System Dynamics and the Sustainable Development of the Electric Power Industry

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ABSTRACT

This paper discusses the successful use of System Dynamics in the electric power industry. It begins with a list of studies and articles documenting the extensive use of System Dynamics to aid corporate and government planners around the world. I then speculate on why this particular industry has been the focus of so many System Dynamics studies. The paper provides a short summary of the long running System Dynamics project for the Bonneville Power Administration in the Pacific Northwest region of the United States. Reflecting on the Bonneville project, I observe two important trends. The first is a trend toward interactive models that are easier for group operation. The second is a trend toward more attention on the consumers of electric power. The paper concludes with results from a recent study of the world aluminum industry, an industry that consumes a tremendous amount of electric power.

INTRODUCTION

System Dynamics has been used extensively in the electric power industry. A review of articles from the System Dynamics Review, for example, shows the following applications:

1. simulating the controllability of feebates for electric vehicles (Ford 1995),
2. description of the energy model used at the US Department of Energy (Naill 1992),
3. analysis of the cost effectiveness of US energy policies to mitigate global warming through (Naill, Belanger, Klinger and Petersen 1992), and
4. an analysis of conservation policies in the Pacific Northwest (Ford and Bull 1989).

And a review of papers published at the annual meetings of the System Dynamics Society shows additional examples:

1. the prospects for American's electric utilities as they prepare for the new competitive environment (Lyneis, Bespolka and Tucker 1994),
2. modeling the privatization of the electricity market in the United Kingdom (Larsen and Bunn 1994),
3. electric power demand forecasting in India (Garga, Gupta, and Thapar 1985), and
4. lessons from the use of System Dynamics in hearings before the New Mexico Public Service Commission (Ford 1981).

Additional examples may be found in the operations research and management science literature (Bunn, Larsen and Vlahos 1993; Ford 1990), the energy and utility policy literature (Ford, Bull and Naill 1987; Bunn and Larsen 1995), reports issued by consulting groups (SSI 1988; AES 1993), and in the early System Dynamics literature made available from the University of Bradford's publication of Dynamica (Zepeda 1975).

DISCUSSION

I believe that a combination of reasons explain the wide spread use of System Dynamics in the electric power industry. The most important reason is the energy crisis of the 1970s which caused researchers to concentrate on the use and consumption of all forms of energy. Another contributing factor is the requirement for long range planning due to the long lead times to acquire large scale generating resources. And a third factor is the public regulation of electric power which requires an open discussion of the utility's operations and resource plans. (Public regulation in the United States is performed at the state level by Public Utility Commissions which are responsible for ensuring that electric rates are sufficient to recover costs and that utility investments in new generating capacity are reasonable.)

I believe a fourth contributing factor is worth mentioning as well. Utility managers often combine management experience with training in engineering. Their background leads to a natural affinity for analytical efforts in general and modeling in particular. Indeed, many electric power companies carry a wide range of computer models to aid in planning the many functions of their business. But these models are usually designed around problems in each function area (operations, finance, rate hearings, etc.) and are not connected together in an integrated fashion. In my opinion, System Dynamicists' main contribution in the electric power business is their ability to help managers tie the separate pieces of the utility system into an integrated system. To illustrate this contribution, I report on the extensive use of System Dynamics to support conservation and electric resource planning in the Pacific Northwest. But first, a historical summary.

HISTORY OF THE BONNEVILLE PROJECT

During the 1980s, electric utility companies in the USA became interested in programs to encourage their customers to invest in conservation. The programs included general information such as advertising, specific information such as audits, and direct financial incentives such as zero interest loans. The programs were needed to help customers overcome market obstacles that limited their investment in measures which would improve the efficiency of electricity use. Utility conservation programs were viewed as a better use of company funds than investment in conventional coal or nuclear power plants.

Conservation was especially important in the Pacific Northwest region of the United States. The region encompasses the states of Washington, Oregon, Idaho and part of Montana, and it is famous for its great rivers and mountainous terrain which provide its huge hydro electric potential. Development of this potential began in 1933 with the Bonneville and Grand Coulee dams. The region now has one of the world's largest hydro-electric systems and, historically, some of the lowest electric rates. Because of the low rates, the region's homes and businesses have not made the same level of investment in conservation as in other parts of the country, and the potential conservation savings is large.

The long period of low electric rates ended in the 1970s when events combined to increase utility spending on new generating capacity. Like many utilities across the country, those in the Pacific Northwest looked to nuclear power plants to meet anticipated growth in demand. And like utilities elsewhere, the Pacific Northwest companies were hit hard by double digit escalation in construction costs and unanticipated reductions in the rate of growth in electric load. The combination of problems led to soaring electric rates, cancellation of several partly constructed plants, major defaults on bonds, and, finally, to the passage of the Pacific Northwest Electric Planning and Conservation Act of 1980.

The Act created the Northwest Power Planning Council to take responsibility for setting broad policies for the regional development of electricity resources. The Act also created major new responsibilities for Bonneville, the arm of the U.S. Department of Energy with authority to market power from federal resources in the region. The Act called for Bonneville to act as a power broker and to take a central role in implementing the best plan for the region. Three provisions of the act are especially relevant to conservation. First, Bonneville was obligated to provide for any future need for electric power in the region. Second, Bonneville now had the authority to acquire resources to meet loads received from other utilities in the region. Third, and perhaps most important, Bonneville was required to consider conservation (along with renewable and cogeneration) preferentially when determining the resources it should acquire to meet future load.

Bonneville's response to the new authority in conservation was swift and multi-faceted. Within two years after the passage of the Act, utilities were operating five region wide Bonneville conservation programs, and conservation planning was upgraded to "Office-Level" status. In 1983, Bonneville's Office of Conservation initiated a project to improve its ability to model the effects of its conservation programs and consumer incentive designs for the Pacific Northwest electric power system. A System Dynamics model was designed to build from the results of existing models and databases and to facilitate rapid analysis of many scenarios.

THE CONSERVATION POLICY ANALYSIS MODELS

Work on the new model began by adapting relevant structure from a simulation model which had proven useful in studies for a major California utility (Ford and Harris 1984). The first step was to design a regional model in which conservation programs, system operation, capacity expansion, and electricity pricing were conducted by a single entity. The next step was to construct a sub-regional model which would distinguish between the loads and resources of the investor-owned utilities (IOUs), the publically owned utilities, and the federal government. The models were known collectively as CPAM, or the Conservation Policy Analysis Models (Ford and Naill 1985; Ford and Bull 1989).

Figure 1 portrays the overall design of the regional version of CPAM by depicting the five important sectors in the utility system. The demand sector is the largest of the five sectors shown in Figure 1; it was singled out for greatest detail to permit direct simulation of the wide range of conservation policy options of interest to Bonneville. The remaining sectors complete the representation of an integrated electric system. The price of electricity, for example, is calculated in the regulatory sector which sets average retail rates based on allowed expenses, allowed return on investment, and the effects of regulatory lag. This sector also keeps track of construction financing and maintains an accounting of the balance sheet and cash flow. The projected rates are passed on to the demand sector to ensure internally consistent projections of customer investment in conservation throughout the simulation.

The five sectors shown in Figure 1 work together to provide an integrated representation of the region's electric system. Information generated in each of the five sectors is available during each time step of the simulation as needed in the remaining sectors. The utility cost from conservation incentive programs, for example, is made available to the price regulation sector where the expenditures are either capitalized or expensed in the rate-making calculations. Electric rates, in turn, are recalculated after the appropriate regulatory lags, and the rates for the next time step are used in the demand sector.

The CPAM approach to model integration will be familiar to members of the System Dynamics community. But this approach is NOT commonly used by utility planners to tie models of different sectors together. The System Dynamics approach should be contrasted with the more common utility approach in which several different models (usually constructed in different departments within the same company) are designed to operate together as shown in Figure 2. In this illustration, one begins with a set of electric rates needed as input for an electricity demand model. The output of the demand model takes the form of electric load projected for each of 20 years in the future, and the load projections are used as input for a capacity expansion model. The output of the capacity planning model is a plan for new power plant construction during the 20 years, and this plan is used to drive a costing model which generates a set of electric rates needed to provide adequate revenues. The electric rates emerging from this sequence of model projections are compared with the electric rates used to start the calculations. If the two sets of rates are significantly different, the starting rates are adjusted, and the sequence is repeated. Through artful manipulation of the starting rates, one hopes to obtain a consistent set of projections within a reasonable number of iterations.

With the iterative approach shown in Figure 2, the output from an early model is not provided to subsequent models until the early model is finished with a full 20 years worth of results. In CPAM, output from the five sectors in Figure 1 are available to other sectors as the model proceeds from one time step to another during the course of a 20 year simulation. The main advantage of the iterative approach is the degree of detail that may be permitted in each individual model in the sequence. Separate models may be coded in different computer languages to allow analysts from different departments to find the best fit with their topic area or to take advantage of existing models. With the CPAM approach, all five sectors were designed from the outset to work together automatically over time. Each approach has compelling advantages, and Bonneville used both approaches in the analysis of conservation policies. The idea was to examine a broad range of conservation policies with CPAM before initiating the iterative process with the more detailed models.

RECENT TRENDS

An important trend in the Bonneville project over the past few years is the emphasis on group operation of the model in meetings designed to promote learning. This trend follows the lead set by System Dynamicists around the world who have shifted their efforts to promote Modeling for Learning Organizations (Morecroft and Sterman 1994). Bonneville's model has been redesigned to operate within a MicroWorlds cockpit (Diehl 1994). The MicroWorlds version may be used in the traditional manner by the small group of analysts familiar with the model details. But the important change in model use comes when wider groups of Bonneville analysts and managers are turned loose to operate the model in group sessions. Each participant is free to explore a variety of policies under different assumptions about the future of the system. Each participant works at his or her pace. With this "learner-directed-learning" approach, the role of the small circle of modeling experts is changed dramatically. They no longer serve as the experts who must teach the wider team about the model insights.

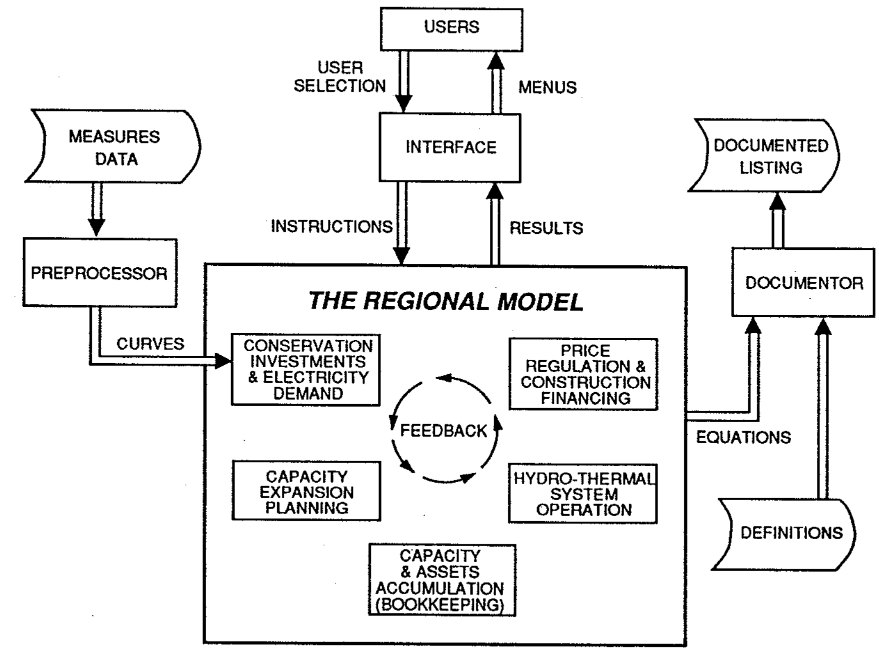


Figure 1. Design of an early version of the Conservation Policy Analysis Model.

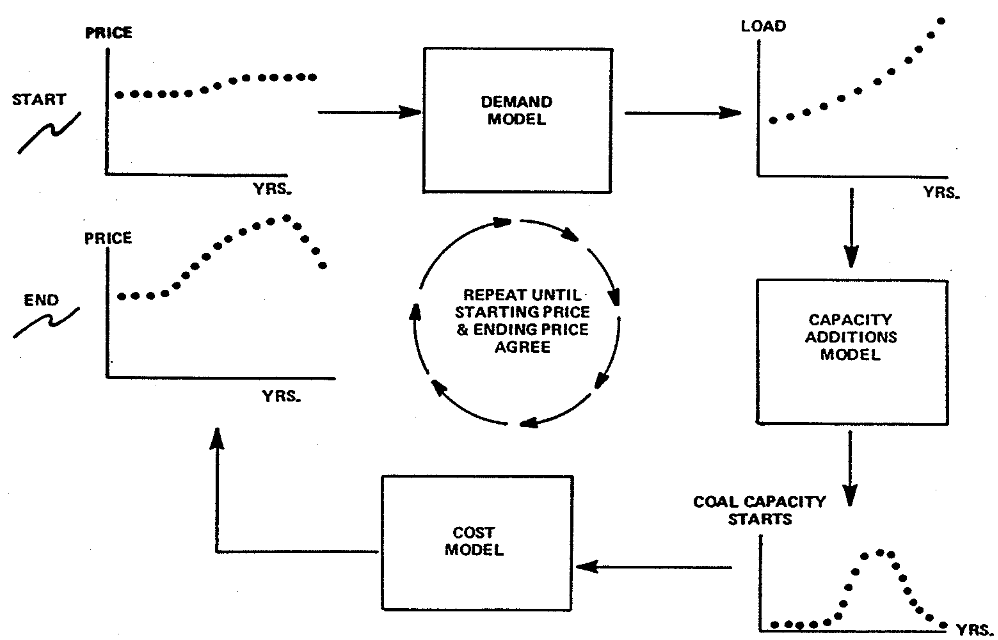


Figure 2. Iterative modeling approach often attempted by electric utility companies.

Rather, the small group now serves the role of coach. Their new role is to allow members of the wider group to explore the results of a variety of policies and arrive at their own conclusions. In this setting, the key insights emerge as each individual conducts explorations with the model. The insights are then confirmed and strengthened in group discussions.

A second trend is important as well. The new trend is toward the customer. The key issues no longer seem to revolve around the choices that electric utilities must make about generating technologies or finance. Rather, the key choices appear to be in the hands of the electricity consumers. The System Dynamics model helps Bonneville planners move in this new direction because the customers' roles in the electric system are treated in considerable detail. Of particular interest are large industrial customers whose electric loads are likely to be sensitive to the price of electricity. Perhaps the most important of these customers are the aluminum smelters.

THE PIVOTAL ROLE OF THE ALUMINUM INDUSTRY

The aluminum industry is a major consumer of electric power around the world. Aluminum smelters locate where power rates are low, often immediately adjacent to the generators. In 1895, for example, a smelting facility was opened next to Niagara Falls in the State of New York. (The smelter was the first customer of the Niagara Falls Power Company.) Aluminum smelters use electrolytic reduction in which the raw material (alumina) is dissolved in a stable solvent. Smelters consume around 7-8 kilowatt-hours of electric energy to produce a single pound of aluminum metal. For large smelters (which can produce 200 thousand metric tons of aluminum per year), the electricity demands are enormous. For example, the ten smelters operating in the Bonneville service area can create an annual average electric load of almost 3,000 megawatts, accounting for around one third of Bonneville's electricity sales in the region.

The price of electricity is perhaps the single most important factor in determining the competitive position of individual smelters in the world aluminum market. Consequently, the electric load from the smelting industry can be quite sensitive to changes in the electric rate. Were the rate to increase, for example, some smelters operating on the edge of profitability might close down. Their closure would cause a loss of revenues to the electric utility. But the electric utility usually faces interest obligations and other fixed costs which must be satisfied. The historical approach has been to raise the electric rate to cover these fixed costs. But this additional rate increase could trigger the closure of additional aluminum smelters, leading, in turn, to further loss of revenues and further rate increases. The prospects of higher and higher rates coupled with lower and lower sales to price sensitive customers is sometimes called the

death spiral

or the "spiral of impossibility (Ford and Youngblood 1983).

Planners disagree whether Bonneville is locked in a "death spiral" with its large aluminum customers. But regardless of one's view of this downward spiral, the large consumers of electric power play a pivotal role in almost any analysis of the future of the Pacific Northwest power system. Even when one is studying some other aspect of the system (ie, the proper incentives for customer conservation in the residential sector), the aluminum companies end up playing an important role because of the information feedback loops that work their way through their corner of the system. Several recent studies have been completed at Bonneville focusing on options to maintain a stable aluminum load. These include incentives for investment in more efficient smelters, rate incentives that respond to changes in the world aluminum price, and rate incentives that incorporate an advance notice requirement if a smelter plans to permanently close operations.

THE MODEL OF THE WORLD ALUMINUM INDUSTRY

The world aluminum industry is of special importance to developing countries contemplating the financial challenges of starting the development of large scale hydro-electric generation. Large aluminum smelters offer a steady customer whose payments can be counted on to provide a large share of cash flow needed to cover interest expenses. When demand growth in the residential and commercial sectors is highly uncertain, a large, predictable aluminum smelter may appear as an ideal partner for initiating the development of a region's hydro electric potential. Because of the importance of this industry to developing countries, I close this paper with a short summary of a System Dynamics model of the world aluminum industry.

The world aluminum model was developed with support from the Idaho National Engineering Laboratory (INEL), one of the major energy laboratories in the Pacific Northwest. INEL operates a variety of research programs on behalf of the US Department of Energy on the aluminum industry, and their managers were interested in the potential for System Dynamics to shed light on the "sunset problems" faced by smelters in the Pacific Northwest. The INEL commissioned the development of a model that would include all the world's smelters (excluding smelters in the CIS, the Confederated Independent States formerly known as the Soviet Union). INEL envisioned a model which would allow planners in the USA to simulate research initiatives that could help USA smelters with "sunset problems" within an industry where the "rising sun" has moved to countries like Australia, Brazil and Canada. Another objective was to understand the great volatility in the world industry that is evident in Figure 3.

The initial version of the world model was quite simple. We started with the stocks and flows shown in Figure 4. We then added the key converters shown in Figure 5. We included the recycling of "old scrap" as shown in Figure 6. The model breaks the demand for aluminum down into nine end use categories (ie, automobiles, buildings, containers, etc.), and allows the recycling parameters to vary from one end use to another. Recycling of "new scrap" was also captured by the variables shown in Figure 7. Figure 8 concludes this brief view of the model structure by portraying the feedback of market price information to govern the aluminum ingot production at each of the 146 smelters in the western world. An overview of the model's system boundaries is portrayed in Figure 9.

To facilitate interactive operation by groups of analysts, the model is embedded in a Micro World's cockpit which permits the user to control key policy and scenario variables without a knowledge of the DYNAMO equations. The MicroWorld's version allows for a wide variety of graphs, tables, and custom tailored reports like the reports shown in Figure 10. The main applications to date have been to explain the underlying causes of the great volatility in the world aluminum market and to test the industry's response to major research initiatives. These applications are portrayed in Figure 11 which shows (1) high price volatility in a base case exploration and (2) the price changes made possible by the assumption that a highly efficient inert anode, stable cathode technology is available starting in the year 2000. The model may also be used to simulate how the impacts of a new technology (like the inert anode, stable cathode technology) play out differently from one country to another in the world aluminum system.

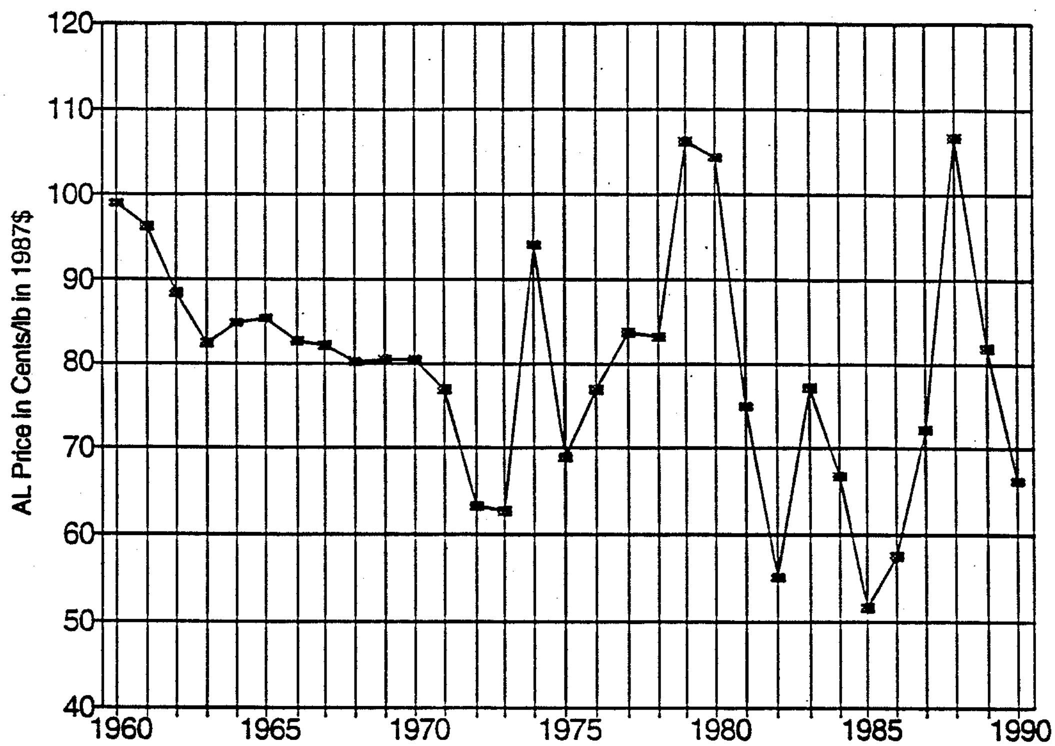


Figure 3. World aluminum price in cents/pound, constant 1987$.

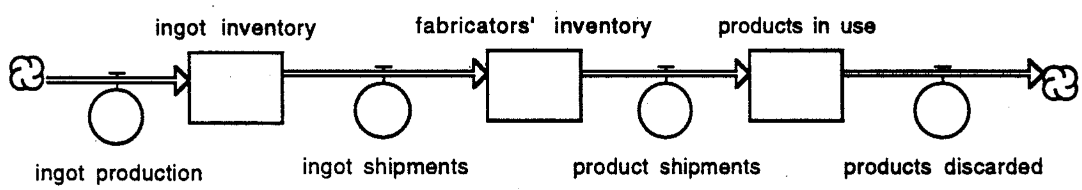


Figure 4. Key stocks and flows in the world aluminum model.

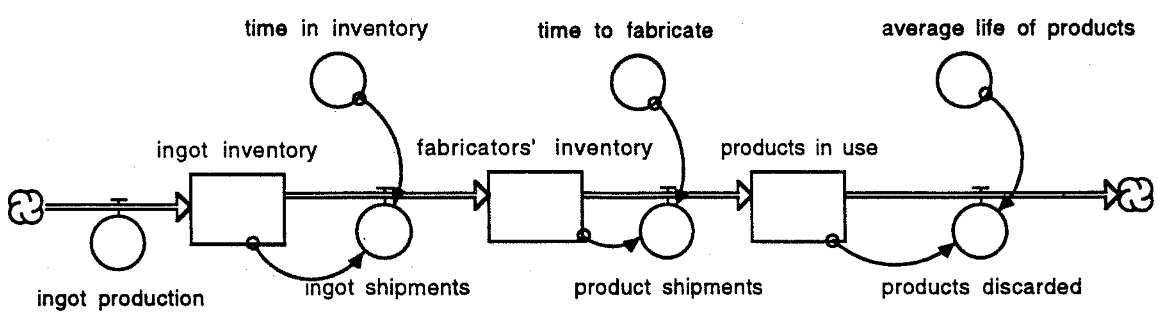


Figure 5. Adding the converters to control key flows in the model.

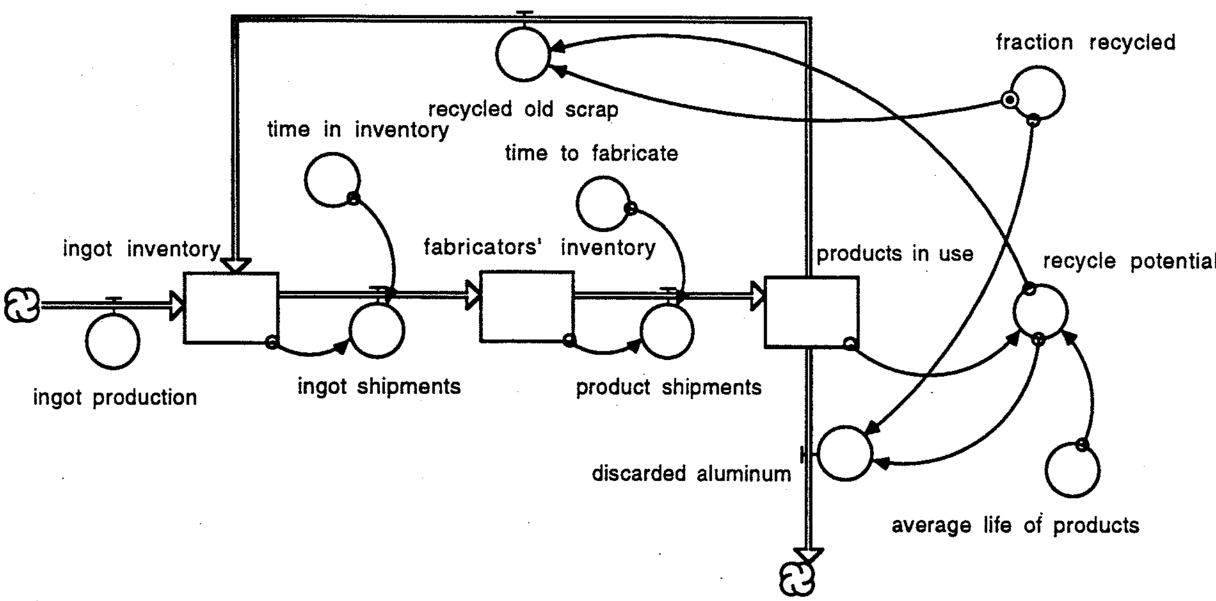


Figure 6. Simulating the recycling of "old scrap" in the world model.

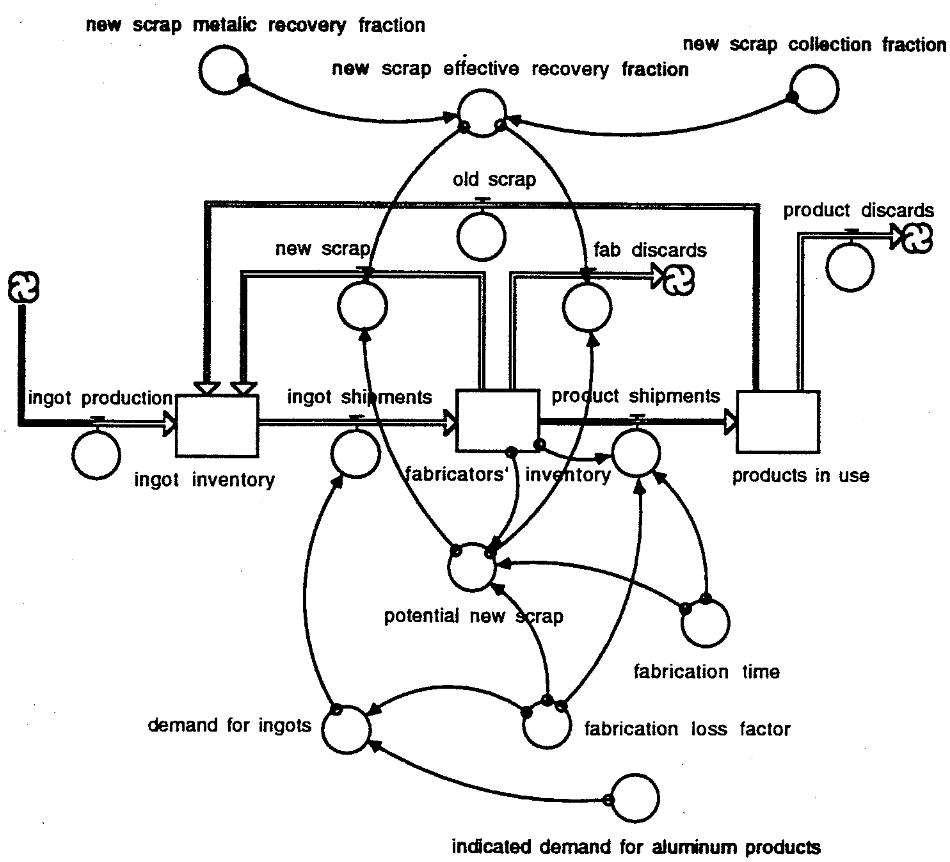


Figure 7. Simulating the recycling of "new scrap" in the model.

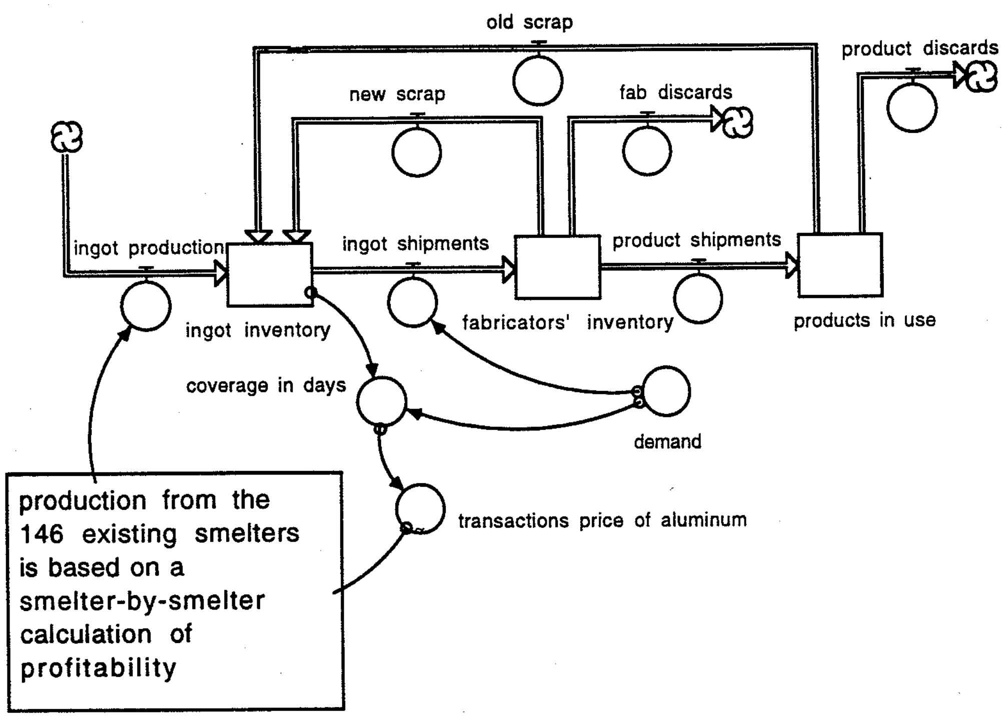


Figure 8. Simulating the loop controlling ingot production from existing smelters.

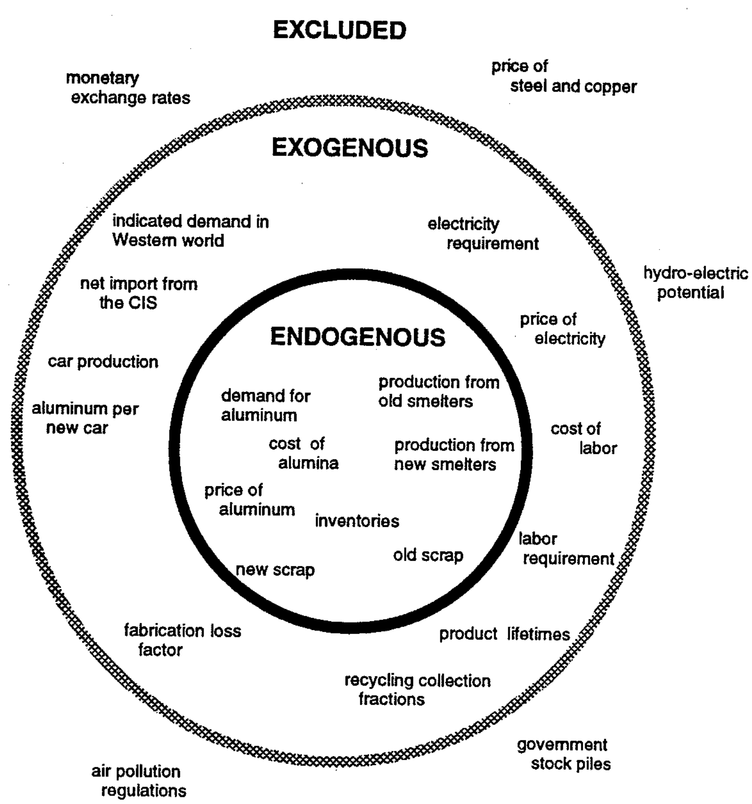
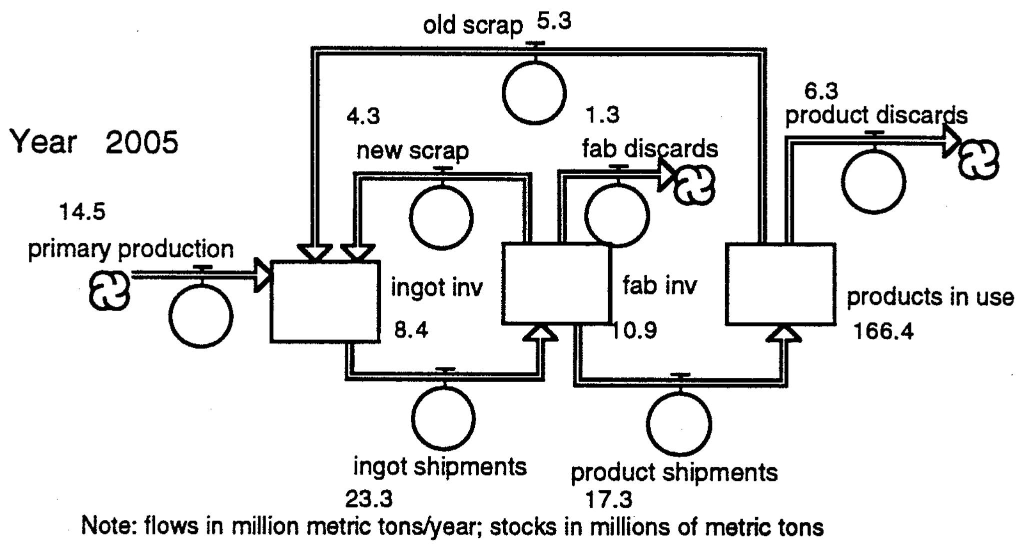


Figure 9. Bull's eye diagram (system boundary diagram) for the world model.

Aluminum Flows: Diagram **World Aluminum 8/15**



Aluminum Flows: Picture **World Aluminum 8/15**

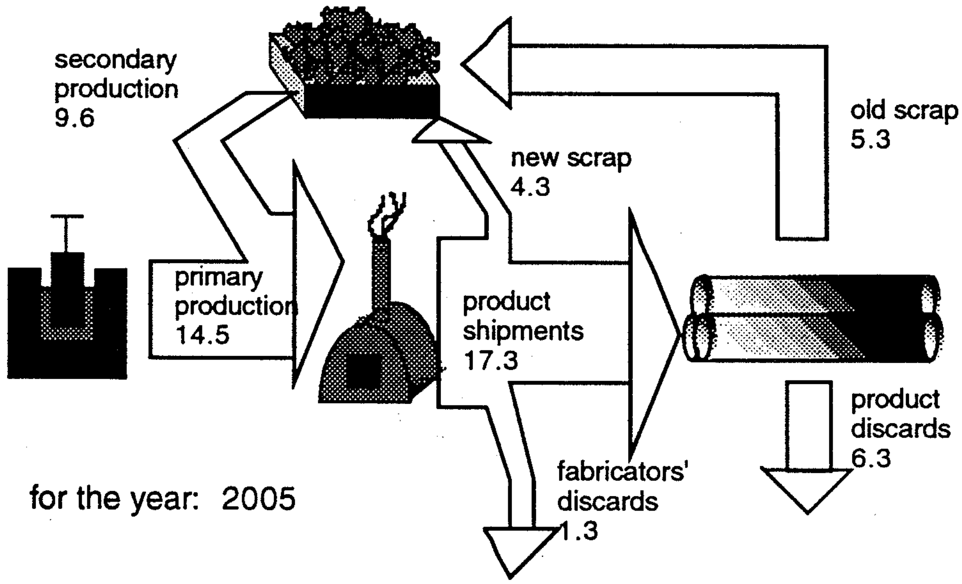


Figure 10. Two Reports from the Micro Worlds version of the world aluminum model mid-way through a base case exploration.

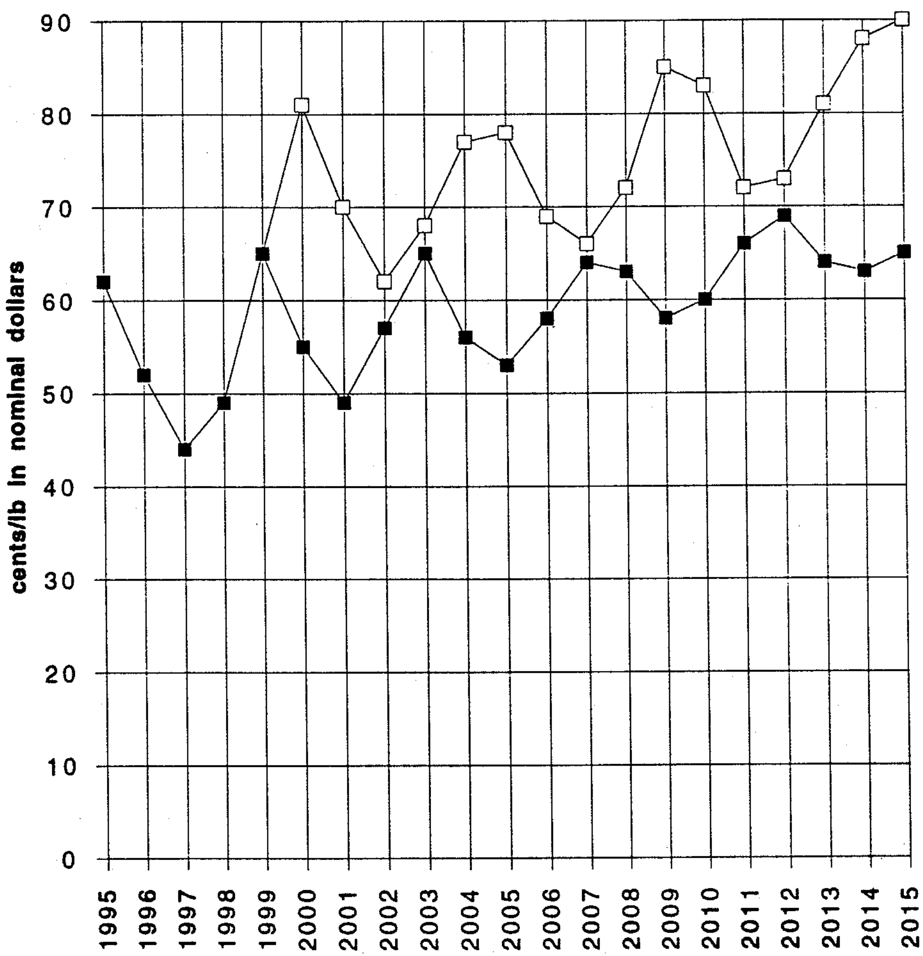


Figure 11. Illustrative simulation results from the world model.

The open squares show the results of a base case exploration to learn if the model can exhibit the price volatility shown previously in Figure 3. The cycles in price shown here are typical of commodity production cycles (Meadows 1970). This volatility emerges from "inside the system." That is, there are only a few, major external changes to disturb the system.

The black squares show a simulation in which the inert anode, stable cathode smelting technology is available in the year 2000. Investment in the new technology is calculated inside the model based on a payback target of 2 years. As smelters around the world adopt the new technology, the market clearing price is around 10 cents/pound lower than in the base case exploration. The magnitude and periodicity of the cyclical behavior is not changed by the introduction of the new smelting technology. Because of the lower market clearing price, the simulated benefit of the new technology for smelter operations in the Pacific Northwest is lower than what one might have expected.

CONCLUSION

System Dynamics has been and continues to be an important approach to aid corporate and government planners in the electric power industry. System Dynamicists have demonstrated an ability to contribute in a "model intensive" industry because of their ability to tie the separate pieces of the utility system together in a holistic manner. In reflecting on the use of System Dynamics for the Bonneville Power Administration, I notice two important and useful trends. The first is increased attention to making models easier to use in group sessions. The second is greater attention to the customers' side of the system. The stronger focus on the customer is especially important for large industrial customers that may be highly sensitive to the price of electricity.

A recently developed model of the world aluminum industry combines these two important trends. The world model is especially important for planners studying the sustainable development of their nation's electric resources. The new aluminum model provides a foundation for building a greater understanding of the complex "partnership" between the electric power industry and the aluminum industry.

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