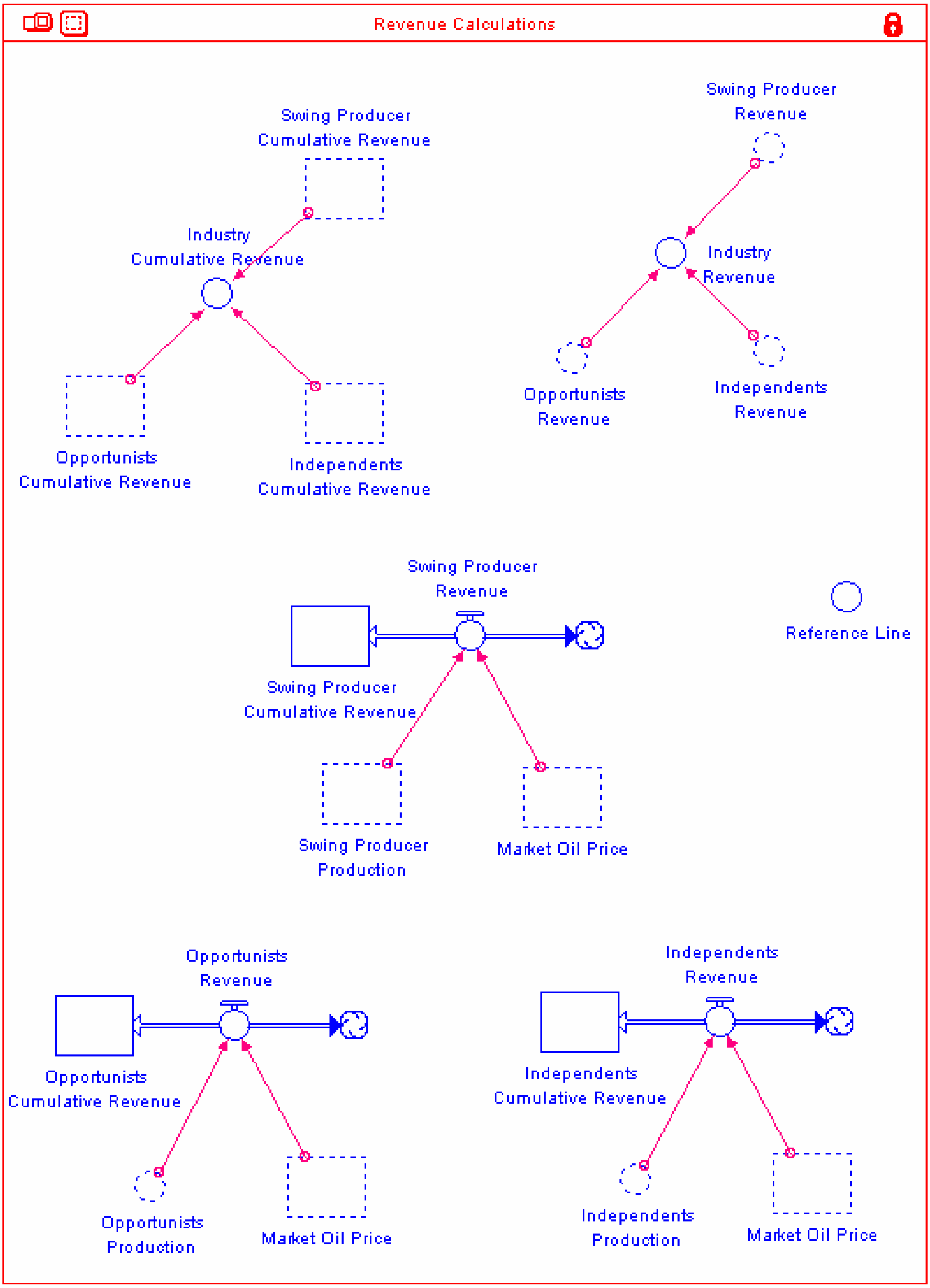

Figure 15: Revenue Calculations

Independents Cumulative Revenue = Independents Cumulative Revenue + dt * (Independents Revenue)
INIT(Independents Cumulative Revenue) = 0 {billions of $}

** Market Oil Price = Market Oil Price + dt * (Change in Oil Price)
INIT(Market Oil Price) = 15 {$ per Barrel}

Opportunists Cumulative Revenue = Opportunists Cumulative Revenue + dt * (Opportunists Revenue)
INIT(Opportunists Cumulative Revenue) = 0 {billions of $}

** Swing Producer Production = Swing Producer Production + dt * (Change in Swing Production)
INIT(Swing Producer Production) = 7

Swing Producer Cumulative Revenue = Swing Producer Cumulative Revenue + dt * (Swing Producer Revenue)

INIT(Swing Producer Cumulative Revenue) = 0 {billions of $}

** Independents Production = Independents Capacity

Independents Revenue = Independents Production*360* Market Oil Price)/1000
{billions of $ per year -- initial value is (26*360*15)/1000 = 140.400}

Industry Cumulative Revenue = Opportunists Cumulative Revenue + Swing Producer Cumulative Revenue + Independents Cumulative Revenue

Industry Revenue = Opportunists Revenue + Swing Producer Revenue +Independents Revenue

** Opportunists Production = MIN(Opportunists Quota, Opportunists Capacity)+ (Opportunists Capacity over Quota*Opportunists Surplus Utilization)

Opportunists Revenue = (Opportunists Production*360* Market Oil Price)/1000
{billions of $ per year -- initial value is (17*360*15)/1000 = 91.800}

Reference Line = 0

Swing Producer Revenue = (Swing Producer Production*360* Market Oil Price)/1000
{billions of $ per year -- initial value is (7*360*15)/1000 = 37.800}

Table 16: Revenue Calculations