Chapter 3

Restructuring the Electric Enterprise

Simulating the Evolution of the Electric Power Industry with Intelligent Adaptive Agents

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Abstract: A model and simulation of the "Electric Enterprise" (taken in the broadest possible sense) have been developed. The model uses autonomous, adaptive agents to represent both the possible industrial components, and the corporate entities that own these components. An open access transmission application and real-time pricing has been implemented. Objectives are: 1) To develop a high-fidelity scenario-free modeling and optimization tool to use for gaining strategic insight into the operation of the deregulated power industry; 2) to show how networks of communicating and cooperating intelligent software agents can be used to adaptively manage complex distributed systems; 3) to investigate how collections of agents (agencies) can be used to buy and sell electricity and participate in the electronic marketplace; and ultimately to create self-optimizing and self-healing capabilities for the electric power grid and the interconnected critical infrastructures.

Key words: Deregulation, Simulation, Intelligent software agents, Adaptive, Modeling and Optimization, Open access, Pricing, Competitive/Cooperative Power Scheduling, E-Commerce, Power Exchange, Auctions

1. INTRODUCTION

1.1 The Electricity Enterprise: Today and Tomorrow

The North American power network may realistically be considered to be the largest machine in the world since its transmission lines connect all the electric generation and distribution on the continent. Through this network, every user, producer, distributor and broker of electricity buys and sells, competes and cooperates in an "Electric Enterprise." Every industry, every business, every store and every home is a participant, active or passive, in this continent-scale conglomerate. Over the next few years, the Electric Enterprise will undergo dramatic transformation as its key participants -- the traditional electric utilities -- respond to deregulation, competition, tightening environmental/land-use restrictions, and other global trends.

While other, more populous, countries, such as China and India, have greater potential markets, the United States is presently the largest national market for electric power. Its electric utilities have been mostly privately owned, vertically integrated and locally regulated. National regulations in areas of safety, pollution and network reliability also constrain their operations to a degree, but local regulatory bodies, mostly at the State level, have set their prices and their return on investment, and have controlled their investment decisions while protecting them from outside competition. That situation is now rapidly changing. State regulators are moving toward permitting and encouraging a competitive market in electric power.

In this chapter we shall present a model and simulation of the "Electric Enterprise" (taken in the broadest possible sense) that has been developed. The model uses autonomous, adaptive agents to represent both the possible industrial components, and the corporate entities that own these components and are now engaged in free competition. The goal in building this tool is to help these corporations evolve new business strategies for internal reorganization, external partnerships and market penetration.

Development of this tool takes advantage of recent research in Complex Adaptive Systems (CAS) which has begun to produce an understanding of complexity in natural systems as a phenomenon that emerges from the interaction of multiple, simple, but adaptive, components. Agents are no strangers to the electronic marketplace, Internet versions of this software are commonly known as "softbots" or just "bots". Most common applications have involved accessing Website contents or search engines. In contrast to earlier software, these goal-seeking agents have been semi-autonomous in achieving their objectives.

From a computer programming point-of-view, agent-based modeling and simulation is a natural extension of the prevailing object-oriented paradigm. Agents are simply *active objects* that have been defined to simulate parts of the model. Discrete event simulations with multiple quasi-autonomous agents (usually called actors or demons) have been used for at least twenty-five years to assist human decision-making in areas such as batch manufacturing, transportation, and logistics. The revolutionary new idea that comes from the computer experiments of CAS is to let the agents evolve, with each one changing in a way that adapts to its environment while that environment is modified by external forces and by the evolutionary changes in the other agents.

The agent community is allowed to evolve by causing innovative changes in the parameters of individual agents to be generated randomly and/or systematically. These parameter changes, in turn, produce changes in the agents' actions and decisions, so that the agents "tinker" with the rules and the structure of the system. Agents subjected to increased stress (resource shortages, environmental pressures, and financial losses) increase their level of tinkering until some develop strategies that relieve that stress. Some individual agents succeed (grow, reproduce, increase their profits) while others fail (shrink, die, are replaced, bought out).

Business enterprises, financial markets and the economy itself can all be viewed as complex adaptive systems and they give rise to practical problems that are often mathematically intractable. The methods developed to study CAS, as well as the insights derived from these studies, have been applied to all these areas with some success in the last decade. Practical market applications of more advanced agents represent buyers and sellers and carry out negotiations on their behalf. Agents are also used to represent stakeholders as they attempt to secure goods and services in an auction setting. Typically, the stakeholder is an individual user bidding for a good. However, auctioning may not be just for individuals. The Electric Power Research Institute, for example, has funded research into agent-based auctioning as a way to address the fierce competition for resources. Electric power marketers have emerged, and wholesale electric customers are learning to shop around for the best electric suppliers. This has peaked interest in bargaining agents that trade on behalf of various stakeholders. Like agents that represent individual human users, the bargaining agents decide how much to buy, who to buy it from, how much to pay, and how they will manage the exchange of goods and money. In a power market, however, there is also concern that the entire market not be harmed by the sale. Thus, looking at how agents complete their transactions and learn from them, provide insight into the dynamics of a complex supply and demand system.

Simulations of multiple, autonomous, intelligent agents, competing and cooperating in the context of the whole system's environment have had considerable success in providing better understanding of phenomena in biology and ecology, and, more recently, in financial markets. A CAS model is particularly appropriate for any industry made up of many, geographically dispersed components that can exhibit rapid global change as a result of local actions -- a characteristic of telecommunications, transportation, banking and finance as well as gas, water and oil pipelines, and, especially, the electric power grid.

The first version of this tool treats several aspects of the operation of the electric power industry in a simplified manner. For instance, it uses a DC model. However, it includes base-classes for agents representing generation units, transmission system segments, loads, and corporate owners. Users may modify and interconnect these agents through a graphical interface. Simple adaptation strategies for the agents have also been implemented. More complex ones have been designed, and implemented. Scenarios have been prepared to illustrate open access and real-time pricing. This simulation tool can be further enhanced to provide greater physical and market realism by the inclusion of an AC model and futures trading, and to model co-generation, retail wheeling, and the effects of new technological developments, such as: storage, power electronics and superconductivity.

1.2 Deregulation, Competition, Re-Regulation and New Institutions

In 1978, the United States Federal Government began the movement toward deregulation by allowing competition in several strategic sectors of the economy, starting with the airlines and followed by railroads, trucking, shipping, telecommunications, natural gas and banking. Adam Smith succinctly stated the philosophy behind this movement in 1776: "Market competition is the only form of organization, which can afford a large measure of freedom to the individual. By pursuing his own interest, he frequently promotes that of society more effectively than when he really intends to promote it." More recently, Prof. Alfred Kahn of Cornell University, who guided the airline deregulation as the head of the Civil Aeronautics Board, expressed it in a different way: "Deregulation is an admission that no one is smart enough to create systems that can substitute for markets."

Throughout most of the history of electric power, the institutions that furnished it have tended to be vertically integrated monopolies, each within its own geographic area. They have taken the form of government departments, quasi-government corporations or privately owned companies subjected to detailed government regulation in exchange for their monopoly status. Selling or borrowing electric power among these entities has been carried out through bilateral agreements between two utilities (most often neighbors). Such agreements have been used both for economy and for emergency back up. The gradual growth of these agreements has had the effect that larger areas made up of many independent organizations have become physically connected for their own mutual support.

In recent years, some of the local monopolies have found it beneficial to be net buyers of power from less costly producers and the latter have found this to be a profitable addition to their operations. For instance, it is typical in the western United States and Canada for surplus hydroelectric power to be transmitted south for air conditioning in the summer; while less expensive nuclear power is transmitted northward in the winter when the reservoirs are low or frozen and only nighttime heating is needed in the south. These wide area sales and the wheeling of power through non-participant transmission systems are international in extent, especially in Europe and the Americas. There is evidence of a worldwide drive to use these interconnections intentionally:

To create competition and choice, with the hope of decreasing prices,

To get governments out of operating, subsidizing or setting the price of electric power, and

To create market-oriented solutions in order to deliver increases in efficiency and reductions in prices.

In order to unbundle the monopoly structure of electric power generation in the United States, Congress passed the National Energy Policy Act of 1992. National monopolies in the United Kingdom, Norway and Sweden have been de-nationalized and unbundled into separate generation, transmission and distribution/delivery companies. In most approaches to deregulation, transmission is kept as a centrally managed entity, but generation is broken into multiple independent power producers (IPP), and delivery is left to local option. New IPP are encouraged or, at least, permitted, as are load aggregators and electric power brokers, both of whom own no equipment, but are deal-makers who operate on commissions paid by the actual producers and users.

The concept behind this arrangement is that electricity, much like oil and natural gas, is a *commodity* that can be sold in the cash or spot market. As a commodity, it is possible to buy and sell future options and more complex derivative contracts based on electricity prices. However, it is not clear that electricity meets all the necessary criteria for commodity trading. The original assumptions of NYMEX and its traders were based on the model of natural gas, which, unlike electricity, can be stored economically. Once a unit of electricity is produced it must be consumed almost immediately; however, a true commodity can be stored for some length of time and consumed when and how desired. Electricity storage devices are capable of handling only a small percentage of an area's electricity requirements. Storage limitations and capacity constraints on inter-regional transfer prevent all available suppliers across the continent from head-to-head competition.

An alternative, and more entrepreneurial, view is that furnishing electricity is a *service* to the end user. Electric service may be segmented into more specific markets such as heating, cooling, lighting, building security, etc., or combined with other consumer services such as telephone, cable TV, Internet connections, etc. Both views may be reconcilable by separating the *product*, handled by generation and transmission companies, from the *service*, performed by distribution companies.

1.3 Modeling the Future

The real issue, not yet being faced in United States (or in many other nations that are moving toward greater competition in electric power) is whether such an open, competitive market can be can fair and profitable to all participants, while continuing to guarantee to the ultimate consumer of power, at the best possible price, secure, reliable electric service, of whatever quality that consumer requires.

Some utilities are contending that sudden deregulation is unfair and are seeking government reimbursement for "stranded assets" -- equipment that, for technical or financial reasons, cannot be made efficient enough to compete. In order to free the most profitable parts of their operations from regulation, other utilities are unbundling into separate and independent generation, transmission and delivery companies; or at least separate services, each optimizing its performance based on different criteria and all operating at arms length from each other. Still other utilities are merging with, buying or being bought by, companies that may not have been in the electric power business at all. Combinations are taking place, or proposed, in which parts of former electric power monopolies join with companies whose chief product or service has been natural gas, telecommunications, cable television, engineering or finance.

Current approaches to predicting the new business structure of the electric power industry are all driven by assumed scenarios. One such scenario, based on the experience of other industries and other nations, expects that in five years there will be only a few dozen companies engaged in the actual generation, transmission and distribution of electricity. The generation companies will be completely deregulated, except for some environmental constraints. The distribution companies will still be regulated, along the lines of today's local telephone companies, but major industrial/commercial customers, and cooperatives of individual residential customers, will generate their own power or buy it from the lowest bidder. The transmission companies will be partly regulated in an attempt to ensure open access and non-discriminatory pricing for "wheeling" power between any generator and any user or distributor, while maintaining some level of system security despite their lack of control of either generation or load. However, this is just one hypothetical future scenario and various other scenarios are emerging.

The topology of these alternative scenarios/business structures dictate features of the future power system infrastructure which, in turn, suggest the most profitable re-arrangements of capital assets and market segments for each company. Hence, the predictive accuracy of this "top-down" approach depends entirely on the actual occurrence of the scenario or family of scenarios postulated. As an alternative approach, EPRI is developing a model and simulation of the "Electric Enterprise" (taken in the broadest possible sense) that uses a "bottom-up" representation of the whole system without any preconceived scenarios. Its major endogenous constraints will be the laws of physics and the cost or availability of possible technological and economic solutions. Autonomous, adaptive agents represent both the possible industrial components, and the corporate entities that own these components and are now engaged in free competition with each other. Political accommodations and corporate restructuring will appear as global emergent behavior from these locally fixed agents cooperating and/or competing among themselves. As these artificial agents evolve in a series of experiments, the simulation should expose various possible configurations that the market and the industry could take, subject to different degrees and kinds of cooperation, competition and regulation. Possible results will be the development of conditions for equilibria, strategies or regulations that destabilize the market, mutually beneficial strategies, the implications of differential information, and the conditions under which chaotic behavior might develop. This view, of course, has considerable similarity to the mathematical theory of games of strategy, but, unlike the generalized games solved by von Neumann or Nash, these are repeated games with non-zero sum payoffs. Information theoretic considerations are pertinent and these may, in turn, be represented by entropy in the state or phase space in which the system operates.

The primary goal in building this tool is to help individual companies evolve new business strategies for internal reorganization, examine the potential of entering into new partnerships or attempting to exploit new market segments. Computer experiments with this model can also provide insight into the evolution of the entire electric power industry. Within this "scenario-free" testbed, all the global behaviors that are possible in the system can emerge from local agents cooperating and/or competing among themselves in response to "what if" studies and computer experiments hypothesizing various forms of exogenous constraints. In addition, the model will serve as a practical way to estimate the benefits of implementing any proposed new technology or making hypothetical changes to existing equipment and operating practices.

2. COMPLEX ADAPTIVE SYSTEMS (CAS)

Development of this tool takes advantage of recent research in Complex Adaptive Systems (CAS) which has begun to produce an understanding of complexity in natural systems as a phenomenon that emerges from the interaction of multiple, simple, but adaptive, components. Researchers associated with the Santa Fe Institute have conducted much of this work. Simulations of multiple, autonomous, intelligent agents, competing and cooperating in the context of the whole system's environment have had considerable success in providing better understanding of phenomena in biology and ecology. Using computer experiments on CAS models that simulate biological phenomena has been called, somewhat extravagantly, "artificial life."

The attractiveness of these methods for general purpose modeling, design and analysis lies in their ability to produce complex emergent phenomena out of a small set of relatively simple rules, constraints and relationships couched in either quantitative or qualitative terms. Inventing the right set of the local rules to achieve the desired global behavior is not always easy, although it often seems obvious afterward. For instance, flocking behavior requires only two basic rules: (1) stay close to the nearest bird, (2) avoid colliding (either with another bird or any obstacle).

Business enterprises, financial markets and the economy itself can all be viewed as complex adaptive systems and they give rise to practical problems that are often mathematically intractable. The methods developed to study CAS, as well as the insights derived from these studies, have been applied to all these areas with some success. Other CAS simulation techniques such as spin glass models, sand piles and random Boolean networks have been, for some time, standard tools in certain relatively narrow areas such as condensed matter physics.

From a computer programming point-of-view, agent-based modeling and simulation is a natural extension of the prevailing object-oriented paradigm. Agents are simply *active objects* that have been defined to simulate parts of the model. Discrete event simulations with multiple quasi-autonomous agents (usually called actors or demons) have been used for at least twenty-five years to assist human decision-making in areas such as batch manufacturing, transportation, and logistics. The revolutionary new idea that comes from the computer experiments of CAS research is to let the agents evolve, with each one changing in a way that adapts to its environment while that environment is modified by external forces and by the evolutionary changes in the other agents. Several pertinent questions arise:

1) What is an agent? Agents have evolved in a variety of disciplines—artificial intelligence, robotics, information retrieval, and so on—making it hard to get consensus on what they are. Most researchers agree, however, that a truly intelligent agent has these attributes:

Reactivity. It can sense the environment and act accordingly
Autonomy. It does not need human intervention
Collaborative behaviour. It can work with other agents toward a common goal
Inferential capability. It can infer various task-related issues from the environment.
Temporal continuity. Its identity and state persist over long periods.
Adaptively. It can learn and improve with experience.

The more advanced agents may also have other attributes, such as mobility (it can migrate from one host platform to another, either by directing itself or following a pre-programmed schedule) and personality (manifesting some human qualities, such as cooperation for the "greater good," caution, and even greed).

2)What types of Agents are there? There are probably as many ways to classify intelligent agents as there are researchers in the field. Some classify agents according to the services they perform. System agents run as parts of operating systems or networks. They do not interact with end users, but instead help manage complex distributed computing environments, interpret network events, manage backup and storage devices, detect viruses, and so on.

Interface agents are intelligent interfaces that use speech and natural language recognition capabilities. Their main job is to reduce the complexity of information systems.

Filtering agents filter out data the user does not need. *Retrieval agents* search and retrieve information from various sources on the web and serve them to the user like an information aggregator. *Navigation agents* help users navigate through external and internal networks, remembering shortcuts, preloading caching information, and automatically bookmarking interesting sites, among other tasks. *Monitoring agents* provide users with information when a particular event occurs, such as a Web page being updated. Amazon.com customers, for example, get Eyes, agents that monitor catalogs and sales and notify customers when particular books are available.

Profiling agents gather information on Web site visitors, which the site uses to tailor presentations for that visitor.

A *heterogeneous agent system* contains two or more agents with different agent architectures.

3) How Adaptive Agents Work? An adaptive agent has a range of reasoning capabilities. It is capable of innovation—developing patterns that are new to it—as opposed to learning from experience (sorting through a set of predetermined patterns to find an optimal response). Adaptive agents can be passive—respond to environmental changes without attempting to change the environment—or active—exerting some influence on its environment to improve its ability to adapt. In effect, an active adaptive agent conducts experiments and learns from them.

Individual agents must be able to respond to environmental conditions and to other agents in a way that enhances their survival or meets other goals. To learn a strategy that increases its "fitness," the agent has to gather and store enough information to adequately forecast and deal with changes that occur within a single generation. The population then adapts through the diversity of its individuals. Some individuals will always survive, and their individual actions benefit the population goals. Thus, the population evolves over many generations, surviving as a recognizable organization.

The agent community is allowed to evolve by causing innovative changes in the parameters of individual agents to be generated randomly and/or systematically. These parameter changes, in turn, produce changes in the agents' actions and decisions, so that the agents "tinker" with the rules and the structure of the system. Agents subjected to increased stress (resource shortages, environmental pressures, and financial losses) increase their level of tinkering until some develop strategies that relieve that stress. Some individual agents succeed (grow, reproduce, increase their profits) while others fail (shrink, die, are replaced, bought out).

3. UNDERSTANDING COMPLEX SYSTEMS

The demonstration market provides an interesting way to gain some insight into the many issues that affect the power market as it struggles with adapting to changes caused by deregulation. To gain insights into any large-scale network, however, we need some way to model the dynamics of the market. Current modeling techniques are unsuitable because they typically rely on top-down, scenario-driven methodologies, limited to a small set of preconceived scenarios. Agent systems offer an attractive alternative because they allow a bottom-up representation of the system that will not be restricted to preconceived or hypothetical scenarios. The North American power grid, for example, can be considered a complex adaptive system because it comprises many, geographically dispersed components and can exhibit global change almost instantaneously from actions taken in only one part of it.

EPRI is using CAS work to develop modelling, simulation, and analysis tools that may eventually make the power grid self-healing, in that grid components could actually reconfigure to respond to material failures, threats or other destabilizers. The first step is to build a multiple adaptive agent model of the grid and of the industrial organizations that own parts of it or are connected to it.

SEPIA (Simulator for Electrical Power Industry Agents) is an example of this adaptive agent model; it is a comprehensive, high fidelity, and scenario-free modelling and optimisation tool developed with funding from EPRI by Honeywell Technology Center (HTC) in conjunction with the University of Minnesota. EPRI members, who sponsored the research, use SEPIA to conduct computational experiments for any kind of scenario, which gives them insights into the true dynamics of the power market, and assists in gaining strategic insights into the electricity marketplace.

SEPIA is an object-oriented, fully integrated Windows application with plug-and-play agent architecture. Users can readily adapt simulations to a parallel computing environment, including multiprocessor PCs and PC networks. SEPIA agents are autonomous modules that encapsulate specific domain behaviours. They are implemented as independent ActiveX applications, which communicate with each other by messages sent through the SEPIA agent bus. The user interface, which is modelled after the Windows GUI, lets users specify agents and agent relationships and modify agents, and provides mechanisms for to guide and monitor the simulation.

Within SEPIA, agents communicate through messages; the messaging mechanism is sufficiently flexible to handle the variety of communication needs necessary (this includes, for example, simulations of electric power transmission, of information flows between corporate agents, and of money transfers). Numerous agent classes have been designed and implemented: generating units, generating companies, loads, consuming companies, power exchanges, and transmission zones.

An open access transmission application has been implemented. Users can conduct simulations by defining scenarios through drag-and-drop operations on icons representing the agents, then interconnecting the agents, and pressing a “run” button. Simulation results are shown dynamically on graphs and reports, and the policies and parameters of agents can be modified dynamically as well.

This work has also resulted in the development of more sophisticated business scenarios for the operations of a deregulated power industry are articulated in some detail next.

The user interface, based on the familiar Windows GUI, allows users to specify agents and agent relationships, permits agent modification, and provides mechanisms for simulation steering and monitoring. SEPIA uses standard file input/output formats, such as the PSS/E data format for transmission networks, that are in common use today, so that EPRI members will be able to base their computer experiments with SEPIA on their own system data.

In Phase 1 of SEPIA, the agent model, the simulation engine and the graphical user interface (GUI) have been implemented. Simple adaptation strategies for the agents have also been implemented (Figure 1). More complex ones have been designed, and their implementation is underway.

The next phases will emphasize improvements to physical and market realism, such as power electronics devices, superconducting cables and various forms of storage, as well as the effects of trading in futures, options and various derivatives. Further enhancements will emphasize greater fidelity in modelling the implication for each transaction of the resulting power flow (stability, security, etc.) on the existing network. The physical realism will be enhanced with an AC model, models of Flexible AC Transmission (FACTS) devices, superconducting cables, and storage. These extensions will allow users to evaluate potential technological investments. Improvements to market realism will include a futures market, exchange and bilateral contracts, and exogenous inputs. This will permit the development of scenarios involving the revenue impact of load forecasting, and various control algorithms. Parallel processing, agent template libraries, and more readily customizable agents will enhance performance and flexibility of the tool itself.

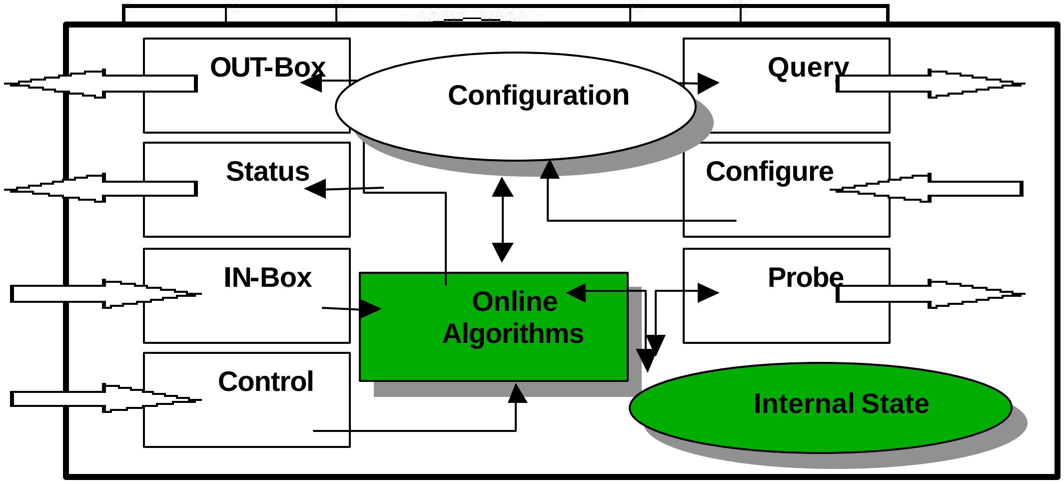

Figure 1. Agent Architecture and Adaptation Agent design determines when and how Online Algorithms modify internal state based on experience

The first version of SEPIA includes base-classes for agents representing: generation unit agents, transmission system agents, load agents, and corporate agents, which may represent either a net power consuming company (LoadCo – Figure 2) or a net power generating company (GenCo). All agents continually make decisions, and these decisions affect the behaviour of other agents. The design and implementation of these agents is sufficiently generic as not to limit how users may extend the system by specializing their classes or by defining new ones to allow for different kinds of generation, transmission, loads, and corporations. All agents consist of layered components, some specific to that particular agent and some applicable to other agents, so that different configurations can be assembled rapidly.

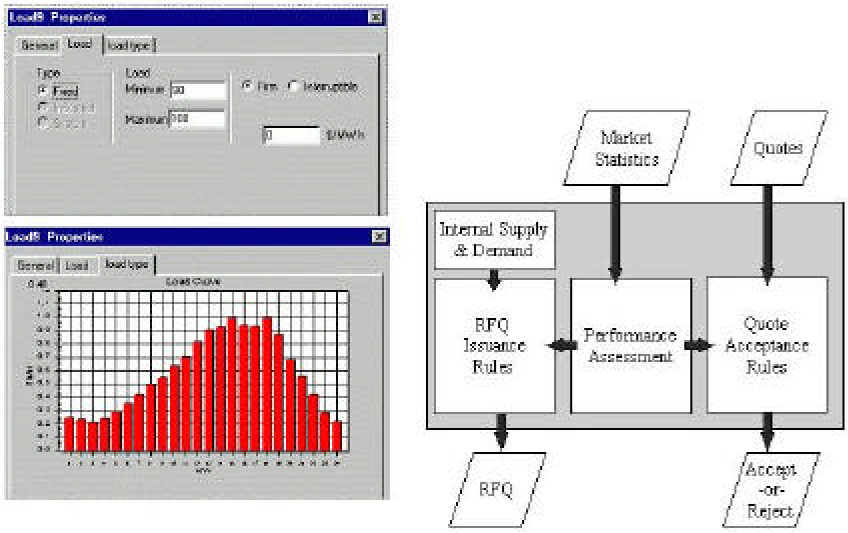

Figure 2. Load schedule function and Load Company Agent (LCA). LCA must decide: When to issue an RFQ; Hours and Amounts in the RFQ; Expiration date for RFQ; Whether to accept a quote; and When to accept a quote

Agent adaptation in SEPIA means that the agent's online algorithms modify its internal state based on experience. Agent design determines when and how this occurs. All learned knowledge is stored in the internal states of agents, but it is also possible to have adaptation at multiple levels of organization, i.e.: distributed over a population of agents, or within a cohort of related agents, as well as internal to a single agent. The current version of SEPIA offers two reusable adaptation algorithms:

Learning Classifier System (LCS) using rule representation, with discovery via a genetic algorithm and blackboard architecture for reinforcement learning. The LCS is implemented as a generic modular LCS C++ class template. The rules, conditions and actions are separate classes of objects and may be reused for different kinds of agents' instantiated with different conditions and actions. The incremental genetic algorithm, triggered periodically, uses crossover, mutation, tournament selection and a simplified bucket brigade algorithm.

As customers pay hourly for energy delivered on contracts negotiated sometime earlier, the money is accumulated in bins tied to the given rate structure (and thereby to the action that produced the rates). If the agent must be "bailed out" by the generator of last resort, the associated debt is also accumulated. At the end of each epoch, these rewards are disbursed to the actions, updating the appropriate cells in the Q-Table. The rewards are normalized and discretized into four values, producing some immunity to small variations caused by load fluctuation.

It is not possible to accurately assess the profit from a contract until after generation takes place. Each agent's profit depends on the whole load on the grid, determined by all the agents. Hence, rewards affect actions two epochs later. The first two epochs in each run can only reflect whatever initial values were selected for rates, not any policy decision on the part of the learner.

When SEPIA is complete, there will be several more adaptation options from which users may select. There will also be hooks to incorporate new, custom algorithms. Continuing use will build up a library of adaptation algorithms. Users will have the freedom to mix multiple algorithms in a single simulation, or even in a single agent, and of course, users can also disable all adaptation.

4. THE REAL TIME PRICING (RTP) SCENARIO

With Open Access to the continental grid and rapidly disseminated information about all bids and offers, Real Time Pricing of electric power is becoming possible, both at immediate spot market rates and at forward prices for various horizons. SEPIA is implementing a scenario that allows its adaptive agents to engage in this market under a wide variety of user-defined hypothetical arrangements.

4.1 Real Time Pricing (RTP) of Electricity

Real-Time Pricing (RTP) in the context of electric power seems to mean many different things. In the case of the recent RTP project, jointly pursued by EPRI, Consolidated Edison (ConEd), Honeywell and the Marriott Manhattan Hotel, ConEd posted an hourly schedule of prices for the next day. There was no negotiation and no alternative sources of power, but the prices were guaranteed, i.e.: ConEd would receive the gain or incur the loss if its estimates of its own costs for power differed from its actual real-time costs at the times when the Hotel drew that power. The Hotel was simply given the opportunity to plan its operations so as to reduce its use of electricity at times of high price. On the other hand, this was a part-contract. The Hotel could buy as much or as little power from ConEd as it wished during each hour.

In this case, RTP means that a utility announces a price schedule at which it will sell electricity at specified future times (and sometimes just to specified customers). The prices announced by the utility are a form of forward price although they do not meet its strict definition: i.e., the price to be paid now for a specified amount of a commodity to be delivered at a specified time in the future. In the case of the Marriott Hotel and ConEd, no payment was required until after delivery and the amount to be purchased was left open. With open access and retail wheeling, the Hotel could, in theory, buy its power from any producer in North America. In fact, it could buy from many different producers, switching, again in theory, every nanosecond!

While every State in the USA might actually impose a different structure on a free market in electricity, the most open arrangement would be to:

- Allow any kind of bilateral contract, between a single producer and a single consumer, or between aggregates of either, entered into at any time up to the actual consumption of the power.
- Allow the formation of multiple market pools with open bidding by both buyers and sellers. These pools would typically take the form of a double Dutch auction, with sellers gradually

lowering their asking price and buyers raising their offers until a series of bilateral contracts clears the market.

- Establish an agreed formula for the imposition on each exchange of a fair price for transmission between seller and buyer. This formula would have to include ways to allocate all the costs of system stability, unintended flows, contingencies, back-up power (when not, itself, included in the bilateral contract), etc.

4.2 RTP in SEPIA

The RTP scenario being incorporated in SEPIA includes only a few of the possibilities mentioned above, and of the many other arrangements needed to make RTP practical. The basic principles behind the RTP scenario for SEPIA are:

Future power may be traded on the power exchange.

Contracts are for 100 kWh lots delivered in specified 1-hour time slots.

A specified margin deposit is required for each open contract.

Variable economic parameters affect both the demand for power and the cost of borrowing.

Corporate agents must honor all contracts and stay within credit limits (or go bankrupt).

Corporate agents try to maximize profits subject to constraints.

Generic goals that affect all corporate decisions include:

Maximize profit by optimizing power production/consumption schedules.

Maintain liquidity by managing cash flow.

Reduce market risk by hedging production /consumption in the Power Exchange.

Reduce production risk by keeping adequate fuel/raw material inventories.

Account for their Economic/Environmental risk using projections to make their budgets and schedules robust.

Agents for this scenario include the Power Exchange, Power Producing Companies (PPC), Power Consuming Companies (PCC), and the Economy/Environment.

The Power Exchange provides a market for buying and selling spot and future power, and acts as clearinghouse for all bids and offers. The Power Exchange has three major functions: Exchange Management, Finance, and Brokerage.

PPCs buy and consume fuel, produce and sell power; PCCs buy power and raw materials, produce and sell manufactured goods. Both classes of agents try to earn a profit, but are required to pay operating, finance and tax expenses and their cash flow is constrained by a limited line of credit.

The agent representing the Economy/ Environment in which the other agents operate provides the inputs they need for making business decisions, for instance:

1. Cost of fuel for electric generation.
2. Short-term interest rates (prime rate).
3. Weather.
4. Rate of economic growth.
5. Consumer demand for manufactured products.
6. Price of raw materials to manufacturers.

It generates the states of these variables at any time from stochastic differential equations representing Poisson processes. The Economy/Environment agent issues periodic market reports predicting the future behaviour of these parameters as well as corrupted estimates of their steady-state values and standard deviations of each state separately. Future extensions to the current RTP scenario include:

Allowing bilateral contract agreements (off exchange).

Handling transmission issues -- zones, independent system operator involvement, transmission costs.

Expanding fuel-types (oil, gas, hydro and nuclear) as well as addressing long-term supply agreements.

Possible plant outages, scheduled and unscheduled.

More detail in financial accounting: i.e., adding structure to the liquid asset portfolio, paying preferred stock dividends, and income tax.

4.3 Scenarios and Examples

To further clarify the types of simulations that can be conducted with SEPIA, we illustrate in this section how the elements of the program discussed above can be combined to create and run scenarios. The first set of scenarios implemented in SEPIA model the wholesale world of open-access electric utility operations. These scenarios involve the types of agents discussed above: generation company agents, generator agents, consumer company agents, load agents, and a transmission network operator agent. In these scenarios, consumer company agents purchase all the energy they need from generation company agents through direct "bilateral" contracts. Periodically, each generation company determines the unmet hourly power needs of each of its loads for the next week and broadcasts a "request for quotes" (RFQ) to all generation company agents. Generation companies receive such broadcasts and determine whether to submit a quote for some or all of the power requested by the RFQ. Deciding whether to respond to an RFQ and determining the price to charge for the energy is a difficult problem that is further complicated by the limits of the transmission network.

All contracts that require power to be transmitted across zone boundaries must be checked against an available transmission capability (ATC) table for each hour; the ATC data are maintained by the transmission network operator agent. As transactions are agreed on by load company agents and generation company agents, the transactions are given to the transmission network operator agent and a new ATC table is calculated and posted. An important last component of these scenarios is the generator of last resort for each zone. These GLRs are always willing to sell energy for a very high, constant price to any consumer company. The purpose of specifying GLRs is to model the behavior of spot market prices and prevent unlimited price escalation due to tacit collusion among all power generation companies.

Figures 3 and 4 illustrate scenarios set up in SEPIA. In the first of these, for example, four zones are defined. Zones 2 and 4 contain one load and one ConCo each. Zones 1 and 3 contain one (nuclear) and two (hydro and fossil) generation plants, respectively, along with separate GenCo's for each.

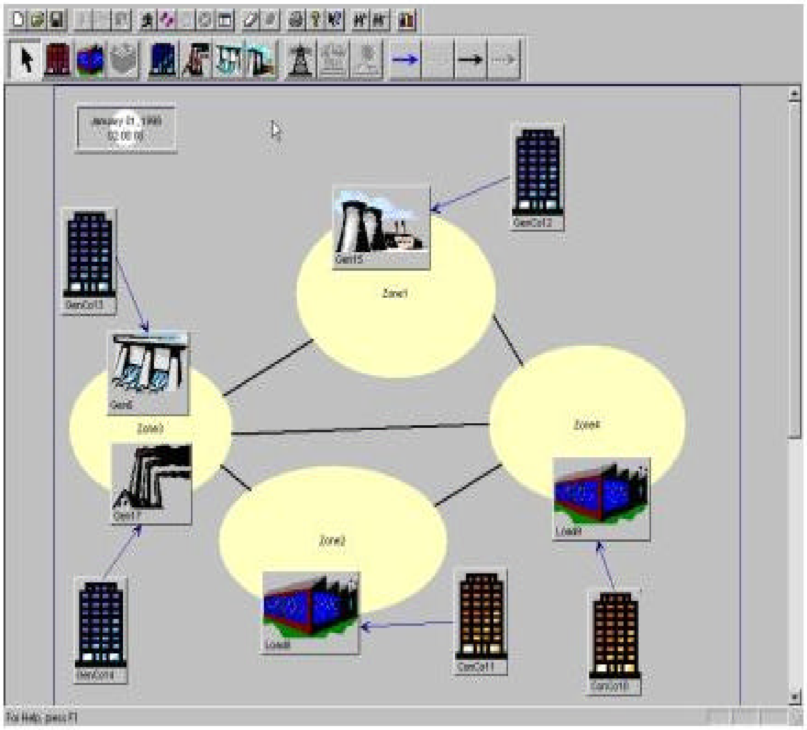

Figure 3. Four-zone scenario with three generators and two loads

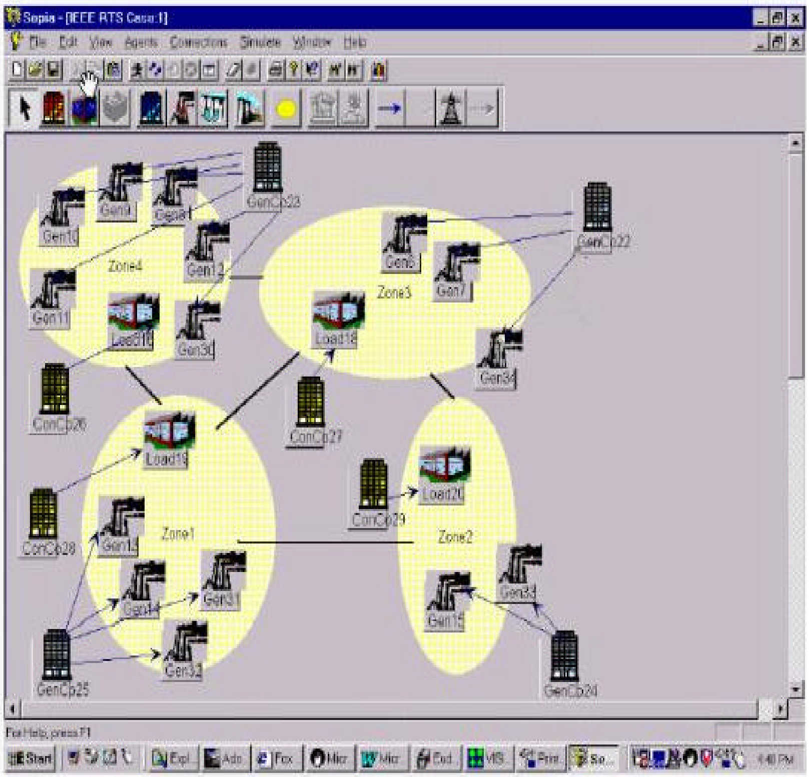

Figure 4. Second example showing four loads and 15 generators

Consumer company agents are responsible for purchasing energy for each of their individual loads. Each consumer company agent operates as an independent business and will try to purchase power for the lowest possible price. Consumer companies can determine their hourly power need profile by aggregating the needs of each of their loads. Once the power need is determined, the consumer company can submit requests to all power generation agents, regardless of zone. Each RFQ will contain the power needs for every hour for the next week and will be valid for a short time period. Once the validity of the RFQ has expired, the consumer company can evaluate all the quotes it has received and accept one, many, or none of them. It is important to note that the burden for securing permission from the transmission network operator falls on the generation company. Therefore, once a consumer company has accepted a quote from a generation company, it can rely on receiving the energy promised by that quote.

Each generation company controls one or more generators and will attempt to maximize its profit by selling its power for the highest possible price. Generation companies will attempt to establish attractive bilateral contracts with consumer company agents by responding to appropriate RFQs. Several factors must be considered when deciding how to respond to an RFQ. SEPIA currently takes into account the generation cost function and the megawatt capacities for each specific generator.

In these scenarios, generation company agents take on the risk and responsibility of delivering all energy they quoted to consumer agents. This means that before they submit a quote, generation company agents will check the public ATC table and will reserve transmission rights as soon as a quote is accepted. It is possible that a transmission that was permissible when a quote was submitted is no longer permitted when the quote is accepted. This is a risk generation company agents assume when doing interzone business. In these rare cases, the generation company agent is responsible for buying energy in the consumer's zone at inflated spot prices (the GLR rate).

The transmission network operator will calculate available transmission capability (ATC) and post ATC for all generation and consumer companies to access. The transmission network operator agent does not allow transactions if they violate transmission limits. The ATC and the accept/not accept decisions on specific transactions are based on security analysis checks (as noted earlier, base case limit checks and first contingency checks are undertaken).

4.4 Open-Access Scenario Example

In this section, we take a simple example scenario and walk through its configuration and simulation. This scenario looks at the competition between two power generation companies located in separate zones with a significant transmission bottleneck. Interested readers can "replay" the discussion below by downloading a self-running narrated demonstration (a Lotus ScreenCam executable for Windows PCs) from http://www.htc.honeywell.com/projects/sepia.

First, SEPIA is used to define the simple scenario. In this example, the user has defined two independent zones and then connected them with a tie line. Next the user adds a load to Zone 2 and a generator to each of the two zones. Two power generation companies and a power consumer company are also added and associated with the generators and the load.

For this simulation, each generator is capable of generating up to 100 MW and the load consumption per hour is a random quantity between 90 and 100 MW. Each of the two power generation companies is set to learning mode and given an initial price of $10/MW. The GLR in Zone 2 is given a fixed price of $60/MW.

Next we modify the electrical properties of the transmission network between the two zones to reduce the maximum transmission capacity. We can access the property sheet for the tie line by simply double clicking on it and effect desired changes.

As an example, we now set the simulation run time to 2000 days (through a property sheet) and start the simulation by selecting the run button. Once the simulation is complete, we can examine the results. SEPIA includes a third-party charting and visualization package through which a variety of simulation-generated data can be displayed in different forms (see Fig. 5).

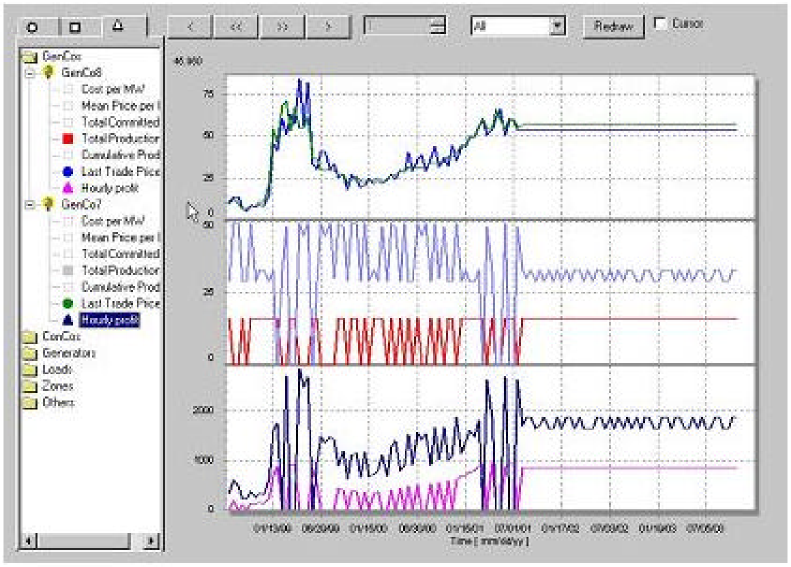

Figure 5. SEPIA chart depicting the competition between two generation company agents

The top graph in Figure 5 displays the price each GenCo charges per megawatt of power throughout the simulation. Both GenCos started raising their prices together from the starting price of $10/MW. Once the price per megawatt exceeded $60, the GenCo's started losing business to the GLR; the price is then lowered and raised again until settling on a level just below $60/MW.

The remote GenCo settles on a price slightly below that of the local GenCo. The local GenCo is content with this arrangement since the transmission operator limits the remote GenCo to a maximum of only around 18 MW. The middle graph displays how much power each GenCo sold at each point in time. Note how the amount of power sold by a GenCo goes to zero once its price goes over $60/MW.

The final state reached by this simulation has the remote company selling all the power it can transmit for a price slightly lower than that of the local GenCo, which is selling all remaining power for a price just slightly lower than that of the GLR.

The bottom graph in Figure 5 displays the profit generated at each hour. This graph mirrors the production graph (middle) fairly well. Note that the production and profit graphs for the local GenCo oscillate because the demand of the load has a random component.

SUMMARY

The U.S. electric power system developed over the last hundred years without a conscious awareness and analysis of the system-wide implications of its current evolution under the forces of deregulation. The possibility of power delivery beyond neighboring areas was a distant secondary consideration. Today, the North American power network may realistically be considered to be the largest machine in the world since its transmission lines connect all the electric generation and distribution on the continent. With the advent of deregulation, unbundling, and competition in the electric power industry, new ways are being sought to improve the efficiency of that network without seriously diminishing its reliability.

To address these and other emergent issues involving economic effects of deregulation on the “Electric Enterprise”, EPRI is developing a “bottom-up,” scenario-free model for exploring the evolution of the power industry, constrained only by the physics of the system components. This model and simulation of the “Electric Enterprise” which uses autonomous, adaptive agents to represent both the possible industrial components and the corporate entities who own these components. In this report, we have presented a brief summary of this model, its objectives, the background against which it is being developed, and the present state of its implementation as a computer simulation.

In many complex networks, for instance in the organization of a corporation, the human participants are both the most susceptible to failure and the most adaptable in the management of recovery. Modeling these networks, especially in the case of economic and financial market simulations will require modeling the bounded rationality of actual human thinking, unlike that of a hypothetical "expert" human as in most applications of artificial intelligence.

Although the focus of this chapter has been on the specific topic of restructuring and SEPIA, I have implied above that electric power systems are one example of a more general class of systems which we can refer to as complex interactive networks. A recent research program being conducted at more than 25 universities in the United States and supported by the U.S. Department of Defense and EPRI is emphasizing this broader perspective. Readers interested in more details on this program, the Complex Interactive Networks/Systems Initiative, are referred to http://www.epri.com/targetST.asp?program=83 and to references indicated below.

How to control a heterogeneous, widely dispersed, yet globally interconnected system is a serious technological problem in any case. It is even more complex and difficult to control it for optimal efficiency and maximum benefit to the ultimate consumers while still allowing all its business components to compete fairly and freely.

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