RESEARCH PROBLEMS:

Purpose of Feature

In this feature DYNAMICA presents problems that have the potential to stimulate research involving the system dynamics perspective. Articles may address real-world dynamic problems that could be approached fruitfully using system dynamics, or methodological problems affecting the field. A submitted paper should concisely motivate and define a problem and start a process of conceptualization or formulation that can open the way for further studies. Manuscripts, not exceeding 2,000 words, should be sent to George P. Richardson, System Dynamics Group, E40-294, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA.

Articles published in this feature will differ substantially in purpose, content, and length from those in other sections of DYNAMICA. The focus will be on problem finding and problem formulation. An article addressing a real-world problem will generally

- describe a dynamic phenomenon or a proposed study of policy alternatives;
- describe the significance of the problem and the anticipated benefits of approaching it from the system dynamics perspective;
- suggest an appropriate system boundary for initial modeling efforts and provide a preliminary sketch of feedback structures of interest;
- include a short introductory bibliography or list of sources.

An article addressing a methodological problem is likely to describe a methodological subtlety or puzzle that has occurred to the author that requires the attention of others in the field. The purpose of each paper published in this feature is to provide a well-formed starting point for others to address a problem. An article might discuss a small conceptual model of the sort urged by Randers* but it would not be appropriate in this feature to describe the results of a completed study.

The feature is intended to promote an interchange of thoughts about problems, to expand the range of problems system dynamicists address, to provide a place for practitioners to describe problems they find interesting but may not have the time to explore fully, and to show different approaches to the conceptual, formative phases of a system dynamics study.

*Jørgen Randers, "Guidelines for Model Conceptualization," in Jørgen Randers, ed., *Elements of the System Dynamics Method* (Cambridge, Ma.: The MIT Press, 1980), 117-139.

Submitted Problem

THE DYNAMICS OF ESTIMATES OF PETROLEUM RESOURCES

Problem submitted by G.P. Richardson,
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THE SETTING

Since the early 1960's there has been increasing concern for the future of world petroleum resources. One result of this concern is an increase in the efforts to estimate the quantity of petroleum that the world will ultimately be able to produce, the so-called "ultimate recoverable resource".

Estimates of the ultimate recoverable petroleum resource have been increasing over time as new information comes to light and new technologies become feasible or foreseeable. Figure 1 shows a pattern of estimates of the world's ultimate recoverable petroleum resources.[1] A similar pattern is evident in estimates of ultimate crude-oil production for the lower forty-eight states of the United States shown in Hubbert[2], (figure 13). There is wide variation in such estimates, even for estimates made in the same year but by different authorities. The tendency of the estimates to increase over time is unmistakable, however; the pattern suggests they will continue to rise, at least in the near future. Some see in these increasing estimates the promise that we need not be concerned about running out of oil.

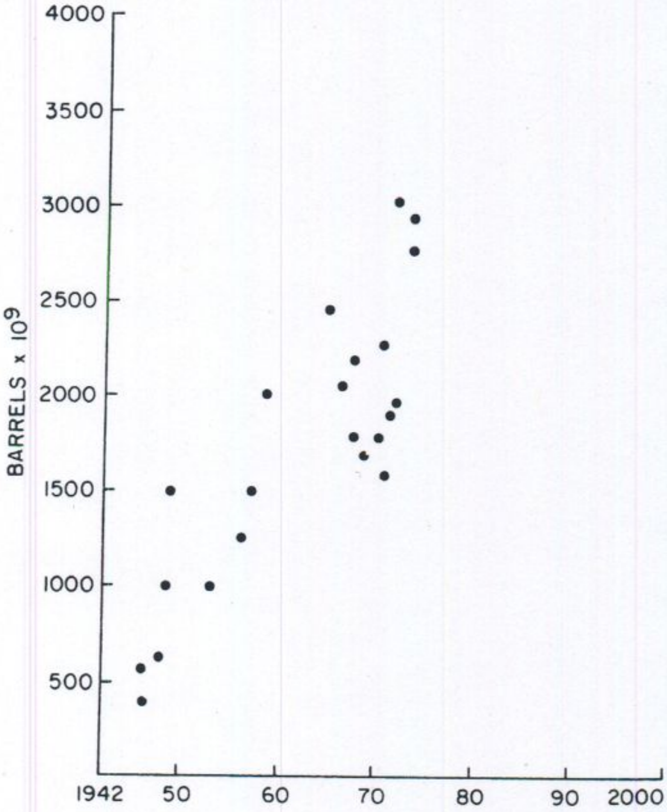

Figure 1: Estimates of the world's ultimate oil resources. 1942-75. (Redrawn from Odell and Rosing[1], p.25)

THE PROBLEM

The generally increasing tendency in the estimates over time raises a number of questions. When will the estimates cease rising? More generally, how will the estimates behave over the lifecycle of the resource? Will the average of the estimates, or the estimates produced over time by the application of one particular method, smoothly approach the actual ultimate recoverable quantity, or are they likely to overshoot their mark and then decline down to it? What effects, if any, do the rising estimates have on the rates of exploration, discovery, and usage of petroleum? Answering these questions would involve trying to determine how information combines to produce estimates, how that processing of information leads to the behavior of estimates over time, what the resulting patterns over time are likely to look like, and how information about estimates feeds back to affect the system that produces them. The nature of these questions suggests that the system dynamics perspective has something to contribute here.

Figure 2 shows two possible patterns of estimates of the world's ultimate recoverable petroleum resource superimposed on a graph of the likely S-shaped pattern of cumulative production. The graphs of estimates in figure 2 are competing reference behavior modes for a possible system dynamics study. We can think of these smooth curves in two ways: each could represent the aggregate average of all types of estimates, or each could stand for the pattern of estimates that would be produced by one estimation method repeated over time. We can think of an estimation technique as an information processing system. The curves in figure 2 are thus idealizations

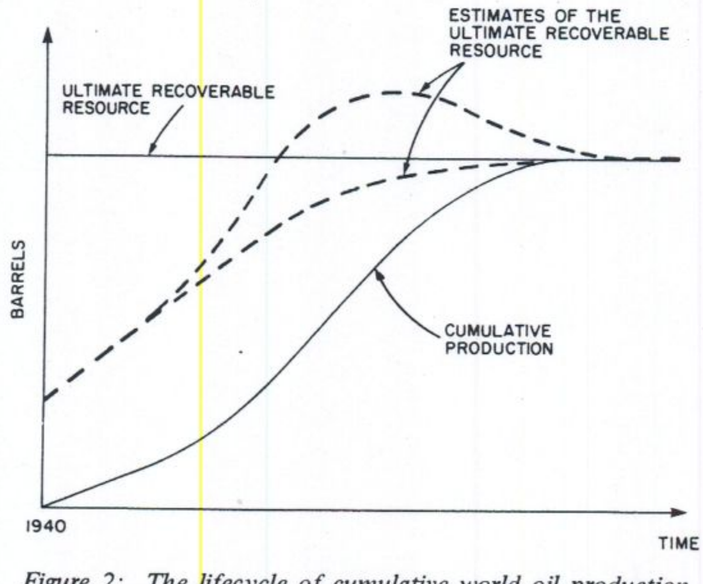

Figure 2: The lifecycle of cumulative world oil production with two potential patterns of the dynamics of estimates of the ultimate recoverable resource.

of the continuous output of one or more kinds of information processing systems. We are interested in how information about exploration, discovery, and usage combine to produce estimates, and how the resulting estimates behave over time.

A POSSIBLE APPROACH

It should be possible to take a system dynamics model of the lifecycle of petroleum as the real world and to embed within the model an estimation sector. The model would endogenously generate in an aggregate but realistic way the dynamics of exploration, discovery, and usage of global petroleum over its lifecycle. The estimation sector would continuously combine information from the real sectors of the model to produce estimates of the ultimate recoverable resource, much of that information is processed in reality to produce estimates. Different estimation strategies would call for different formulations of the estimation sector in the model. Conceivably, different patterns of the estimates over time might result. Because the model would run through the lifecycle of the resource, the actual value of the model's ultimate recoverable resource would be known, being simply the final value of cumulative production. Thus besides observing the pattern of estimates over time, the modeler could also evaluate, in some gross nonstatistical sense, the reliability of a particular estimation strategy, at least as it functions within the model's "reality". Do any of the prevalent ways of combining information consistently lead eventually to overestimates or underestimates, and, if so, why?

To get a quick start, one could base a model of the lifecycle of global petroleum on the model of the discovery lifecycle of a finite resource described in Naill[3].

MODELING AN ESTIMATION PROCESS

The literature discussing the future of petroleum reserves is quite explicit about the ways information is processed to produce estimates. (For examples see Odell and Rosing[1], Hubbert[2], Grenon[4], Meyer[5], Miller[6], Renshaw and Renshaw[7] and Zapp[8]). The methods fall generally into two categories. One approach, represented by Hubbert's analyses, combines data of the past history of petroleum exploration, discovery and usage, with assumptions about the mathematical form of the pattern of discovery and usage over time. The ultimate total recoverable resource comes out as the area under a production curve fitted to the data. The other type of approach looks in detail at estimates and guided guesses of the potential oil in place all over the world. Knowing the types of geological formations in which oil has been found before, potential areas remaining to be explored, and potential technologies for getting oil out of the ground, estimates of the ultimate recoverable resource are formed as the sum of:

- cumulative production – a quantity known from past history;
- proven primary reserves – petroleum in known fields believed recoverable in the future under currently existing economic and operating conditions;
- supplemental recovery – additional petroleum from known fields that is potentially recoverable using technologies that eventually may become workable and cost-effective;
- growth of appreciation or fields – additional potential recovery from the expansion of known fields;
- expectations from future discoveries – guided guesses of the potential for discovery of new fields, together with estimates of their future potential petroleum output.

Thus this type of estimation approach combines selected information about trends in discovery, usage, price, cost, substitution and technological advances.

Proven reserves is the fraction of known oil in place that is economically recoverable with existing technology. (Currently the fraction recoverable averages about 30-to-35 percent). Presumably, supplemental recovery estimates are based on perceived trends in technology and the fraction recoverable, with some consideration of the ultimate maximum fraction recoverable. To be able to embed an estimation procedure in the Naill model that uses these notions, it is necessary to add some structure to represent explicitly a growing stock of technological improvements in exploration, discovery, and recovery techniques. The structure for technology in Behrens[9] is suggestive. Looking for realistic variation in the rate of discovery, one might also want to multiply in a considerable quantity of noise. The goal of the reformulations should be to produce an elegant structure that mimics well the exploration-discovery-usage lifecycle of the world's petroleum in the aggregate and contains the essential information streams that people use to make estimates of future production.

The estimation sector added to such a model would try to capture the information-processing structure of a given technique or class of techniques, not the details of its statistical machinery. Are technological advances projected from past trends? How is information about past discoveries used? Are projections of demand or resource substitution taken into consideration? The questions asked are much like those a system dynamicist might ask in the context of a corporate consulting study. Essentially, the modeling effort will boil down to finding out what information comes together at important policy locations.

Using the model to test Hubbert's approach presumably would be somewhat different. The curve-fitting technique might be hard to formulate endogenously, and it could be done easily outside the model. Hubbert used cumulative discoveries and cumulative production in one approach and the discovery rate per foot of exploratory drilling in another. The modeler could take similar data from a model run every ten years or so and process it outside the model as Hubbert describes[2], thereby producing patterns of estimates over time that can be compared with the actual model output. (On the other hand, formulating the process endogenously might be a very interesting challenge that advances our knowledge of what is possible using current System Dynamics software packages).

SIGNIFICANCE OF THE STUDY

The first significant result of such a study is the bridging of a perceptual, perhaps philosophical gap. It should find in one internally consistent model the rigid assumption of a finite resource base and the observed pattern of rising estimates of that resource base. It places the "limits to growth" assumption side-by-side with the observations of the technological optimist that our perception of the quantity of resources remaining keeps increasing. It's a small bridge, but we need all the bridges we can build.

Secondly, the study has the potential to identify more reliable estimation procedures from less reliable ones, in a certain limited (nonstatistical) sense. Some ways of combining information produced patterns of estimates that definitely overshoot the ultimate recoverable resource. Other ways probably do not. Which techniques tend to be the most robust over a wide range of sensitivity tests and model lifecycle scenarios, and more importantly, why? The Naill model, for example, shows a steep drop in the discovery rate as scarcity sets in and costs rise; the discovery rate curve is not symmetric about its peak. Thus one can ask how and to what extent can assuming symmetry in the discovery and production curves (as in Hubbert's approach) interfere with the accuracy of the predictions over time? To claim that the answers to these questions of accuracy apply in reality as well, will require some careful analysis, exploration, and thought that by itself may be a contribution to our understandings of the roles of formal models. For the study to have an effect on strategies for estimating a resource base, the models developed will have to be very carefully matched to the audiences the study tries to reach.

Thirdly, the study could progress to the point of trying to address an intriguing feedback question. Estimates of the ultimate recoverable resource base are a function of information about exploration, discovery, and usage. How, or to what extent, do estimates feed back in turn to influence exploration, discovery, and usage? One might also ask whether the estimates themselves influence future estimates. In tracing the history of estimates for the lower 48 states of the United States, Hubbert[2] suggests as much. The documentation of some self-reinforcing tendencies could be an important contribution to our understanding of the estimation process.

Finally, the study could open up an approach for addressing questions about the estimation of unobservable quantities, such as natural resources and animal or fish populations. It would give some indication of the potential of simulation modeling that includes not only the structure and dynamics of the unobservable quantity but also the structure and dynamics of the way information is processed to estimate it.

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