From Physics to Finances:

Complex Adaptive Systems Representation of Infrastructure Interdependencies

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Abstract

Modern infrastructures with complex physical architectures must obey the laws of physics. The organizations that own and operate these infrastructures must survive in an intricate financial sphere as well. How these organizations choose to operate their interdependent infrastructures in the marketplace is as important as the physics that constrains their plans. Managing the growing interdependencies among infrastructures requires not only a grasp of the physics but also an understanding of their market and financial behavior. Achieving this understanding is challenging because the markets are complex, nonlinear, self-organizing, emergent, and sometimes, chaotic. Traditional tools, such as linear programs, are ill suited to represent these dynamics. An object-oriented complex adaptive system (CAS) approach is being used to represent both the physics and the finances of highly fluid, interdependent-infrastructure markets.

Keywords: Infrastructure interdependency, agent-based simulation, ABS, complex adaptive systems, CAS, electric power system modeling, natural gas system modeling.

1 Introduction (heading)

Modeling a modern infrastructure is a daunting task. The systems employed in any given industry are highly complex, with dynamic feedback and response mechanisms. Through years of technological evolution, the processes and materials that make modern life possible have grown increasingly interconnected. Leveraging the advances in other sectors, individual industries have improved their ability to efficiently compete in the marketplace. Through this leveraging, the nation's infrastructures have coalesced in varying degrees, forming larger interdependent systems.

The effort to model interdependent systems immediately faces formidable challenges. Obtaining a physical system representation in a particular industry is mostly a matter of obtaining the right data and software packages. Much of this is available in the commercial marketplace. The natural approach to interdependence modeling is acquiring the proper software packages for several industries and trying to run them together. Even if the effort were successful, the resulting model would lack the operators and other decision-makers that affect the commodity or service delivery. After all, these systems are subject to the laws of business, which are constantly changing, as well as the laws of physics, which are generally absolute.

Most large-scale infrastructures are highly interconnected with other infrastructures. Each interconnected infrastructure affects all of the others. For example, the proliferating use of natural gas-fired electric generators highlights the increasingly interdependent nature of the electric power (EP) and natural gas (NG) industries.

Corporations and other large organizations acting within markets operate infrastructures according to a myriad of marketplace, legal and regulatory, and financial considerations. How corporations ultimately choose to operate their interdependent infrastructures is as important as the physics that constrains their plans. Simulating these organizational choices in the appropriate physical context is important to better understanding large-scale, interconnected infrastructures.

Simulating infrastructures in isolation is beneficial for design, maintenance and operation. However, considering the importance of interdependencies, more needs to be done. Simulations must examine the relationships between infrastructures as well as the components within a given infrastructure. Simulating these relationships between infrastructures is only the beginning.

This paper describes research to date in designing a complex adaptive system (CAS) simulation that captures both market and physical behaviors between the natural gas and electric power industries.

2 Modeling Challenge (heading)

A wide variety of tools exist to study physical infrastructures. These tools generally take an engineering view of a single infrastructure and then simulate either a specific system state or a sequential time series of system states. The simulation results give a strong indication of the allowable states within which the system can operate. In more advanced simulations, highly desirable or even optimal physical states also can be identified, based on the known physical constraints of the system.

Several problems arise in combining existing simulation tools to create broader simulations. Useful tools result from substantial investments of time, money, and intellectual capital. Unsurprisingly, the best tools tend to be expensive and proprietary. Lashing several such tools together in an interactive environment has proven extremely difficult and woefully inadequate. Interfacing models at this level is much more than merely getting one model to communicate with another. Basic design assumptions and decisions lead to deep-seated incompatibilities.

Aggregated models presuppose an understanding of system behavior at a gross level. Models constructed to deal with commodity flows between countries cannot easily represent specific commodity streams that contribute to that flow. Likewise, tailored models that address a commodity stream cannot be simply multiplied to represent the total flow. This distinction between behaviors at the microscopic and macroscopic levels is important. When engineering requirements are imposed on the representative model, the challenges grow.

The power flow equations provide a viable global approach to solving power transmission problems. Similar equations exist to describe fluid flow through a pipeline. As yet, there are no mathematical descriptions of the interdependent behavior between a power grid and a fuel pipeline. Without an adequate global formulation of the system to be modeled, we are reduced to heuristic estimates of causal response. Such a global formulation would be challenged to address local interactions that are important because they are the essence of infrastructure interdependence.

Questions to Address (subheading)

It is clear that there are linkages between infrastructures, but how interdependent are these systems – can the degree of interdependency be quantified? Other important questions ask how the effects in one system are amplified in another system? If so, under what conditions? Can and will the systems adapt or adjust to interruptions? Can we identify ways in which the systems can be prompted to adapt or adjust?

A framework is needed for quantifying the extent of the interdependencies. An equally important question asks how such a model of multiple infrastructures could be used. How are we to model multiple infrastructures in the same analytical environment? This last question is the research question that motivated this investigation.

A distinct advantage of a combined model is the reduction of bias associated with the constituent disciplines. A pipeline engineer could give a credible response to the impact of a pipeline failure on the physical system, but he would be hard pressed to address the subsequent market response of consumers in any detail. Similarly, a broker in the electric power market would make transactional decisions based on a variety of factors, including the reduced supply, but could not be expected to fully comprehend the pipeline or power generator operational responses. However, a model that provided sufficient environmental stimuli to each one of these decision-makers would permit each to respond in his element. With adequate linkages, events could ripple through both the physical and the financial realms.

The complexity of modern systems and markets leads to the need to model the response of both the physical and financial infrastructures, to events in either infrastructure, in the environment defined by policy. The potential usefulness as a policy-testing platform is alluring. To have a model that captures both engineering and market constraints allows a wide variety of policy questions to be explored before implementation. Adjustments in the behavioral rules for one class of decision-maker could have significant physical and financial impacts. Market shifts that create high demand for a particular commodity could be stymied by insufficient capacity to meet that demand. This imbalance would feed back into the market with unpredictable results, depending on available alternatives. Thus, local interactions can have system-wide impact.

Another advantage of a combined model is the exploration of a larger range of possible responses. While not predictive, such a model could expose potential behaviors that would not otherwise be considered. The model is not constrained in its ability to adapt to new circumstances. Perhaps not all observed model behaviors would be immediately explainable, but to observe these behaviors in a reasonable model forces one to consider the possible responses.

Changing Nature of Infrastructures (subheading)

Managing the growing interdependencies among infrastructures requires not only a grasp of the physics of infrastructures but also an understanding of their market and financial behaviors. Achieving this understanding is challenging because of the complex, nonlinear, self-organizing, emergent, and sometimes, chaotic nature of markets; e.g., the new deregulated electric power market and its predecessor, the traditional electric power market.

The traditional electric power market revolved around vertically integrated electricity companies operating in well-defined, franchised territories. Traditional tools could be used to model this electricity market, since there was a single company decision-maker and there were no choices for consumers. Single parameter optimization, typically least cost, was used for both dispatching of plants to meet demand and for expansion planning. This use was possible, since there are straightforward ways to represent constraints, such as system reliability and environmental emission standards, when they are centrally managed. This simple structure contributed to predictable historical performance. Unfortunately, the new deregulated electricity market is not so easily analyzed.

A variety of transformations are revolutionizing the new deregulated electricity market. Services, including generation, transmission, and distribution, are being unbundled at many levels. Commodity markets are being formed by power exchanges to dispatch generators. Competitive markets with new contract types are being implemented. Unknown reliability effects are surfacing, including smaller reserve margins. Many new participants are now present with over 3,200 electric utilities managing more than 10,500 units. Complex operation - with hourly bidding on electricity prices, distributed generation, and large-scale power movement across shared lines - is now commonplace. Complex measures of success, including profit, market share, reliability, and cost, are being applied. Participant learning and adaptation are causing continuing change. Furthermore, there are already signs that the new electricity market will continue to become increasingly difficult to understand. These signs include radically changing technologies and increasing price volatility.

Extreme electricity price volatility is becoming more and more common. For example, in California in the year 2000, prices commonly rose to more than double the estimated marginal production costs[1]. During the summer of 1998 in Illinois, ComEd paid more than $6/kWh on the electricity spot market, several orders of magnitude greater than typical prices.

Many electric power infrastructures depend on natural gas-fired generators to supply a significant percentage of the required electric power[2]. These generators tie the electric power infrastructure directly to the natural gas infrastructure. A natural gas delivery failure can quickly spill over into the electric system to produce a generation failure. In this case, simulating the electric power infrastructure in isolation is not sufficient to understand its overall operation.

All of these changes underscore the increasing complexity of the new deregulated electricity market and the changing nature of the natural gas industry. Traditional tools, such as linear programs that solve for system-wide optimum solutions, are ill suited to represent such dynamism.

3 Technical Approach to Modeling Infrastructure Interdependencies (heading)

Agent-Based Simulation (subheading)

A new approach to systems simulation, agent-based simulation (ABS), has been developed and has begun to be applied to modeling real-world applications. It offers the opportunity to gain new insights into the operation of large-scale, interconnected infrastructures and explicitly represents the behaviors of individual decision-makers. An ABS in the infrastructure interdependency context consists of a set of agents and a framework for simulating the agents' decision-making processes and interactions over time.

Agent simulations that allow agents to have adaptive behavior often exhibit system-wide emergent behaviors. Emergent behavior occurs when the behavior of a system is more complicated than the simple sum of the behaviors of its components. The behavior of large-scale, interconnected infrastructures is more complicated than the simple sum of their component's behaviors when the market decision-making behavior is coupled with the physical operations of the components. Furthermore, modern infrastructures exhibit unstable coherence in spite of constant disruptions and a lack of central planning. Traditional simulation techniques such as linear programming do not include emergent behavior - ABS emphasizes it. Many insights can be gained by viewing the new energy market from the ABS-emergent-behavior perspective.

A conscious focus on dynamics is one of the major differences between ABS and more traditional approaches. This focus on dynamics gives ABS modelers an enhanced ability to investigate change. To be effective, this enhanced ability must be coupled with increased attention to “dynamic stability.” Most actual large-scale systems are moderately stable until they reach some form of crisis. However, this stability is often chaotic and unpredictable, hence, the term dynamic stability. Creating models of these systems requires careful attention to the “forces” that contribute to the dynamic stability.

Emergent behavior is sometimes called “swarm intelligence”, since it often arises from a group of individuals cooperating to solve a common problem[3]. Diversity drives swarm intelligence and provides a source for new ideas or approaches. The key is to balance the level of diversity. Too little diversity leads to stagnation. Too much diversity prevents exploitation of existing good ideas. Achieving a balance between these extremes of diversity is crucial to system survival. The infrastructure simulation will allow exploration of emergent behavior and provide insights into the ways that individual organizations influence their markets, as well as how each market influences its participants. These insights can enhance the understanding and management of infrastructure interdependence.

The nature of how emergent properties arise in systems and of how systems adapt over time is being studied in the field of complexity theory. The area most relevant to modeling interdependent infrastructures is that of complex adaptive systems (CAS). An important aspect of CAS that are operating under conditions of high stress is that, although they may be operating at or near optimal efficiency, they can be close to a breaking point at which a small, added stress results in a dramatic change in the behavior of the system. The system undergoes what is akin to a phase-change in a physical system or an “avalanche” effect and shifts to a drastically different state[4].

Complex Adaptive Systems (subheading)

Holland[5] has analyzed CAS extensively and drawn conclusions on their common characteristics. He has identified seven basic features common to all CAS - four properties (aggregation, nonlinearity, flows, and diversity) and three mechanisms for change (tagging, internal models, and building blocks). Any CAS simulation model of interdependent infrastructures should emphasize these features.

Other aspects of CAS have relevance to the development of agent-based models of the infrastructure. Stigmergy occurs when the environment surrounding an agent acts as a dominant state variable that structures and sequences the agent's behavior[3]. Thus, the agent's memory is composed of the agent's own storage capacity plus that of the environment. This situation echoes the declarative approach in the sense that agents must have a discrete set of rules that are activated when appropriate environmental cues occur. The environment structures an agent's behavior. An example is an ant adding to an anthill. The new work the ant does is prompted by the existing layout of the hill. This work modifies the anthill, resulting in a feedback loop. The critical issue is feedback that allows the environment to be part of an agent's "memory."

Agents (subheading)

Modern infrastructures consist of a large number of participants, or agents, that are diverse in both form and capability. Participants are both physical and economic in nature, and have inputs and outputs and decision-making capability. Economic participants include energy companies, transmission companies, and consumers. Specifically, economic agents of the electric power system include independent system operators, real-time dispatchers, demand aggregators, customers, generation companies, power generators, transmission companies, and regulators. Decision-makers can be characterized as having different objectives and constraints with a limited ability to process information. They receive incomplete information and have a limited (dynamic) set of choices. In the physical system, physical components are regarded as agents, but economic factors and policy set the environment in which they operate.

An agent in the simulation, as defined here, is a software representation of a "decision-making" unit. Following Holland, an agent's behavior is modeled with a set of simple decision rules that are able to change and adapt over time in response to repeated interactions with other agents and with the environment (see Figure 1). The interactions among individual agents may be simple, but the complex chains of interdependencies among agents may result in counter-intuitive, unpredictable, and chaotic patterns of system behavior.

Adaptation, in the biological sense, is the process whereby an organism fits itself to its environment. In an agent simulation, an agent adapts by changing its rules as experience accumulates, thereby positioning itself to better fit its environment. If agents do not learn or are unable to adapt quickly enough to a changing environment, they can be replaced by others likely to perform better. This is social learning versus individual learning. Both aspects of learning would be present in a CAS model of agent representation for the EP and NG infrastructures. Agents are specialized traditional object-oriented software engineering objects containing some form of intelligence[6].

Temporal Issues (subheading)

A particular technical challenge of modeling combined infrastructures is the treatment of time. System behavior is determined by decisions made over a variety of time scales, and creating agent models that cover the full range of time scales is critical to understanding complex infrastructure interdependencies. Human economic decision-making dominates longer time scales while physical laws dominate shorter time scales. The focus of each agent's rules vary to match the time scale in which it operates.

Model of Interdependent Infrastructures (subheading)

Figure 2 illustrates what a model of interdependent infrastructures could look like. The model consists of five layers, one for each of the physical infrastructures, one for the corresponding industries, and a consumer layer that is common to all infrastructures.

The infrastructure layers contain physical network models for EP and NG; e.g., generating units, power plants, transformer stations and distribution stations are nodes and transmission lines are links for EP.

Processing plants, compressor stations, and storage facilities are nodes and pipelines are links for NG. Not every physical component is modeled in the infrastructures; rather, the physical infrastructure is modeled only to the level of detail required to reproduce aggregate system features, such as total energy flow, at a reasonable level of accuracy.

The EP and NG industrial layers consist of the decision-making entities within these respective industries. The industry layers are where the identities of agents are established based on economic considerations. Financial decisions regarding the operation of and investment in the respective infrastructures are made at this level based on revenues from consumers.

The infrastructure and industry layers are also linked through consumers. Consumers receive energy and pay the utility or energy companies. NG and EP may be substitutes or complements at the consumer level, depending on their end uses. In addition, the capacity for consumers to produce electricity, possibly from natural gas, and sell it back to the grid needs to be considered in the longer term.

In addition to the financial realm, interdependencies also arise in the form of the physical connections; e.g., the EP industry will soon add a large number of NG units, enormously increasing the demand for natural gas to supply electric power needs. Modeling the financial and energy flows in this way allows for the formation of the feedback loops that could exist between these infrastructures. It also allows for explicit accounting of financial as well as energy resources, giving an indication of the organizational possibilities for survival, growth, acquisition, and bankruptcy within the industry.

4 Model Development (heading)

A research effort was initiated in fiscal year 2000 by the Joint Program Office for Special Technology Countermeasures' Infrastructure Assurance Program to explore various aspects of using CAS methodologies to represent agent behavior and systems for the modeling and simulation of infrastructure behavior and infrastructure interdependencies. Two related models developed by Argonne National Laboratory were used in this research:

- Spot Market Agent Research Tool (SMART) models. These represent, at various level of sophistication, an electric power generation and transmission system, and portions of the natural gas infrastructure. SMART is written in the Swarm agent simulation language[7]. Figure 3 shows a typical model state.

- Flexible Agent Simulation Toolkit (FAST). This model allows investigation of complex infrastructure interdependencies, such as those between the EP and NG markets. FAST builds on the SMART models by including many of its features along with improvements in modeling infrastructure detail and fidelity. FAST is written entirely in Java, has a fully distributed computation engine that uses Java Remote Method Invocation for internal communications between multiple symmetric hosts, supports external CORBA clients, has fully distributed object persistence, and has a multithreaded scheduler that focuses on maximizing parallel execution.

Among the key research issues being explored with the SMART and FAST models are time management, the role of individual intelligence versus group or swarm intelligence, and self-direction in the design and implementation of agents. Figure 4 shows a typical result – the dynamic linkage of EP and NG prices and utilization.

Time management is a critical issue for most types of modeling, including ABS. Over the years, many different approaches have been taken, from the simplest time-step methods to the most advanced distributed discrete event systems. Sophisticated modeling systems typically focus on discrete event simulation. Agent simulations go beyond the discrete event methodology by giving each agent in the system far greater power to adapt to its environment and by attempting to solve problems through emergent behavior rather than simple pattern matching. Most agents representing real-world entities have a set of core functions that are activated on a periodic basis during each model run. The activations typically occur at hourly, daily, weekly, monthly, or yearly intervals reflecting the appropriate decision level. Creating a simple and uniform set of methods to act as building blocks for each time step will allow diverse groups of agents to use the same simulation engine.

Agent templates are proving useful in modeling agent behavior. Much like building blocks, templates are patterns that are used to construct other patterns. Templates can be used to form a wide variety of dynamic structures, including individual strategies, corporations, and even complete markets. Individual strategies can be formulated by starting with a plan template taken from a large space of options. This plan can then be elaborated and evolve through the addition of alternative possibilities and choices.

5 Conclusion (heading)

The increasing complexity and interconnectedness of infrastructure systems and processes must be addressed from physical as well as financial and other (e.g., legal and regulatory) perspectives to develop a meaningful understanding of infrastructure interdependencies and the behaviors of individual infrastructure participants (agents). This effort requires developing and applying flexible and adaptable analytic frameworks that account for marketplace dynamics and answer "what if" questions in a timely fashion. Ultimately, such information is essential to support defensible short- and long-term operation and management decisions. New approaches for simulating infrastructures, such as those based on the theories and techniques of ABS and CAS, are needed and offer promising avenues for increasing our understanding of society's increasingly complex and interdependent infrastructures. They allow exploration of emergent behavior and provide insights into the ways that individual organizations influence their markets, as well as how each market influences its participants.

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The Authors (heading)

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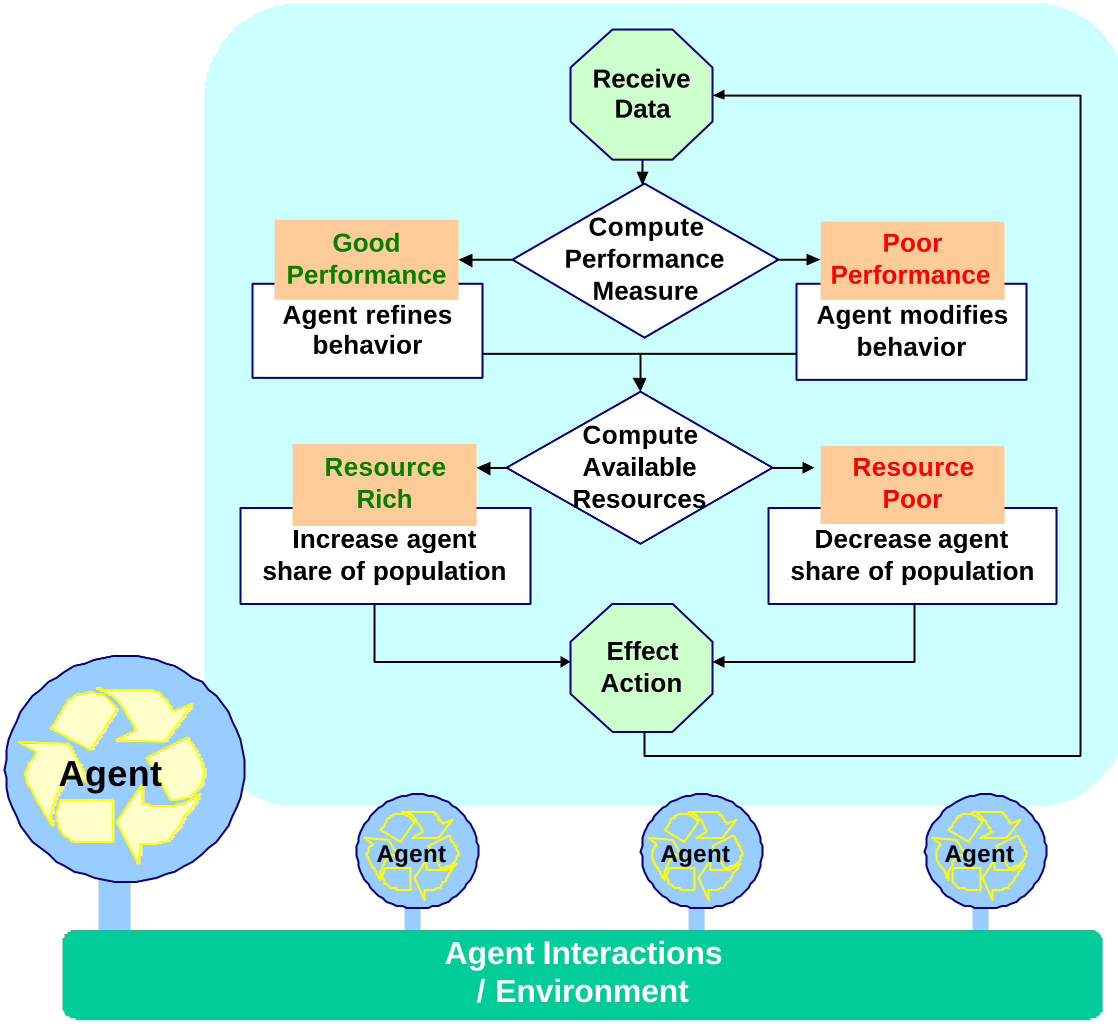

Figure 1 Agent Representation

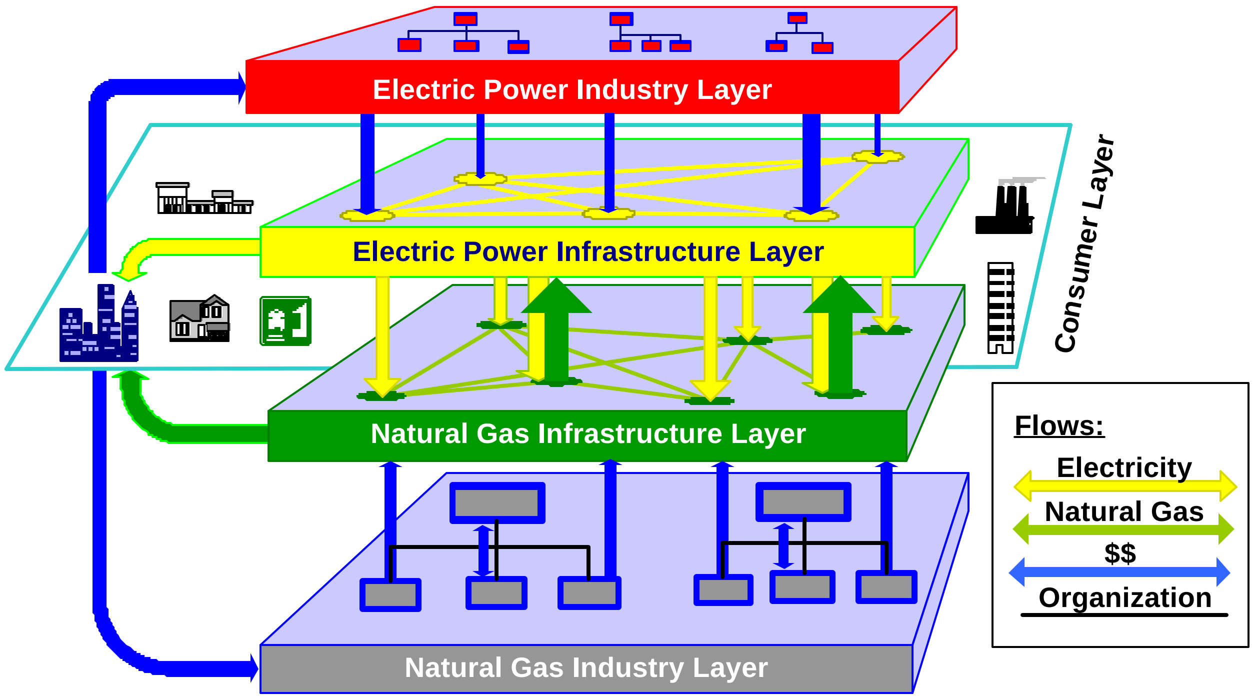

Figure 2 Model of Interdependent Financial and Physical Infrastructures

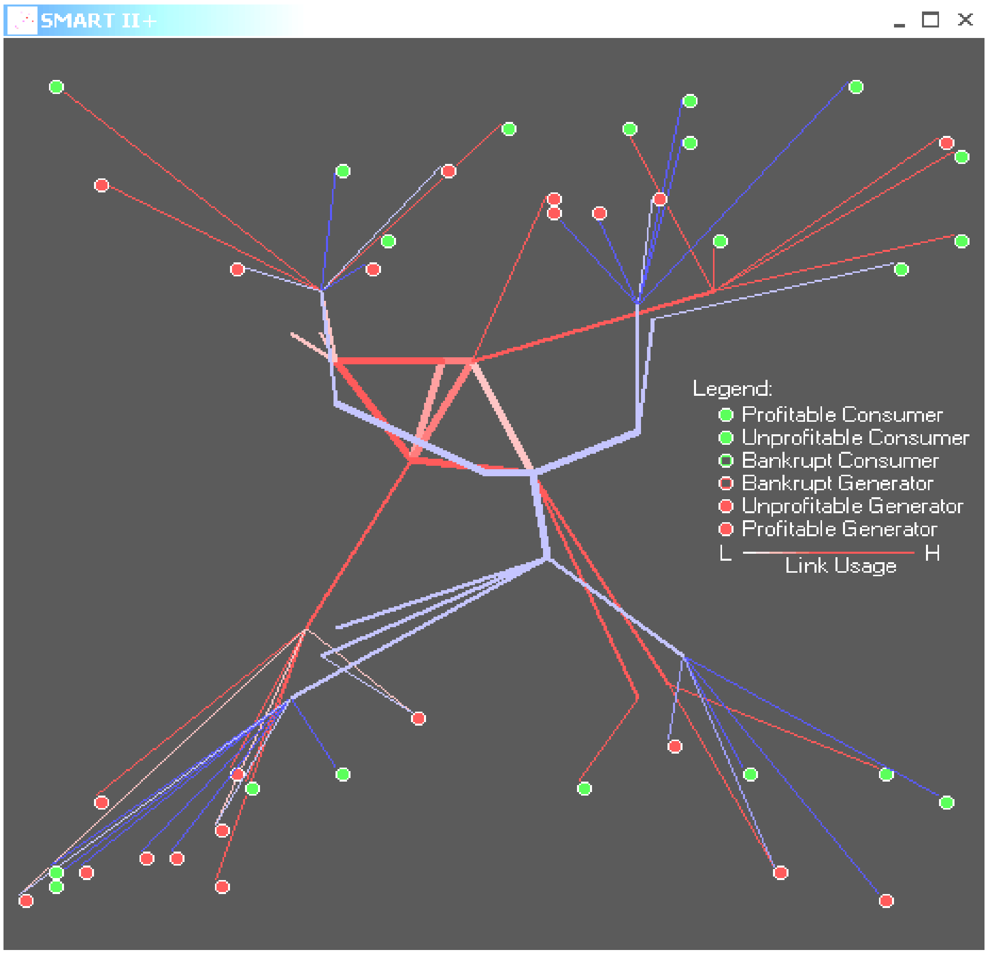

Figure 3 An example integrated natural gas and electricity system from SMART II+

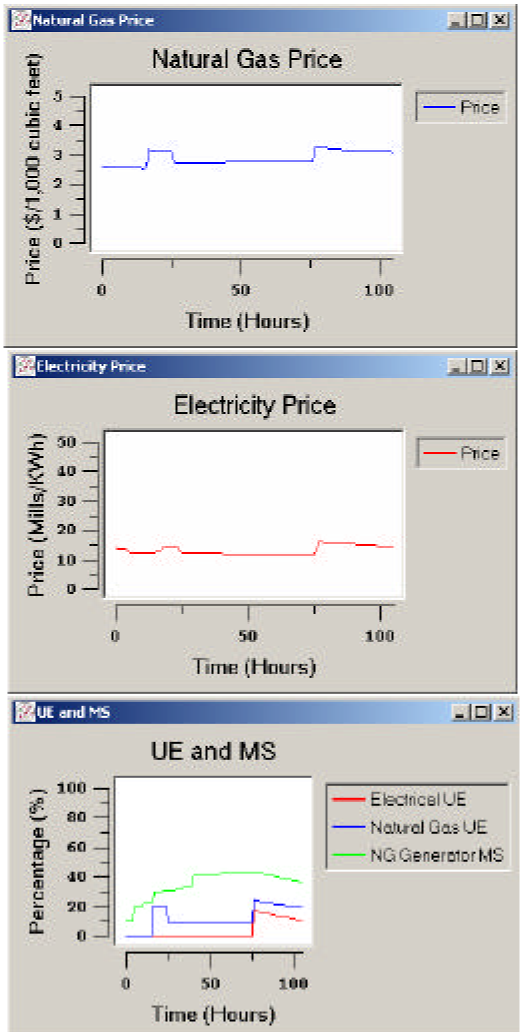

Figure 4 SMART Model Results Showing Dynamic Linkage Between Energy Prices, Unserved Energy (UE), and Market Share (MS