# Revisiting Classic Energy Models for Evolutionary System Insights

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## *Abstract*

*This paper reports the results of a comparison of quantitative and qualitative approaches to systems analysis. The primary goal of the investigation was to test a heuristic for qualitative analysis previously proposed by the author that is intended to improve recognition of potential sources of failure for models used for forecasting. A series of papers published by John Sterman, George Richardson, and Pål Davidsen in the mid- to late-1980s examining resource estimation methods and the petroleum lifecycle were selected for analysis based on their completeness and perceived high quality of the models – both quantitative and qualitative. The quantitative results presented in those papers are compared to published data and some potential sources of deviation are identified. The paper then presents an analysis of the qualitative models contained in the papers, highlighting the differences in the nature of insights available from the qualitative and quantitative analyses and illustrating how this expanded logic for qualitative analysis may contribute to the formulation and bounding process for predictive system dynamic models.*

Quantitative models based on systems thinking and system science are routinely used to explore and anticipate the behavior of broad and highly complex issues. This paper revisits the quantitative results presented in a series of classic papers by John Sterman, George Richardson, and Pål Davidsen (Sterman & Richardson, 1985) (Davidsen, Sterman, & Richardson, 1990; Richardson, Sterman, & Davidsen, 1988) on the petroleum industry and its life cycle and compares their projections to what has transpired over the twenty years since publication. The underlying qualitative models are analyzed using a logic proposed by the author for inferring evolutionary tendencies of systems from qualitative system characteristics (Forrest, 2004). The three papers analyzed were based on a series of very similar models and were chosen for this analysis based on the perceived quality and clarity of their conclusions and on the explicitness and thoroughness of their underlying qualitative models. (The models underlying the other 15 papers reviewed were either not communicated clearly, or judged to be significantly inferior to the papers selected.) While the models presented in the three papers are essentially identical they offer different insights and provide a rich contrast for the comparison to the insights from qualitative analysis. The models also include broadly based elements to allow them to represent the full range of potential influences. This paper presents an overview of the models, the key learnings reported by the authors, and a comparison of the projections presented to subsequent history. This retrospective examination of the models helps fill a gap in the literature of system dynamics of examining predictive models for accuracy.

Two papers used the models to examine methods for estimating ultimate recoverable petroleum. Those analyses have proven to be reasonably accurate and correctly identified the key predictive characteristics of the two primary methods for estimating petroleum reserves as is discussed in the following section and illustrated in Table 1. The success of the models in capturing subtle characteristics of the estimation methods reinforces the benefit of using system dynamics to understand processes and their characteristics where quantification is practical. In this case the subjects were two mathematical processes that lend themselves to quantification. System dynamic modeling achieved good success in anticipating the impacts of those methodologies.

All of the quantitative models reproduced history with very good accuracy as illustrated later in Figure 2, Figure 3, and Figure 4. The patterns projected into the future generally continued to show some relationship to reality over the first five to ten years with accuracy gradually decaying over that period. The projections and actual values beyond ten years (past the mid-1990s) do not correlate well. The growing discrepancy over time appears to be primarily related to a combination of eroding assumptions related to both the relationship between petroleum price and in investment in exploration and technology, and to an excessively high petroleum price assumption over much of the past twenty years. Of particular note, the projected relationship between domestic petroleum production and petroleum price has thus far proven to be in serious error. It appears the models' assumptions and values would require substantial revision to mimic the petroleum life-cycle behaviors over the twenty years since the publication of the papers. In summary, these models provide valuable insight to historical dynamics, show value for understanding current and near term dynamics, and serve as a platform for testing procedural logic – such as the logic for estimating reserves. However, the longer-term deviation of projections from reality confirms the importance of robust assumptions for predictive models.

A qualitative analysis of the underlying causal models was performed in an effort to evaluate a logic of heuristics for inferring system behavior and evolution from qualitative system characteristics. Of particular interest was the differing nature of insights available from qualitative analysis and the potential for this logic to enhance the process of qualitative analysis that precedes and accompanies the development of quantitative model.

The qualitative analysis provided very different insights from those gained by quantitative analysis. For example, the qualitative analysis shed no significant light on the methods of estimating ultimate recoverable petroleum. However, the qualitative analysis did suggest possible boundary issues and questions regarding assumptions affecting the life-cycle model. More significantly, the qualitative analysis identified several industry-wide evolutionary patterns that have occurred over the past twenty years and identified other areas where historically based assumptions might be vulnerable to change. The end result was a vision of the future petroleum industry, the uncertainties it faced, and likely patterns of industry evolution that could have proven useful in establishing bounding or qualifying the pertinence of the original models.

It should be acknowledged that hindsight is relatively easy. The goal in preparing this qualitative analysis was to capture the mindset of the early and mid-1980s and to view the trends and uncertainties that shaped the interpretation of the qualitative analysis from that period. The end result is not a singular vision of the future, but a web of possibilities and scenarios. As a result the conclusions of the qualitative analysis are less deterministic and more conjectural in nature than the results of traditional quantitative analysis. The purpose of this analysis was not to criticize prior work, but rather to evaluate this heuristic on historical models. Successful qualitative insights imply potential value for the qualitative methodology and for qualitative modelers striving to build predictive quantitative models.

This analysis ultimately arrives at four primary conclusions based upon these specific models:

- Quantitative models can provide useful insight into historical and current system dynamics and provide a valuable platform for examining system-related logic.

- The projections in these papers supports the use of quantitative models to evaluate procedures and process methods where the processes can be accurately quantified.

- The supply, demand, and life cycle projections in these papers do not support the use of quantitative models to project future dynamic behavior beyond the near term future. Their utility is limited by the life of the validity of the underlying assumptions.

- Qualitative system analysis demonstrates potential value in understanding future dynamics – for suggesting possible patterns of system evolution, and for identifying areas of potential vulnerability (of assumptions and systemic relationships) in systems models.

While the qualitative analysis based on a 1985 perspective identified potential sources of structural change and potential turbulence for the petroleum industry, it remains to be seen if the heuristic will hold significant value in developing more robust quantitative models. This uncertainty results in part from to a conflict between the specific problem context that historically defines system dynamics and the whole system logic underlying the qualitative heuristic. Still, the results of this study and preliminary experiments with students reinforce that the heuristic holds value during the expansive phase of bounding models addressing future behavior and stimulates deeper examination of the boundaries under consideration.

# The System Dynamic Models and Model Results

## *The Sterman/Richardson and Sterman/Richardson/Davidsen Resource Estimation Models*

In *An Experiment to Evaluate Methods for Estimating Fossil Fuel Resources* by John D. Sterman and George P. Richardson (Sterman & Richardson, 1985), the authors used system dynamics to model estimation of global petroleum reserves and to evaluate the potential accuracy of the two dominant methods for estimating ultimate recoverable crude oil – the Hubbert life cycle approach and the USGS geologic analogy method. The same authors subsequently collaborated with Pål Davidsen (Richardson et al., 1988) on a similar paper to examine the same approaches for estimating domestic US petroleum reserves. Both modeling efforts concluded that the Hubbert life cycle approach could generate an accurate estimate of reserves up to twenty years before the peak of global production (once depletion began to dominate other forces), and that the USGS methodology consistently overestimated the resource base throughout the life cycle of the resource.

The model used in the Sterman/Richardson paper provides a clear mental model for the petroleum industry. The Sterman/Richardson/Davidsen model appears to be essentially identical, differing primarily by being populated with US-only values as opposed to global values in the earlier paper. While the authors used these models to examine only one facet of the petroleum system for this paper – estimation of resources – the completeness and clarity of the model make it an attractive target for qualitative analysis of evolutionary patterns of the petroleum exploration and production industries.

An overview of the models used by these authors is presented in Figure 1. While a more detailed structural model can be assembled from the ten sectoral, causal models presented in the reviewed papers, this overview should be adequate for the purposes of this paper. This paper will briefly compare the conclusions of the authors to current data and estimates and will then proceed to explore the model for evolutionary tendencies.

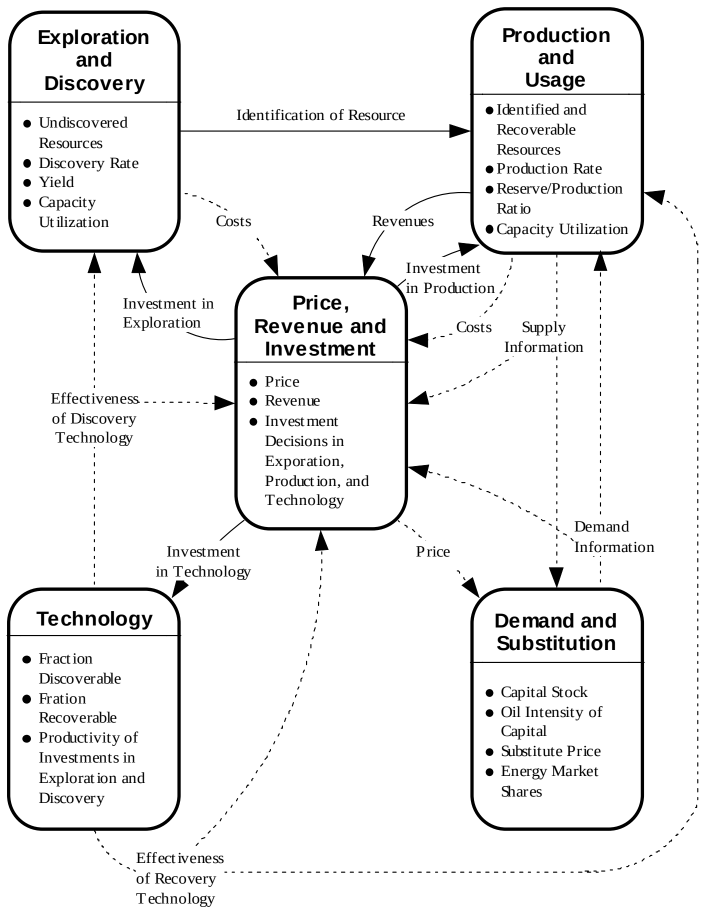


**Figure 1. The Sterman/Richardson Fossil Fuel Resource Estimation Model.**

As was previously indicated, the authors concluded that the Hubbert life cycle approach tends to grow increasingly accurate over the life of the resource being estimated. The USGS geologic analogy approach, on the other hand, tends to overestimate potential reserves throughout the life of the resource. It was further shown that the Hubbert life cycle method could accurately estimate the ultimate recoverable crude up to 20 years prior to peak production – when depletion began to dominate the resource dynamics. Some of the key conclusions from the two papers are summarized in Table 1 along with recent data – nominally twenty years past the development of the model estimates.

**Table 1 Model Results Comparison to Subsequent History**

<table>
<tr><th>Item</th><th>Model Results for Year 2000</th><th>Model Results Ultimate Est.</th><th>Recent Data/Estimates</th></tr>
<tr><td>Hubbert Global Est. Recoverable Crude (trillion barrels)</td><td>3.0</td><td>2.7</td><td rowspan="2">3.0 (2.2 – 3.9) EIA<br>3.0 Edwards<br>2.3 Riva<br>2.3 Masters<br>2.1 OPEC<br>1.8 Campbell</td></tr>
<tr><td>USGS Global Ult. Recoverable Crude (trillion barrels)</td><td>3.5</td><td>3.0</td></tr>
<tr><td>Hubbert US Estimate of Recoverable Crude (billion barrels)</td><td>213</td><td>225</td><td rowspan="2">329 Edwards<br>214 EIA (proven)</td></tr>
<tr><td>USGS US Estimate of Ultimate Recover-able Crude (billion barrels)</td><td>289</td><td>228</td></tr>
<tr><td>Global Production (billion barrels/year)</td><td>34</td><td>N/A</td><td>27.7 API</td></tr>
<tr><td>US Production (billion barrels/year</td><td>1.7</td><td>N/A</td><td>2.5 EIA</td></tr>
</table>

Recent estimates for ultimate recovery tend to be somewhat below the values predicted in the papers, but the patterns of overshoot for the USGS method and the relative accuracy of the Hubbert method are generally substantiated. The lower current forecasts for global recoverable reserves primarily relate to reductions in estimated reserves (partially due to restatements of existing reserves by both petroleum companies and countries) and to reductions in expectations of new deposits to be discovered. Given the data available in 1987, the general accuracy of the model seems quite good and the study's observations regarding the performance of the two estimation methods valid.

Production estimates have proven less accurate. The global model overestimated year 2000 production by 20 percent based upon projected crude prices in the $20 range as compared to an actual price of $15 (1982 dollars). This makes sense as the model structure shows that lower prices should result in reduced production. The United States model underestimated domestic production by 30 percent despite projecting crude oil prices in the $30 dollar range – double the $15 actual price (1982 dollars). Again, lower prices would be expected to translate into lower production as happened in the global case. This leads to the conclusion that the relationships between petroleum price, production, and demand are generally flawed in both models. It should, however, be noted these models were not intended for the purpose of predicting demand or production so it is inappropriate to focus too keenly on these shortcomings.

The cumulative effect is that the Sterman/Richardson/Davidsen paper offered relatively accurate predictions for estimated ultimate recovery (EUR) for the US – using the Hubbert estimation method. The earlier Sterman/Richardson paper that addressed global EUR was somewhat less accurate in its estimates but still captured the essential characteristics of the estimation methods. These papers merit note for their clever and innovative use of an industry model to investigate the dynamics of resource estimation methodologies – calculational protocols. Their success strongly supports the argument that quantitative models can be useful in evaluating policies and processes where they can be reasonably quantified.

## *The Davidsen/Sterman/Richardson Life Cycle Model*

Sterman, Richardson, and Davidsen continued to develop the model shown in Figure 1 and subsequently used an expanded version to explore the dynamics of the US petroleum supply (Davidsen et al., 1990). This model endogenously generated the entire life cycle of petroleum, integrating multidisciplinary perspectives and issues including geology, technology, economics, and substitution of synthetic fuels. The paper presents learning related to base assumptions regarding economic impacts, petroleum demand, pricing, and substitution and suggests that the model has value as a tool for application to a variety of petroleum issues. The paper continues by comparing its approach to similar energy models that were predominantly macroeconomic and non-structural. The paper presented that model along with a discussion of the learnings from the model related to the interrelationships of technology, investment, substitution, price, and demand.

The paper is noteworthy from several key aspects. The clarity of its structural model makes it substantially more transparent and accessible than its contemporary macroeconomic models. The underlying logic is readily available and provides clear support to the learnings and observations presented in the papers. It is also noteworthy that all of the behavior is achieved with only two exogenous variables – GNP and international petroleum price. The section relating the model behavior to historical records and the explanation of that behavior reads well and is illuminating.[1] The model's reproduction of key historical data to 1985 is good and the use of systems logic to communicate the historical issues is particularly effective. While changes in government reporting since the publication of the paper complicate assessment of some of the forecast details in the paper, data is adequate for a general assessment though a detailed assessment is impaired by a lack of model quantification details.

Though the model predicted historical petroleum demand rather accurately it did depart from reported values during the petroleum crisis of the late 1970s as shown in Figure 2. The model predicted a slump in petroleum demand in the early 1980s but the actual

[1] As a consultant to the petroleum and chemical industry when these articles were in preparation, this author found the analysis in these papers strikingly clear and insightful relative to what he recalls being discussed in that era. The historical and current analysis was in his opinion excellent!

slump was somewhat greater than predicted by the model. The model went on to predict very modest demand growth to a peak near the year 2000 followed by a gradual decline. Actual demand has shown near-steady growth since demand bottomed in the early 1980s.

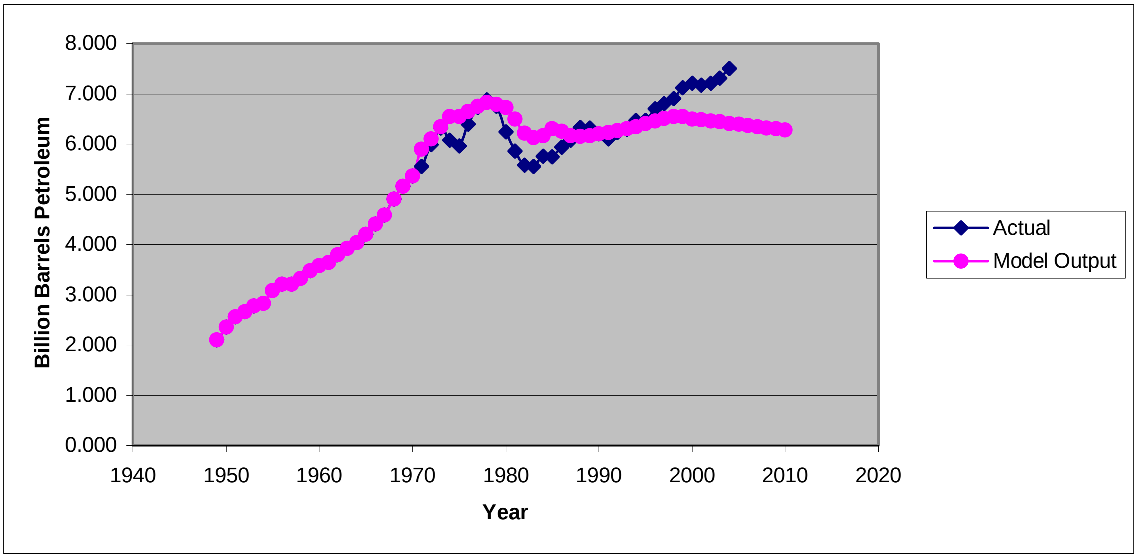


**Figure 2 US Petroleum Demand (*International Energy Outlook 2004*, 2004)**

The primary error in the demand forecast appears to be associated with the crude oil price assumptions used in the base case as illustrated in Figure 3. The model assumed that crude oil prices would rise $1 per barrel per year and those increases have not occurred. Lower prices would reduce the incentive for conservation, leading to higher demand but would not stimulate production. The qualitative models suggest that lower petroleum prices decrease incentive to invest in exploration, production and in technical innovation – actions that the models and related discussion indicate should over time reduce crude discovery and thus availability.

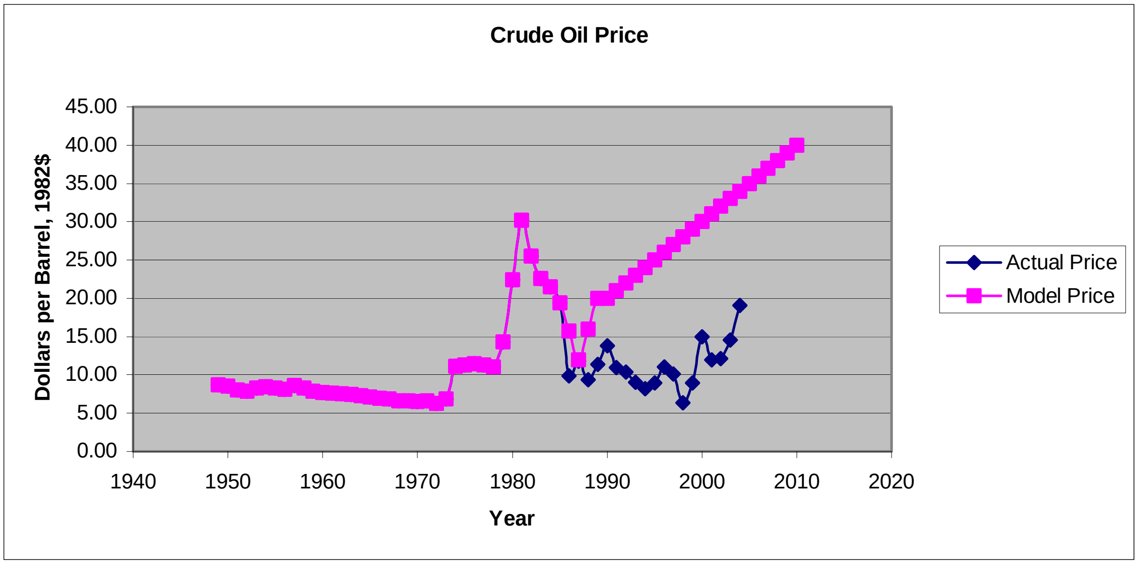


**Figure 3 Crude Oil Price (*International Energy Outlook 2004*, 2004)**

Figure 4 shows that the model captured domestic "lower 48" crude oil production rather accurately up to 1990. However, actual production since that date has shown only gradual decline as opposed to the significant decline projected by the model.

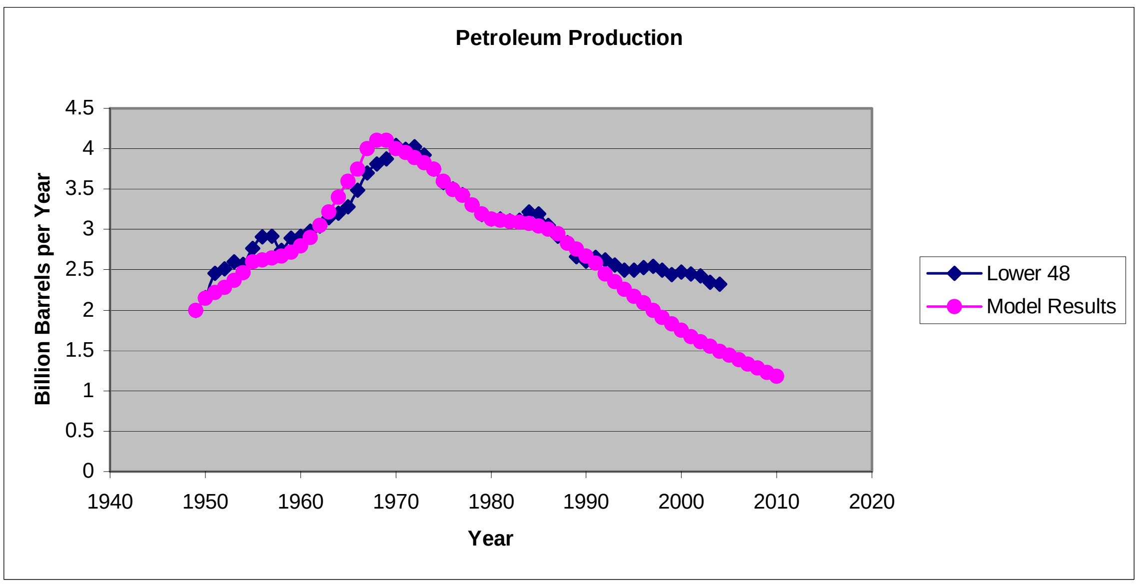


**Figure 4 Domestic US Petroleum Production (*International Energy Outlook 2004*, 2004)**

To date persistent shortfalls in crude oil supply as predicted by the model have not occurred. Crude oil has until recently generally been available in adequate volumes despite the low price. The model's assumption of a cost of $40 per barrel in the year 2000 (1982$) has proven to be excessively high. Canadian firms are increasingly investing in facilities to produce synthetic crude from tar sands and that crude is flowing to the United

States in increasing volumes at prices well below those projected. Similarly, plans for producing shale oil in significant volumes is gaining interest. These facts imply that the general relationships incorporated in the model for crude price to investment in both exploration and technology were pessimistic (i.e. assumed more incentive was necessary than has been experienced). The paper specifically projected that the impact of marginal investment in technology would decline. Given the impact of computers on seismic data processing and improvements in locating crude oil deposits, this assumption appears invalid over the past twenty years. It also seems likely that production from both older and newly discovered fields has exceeded the levels predicted in the models given the level of domestic US production. In absence of precise model details it is impossible to establish the detailed contributions of these factors. It seems evident that historical relationships that worked well in modeling history failed to persist into the future and contributed to predictive failure. In any event, the clarity of the models and their results provide a valuable reference for appraising the differing insights available from qualitative analysis.

## A Qualitative Review of the Models

The completeness of the Sterman/Richardson model and its performance made it an attractive model for applying the qualitative heuristic. The heuristic was presented at the System Dynamics Conference in Oxford (Forrest, 2004) and keys on identifying structural and behavioral shifts in the system that may shift model behavior and lead to obsolescence of model predictions. The heuristic views the model from eight separate perspectives to generate a set of disparate views and expectations that are resolved and merged into a cohesive expectation following the logic illustrated in Figure 5.

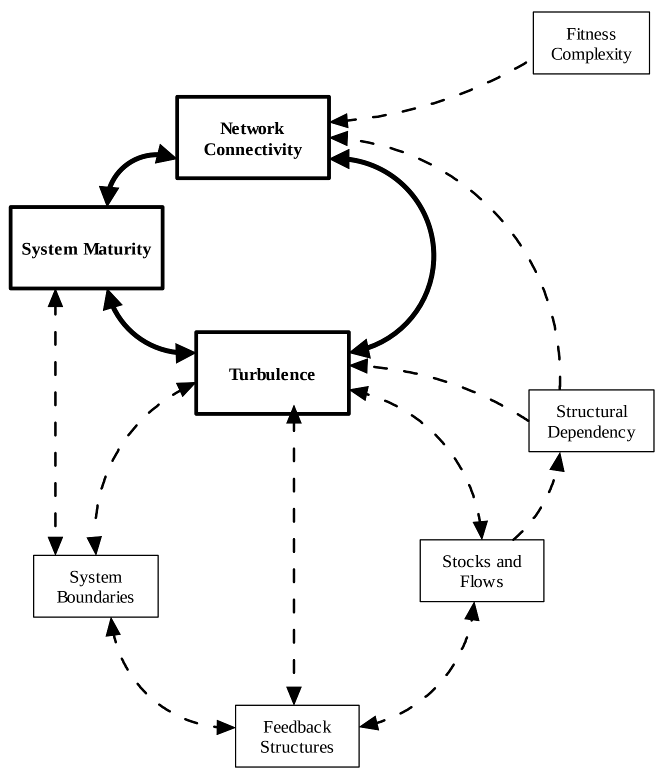


**Figure 5. Qualitative Analysis Heuristic**

At the core of this process is the balance between three perspectives: the maturity of a system, the level of turbulence within and surrounding the system, and the level of redundancy as expressed in the level of network connectivity of the system. The other five perspectives provide insight into sources of potential turbulence and to optimal connectivity patterns – inputs for testing and refining the perceived balance of the three core perspectives. The iterative nature of the process encourages development of a holistic vision of the system, expanding the problem-oriented "system in focus" perspective developed in conventional quantitative modeling.[2] One of the objectives of this process is to recognize potential sources of turbulence and change – suggesting extensive exploration of parameters that are likely to be external to conventional models and thinking. The extensiveness of that exploration can vary widely depending upon such considerations as the time available and the perceived need for longevity of the model. The insights from the disparate perspectives are then explored in a cyclical process to refine system understanding. The process can be expanded or contracted as time and resources allow. The qualitative analysis in this paper consists of a survey from the eight perspectives presented in a simplified form at the end of this paper. The following discussion touches upon the highlights of that analysis and presents a discussion of the cross-impacts. These observations are derived from the more extensive, but simplified analysis that follows the text of this paper. In a more extensive study, more sophisticated cross-impact methodologies would be used along with increased recycling through the perspectives and cross-impacts to build a stronger, more detailed analysis.

The primary observations from the qualitative analysis follow. Details and logic underlying these observations are provided in subsequent sections.

- The forces surrounding the industry were poised to challenge the industry and its ability to adapt and thrive.
    - Increasing competition over shrinking opportunities
    - International instabilities threatening reliable crude oil supplies (blocs of producing nations, nationalization of assets, national control of the industry, and political/resource concerns in the Middle East)
- Technological change was poised to impact on exploration for petroleum in the form of computers and in production in the form of miniaturized sensors.
- Mergers and acquisitions were likely as regional expansions offered opportunities for growth and efficiency as opposed to vertical integration (as global and national companies were generally already fully integrated from exploration to retail sales.

The overall resulting impression was that the existing companies were likely to struggle with disruptions from international turbulence and to pursue mergers and acquisitions to increase their competitiveness. International considerations appeared likely to play a major role in determining which companies would be leaders within the industry.

[2] Recognizing that most readers have probably not seen this logic before or the underlying bases, the author tried to keep this analysis comprehensible without getting bogged down in the supporting details. Readers who wish to understand the individual perspectives and related guidelines/heuristics are referred to the original paper from Oxford or more recent papers available at the author's web site.

It should be noted that this approach leads to observations that are quite different from those presented in the Sterman/Richardson papers and which might not have been useful to those authors in developing their papers. This occurs in part because the nature of this qualitative logic is to view the system comprehensively and not from the problem targeted approach generally endorsed in system dynamics. As a result these observations should not be construed as criticism of the bounding and formulation of the models underlying the papers. It should further be noted that while there are minor differences between the qualitative models underlying the series of papers, the similarity of the causal structures allows combining the qualitative analysis.

The following discussions by topic build on and integrate the disparate insights surfaced in the preceding table and develop the cross impacts of the perceived implications.

**System Maturity and Phases of System Evolution**

In the mid-1980s the petroleum industry was perceived as approaching the peak of its production and known reserves implying the industry was relatively mature – in what is commonly termed the maturation phase in evolutionary ecology. The primary structural changes in systems having moderate to advanced maturity are typically related to the pursuit of efficiency combined with a paring of inefficient connections.

A key focus during maturation is on efficiency. In industry that translates into “doing what you do better.” To that end one would have expected the industry to be focused on honing existing activities – getting more efficient at locating, tapping, and producing crude deposits, of processing crude into gasoline and other products, and for distributing and marketing those products. Given constrained domestic crude oil supplies, one would have expected domestic petroleum companies to pursue technology to improve efficiency. Computers were a rather immature technology in 1984 that clearly offered potential for gaining efficiency, and were being used increasingly in the petroleum industry. While the ultimate impact of computers was clearly not yet visible in the 1980s, it was evident that computer technology would impact the technology front, potentially offering increased efficiency, and effectively reducing the maturity level of petroleum exploration and production as new concepts and abilities surfaced. As a result computers were a clearly a potential source of change to the historic trends and assumptions.

In 1984 the dominant US petroleum companies were integrated (from exploration through gasoline marketing) and operated primarily on a regional basis. None of the companies marketed across the entire United States and in each geographic area one company typically held the dominant position. Opportunities for expanding further upstream or downstream to gain efficiency were generally limited, but mergers to increase scale and improve national marketing presence were practical. As a result, the state of the industry in 1984 suggested that mergers and acquisitions would be expected as a means of further improving efficiency. That process had already begun with the acquisitions of Getty by Texaco and Gulf by Chevron. (Pirog & Stamos, 1985) Subsequent merger/acquisitions of Exxon/Mobil, Shell/Texaco, and others support the validity of this analysis and interpretation.

In conjunction with maturation and resource decline, it was clear the petroleum industry would need to increasingly explore and contract internationally for sources of crude to meet domestic demand, making the industry increasingly vulnerable to international turbulence (political, supply, demand, etc.).(Chichilnisky & Heal, 1984; Yergin, 1980) Given the relatively advanced maturity of the industry, one would expect relatively bureaucratic, rigid management in the industry and that the corporate infrastructures and practices might be strained by turbulence. That strain suggested that companies with more domestic focus would be more vulnerable to decline or diminished growth than those with greater international experience and focus.

It is also appropriate to contemplate the maturity of the petroleum demand. Low prices and ready availability in the US, in particular, encouraged the demand infrastructure to exhibit immaturity in the form of being relatively inefficient. In Europe where energy prices were higher the patterns of energy consumption were more efficient and more mature. In developing countries without significant petroleum resources, the petroleum demand infrastructure was generally limited by availability and economic considerations. This set the stage for tremendous demand growth, with globalization squeezing the fitness landscape as the economies of developing countries rise toward the median and increase energy demand. (The fitness landscape implications are discussed in more detail under the topic of fitness complexity.) It is worth noting, however, that the relative immaturity and related inefficiency of the US petroleum demand infrastructure also gave more opportunity for conservation as a means of compensating for reduced petroleum availability relative to other developed countries.

**Turbulence**

Three areas of potential instability and turbulence were particularly visible in 1984:

- Computerization (and miniaturization)
- Peaking of petroleum production with potential market shortfalls
- International instabilities

The potential impact of computers was introduced under the topic of Maturity and will be considered in more detail under Stocks for specific potential impacts. At this point it is enough to recognize that computers posed a potential source of change and turbulence to the petroleum industry as recognized by numerous authors. (Hall, 1985) (Hayes, M., & Viellenave, 1984)

The peaking of petroleum production in the United States had already occurred by the time the original articles were written. (Chichilnisky & Heal, 1984) The global production peak appeared to be clearly in the future and rising global production appeared capable of replacing the declines in US production over the moderate term. While not significant to end-users, the replacement of domestic production was forcing a shift in industry activities. With opportunities for domestic exploration becoming more limited, petroleum companies were forced to look internationally for opportunities to locate and produce petroleum, and to increasingly purchase petroleum to fill their refineries. With the bulk of global petroleum reserves in the Middle East it was evident that the companies would have to focus on international activity if they wished to participate in the relatively lucrative exploration/production phase of the petroleum industry. The major petroleum companies would clearly need to become more international and would be likely to begin to explore alternative sources of crude such as tar sands and oil shale.

It was well evident in the mid 1980's that international borders and politics would serve as a fluctuating boundary for expansion of the international oil companies and potentially force the international companies to reconfigure their activities. (Yergin, 1980) OPEC had initiated the first oil shock. The Iranian revolution had initiated the second. Nationalization of international corporate assets had occurred in Mexico, Libya, and a number of other petroleum exporting countries. Meanwhile OPEC was growing more sophisticated in their management of pricing and of partnering. The major integrated oil companies were facing limits as nationalization influenced their ability to explore, discover, develop, and produce internal sources of petroleum. As production of existing fields fell, the integrated companies clearly faced a dilemma of replacing the lost production and it appeared likely that they would have to either acquire sources of petroleum (either acquiring fields from independent explorers and wildcatters or purchasing the company itself) or be increasingly dependent upon external sources. With the majority of fields in the US approaching decline, this portended turbulence for the industry. It is particularly noteworthy that the acquisition of smaller fields implied increased inefficiency, which contradicts the normal pattern of maturity of pursuing efficiency – thus creating a potential conflict and stress for the organization.

**Network Connectivity**

During the mid-1980's the bulk of the relationships within the petroleum industry were relatively linear, straightforward, and not complex – particularly for domestic petroleum within the United States. While there were numerous sources of potential supply, at any single location the number of sources utilized was few. Most refineries were originally optimized to use locally available crudes. In most cases refinery crude supplies were predominantly obtained from a sister division of the same company. Purchased crude was dominantly from preferred suppliers based upon the logistics, availability, and the capabilities of the refinery. By the mid-1980's declining domestic production had begun stimulating refinery modifications to allow use of alternative, and often foreign, crudes. Expectations of further declines in domestic crude supply implied that increasing supply complexity could be anticipated as international sources replaced declining domestic supplies. As a result it was evident in the mid 1980's that petroleum producers would be operating in an increasingly complex business climate.

The relatively linear supply chains of the 1980's would have satisfied the guideline that at least one source must supply at least 30 percent of each supply. The continued growth of international trade and supply might appear to offer an opportunity for breaking this guideline. However, inefficiencies in shipping costs, processing costs, and product optimization from less than optimal crudes suggests that refineries will self-optimize to favored crudes so that one should expect each refinery to draw at least 30 percent of its crude from one source. Thus, the potential proliferation of supply alternatives is not likely to be seen at the local level although an expanded purchasing network would be expected to evolve in order to cope with supply turbulence.

**Fitness Complexity**

Increasing connectivity as evidenced in globalization and increased international relationships implies that evaluating the fitness of actors in the system will be increasingly complex. Research in mathematical biology strongly suggests that increasing connectivity compresses the fitness of actors in the system as increased dependency and shared relationships make it increasingly difficult for actors within the system to maintain advantages. In addition, increased connectivity implies higher levels of turbulence since it allows disruptive events to ripple through the system and impact more participants. While there is some arguable evidence that the "fitness" of the major petroleum companies has been compressed over the past twenty years, persuasive comparative metrics are lacking. However, it does seem evident that the overall petroleum industry operating environment has grown far more complex and turbulent since the 1980's. In addition, major petroleum countries have shown substantial decline in "fitness" as measured by dominance of petroleum ownership and production, as the Seven Majors ownership of the world's oil declined from 61 percent in 1970 to 22 percent in 1981 (Pirog & Stamos, 1985). By 2000 nationalized oil companies owned 82 percent of the worlds reserves (Bell, 1997) implying the Seven Majors had continued their decline. The implications of this increased international dependence and its potential impact was recognized by Daniel Yergin (Yergin, 1980) when he stated, "All this means that the United States and other western countries are more and more dependent today on an accident-prone, crisis-prone international energy system."

Mathematical biology further suggests that increased connectivity tends to lead to a rise in the fitness of actors below the median fitness. As a result, globalization – the increasing global trade and communication – would be expected to elevate at least some of those below the median. Since 1980 we have seen a steady progression by South Korea, Singapore, India, and China, among others, as they become increasingly connected, communicating, and trading with the rest of the world. Those economic activities would encourage increased petroleum consumption and a further tightening of the global petroleum supply/demand balance.

**System Boundaries**

One of the key facets of the model underlying the papers is one of system boundaries. The Sterman/Richardson/Davidsen model was designed to produce its behavior endogenously. The model was highly agglomerated, with no external perturbations to confuse the output. While agglomeration can represent expanded boundaries and scope and facilitate quantitatively exploring model dynamics, the lack of specificity may mask dynamics that could lead to behavioral shifts. Disaggregating stocks and recognizing enabling stocks offers a route for revealing potential sources of shift.

**Stocks**

The original papers identified the primary agglomerated stocks involved in the petroleum lifecycle. The appraisal of the behavioral implications of those stocks fits within the normal logic of system dynamics. The key addition to the conventional systems logic is the consideration of enabling stocks – those not explicitly included in the models but necessary for the models to function – and the explicit consideration of uncertainties surrounding stocks. Some of the key stocks inherent in the models, their key characteristics, certainties, and uncertainties include the following:

- **Known Petroleum Reserves** – Increases with discoveries, decreases with depletion. A function of **Technology** to some extent. However, is only an estimate and is subject to optimism and overstatement.

- **Automobile Fleet** – A key element of petroleum demand along with driving habits (annual miles driven). This is a strong stabilizing factor to **Petroleum Demand** as automobiles exhibit a half-life of approximately ten years. On a short-term basis **Petroleum Demand** can be thought of as primarily a function of **Annual Miles Driven**. **Average Fleet MPG** improvement is damped by the slow turnover/retirement of vehicles. As a result there is no easy fix for fuel shortages as infrastructure limitations dampen possible response, other than reducing driving – which has short-term limits.

- **City and Highway Infrastructure** – Low fuel prices encouraged urban sprawl and led to creation of a rather inefficient city structure in the United States. Commutes grew longer, encouraging increasing **Annual Miles Driven** and this trend continues. **City and Highway Infrastructure** also complicate quick response to fuel shortages as alternative transportation is generally not available. Car-pooling and multiple purpose trips are essentially the only short-term response available to shortages.

- **Petroleum Production Rate** – Presented in the papers as a function of **Demand for Production** and **Production Potential** which is presented as dependent upon investment and technology. As a result, political and national uncertainties were omitted though the authors did suggest that the model might be used to explore issues such as OPEC and non-OPEC supply and pricing policies. Given that international instabilities were already a concern, the assumptions in this section were simplistic. A futurist's perspective would suggest production/supply instabilities were to be expected and that a projection of continuity was an unlikely scenario. (Once again, this should not be taken as criticism of the papers for their purposes were different – with narrower boundaries – and quantitative modeling of uncertainties would have clouded the learnings from the papers. Rather, this observation is intended to highlight a difference in the types of learning and implications available from qualitative and quantitative analysis of models.)

- **Petroleum Exploration, Production, and Processing Technology** – A deeper look at petroleum technology would suggest that refinery technology was quite mature, using processes that were well understood and were already being mathematically modeled. Computers could clearly aid in optimizing refinery operations but the benefits would be expected to be incremental and not revolutionary. Exploration and production were less mature as a quantitative technology and were considered more of an art than a science. While it was not clear how computers could impact exploration and production, the opportunities – if realized – would likely be more revolutionary than for refining. It is also worth noting that both exploration and production activities involve measurement of properties far below the surface of the earth. Exploration had increasingly involved remote measurement using seismic data sensing and processing which could clearly benefit from improved sensors and ability to process the resulting data. Miniaturization of sensors as solid state electronics continued to shrink offered potential for improved production techniques. Thus it seems reasonable to anticipate that technology and computers would have greater impact on production than refining.

**Summation**

The pending peaking of production and continuing growth of demand further implied that corporations would be likely to begin looking for alternative sources of crude oil and to alternative technologies to enable their continuation. These efforts would naturally be less mature and would be expected to be more turbulent, with false steps and failures as experiments fail. From an historical perspective mature companies have struggled with creating a climate suitable for innovation and entrepreneurism (Adizes, 1988). The strains of entrepreneurial activities would be expected to challenge the relatively mature industry. The large size of the integrated oil companies encouraged them to pursue large potential sources of crude and to ignore smaller fields as their need for large flows of crude made pursuing smaller fields less significant and attractive. As a result exploration and development of smaller fields has generally fallen to smaller firms and wildcatters. This is also consistent with mature ecologies and industries as specialization allows pursuit of niche opportunities that larger actors cannot fill. As a result one would expect to see a continued polarized industry mix of large integrated firms and smaller, more adroit actors.

## *Conclusion*

Quantitative modeling offers benefits for understanding history and potentially current and near-term dynamics and is demonstrated as useful in evaluating processes that lend themselves to quantification, including protocols such as the petroleum reserve estimation methodologies and by implication, policy impacts. The difficulties of predicting the future using quantitative models is reaffirmed by the deviation of model predictions from reality over the past twenty-five years as the validity of firm assumptions in the model declined. Over time, assumptions and relationships change in ways that render predictions inaccurate. In 1980 Daniel Yergin captured that problem when he stated,

> "Politics, passion, and accidents are just as important as market forces, if not more so. Every major change in the world oil market since the middle 1960s has been the result of an accident: the 1967 war with the closing of the Suez Canal, the cutting of the tap line, the overthrow of King Idris in Libya, the 1973 war, and finally the fall of the Shah of Iran and the seizure of the US Embassy by the militants. It is obvious that events of this kind are at least as important as market forces, yet the point tends to get lost."(Yergin, 1980)

Turbulence in the form of wildcard events defies specific prediction but qualitative analysis allows one to scan the system under study for possibilities (emerging trends, issues, and wildcards that threaten to force changes to the system), vulnerabilities (structural factors that lack redundancy or flexibility to accommodate change), and natural evolutionary tendencies. The resulting qualitative insights though more tentative than those derived from quantitative modeling of systems, provide insights into a range of alternative scenarios for the system under study. Qualitative analysis also suggests points for proactive strategies for shaping a system to better accommodate potential challenges. Given that some level of qualitative analysis precedes and accompanies the development of all quantitative models, it is logical that stronger qualitative analytical logic can lead to stronger quantitative models. This analysis supports the conclusion that the qualitative logic presented holds value for:

- Building stronger quantitative models through better understanding of the boundaries and vulnerabilities of the quantitative model,
- Anticipating evolutionary patterns of structural change of the model – of the patterns of connectivity of the system
- Providing useful insights quickly, and
- Providing a framework for integrating expert views and opinions.

The results of this analysis also support the conclusion that the qualitative analytical logic presented holds value for practitioners of both systems dynamics and futures studies.

| Perspective | Analysis from the 1985 perspective | Implication |
| --- | --- | --- |
| **Maturity** | Industry is generally mature to very mature<br>• Domestic production rate had peaked<br>• Global production approaching peak<br>• Technology slowly evolving | Corporate focus on efficiency – streamlining, mergers for scale. |
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| **Turbulence** | Governments in major consuming countries had long strived to make the business climate predictable to facilitate corporate success. Environmental laws and international relations and dependencies were a growing source of turbulence for the industry. | The mostly stable, predictable business climate encouraged evolution toward streamlined, bureaucratic structure of the major companies with limited duplication/redundancy or spare capacity. |
| **- Social Turbulence** | Demographic and social trends were perceived as stable and reliable<br>• Population and household growth were consistent trends.<br>• Vehicles per household were stable in the US.<br>• Miles driven per vehicle oscillates in the US but was generally stable and was growing in developing countries. | Continued growth in demand. Any demand related turbulence would have been anticipated to result from shortages in supply rather than sudden shifts in demand. |
| **- Technological Turbulence** | Basic petroleum technology was slowly evolving. Computers offered potential to modify technology throughout the petroleum industry but that turbulence remained in the future. Miniaturization also offered potential impact on technology of exploration and recovery. | Refining technology was highly quantifiable and modeled. Production and Exploration technologies were more of an art than a quantifiable science. For refineries computers offered a potential to do the calculations better/faster providing a step improvement in ability to operate refineries. In refineries one might have expected incremental improvements in efficiency (productivity) of producing fuels from petroleum, marginally reducing crude demand. In exploration and production computers offered a potential for whole new insights and approaches that could invalidate historically based and incremental assumptions. |
| **- Economic Turbulence** | Peaking of domestic petroleum production and continuing demand growth, generally with GDP (tempered by efficiency improvements). Globalization impacts were becoming visible. Economic actions and problems | Peaking domestic production implied increased reliance on international sources and markets for crude supply as domestic sources decline. Also implied a close association between sources of supply (OPEC) and price with a |

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| | anywhere were beginning to ripple through the global economy. | possibility of market turbulence. Increasingly global economic webs imply increasing fitness complexity and increased turbulence. |
| **- Environmental Turbulence** | Potentially troublesome. Environmental policies had been disruptive in the 70's and 80's and required large investment and creation of new activities in oil companies. Regulations were effectively preventing construction of new refineries in consideration of eventual remediation. Rising carbon dioxide was already recognized – a red flag. | As policy/law driven rather than normal causality, environmental issues could be expected to shock the industry. The primary defense against legal shocks would be the size and criticality of the industry combined with lobbying. Made political activism of petroleum companies likely to expand. |
| **- Political Turbulence** | The governments of oil-rich countries had generally nationalized petroleum industries over the previous twenty years. Predictability of international business opportunities and relationships were less than certain. | Declining domestic petroleum supplies would force increased reliance on international supplies and force companies to participate internationally if they were to grow. Companies would become increasingly vulnerable to international turbulence – from political, economic, crude demand, and crude availability perspectives. |
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| **Network Connectivity** | On a domestic basis the bulk of exploration and production was controlled by large integrated oil companies. Primary flows in majors were internal. | The internal, linear, highly optimized flow patterns were typical of mature systems. The linearity of the supply chain appeared likely to become more complex in both intercorporate and international complexity. |
| | Internationally the petroleum supply and price from oil-rich countries were generally controlled by the government of the country. | National interests implied that national petroleum supplies would remain "independent", thus increasing the complexity of international petroleum supply and growing interdependence. |
| | Major companies were dominantly regional. On a geographical basis the companies generally have areas where they are a main competitor and others where they are minor. No companies were strongly represented across the entire nation in 1985. | Expect mergers to build national presence and increase efficiency. Presence on a local basis would no doubt remain uneven with one company dominating (more than 30 percent of the market) in one area, and other companies having the advantage in other areas. |
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| **System Boundary** | The traditional boundaries of the petroleum industry and its influencing factors was clearly approaching change due to increasing international activity, technological change and turbulence, and the impact of growing demand combined with peaking production. | Traditional boundaries and mechanisms would be unlikely continue to be adequate as the future unrolls. Expanding boundaries imply more complex relationships and increasing fitness complexity. |
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| **Fitness Complexity**[3] | The complexity of the international petroleum system was growing more complex with an outlook of increasing complexity as international interdependence grows | It should grow increasingly difficult for petroleum companies to maintain uniquely superior financial performance as increased interdependence flattens the fitness landscape and products become more commoditized. Additionally, the increased complexity implies increased turbulence. Given the critical nature of petroleum for powering developed economies this translated to increasingly turbulent domains for not only the petroleum companies, but citizens and governments as well. Also implies that it will be increasingly difficult for the leading economies to retain their edge. Implications for the petroleum industry were growing economic challenges. |
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| **Stocks and Flows** | This section focuses on some important enabling stocks not included in the models and comments. | |
| **- Byproducts** | Key accumulating byproducts<br>- Carbon Dioxide<br>- Air, Water, Soil Pollution | Implied increasing environmental scrutiny and public ad political pressure |
| **- Social Stocks** | Growing total population both US and global. | Implied growing domestic demand and growing international shortfall as production declines barring changes in consumption patterns |
| | Migration to cities combined with urban sprawl (combination of housing and street/highway infrastructure stocks). | Implied growing commute distances In absence of alternative transportation, implies growing auto fuel demand and inflexibility to accommodate shortages gracefully. |
| **- Technological Stocks** | Exploration technology was evolving rather rapidly as seismic methods grew more sophisticated but clearly left much room for improvement. | Implied potential for breakthroughs in exploration technology. |
| | Production technology was also evolutionary and left room for improvements. | Implied potential for breakthroughs in production technology. |
| | Refinery technology relatively mature and quantified. Improvement opportunities related to crude oil appeared incremental. Potential for synthetic crude (from tar sands, natural gas, and coal). | Implied less potential for a breakthrough related to crude. Turbulence is more likely to relate to alternative supplies and fuel demands. |
| | Vehicular technology was mostly quite old. Some improvements possible for gasoline/diesel engines, but major | Implied potential shifts to alternative fuels would likely require substantial infrastructure and investment. |

[3] The concept of fitness complexity comes from the discipline of mathematical biology and suggests that, as a system grows more interconnected and thus complex it becomes increasingly difficult to achieve uniquely high "fitness" relative to others in the system and implies increased turbulence as upsets ripple through the dependencies from one actor to another.

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| | potential was for alternative fuels. The hybrid concept had surfaced but enabling computers were still in the future. | |
| **- Economic Stocks** | Auto fleet has a half-life of ten years. | Would take twenty years by historical standards to retire ¾ of existing vehicles. The continued use of existing vehicles diminishes ability to change fuels or demand quickly. Implied that shortages will be traumatic and have high economic impact. |
| | Growing Asian economies and per capita income (though the boom in Chinese and Indian economies were not yet particularly visible). | Implied increasing Asian demand for raw materials including crude oil. |
| **- Environmental Stocks** | The primary product of crude oil consumption is carbon dioxide. Rising levels of atmospheric carbon dioxide had already been identified as a potential source of warming and concern for rising carbon dioxide was increasingly visible in environmental literature. | Implied that carbon dioxide and global warming were potential sources of turbulence to the industry. |
| | Two other key environmental stocks are environmental legislation/laws and public opinion. | Implied that public opinion and legislation appeared likely to provide some ongoing turbulence to the petroleum industry related to environmental issues. |
| **- Political Stocks** | International politics and policies shape the framework in which petroleum companies must operate. | It is futile to anticipate specific details of shifts in political issues, legislation, etc. due to their perceptual bases. In absence of an anticipated specific direction, one should anticipate that shifts will occur and that they will introduce turbulence in some form. Due to the ongoing efforts of the US government to create a stable business climate one can anticipate that international politics will be a more significant source of turbulence than domestic politic. |
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| **Feedback Structures** | Expansion of the boundaries of the original models combined with a suggestion of technological and political turbulence to suggest a number of additional feedback structures, including:<br>• Petroleum price to investment in alternative crude sources (such as tar sands and coal shale) to petroleum supply to petroleum price - long delay negative feedback structure (this loop is arguably included | Implied that the key feedback loops outside the models used in the Sterman, et al papers would be able to only slowiy shift the dynamics of the model. |

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| | in the models, though not explicitly)<br>• Petroleum price to investment in competing technologies to petroleum demand to petroleum price – long delay negative feedback structure | |
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| **Structural Dependency**[4] | Several structural dependencies serve to increase the impact of potential turbulence:<br>• Crude oil supply collaboration such as OPEC (political turbulence)<br>• Shipping Infrastructure – ports, ships, trade law, and pipelines (supply turbulence)<br>• Relatively concentrated refinery facilities (relative to uniform distribution) (demand turbulence)<br>• Environmental movements and law | The threat of OPEC supply turbulence should stimulate pursuit of more reliable sources of crude from non-OPEC sources. Other redundancies enhanced the vulnerability to industry turbulence via hurricanes, earthquakes, terrorism, and such. The arbitrariness and scope of environmental movements and law creates a potential source of turbulence that could be difficult to anticipate or prepare for. |

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[4] The concept of structural dependency relates to shared dependencies that underlie seemingly (or casually) independent system structures and thereby make those features less reliable than if they were truly independent.

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