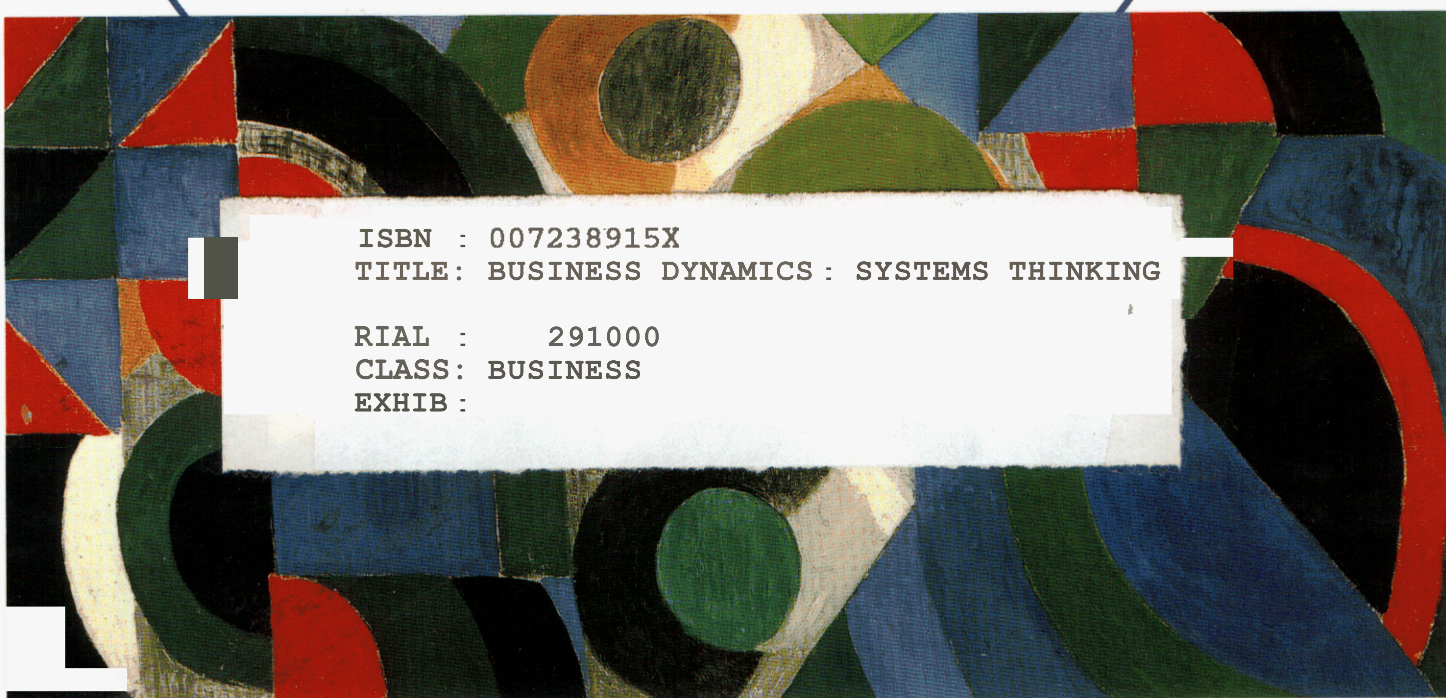
BUSINESS DYNAMICS

Systems Thinking and Modeling for a Complex World

John D. Sterman



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Sterman

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Business Dynamics

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This book is printed on acid-free paper.

4 5 6 7 8 9 0 KGP/KGP 0 9 8 7 6 5 4 3 2

ISBN 0-07-231135-5

Publisher: *Jeffrey J. Shelstad*

Senior sponsoring editor: Scott *Isenberg*

Marketing manager: *Zina Crafi*

Senior project manager: *Gladys True*
Senior production supervisor: *Lori Koetters*
Freelance design coordinator: *Mary L. Christianson*
Freelance cover designer: *The Visual*
Cover image: © *Sonia Delaunay/L & M Services, Amsterdam/Tate Gallery, London/Art Resource, NY*
Compositor: *GAC/Indianapolis*
Typeface: *11/13 Times Roman*
Printer: *Quebecor Printing Book Group/Kingsport*

Library of Congress Cataloging-in-Publication Data

Sterman, John.
Business dynamics : systems thinking and modeling for a complex world / John D. Sterman.
p. cm.
Includes hibliographical references and index.
ISBN 0-07-231135-5 (alk. paper)
1. Industrial management. 2. System theory. 3. Management information systems. I. Title.

HD30.2.S7835 2000
658.4'038'011—dc21

99-056030

http://www.mhhe.com

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John D. Sterman is J. Spencer Standish Professor of Management at the Sloan School of Management of the Massachusetts Institute of Technology and Director of MIT's System Dynamics Group. His research centers on the development of practical methods for systems thinking and dynamic modeling of complex systems, with applications to organizational learning and change, operations management, corporate strategy, and nonlinear dynamics in a wide range of systems, from supply chains to scientific revolutions. He has pioneered the development of management flight simulators of corporate and economic systems. These flight simulators are used in research to understand and improve managerial decision making in complex dynamic systems; more importantly, they are now widely used by corporations and universities around the world for teaching, problem solving, and policy design. Professor Sterman discovered system dynamics modeling in high school, studied it as an undergraduate at Dartmouth College, and received his PhD from MIT. He has been awarded the Jay W. Forrester Prize, given for the best published work in the field of system dynamics over the prior five years, and has four times won awards for teaching excellence from the students of the Sloan School.

Preface

Accelerating economic, technological, social, and environmental change challenge managers and policy makers to learn at increasing rates, while at the same time the complexity of the systems in which we live is growing. Many of the problems we now face arise as unanticipated side effects of our own past actions. All too often the policies we implement to solve important problems fail, make the problem worse, or create new problems.

Effective decision making and learning in a world of growing *dynamic complexity* requires us to become systems thinkers—to expand the boundaries of our mental models and develop tools to understand how the structure of complex systems creates their behavior.

This book introduces you to system dynamics modeling for the analysis of policy and strategy, with a focus on business and public policy applications. System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems. System dynamics is also a rigorous modeling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations. Together, these tools allow us to create management flight simulators—microworlds where space and time can be compressed and slowed so we can experience the long-term side effects of decisions, speed learning, develop our understanding of complex systems, and design structures and strategies for greater success.

The field of system dynamics is thriving. Over the past decade, many top companies, consulting firms, and governmental organizations have used system dynamics to address critical issues. More innovative universities and business schools are teaching system dynamics and finding enthusiastic and growing enrollments. Hundreds of primary and secondary schools, from kindergarten to high school, are integrating systems thinking, system dynamics, and computer simulation into their curricula. Tools and methods for system dynamics modeling, the library of successful applications, and insights into the effective use of the tools with executives and organizations are all expanding rapidly.

modeling study can be your academic colleagues, the public at large, or even yourself. In the discussion that follows, I will focus on modeling projects conducted for organizations. The process, however, is similar for these other contexts as well.

To be effective the modeling process must be focused on the clients' needs. The clients for a modeling project are busy. They are embroiled in organizational politics. They are looking out for their own careers. Their concern is solving a problem and taking action in the real world. They care little for the elegance of your theory or cleverness of your model. Modeling is done to help the client, not for the benefit of the modeler. The client context and real world problem determine the nature of the model, and the modeling process must be consistent with the clients' skills, capabilities, and goals. The purpose is to help the clients solve their problem. If the clients perceive your model does not address their concerns or lose confidence in it, you will have little impact. Focus your modeling work on the problems that keep the clients up at night.

The political context of modeling and the need to focus on the clients' problem does not mean modelers should be hired guns, willing to do whatever the clients want. Modelers should not automatically accede to clients' requests to include more detail or to focus on one set of issues while ignoring others, just to keep the clients on board. A good modeling process challenges the clients' conception of the problem. Modelers have a responsibility to require their clients to justify their opinions, ground their views in data, and consider new viewpoints. When the clients ask you to do something you think is unnecessary or misguided, you must work with them to resolve the issue.

Unfortunately, far too many clients are not interested in learning but in using models to support conclusions they've already reached or as instruments to gain power in their organizations. Sadly, far too many consultants and modelers are only too eager to oblige. As a modeler you have an ethical responsibility to carry out your work with rigor and integrity. You must be willing to let the modeling process change your mind. You must "speak truth to power," telling the clients that their most cherished beliefs are wrong, if that is what the modeling process reveals, even if it means you will be fired. If your clients push you to generate a result they've selected in advance or that is not supported by the analysis, push back. If your clients' minds are closed, if you can't convince them to use modeling honestly, you must quit. Get yourself a better client.[2]

3.3 STEPS OF THE MODELING PROCESS

In practice, as a modeler you are first brought into an organization by a contact who thinks you or your modeling tools might be helpful. Your first step is to find out what the real problem is and who the real client is. Your initial contact may not be the client, but only serve as a gatekeeper who can introduce you to the client. As the modeling project proceeds, you may find the client group expands or changes. Assume that you've successfully negotiated entry to the organization and

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[2]Wallace (1994) provides a good collection of articles addressing the ethical issues facing modelers.

TABLE 3-1
Steps of the modeling process

1. **Problem Articulation (Boundary Selection)**
   - **Theme selection:** What is the problem? Why is it a problem?
   - **Key variables:** What are the key variables and concepts we must consider?
   - **Time horizon:** How far in the future should we consider? How far back in the past lie the roots of the problem?
   - **Dynamic problem definition (reference modes):** What is the historical behavior of the key concepts and variables? What might their behavior be in the future?
2. **Formulation of Dynamic Hypothesis**
   - **Initial hypothesis generation:** What are current theories of the problematic behavior?
   - **Endogenous focus:** Formulate a dynamic hypothesis that explains the dynamics as endogenous consequences of the feedback structure.
   - **Mapping:** Develop maps of causal structure based on initial hypotheses, key variables, reference modes, and other available data, using tools such as
     - Model boundary diagrams,
     - Subsystem diagrams,
     - Causal loop diagrams,
     - Stock and flow maps,
     - Policy structure diagrams,
     - Other facilitation tools.
3. **Formulation of a Simulation Model**
   - **Specification** of structure, decision rules.
   - **Estimation** of parameters, behavioral relationships, and initial conditions.
   - **Tests** for consistency with the purpose and boundary.
4. **Testing**
   - **Comparison to reference modes:** Does the model reproduce the problem behavior adequately for your purpose?
   - **Robustness under extreme conditions:** Does the model behave realistically when stressed by extreme conditions?
   - **Sensitivity:** How does the model behave given uncertainty in parameters, initial conditions, model boundary, and aggregation?
   - **. . . Many other tests** (see chapter 21).
5. **Policy Design and Evaluation**
   - **Scenario specification:** What environmental conditions might arise?
   - **Policy design:** What new decision rules, strategies, and structures might be tried in the real world? How can they be represented in the model?
   - **"What if . . ."** analysis: What are the effects of the policies?
   - **Sensitivity analysis:** How robust are the policy recommendations under different scenarios and given uncertainties?
   - **Interactions of policies:** Do the policies interact? Are there synergies or compensatory responses?

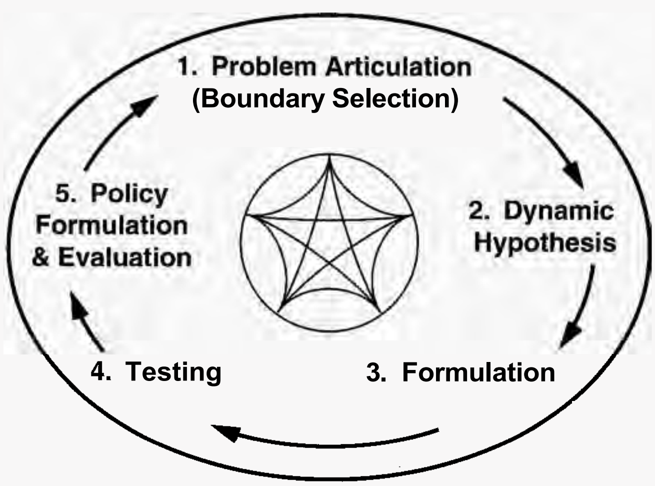
identified the (initial) clients. How do you proceed to develop a model which can be helpful to them?[3]

There is no cookbook recipe for successful modeling, no procedure you can follow to guarantee a useful model. Modeling is inherently creative. Individual modelers have different styles and approaches. Yet all successful modelers follow a disciplined process that involves the following activities: (1) articulating the problem to be addressed, (2) formulating a *dynamic hypothesis* or theory about the causes of the problem, (3) formulating a simulation model to test the dynamic hypothesis, (4) testing the model until you are satisfied it is suitable for your purpose, and *(5)* designing and evaluating policies for improvement. Table 3-1 lists these steps along with some of the questions each step addresses and the principal tools used in each (see also Randers 1980).

3.4 MODELING IS ITERATIVE

Before discussing each of these steps in more detail, it is important to place the modeling process in context with the ongoing activities of the people in the system. Modeling is a feedback process, not a linear sequence of steps. Models go through constant iteration, continual questioning, testing, and refinement. Figure 3-1 recasts the modeling process shown in Table 3-1 more accurately as an iterative cycle. The initial purpose dictates the boundary and scope of the modeling effort, but what is learned from the process of modeling may feed back to alter our basic understanding of the problem and the purpose of our effort. Iteration can occur from any step to any other step (indicated by the interconnections in the center of the diagram). In any modeling project one will iterate through these steps many times.[4]

FIGURE 3-1
The modeling process is iterative.
Results of any step can yield insights that lead to revisions in any earlier step (indicated by the links in the center of the diagram).



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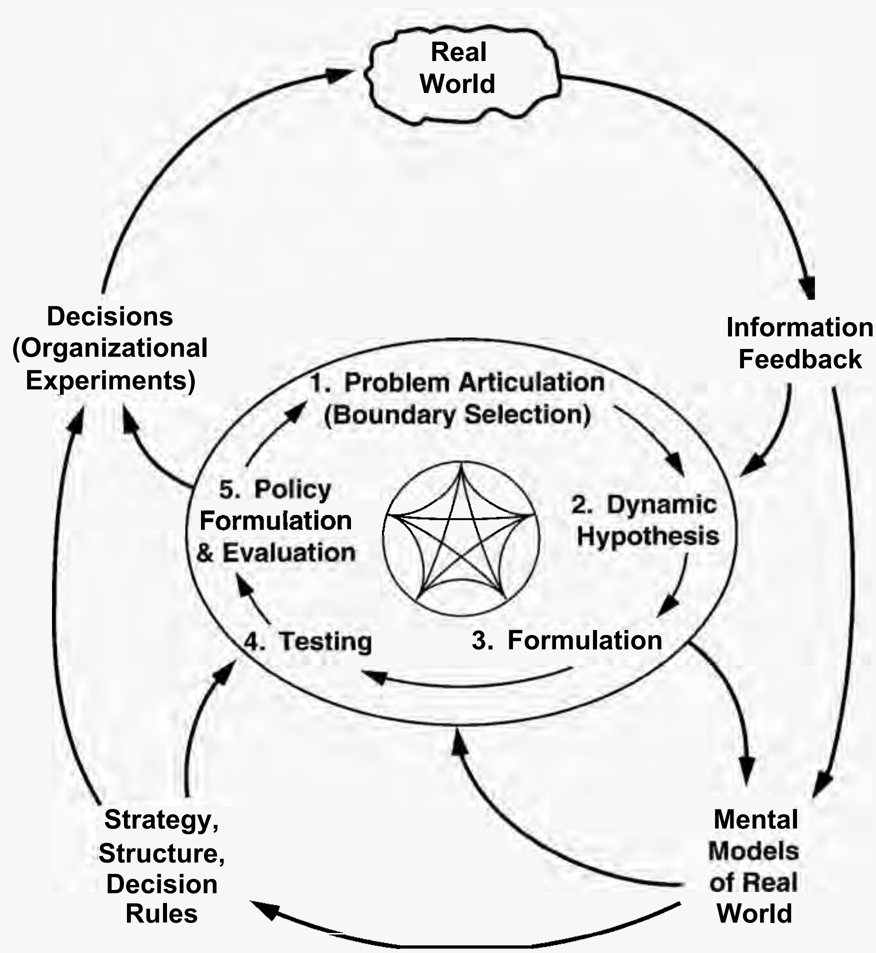
[3]There is a huge literature on methods for planned organizational change and group interventions. See particularly Argyris and Schon (1996), Beckhard and Harris (1987), Dyer (1995), Michael (1997), and Schein (1987, 1988).

[4]Homer (1996) provides an excellent discussion of the value of iteration and rigor in system dynamics, not only in academic research but also in consulting work, with a variety of examples.

Most importantly, modeling is embedded in the larger cycle of learning and action constantly taking place in organizations (and described in chapter 1). Pilots step into an aircraft flight simulator and learn more quickly, effectively, and safely how to operate the real aircraft, then put these skills to use in the real thing. They feed back what they learn flying the real thing to the simulator designers so the simulators can be continually improved. What pilots and designers learn in the simulator is used in the real world. And what they learn in the real world is used to change and improve the virtual world of the simulator. So it is with management flight simulators and system dynamics models. Figure 3-2 shows the modeling process embedded in the single- and double-loop learning feedbacks discussed in chapter 1. Simulation models are informed by our mental models and by information gleaned from the real world. Strategies, structures, and decision rules used in the real world can be represented and tested in the virtual world of the model. The experiments and tests conducted in the model feed back to alter our mental models and lead to the design of new strategies, new structures, and new decision rules. These new policies are then implemented in the real world, and feedback about their effects leads to new insights and further improvements in both our formal and

FIGURE 3-2
Modeling is embedded in the dynamics of the system.
Effective modeling involves constant iteration between experiments and learning in the virtual world and experiments and learning in the real world.



mental models. Modeling is not a one-shot activity that yields The Answer, but an ongoing process of continual cycling between the virtual world of the model and the real world of action.

3.5 OVERVIEW OF THE MODELING PROCESS

3.5.1 Problem Articulation: The Importance of Purpose

The most important step in modeling is problem articulation. What is the issue the clients are most concerned with? What problem are they trying to address? What is the real problem, not just the symptom of difficulty? What is the purpose of the model?

A clear purpose is the single most important ingredient for a successful modeling study. Of course, a model with a clear purpose can still be misleading, unwieldy, and difficult to understand. But a clear purpose allows your clients to ask questions that reveal whether a model is useful in addressing the problem they care about.

Beware the analyst who proposes to model an entire business or social system rather than a problem. Every model is a representation of a system—a group of functionally interrelated elements forming a complex whole. But for a model to be useful, it must address a specific problem and must simplify rather than attempt to mirror an entire system in detail.

What is the difference? A model designed to understand how the business cycle can be stabilized is a model of a problem. It deals with a specific policy issue. A model designed to explore policies to slow fossil fuel use and mitigate global warming is also a model of a problem; it too addresses only a limited set of issues. A model that claims to be a representation of the entire economy is a model of a whole system. Why does it matter? The usefulness of models lies in the fact that they simplify reality, creating a representation of it we can comprehend. A truly comprehensive model would be just as complex as the system itself and just as inscrutable. Von Clausewitz famously cautioned that the map is not the territory. It's a good thing it isn't: A map as detailed as the territory would be of no use (as well as being hard to fold).

The art of model building is knowing what to cut out, and the purpose of the model acts as the logical knife. It provides the criteria to decide what can be ignored so that only the essential features necessary to fulfill the purpose are left. In the example above, since the purpose of the comprehensive model would be to represent the entire economic system, nothing could be excluded. To answer all conceivable questions about the economy, the model would have to include an overwhelming array of variables. Because its scope and boundary are so broad, the model could never be completed. If it were, the data required to use it could never be compiled. If they were, the model's underlying assumptions could never be examined or tested. If they were, the model builders could never understand its behavior and the clients' confidence in it would depend on the authority of the modeler and other nonscientific grounds. Mihailo Mesarovic, a developer of early global simulations, captured the impossibility of building models of systems when he said, "No matter how many resources one has, one can envision a complex enough model to render resources insufficient to the task." (Meadows, Richardson, and Bruckmann 1982, p. 197).

A model designed for a particular purpose such as understanding the business cycle or global climate change would be much smaller, since it would be limited to those factors believed to be relevant to the question at hand. For example, the business cycle model need not include long-term trends in population growth, resource depletion, or climate change. The global warming model could exclude short-term dynamics related to interest rates, employment, and inventories. The resulting models could be simple enough so that their assumptions could be examined. The relation of these assumptions to the most important theories regarding the business cycle and climate change could then be assessed to determine how useful the models were for their intended purposes. Of course even models with well-defined purposes can be too large. But without a clear purpose, there is no basis to say "we don't need to include that" when a member of the client team makes a suggestion. In sum: Always model a problem. Never model a system.

Usually the modeler develops the initial characterization of the problem through discussion with the client team, supplemented by archival research, data collection, interviews, and direct observation or participation. There are many methods available to work with a group to elicit the information needed to define the problem dynamically while still keeping the conversation focused firmly on the clients and their problem.[5] Two of the most useful processes are establishing *reference modes* and explicitly setting the *time horizon.*

Reference Modes

System dynamics modelers seek to characterize the problem dynamically, that is, as a pattern of behavior, unfolding over time, which shows how the problem arose and how it might evolve in the future. You should develop a *reference mode,* literally a set of graphs and other descriptive data showing the development of the problem over time. Reference modes (so-called because you refer back to them throughout the modeling process) help you and your clients break out of the short-term event-oriented worldview so many people have. To do so you and the clients must identify the time horizon and define those variables and concepts you consider to be important for understanding the problem and designing policies to solve it.

Time Horizon

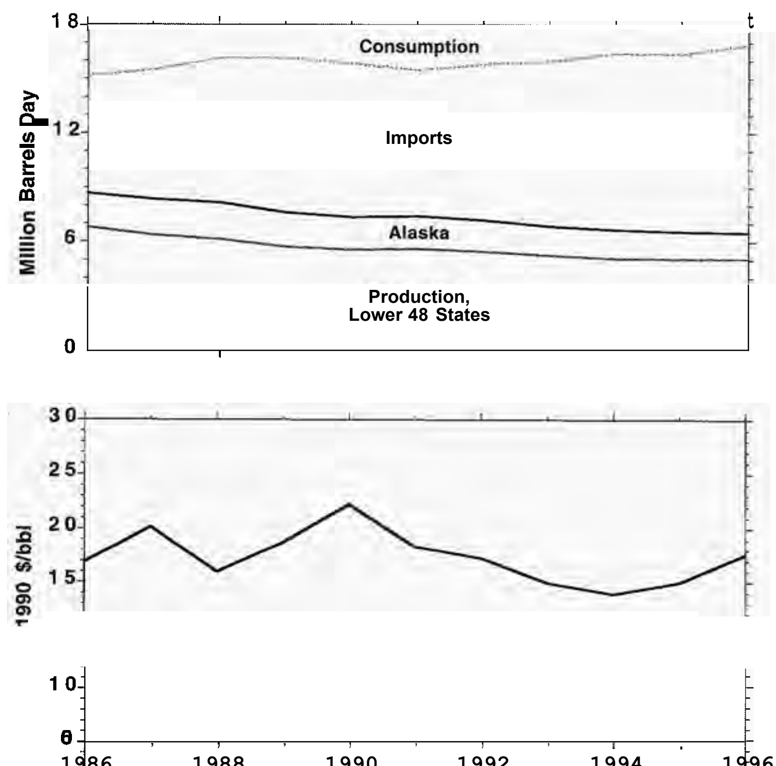
The time horizon should extend far enough back in history to show how the problem emerged and describe its symptoms. It should extend far enough into the future to capture the delayed and indirect effects of potential policies. Most people dramatically underestimate the length of time delays and select time horizons that

[5]See the references in note 9 for modeling tools that are effective for real time modeling with organizations and teams including eliciting and structuring the mental models of a group to define the problem.

are far too short. A principal deficiency in our mental models is our tendency to think of cause and effect as local and immediate. But in dynamically complex systems, cause and effect are distant in time and space. Most of the unintended effects of decisions leading to policy resistance involve feedbacks with long delays, far removed from the point of decision or the problem symptom. Work with your clients to think about the possible reactions to policies and how long they might take to play out and then increase the time horizon even further. A long time horizon is a critical antidote to the event-oriented worldview so crippling to our ability to identify patterns of behavior and the feedback structures generating them.

The choice of time horizon dramatically influences your perception of the problem. Figure 3-3 shows production, consumption, and imports of petroleum in the United States from 1986 to 1996. The historical time horizon is 10 years, already a long time relative to most discussion of energy policy (the oil shocks of the 1970s are considered ancient history in most policy debate today). The graphs show production slowly trending down, consumption trending slowly up, and therefore imports growing modestly. Prices fluctuate in a narrow band between $14 and $23 per barrel, lower than any time since the first oil crisis in 1973 (though prices did spike to $40/barrel after the Iraqi invasion of Kuwait, they soon fell back). The energy system appears to be relatively stable; there is little evidence of a long-term problem.

FIGURE 3-3
US oil production, consumption, imports, and price over a 10-year time horizon

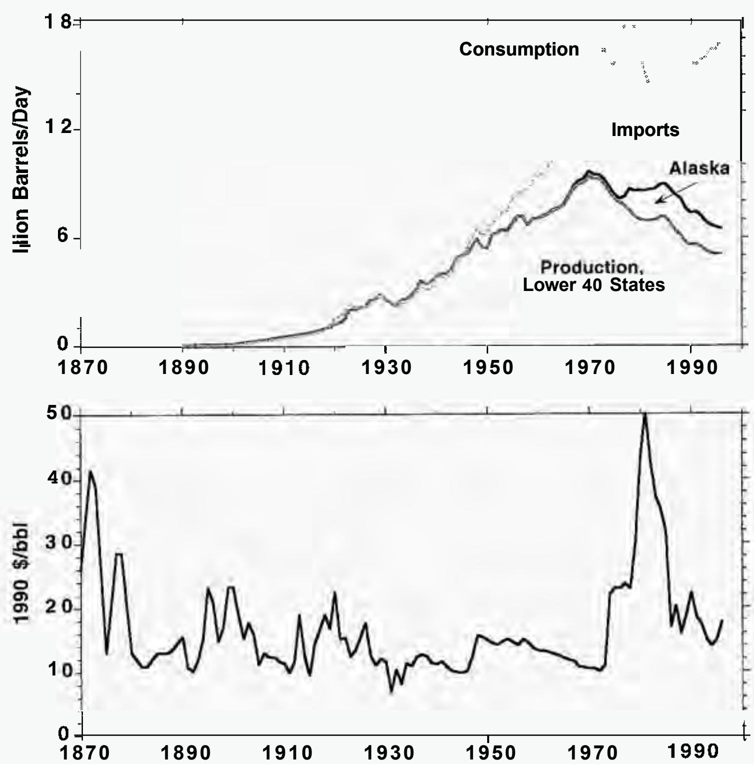


Source: EIA (US Energy Information Agency) *Annual Energy Review.*

Now consider Figure 3-4, showing the same variables from near the beginning of the oil era (the petroleum industry began in earnest in 1859 with Colonel Drake's famous well in Titusville, Pennsylvania). The impression is completely different. The history of the oil industry in the United States is divided into two regimes. From 1920 through 1973, consumption grew exponentially at an average rate of 4.3%/year. Production nearly kept pace, as exploration and better drilling techniques more than offset depletion. Starting in the 1950s, imports grew slightly, stimulated by the availability of cheap foreign oil. Prices fluctuated, often dramatically, but along a slowly declining trend as technology improved. All this changed in 1970. In 1970, domestic production of oil peaked. It's been falling ever since, despite the intense exploration stimulated by the much higher prices of the 1970s and early 1980s. US production from the lower 48 states and adjacent offshore area in 1996 stood at only 54% of its peak level. Even the addition of Prudhoe Bay and the trans-Alaska pipeline did not halt the slide, and Alaskan production peaked in 1988. Higher prices following the 1970s oil shocks, along with the deepest recessions since the Great Depression, cut the growth of consumption, but imports nevertheless reached 61% of total oil consumption by 1996.

Changing the time horizon completely changes the assessment of the problem. Viewed with a time scale consistent with the life of the resource, it is clear that the petroleum problem wasn't solved in the 1980s but has been steadily getting worse.

FIGURE 3-4
US oil production, consumption, imports, and price over a 130-year time horizon

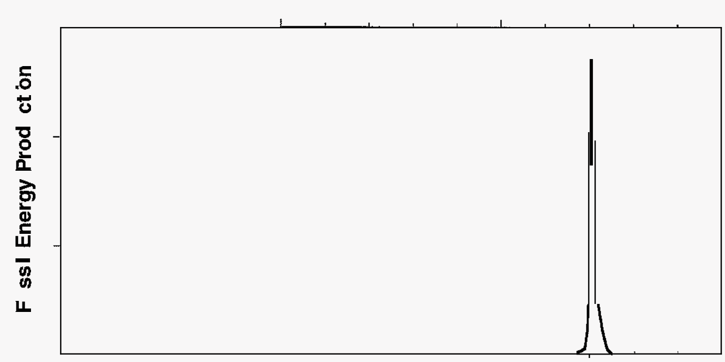


Source: Production & consumption: 1870–1949, Davidsen (1988); 1950–1966, EIA Annual Energy Review, Price: 1880–1968, Davidsen (1988); 1968–1996, EIA Annual Energy Review, Refiners Acquisition Cost.

Petroleum is a finite nonrenewable resource. In the **US,** depletion began to dominate finding rates in the 1960s, leading to an inevitable decline in production, a decline that began in 1970. The United States is the most heavily explored and densely drilled region of the world. The very success of early wildcatters in finding oil means there is less left to find now. While not all the petroleum in the US has been found or recovered, consumption continues to exceed the rate at which what remains is found. Consequently, imports continue to grow, leading to still greater dependency on the unstable Persian Gulf region, still more political and economic power for the oil exporting countries and less for the **US,** and, eventually, higher oil prices, either at the pump or in the defense budget.[6]

The oil industry illustrates the dangers of selecting a time horizon too short to capture the important dynamics and feedbacks creating them. Of course, one can err too far in the other direction. Figure 3-5 shows a graph developed by the late petroleum geologist M. King Hubbert. Hubbert invented the most successful technique for forecasting fossil fuel production ever created. In 1956 he estimated the ultimate recoverable petroleum resources of the US to be between 150 and 200 billion barrels and forecast that "the peak in production should probably occur within the interval 1966-1971" (Hubbert 1975, p. 371). His prediction of decline came at a time when the **US** Geological Survey projected ultimate recoverable resources nearly three times as large and claimed "the size of the resource base would not limit domestic production capacity 'in the next 10 to 20 years at least, and probably [not] for a much longer time' " (Gillette 1974). The actual peak occurred in 1970 at almost the precise value Hubbert had predicted, one of the most accurate long-term forecasts on record. Hubbert's success lay in explicitly modeling oil as a nonrenewable resource. Production could grow exponentially in the early phases

FIGURE 3-5
The fossil fuel era shown with a time horizon of 151,000 years



[6] There is a large literature of energy modeling in system dynamics, originating with work in Meadows et al. (1974). See, e.g., Backus (1996), Bunn and Larsen (1997), Fiddaman (1997), Ford (1990, 1997, 1999), Ford and Bull (1989), Naill (1977, 1992), and Naill et al. (1992) for work on national and global energy markets, electric utilities, global climate change, and other energy policy issues.

of its life cycle but had to fall to zero as it was depleted, forcing a transition to renewable energy source~To emphasize the transitory nature of fossil fuel civilization, Hubbert showed the production of fossil fuels on a time scale from the beginning of the agricultural revolution 10,000 years ago to 5000 years in the future. Against this backdrop, the fossil fuel era is seen as a transitory spike—a unique period during which humanity lives extravagantly off a rich inheritance of irreplaceable natural capital. The picture is sobering. But Hubbert's pimple, as it was called by critics, takes a time horizon too long to be useful to policy makers who influence public policy or corporate strategy affecting energy prices, regulations, capital investment, and R&D.

The choice of time horizon can dramatically influence the evaluation of policies. In the early 1970s a US government agency concerned with foreign aid sponsored a model focused on the Sahel region of sub-Saharan Africa. The Sahel was then experiencing rapid population growth at the same time the desert was expanding southward, reducing grazing land for the nomadic herders' cattle. The purpose of the model was to identify high leverage policies to spur economic development in the region. The model was used to assess the effects of many of the policies then in use, such as drilling bore holes to increase the water supply for cattle by tapping deep aquifers or subsidizing crops such as sorghum and ground nuts. Running the model to the year 2000, a round number several decades in the future at the time, showed that the policies led to improvement. Subsidies increased agricultural output. Bore holes permitted cattle stocks to grow, increasing the supply of milk and meat and the wealth of the herders. However, running the model into the first decades of the 21st century showed a different outcome: larger stocks of cattle began to outstrip the carrying capacity of the region. As the cattle overbrowsed and trampled the grasslands, erosion and desertification increased. The cattle population dropped sharply, creating a food deficit in the region. Selecting a time horizon too short to capture these feedbacks favored adoption of policies counter to the long-term interests of the region's people and the mission of the client organization.*

Modelers must guard against accepting the client's initial assessment of the appropriate time frame. Often these are based on milestones and round numbers having little to do with the dynamics of the problem, such as the end of the fiscal year, or the next 5-year planning cycle. A good rule of thumb is to set the time horizon several times as long as the longest time delays in the system, and then some.

3.5.2 Formulating a Dynamic Hypothesis

Once the problem has been identified and characterized over an appropriate time horizon, modelers must begin to develop a theory, called a *dynamic hypothesis,* to

[7] Sterman and Richardson (1985), Sterman et al. (1988), and Sterman, Richardson, and Davidsen (1990) model the world and US petroleum life cycles and study the evolution of estimates of the resource base, showing why Hubbert was so accurate while other estimation methods proved so wildly overoptimistic.

[8] Picardi and Seifert (1976) describe one of several models of the Sahel region (the model described above was not published).

account for the problematic behavior. Your hypothesis is dynamic because it must provide an explanation of the dynamics characterizing the problem in terms of the underlying feedback and stock and flow structure of the system. It is a hypothesis because it is always provisional, subject to revision or abandonment as you learn from the modeling process and from the real world.

A dynamic hypothesis is a working theory of how the problem arose. It guides modeling efforts by focusing you and your clients on certain structures. Much of the remainder of the modeling process helps you to test the dynamic hypothesis, both with the simulation model and by experiments and data collection in the real world.

In practice, discussion of the problem and theories about the causes of the problem are jumbled together in conversation with client teams. Each member of a team likely has a different theory about the source of the problem; you need to acknowledge and capture them all. Many times the purpose of the model is to solve a critically important problem that has persisted for years and generated great conflict and not a little animosity among members of the client team. All will tenaciously advocate their positions while deriding the views of others in the group. Early in the modeling process, the modeler needs to act as a facilitator, capturing these mental models without criticizing or filtering them. Clarifying and probing questions are often useful, but the modeler's role during this early phase is to be a thoughtful listener, not a content expert. A variety of elicitation techniques and diagramming tools have been developed to assist you in facilitating a productive conversation to elicit people's theories about the causes of the problem.[9] Your goal is to help the client develop an endogenous explanation for the problematic dynamics.

Endogenous Explanation

System dynamics seeks endogenous explanations for phenomena. The word "endogenous" means "arising from within." An endogenous theory generates the dynamics of a system through the interaction of the variables and agents represented in the model. By specifying how the system is structured and the rules of interaction (the decision rules in the system), you can explore the patterns of behavior created by those rules and that structure and explore how the behavior might change if you alter the structure and rules. In contrast, a theory relying on exogenous variables (those "arising from without," that is, from outside the boundary of the model) explains the dynamics of variables you care about in terms of other variables whose behavior you've assumed. Exogenous explanations are really no explanation at all; they simply beg the question, What caused the exogenous variables to change as they did? The focus in system dynamics on endogenous explanations does not mean you should never include any exogenous variables in your models. But the number of exogenous inputs should be small, and each candidate for an exogenous input must be carefully scrutinized to consider whether

[9] The literature on group model building is growing rapidly. Reagan-Cirincione et al. (1991), Morecroft and Sterman (1994), Vennix (1996), and Vennix et al. (1997) provide good overviews of tools and techniques to elicit and capture the mental models of teams and client groups.

there are in fact any important feedbacks from the endogenous elements to the candidate. If so, the boundary of the model must be expanded and the variable must be modeled endogenously.

The consequences of narrow model boundaries and reliance on exogenous variables are often serious. A typical example is provided by the Project Independence Evaluation System (PIES) model, a hybrid model based on linear programming, econometrics, and input/output analysis used in the 1970s by the US Federal Energy Administration (FEA) and later by the US Department of Energy. As described by the FEA, the purpose of the model was to evaluate different energy policies according to the following criteria: their impact on the development of alternative energy sources; their impact on economic growth, inflation, and unemployment; their regional and social impacts; their vulnerability to import disruptions; and their environmental effects.

Surprisingly, considering the stated purpose, the PIES model treated the economy as exogenous. The model economy (including economic growth, interest rates, inflation, world oil prices, and the costs of unconventional fuels) was completely unaffected by the energy situation (including prices, policies, and production). In the model, even a full embargo of imported oil or a doubling of oil prices would have no impact on the economy.

Treating the economy exogenously made the PIES model inherently contradictory. Because it assumed high rates of economic growth and low price elasticities, it projected huge increases in energy demand, requiring even greater increases in the capital requirements of the energy sector as cheap domestic oil was consumed. In the model, these huge investments in energy production were satisfied without reducing investment or consumption in the rest of the economy and with no impact on interest rates or inflation. In effect, the model let the economy have its pie and eat it too.

In part because it ignored the feedbacks between the energy sector and the rest of the economy, the PIES model consistently proved to be overoptimistic. In 1974 the model projected that by 1985 the US would be well on the way to energy independence: energy imports would be only 3.3 million barrels per day and production of shale oil would be 250,000 barrels per day. Furthermore, these developments would be accompanied by oil prices of about $22 per barrel (1984 dollars) and by vigorous economic growth. It didn't happen. Imports in the late 1980s were about 5.5 million barrels per day and grew to more than half of oil consumption by the mid 1990s. Shale oil and other exotic synfuels never materialized. This situation prevailed despite huge reductions in oil demand caused by oil prices in the early 1980s greater than $30/bbl and the most serious recession since the Great Depression.

A broad model boundary that captures important feedbacks is more important than a lot of detail in the specification of individual components. It is worth noting that the PIES model provided a breakdown of supply, demand, and price for dozens of fuels in each region of the country yet its aggregate projections weren't even close. What purpose was served by the effort devoted to forecasting the demand for jet fuel or naphtha in the Pacific Northwest when the basic assumptions were so palpably inadequate and the main results were so woefully erroneous?

Mapping System Structure

System dynamics includes a variety of tools to help you communicate the boundary of your model and represent its causal structure. These include model boundary diagrams, subsystem diagrams, causal loop diagrams, and stock and flow maps.

Model boundary chart. A model boundary chart summarizes the scope of the model by listing which key variables are included endogenously, which are exogenous, and which are excluded from the model.

To illustrate, Table 3-2 shows a model boundary diagram for a model designed to study the feedbacks between the energy system and the economy (Sterman 1983). Partly in reaction to the limitations of existing models such as PIES, the Department of Energy in the late 1970s sought to develop dynamic models with a broader boundary (Naill 1977, 1992). The purpose of the model was to explore the impact of higher energy prices on economic growth, unemployment, inflation, and interest rates and how these macroeconomic considerations might constrain the development of new energy sources. The time horizon of the model was quite long (1950-2050) to capture the full transition from fossil fuels to renewable or other energy sources and consistent with the long time delays in the development, construction, and useful life of energy-producing and energy-consuming capital stocks.

In contrast to nearly all models used to address these issues at the time, the model had a broad boundary, with all major macroeconomic variables generated endogenously. Unlike the PIES model, the capital, labor, and energy requirements

TABLE 3-2 Model boundary chart for a long-term model of energy-economy interactions

Endogenous	Exogenous	Excluded
GNP	Population	Inventories
Consumption	Technological change	International trade (except with OPEC)
Investment	Tax rates	Environmental constraints
Savings	Energy policies	Nonenergy resources
Prices (real and nominal)		Interfuel substitution
Wages (real and nominal)		Distributional equity
Inflation rate		
Labor force participation		
Employment		
Unemployment		
Interest rates		
Money supply		
Debt		
Energy production		
Energy demand		
Energy imports		

Source: Sterman (1983).

of the energy industries were endogenous and the energy industry had to compete against other sectors for these resources. The model still contained several exogenous variables. These include population, the rate of overall technological progress, and the price of imported oil. Were these exogenous variables acceptable? Population growth and the overall rate of technical progress might be affected by changes in energy prices and consequent changes in the rate of economic growth. However, these feedbacks seemed likely to be small. The decision to model the price of imported oil exogenously is more problematic. Clearly the price of oil affects both the demand for and supply of energy in the United States, determining the quantity imported. As a major importer, changes in US oil imports can dramatically alter the supply/demand balance of the oil exporting nations, feeding back to the price of oil in the world market. Treating import prices exogenously cuts an important feedback loop. In discussing the boundary of the model I argued that there were in fact important feedbacks between the US energy system and the world oil market. But I also argued that the dynamics of the world price were so complex that incorporating them endogenously was beyond the scope and purpose of the project. I had previously helped build a model of the world oil market for the US Department of Energy and hoped that ultimately the two models could be joined. The model boundary chart alerted the clients to a questionable assumption so they could evaluate what the effect of the missing feedback might be.

The list of excluded concepts also provides important warnings to the model user. The model omitted inventories of goods and materials (and hence short-term business cycles)—no problem in such a long-term model. International trade was excluded, except for the flows of oil, goods, capital, and money between the US and the oil exporting nations. The petrodollars flowing to OPEC and their recycling as exports or foreign investment had to be included, but to include nonenergy trade would have expanded the model into a global macroeconomic system, and I would probably still be working on it. Environmental constraints and nonenergy resources such as water that might limit new energy sources like synfuels were excluded, meaning conclusions about the rate of development of these exotic energy sources would be overoptimistic. The model also treated the energy system in a fairly aggregate fashion, so interfuel substitution (oil vs. gas, for example), was not considered, another optimistic assumption. Finally, the model did not consider income distribution, even though some energy policies such as gasoline taxes are regressive unless offset by changes in the income tax code. The purpose of listing all these omissions from the model was to help model users decide for themselves whether the model was appropriate for their purpose.

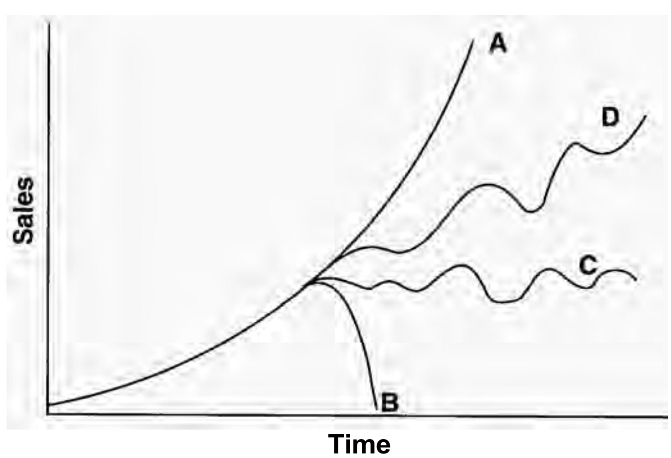
Model boundary diagrams are surprisingly useful and shockingly rare. Often, models are used not as tools of inquiry but as weapons in a war of advocacy. In such cases modelers seek to hide the assumptions of their models from potential critics. But even when the modelers' motives are benign, many feel uncomfortable listing what they've left out, see the omissions as flaws and prefer to stress the strengths of their model. While this tendency is natural, it undercuts the utility of your model and weakens the ability of people to learn from and improve your work. By explicitly listing the concepts you have chosen not to include, at least for now, you provide a visible reminder of the caveats to the results and limitations of the model. Without a clear understanding of the boundary and assumptions, models constructed for one purpose are frequently used for another for which they are ill-suited, sometimes producing absurd results. All too often models with completely inappropriate and even bizarre assumptions about exogenous and excluded variables are used in policy making because the model users are unable to examine the boundary of the models themselves and the modelers have not provided that information for them (chapter 21 provides examples; see also Meadows and Robinson 1985).

Subsystem diagram. A subsystem diagram shows the overall architecture of a model. Each major subsystem is shown along with the flows of material, money, goods, information, and so on coupling the subsystems to one another. Subsystems can be organizations such as the firm and the customer or organizational subunits such as operations, marketing, and product development. Subsystem diagrams convey information on the boundary and level of aggregation in the model by showing the number and type of different organizations or agents represented. They also communicate some information about the endogenous and exogenous variables.

In the 1960s Jay Forrester served on the boards of several successful high-tech companies and became interested in the dynamics of corporate growth. To help him think about the strategic issues facing these firms, Forrester (1964, p. 32) created a model designed "to show how the differing kinds of corporate growth patterns can be created by different corporate policies and management attitudes and by the interactions between a company and its market." Figure 3-6 shows the reference mode. Forrester (pp. 32-33) explained:

> The very rare company grows smoothly, as in curve **A,** and eventually reaches a healthy sustained plateau of mature life. More frequently, the company follows a pattern, as in curve B, where it appears to succeed at first and then encounters a severe crisis that leads to bankruptcy or merger. Often, the pattern is growth stagnation, as in curve C, marked by neither success nor failure. Of those companies which do show a long-term growth trend, the most common pattern is that in curve D, where growth is accompanied by repeated crisis.

FIGURE 3-6
Patterns of corporate growth



Source: Adapted from Forrester (1964).

Forrester argued that "contrary to first impressions, one cannot explain these differences on the basis of the particular industry or the type and design of products.. . One must therefore look deeper into the structure of information flows and the policies which guide operating decisions" (p. 33). To do so the model consisted of two subsystems, the company and the market (Figure 3-7).

The two subsystems are coupled by the obvious flows of orders, product, and money: The firm receives orders from the market, ships product, and receives payment. But in addition, the firm sends signals to the market including the price of the product, its availability (measured by the delivery delay), its functionality, quality, suitability to customer needs, and other intangible attributes of the company's reputation. The market responds to these signals through the order rate and through customer feedback about price, quality, service, product features, and so on. The diagram elegantly presents the essential feedback processes coupling a firm to its market, stresses that orders depend on much more than price, and begins to suggest the structure which must be captured within each subsystem. Forrester reflected on the importance of this conceptual framework in his thinking:

> Defining the system boundary and the degree of aggregation are two of the most difficult steps in successful modeling. In this particular study, part-time effort for about two years was devoted to false starts before arriving at the point shown in [Figure 3-71. Thereafter, only eight weeks were required to create the entire system of some 200 equations.

Chapter 15 presents a simple version of this model, Forrester's "market growth model," and shows how different management policies can create the patterns of growth described in Figure 3-6.

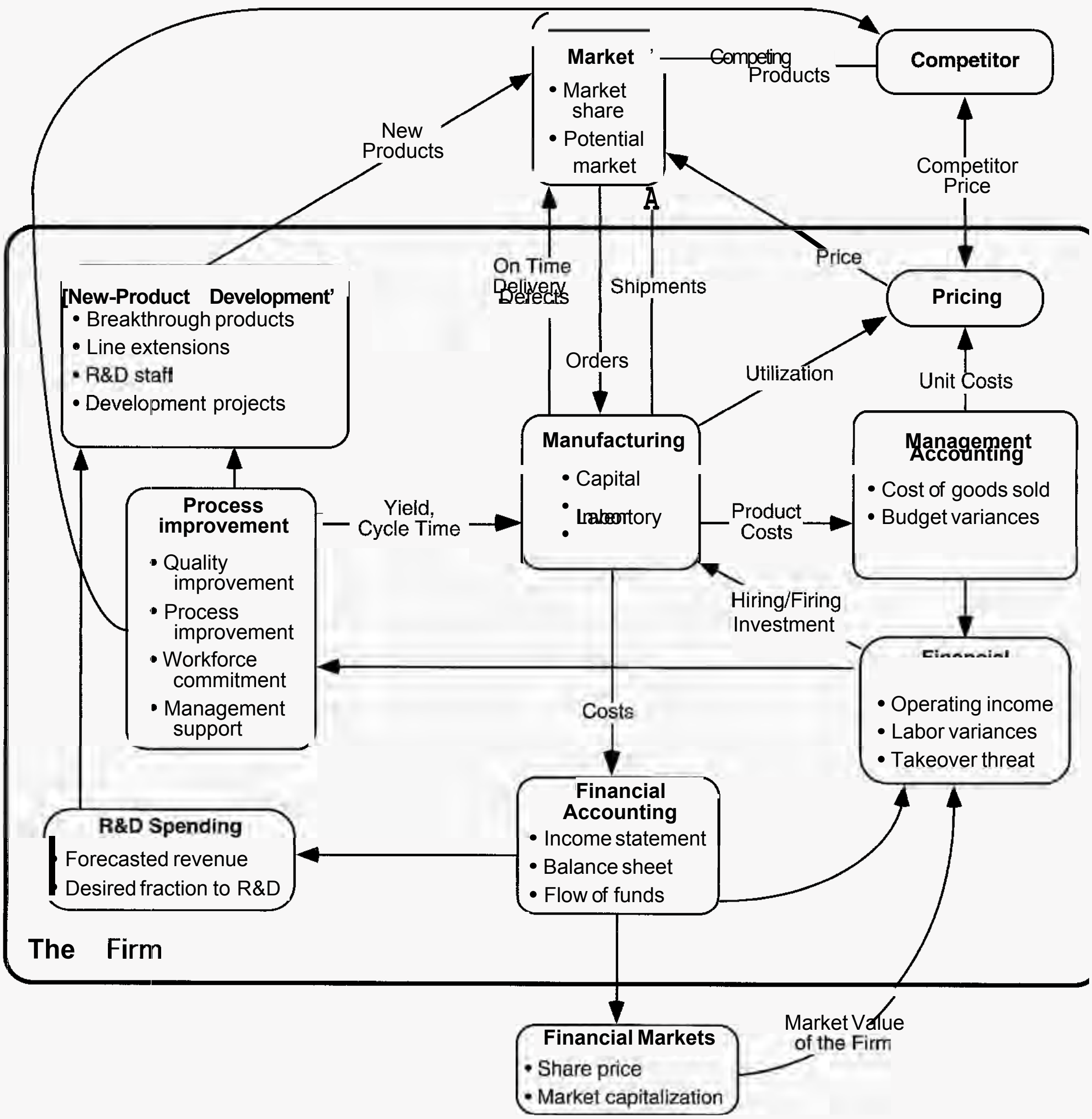
A more detailed subsystem diagram is shown in Figure 3-8. The diagram shows the architecture for a model of a semiconductor manufacturer (Sterman, Repenning, and Kofman 1997). The purpose of the model was to explore the dynamics of process improvement programs. The firm had implemented a very

FIGURE 3-7 Subsystem diagram for Forrester's corporate growth model

Source: **Adapted** from Forrester (1964).

successful quality improvement program. However, despite dramatic improvements in quality, productivity, and customer responsiveness, operating profit and the stock price fell, leading to layoffs. Exploring this paradox required a model with a broad boundary both within the representation of the firm and in interactions of the firm with its environment. Besides the usual subsystems for manufacturing, product development, and accounting, the model includes a process improvement sector and a sector labeled "Financial Stress." The Financial Stress subsystem is not an organizational subunit but represents top management decisions regarding layoffs, investment, and the attention given to process

FIGURE 3-8 Subsystem diagram for model of a semiconductor firm and its quality improvement ∑program



Source: Adapted from Sterman, Repenning, and Kofman (1997).

improvement. These decisions were affected by the firm's financial health and the threat of takeover (as influenced by the market value of the firm relative to book value and cash flow). The diagram also shows that the firm's sales and market share are endogenous, as is competitor behavior (note that competitors respond not only to the firm's price but also to its quality improvement efforts). The stock price and market valuation of the firm are also endogenous.

Subsystem diagrams are overviews and should not contain too much detail. The diagram in Figure 3-8 is quite complex; subsystem diagrams should generally be simpler. Multiple subsystem diagrams can be used to convey the hierarchical structure of large models.

Causal loop diagrams. Model boundary charts and subsystem diagrams show the boundary and architecture of the model but don't show how the variables are related. Causal loop diagrams (CLDs) are flexible and useful tools for diagramming the feedback structure of systems in any domain. Causal diagrams are simply maps showing the causal links among variables with arrows from a cause to an effect. Chapter 2 provides examples; chapter 5 covers the rules for their construction and interpretation in depth.

Stock and flow maps. Causal loop diagrams emphasize the feedback structure of a system. Stock and flow diagrams emphasize their underlying physical structure. Stocks and flows track accumulations of material, money, and information as they move through a system. Stocks include inventories of product, populations, and financial accounts such as debt, book value, and cash. Flows are the rates of increase or decrease in stocks, such as production and shipments, births and deaths, borrowing and repayment, investment and depreciation, and receipts and expenditures. Stocks characterize the state of the system and generate the information upon which decisions are based. The decisions then alter the rates of flow, altering the stocks and closing the feedback loops in the system. Chapter 2 shows examples; chapters 6 and 7 discuss the mapping and behavior of stocks and flows.

Policy structure diagrams. These are causal diagrams showing the information inputs to a particular decision rule. Policy structure diagrams focus attention on the information cues the modeler assumes decision makers use to govern the rates of flow in the system. They show the causal structure and time delays involved in particular decisions rather than the feedback structure of the overall system. Chapter 15 provides examples; see Morecroft (1982) for details.

3.5.3 Formulating a Simulation Model

Once you've developed an initial dynamic hypothesis, model boundary, and conceptual model, you must test them. Sometimes you can test the dynamic hypothesis directly through data collection or experiments in the real system. Most of the time, however, the conceptual model is so complex that its dynamic implications are unclear. As discussed in chapter 1, our ability to infer correctly the dynamics of a complex model is extremely poor. Further, in many situations, especially human systems, it is difficult, dangerous, unethical, or simply impossible to conduct the real world experiments that might reveal the flaws in a dynamic hypothesis. In the majority of cases, you must conduct these experiments in a virtual world. To do so, you must move from the conceptual realm of diagrams to a fully specified formal model, complete with equations, parameters, and initial conditions.

Actually, formalizing a conceptual model often generates important insight even before it is ready to be simulated. Formalization helps you to recognize vague concepts and resolve contradictions that went unnoticed or undiscussed during the conceptual phase. Formalization is where the real test of your understanding occurs: computers accept no hand waving arguments. Indeed, the most experienced modelers routinely write some equations and estimate parameters throughout the modeling process, even in the earliest phases of problem articulation and conceptualization—often with the clients—as a way to resolve ambiguity and test initial hypotheses. System dynamics practice includes a large variety of tests one can apply during the formulation stage to identify flaws in proposed formulations and improve your understanding of the system.

3.5.4 Testing

Testing begins as soon as you write the first equation. Part of testing, of course, is comparing the simulated behavior of the model to the actual behavior of the system. But testing involves far more than the replication of historical behavior. Every variable must correspond to a meaningful concept in the real world. Every equation must be checked for dimensional consistency (so you aren't adding apples and oranges). The sensitivity of model behavior and policy recommendations must be assessed in light of the uncertainty in assumptions, both parametric and structural.

Models must be tested under extreme conditions, conditions that may never have been observed in the real world. What happens to the GDP of a simulated economy if you suddenly reduce energy supplies to zero? What happens in a model of an automaker if you raise the price of its cars by a factor of one billion? What happens if you suddenly increase dealer inventories by 1000%? Even though these conditions have never and could never be observed, there is no doubt about what the behavior of the system must be: Without energy, the GDP of a modern economy must fall nearly to zero; with a price one billion times higher, the demand for the firm's cars must fall to zero; with a huge surplus of cars on dealer lots, production should soon fall to zero but cannot become negative. You might imagine that models would never fail to pass such obvious tests, that production without energy, demand for goods that cost more than the total wealth of many nations, and negative production would never arise. But you'd be wrong. Many widely used models in economics, psychology, management, and other disciplines violate basic laws of physics, even though they may replicate historical behavior quite well (see section 9.3.2 and chapter 21). Extreme conditions tests, along with other tests of model behavior, are critical tools to discover the flaws in your model and set the stage for improved understanding.

3.5.5 Policy Design and Evaluation

Once you and the client have developed confidence in the structure and behavior of the model, you can use it to design and evaluate policies for improvement.

Policy design is much more than changing the values of parameters such as a tax rate or markup ratio. Policy design includes the creation of entirely new strategies, structures, and decision rules. Since the feedback structure of a system determines its dynamics, most of the time high leverage policies will involve changing the dominant feedback loops by redesigning the stock and flow structure, eliminating time delays, changing the flow and quality of information available at key decision points, or fundamentally reinventing the decision processes of the actors in the system.

The robustness of policies and their sensitivity to uncertainties in model parameters and structure must be assessed, including their performance under a wide range of alternative scenarios. The interactions of different policies must also be considered: Because real systems are highly nonlinear, the impact of combination policies is usually not the sum of their impacts alone. Often policies interfere with one another; sometimes they reinforce one another and generate substantial synergies.

3.6 SUMMARY

This chapter described the modeling process. While there are certain steps all modelers go through, modeling is not a cookbook procedure. It is fundamentally creative. At the same time, modeling is a disciplined, scientific, and rigorous process, challenging the modeler and client at every step to surface and test assumptions, gather data, and revise their models—both formal and mental.

Modeling is iterative. No one ever built a model by starting with step 1 and progressing in sequence through a list of activities. Modeling is a continual process of iteration among problem articulation, hypothesis generation, data collection, model formulation, testing, and analysis. There are revisions and changes, blind alleys and backtracking. Effective modeling continually cycles between experiments in the virtual world of the model and experiments and data collection in the real world.

Models must be clearly focused on a purpose. Never build a model of a system. Models are simplifications; without a clear purpose, you have no basis for excluding anything from your model and your effort is doomed to failure. Therefore the most important step in the modeling process is working with your client to articulate the problem—the real problem, not the symptoms of the problem, the latest crisis, or the most recent fad. Of course, as the modeling process leads you to deeper insight, your definition and statement of the problem may change. Indeed, such radical reframings are often the most important outcome of modeling.

The purpose of modeling is to help the clients solve *their* problem. Though the modeling process often challenges the clients' conception of the problem, ultimately, if the client perceives that your model does not address their concern, you can have little impact. The modeler must not grow attached to a model, no matter how elegant or how much time has been invested in it. If it doesn't help the clients solve their problem, it needs to be revised until it does.

Modeling takes place in an organizational and social context. The setting may be a business but can also be a government agency, a scientific community, a public policy debate, or any other organization. Modelers are inevitably caught up in the politics of the community and personalities of its members. Modelers require both first-rate analytical skills and excellent interpersonal and political skills.

Finally, modelers have an ethical responsibility to pursue the modeling process with rigor and integrity. The fact that modeling is embedded in an organizational context and subject to political pressures does not relieve you of your responsibility to carry out your work with the highest standards of scientific inquiry and professional conduct. If your client is not willing to pursue the modeling process honestly, quit and find yourself a better client.

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