Towards Strength and Stability:
Agent-Based Modeling of Infrastructure Markets

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Abstract: Complex Adaptive Systems (CAS) can be applied to investigate complex infrastructures and infrastructure interdependencies. The CAS model agents within the Spot Market Agent Research Tool (SMART) and Flexible Agent Simulation Toolkit (FAST) allow investigation of the electric power infrastructure, the natural gas infrastructure and their interdependencies.

Keywords: Complex adaptive systems (CAS), Agent-based modeling (ABM), Electric power system modeling, Natural gas system modeling, Infrastructure interdependency, Swarm, RePast, CAVE, Virtual reality (VR).

1. Introduction

Many insights can be gained by viewing energy analysis from a Complex Adaptive Systems (CAS) agent-based modeling perspective. Argonne has taken such a perspective to produce integrated models of the electric power and natural gas markets. The agents within the present Spot Market Agent Research Tool (SMART) and the future Flexible Agent Simulation Toolkit (FAST) allow investigation of the electric power infrastructure, the natural gas infrastructure and their interdependency.

2. Background

ABM represents a new approach to the construction of models. Like all new techniques, ABM builds on existing approaches. Two key issues are identifying meaningful insights and managing time.

2.1. Identifying Meaningful Insights

One of the key issues in most types of modeling is identifying meaningful insights. This is particularly true for agent-based modeling. Furthermore, this is one of the areas that most clearly differentiate CAS modeling from some more traditional approaches.

Modeling approaches such as linear programming identify final states of computations as representing the real world while such things as individual simplex iterations are considered artifacts. With these approaches the numeric path taken by a computation is not considered meaningful. Only the final optimized or stable state has meaning.

An important question to ask when looking at any model is, "which states represent the real world and which are computational artifacts?" With CAS modeling the answer is that individual computational steps are considered meaningful up to some resolution limit.

Defining the resolution limit is a critical CAS model design issue. For example, the SMART electrical and natural gas CAS models include a market for each commodity. These markets require competitive bidding. The market outputs represent decision making in the real world. However, the internal bidding process implementations do not necessarily reflect the real world step by step.

Real-world bidding processes that use telephones to place bids and wall clocks to time calls are replaced by polling processes. Thus the individual market steps represent the real world but the steps by which bids are collected may not. Accurately defining this resolution allows model output to be properly understood and applied. It also shows the flexibility of the CAS approach since resolution is only limited by the willingness of the designers to include more detail.

The extended electrical and natural gas CAS models that that are currently under construction will include not only real-world markets but will also include an accurate representation of the bidding process.

2.2. Managing Time

Time management is a critical issue for most types of modeling, including agent-based modeling. 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.

Discrete event simulation is an effective implementation strategy for agent-based modeling. Models implemented using this approach go beyond the discrete event methodology by giving each agent or element in the system far greater power to adapt to its environment and by attempting to solve problems through emergent behavior rather than simple analysis.

Most agents representing real-world entities will likely 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, and yearly intervals during runs. Creating a simple and uniform set of functions or methods for each time step will allow diverse groups of agents to all use the same simulation engine.

Object Oriented Programming (OOP) texts refer to the ability to call methods appropriate to each object using the same uniform name as "polymorphism" [1]. In Java, this is implemented as either a common base class or as a formal Interface. In Swarm, this is implemented using either a common method name or a formal Protocol.

In addition to the core periodic methods, several conditionally activated methods may be used. These "triggers" are used either for efficiency or for convenience. They can make a system more efficient by only being checked and activated when the associated conditions occur. They can also simplify programming by providing a simple scheduling mechanism. Swarm uses an advanced scheduler to setup such triggers.

Taking an OOP approach to CAS is consistent with the approach taken by most CAS model developers.

3. The Present and Future

Several tools presently exist:

- SMART Version 2.0 (SMART II) is a Swarm model with an integrated set of agents and interconnections representing the electric power marketing and transmission infrastructure.
- SMART II VR is a virtual reality (VR) interface for SMART II.
- SMART II+ is an extension to SMART II that includes an integrated set of agents and interconnections representing the electric power infrastructure, the natural gas infrastructure and connections between them in the form of natural gas-fired electric generators.

FAST is currently under construction. FAST is a complete redesign of SMART II+ that includes improvements in the modeling environment, model detail and representational fidelity.

4. SMART II

SMART II is a Swarm-based [2-3] model that uses a set of agents and interconnections to represent electric power systems. SMART II is the Swarm Development Group 2000 Conference (SwarmFest 2000) Best Presentation winner. SMART II itself builds on several other models [4-5]. SMART II includes three different kinds of components as follows:

- Generation agents produce electric power.
- Consumer agents use electric power.
- Interconnections represent the transmission grid.

SMART II considers important economic issues such as production costs, investment capital, demand growth for successful consumers, new generation capacity for profitable producers, and bankruptcy for noncompetitive organizations.

SMART II uses two different kinds of agents to model the electric spot market. Specifically, agents are either electric power generators or consumers.

Generation agents choose whether or not to sell power based on cost curves similar to that shown in Figure 1. Generators determine their production level based on the potential profit to be made. Each generator has investment capital that is increased by profits and reduced by losses. If a generator reaches a predetermined level of investment capital, it can purchase additional production capacity in the form of new generators.

New generators are similar to their owner, and can connect to the distribution network in either the same location or a new one. Generators that run out of investment capital go bankrupt and no longer participate in the market.

The generator agent rules are:

- If the agent made a profit in the last hour, then attempt to increase sales.
- If the agent posted a loss in the last hour, then attempt to decrease sales.
- If the total profit has risen above the investment level for a new unit, then purchase a new generator.
- If the total profit has fallen to zero, then go bankrupt.

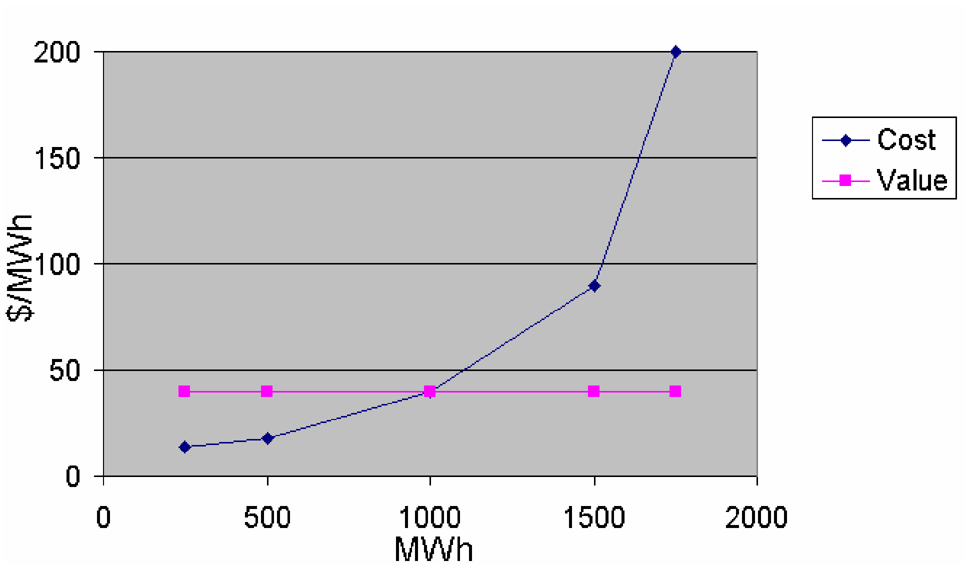


Figure 1: Example SMART I agent cost and value curves

Consumer agents choose whether or not to sell power based on cost curves similar to those shown in Figure 1. Consumers buy electric power for their own use. Consumers buy on the basis of the potential to use the purchased power to make a profit. This can include industrial users who produce goods based on electric power and populations of individuals who vary their demand based on power prices. If a consumer reaches a predetermined level of investment capital, it can grow in the form of new consumers.

New consumers are similar to their originator and can connect to the distribution system in either the same location or a new one. This can represent the growth of electric power-based businesses or an influx of people due to favorable economic conditions, particularly employment opportunities. Consumers that run out of investment capital go bankrupt and no longer participate in the market. Bankruptcy represents the decline of electric power-based businesses or the departure of people due to unfavorable economic conditions.

The consumer agent rules are:

- If the agent made a profit in the last hour, then attempt to increase purchases.
- If the agent posted a loss in the last hour, then attempt to decrease purchases.
- If the total profit has risen above the investment level expansion, then grow by creating new consumers.
- If the total profit has fallen to zero, then go bankrupt.

SMART II has undergone initial qualitative validation by matching its outputs to the following basic analytic predictions:

- Markets with a single superior producer among a large number of higher cost competitors have been tested.
- Markets with many identical participants have been tested.

Much more work is clearly required to quantitatively validate and calibrate SMART II therefore only limited qualitative insights are currently being derived.

The SMART II interface is shown in Figure 2 and the price graph is shown in Figure 3.

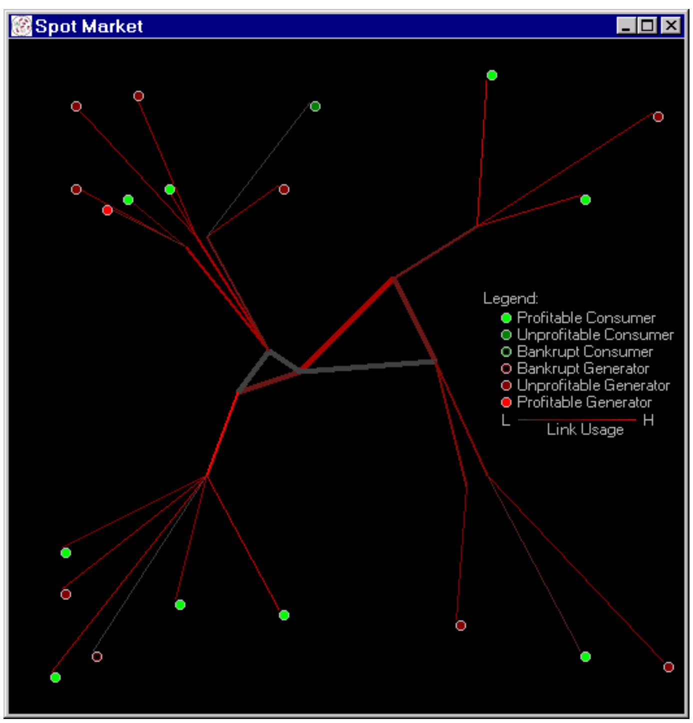


Figure 2: The SMART II Interface

As originally presented at SwarmFest 2000, qualitative insights from SMART II indicate that certain transmission line configurations may encourage price spikes. Soon after

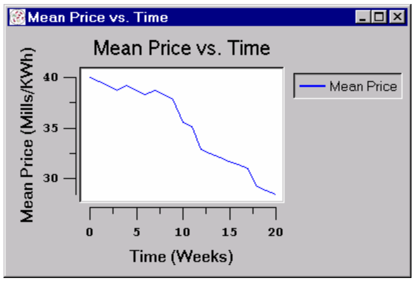


Figure 3: The SMART II Price Graph

SwarmFest 2000, this insight was borne out.

As was specifically noted at SwarmFest 2000, the California electrical grid has a configuration of a type that may cause price spikes. Substantial price spikes of the kind predicted by SMARTII where recently observed in this market.

Further qualitative insights suggest that greater electrical market price stability may be gained by consciously avoiding specific configurations that encourage instabilities. In other words, qualitative insights from SMART II can help us make things better by not making things worse.

5. SMART II VR

SMART II VR is a prototype agent visualization tool. SMART II VR is intended to explore the use of advanced interactive three-dimensional visualization in agent-based modeling.

SMART II is a CAVE Automatic Virtual Environment (CAVE)-based virtual reality interface for SMART II. The CAVE is a virtual reality library co-developed by the University of Illinois at Chicago and Argonne. From the CAVE User's Guide [6]:

> The CAVE is a projection-based VR system that surrounds the viewer with four screens. The screens are arranged in a cube made up of three rear-projection screens for walls and a down-projection screen for the floor; that is, a projector overhead points to a mirror, which reflects the images onto the floor. A viewer wears stereo shutter glasses and a six-degrees-of-freedom head-tracking device. As the viewer moves inside the CAVE, the correct stereoscopic perspective projections are calculated for each wall. A second sensor and buttons in a wand held by the viewer provide interaction with the virtual environment.

SMART II VR includes an interactive multifunction wand and two rendering modes.

The interactive multifunction wand is sensitive to wand position and wand orientation and includes buttons and a joystick. The wand buttons control interactions. The wand angle selects the joystick feature:

- Above 45^0 the wand controls elevation and rotation:
    - Moving the joystick forward and back controls elevation:
        - Forward moves the viewer up.
        - Back moves the viewer down.
    - Moving the joystick left and right controls rotation.
- Between 45^0 and -45^0 the wand controls planar translation:
    - Moving the joystick forward and back changes the X-axis location.
    - Moving the joystick left and right changes the Z-axis location.
- Below -45^0 the wand controls the model run and the rendering mode:
    - Moving the joystick forward and back controls the model run:
        - Forward starts the model run.
        - Back stops the model run.
    - Moving the joystick left and right controls the rendering mode:
        - Left selects detail-rendering mode.
        - Right selects speed-rendering mode.

The wand buttons allow object resizing. Pressing a button while the wand is in contact with an object activates resizing. Holding the button and dragging the object selects a new size. The wand display color gives grip feedback. A red glow surrounding the wand when the wand buttons are pressed means that the wand is not currently interacting with a target. A green glow surrounding the wand when the wand buttons are pressed means that the wand is interacting with a target.

Detail-rendering mode focuses on rendering quality. Directional lighting is included. Agents are rendered as lighted spheres. A texture-mapped floor with shadows and first order reflections is included. This mode allows SMART II VR to take advantage of computers with high graphics performance. An example is shown in Figure 4.

Speed-rendering mode focuses on rendering time. Agents are rendered as flat shaded cubes. This mode allows SMART II VR to be used on low performance personal computers. An example is shown in Figure 5.

In SMART II VR, generation agents are shown as green spheres or cubes. Spheres are shown in detailed rendering mode and cubes are shown in speed rendering mode. The size of each object represents its total normalized investment capital level. Size can be interactively changed with the CAVE wand. Each object's color intensity represents its hourly profit level.

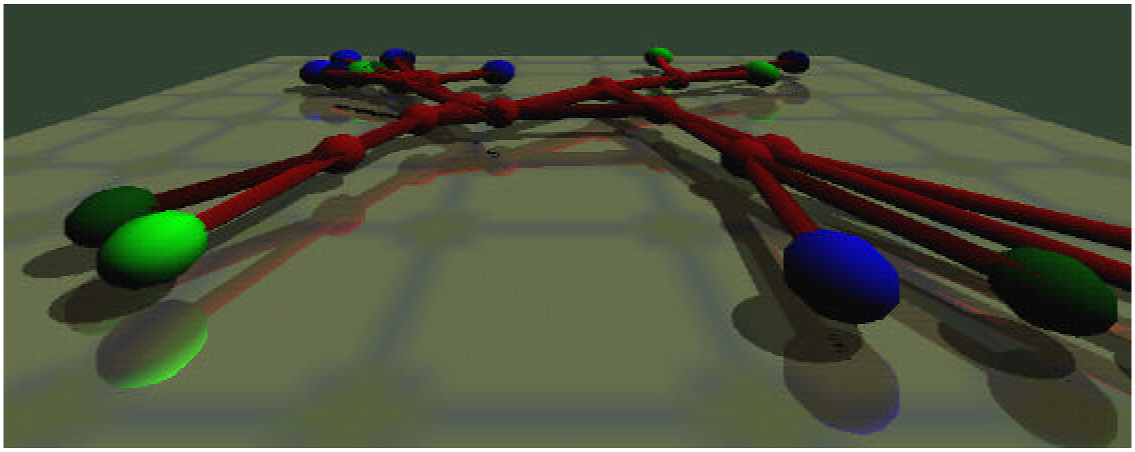


Figure 4: SMART II VR Detail Mode

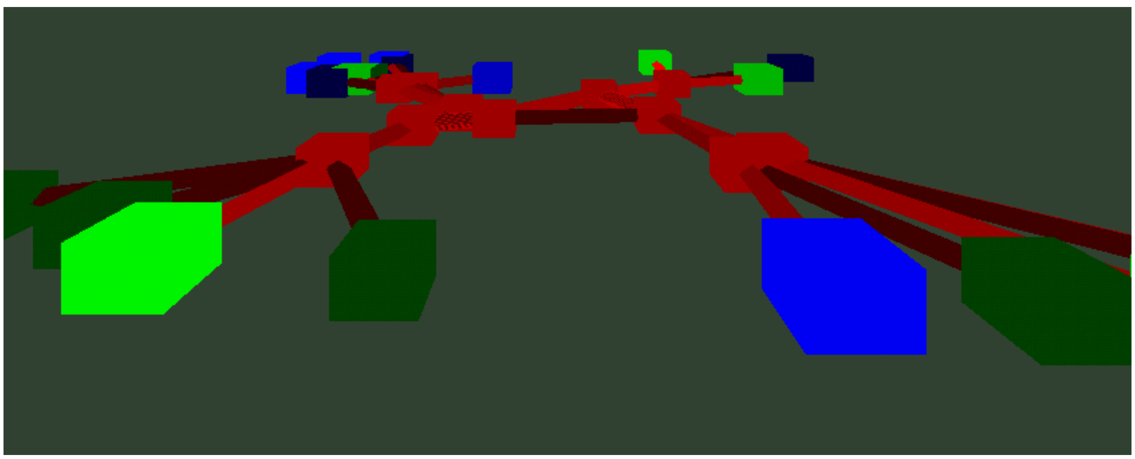


Figure 5: SMART II VR Speed Mode

In SMART II VR, consumer agents are shown as blue spheres or cubes. Spheres are shown in detailed-rendering mode and cubes are shown in speed-rendering mode. The size of each object represents its total normalized investment capital level. Sizes can be interactively changed with the CAVE wand. Each object's color intensity represents its hourly profit level.

In SMART II VR, interconnections are displayed as red tubes. The size of each tube represents its normalized transmission capacity level. Sizes can be interactively changed with the CAVE wand. Each tube's color intensity represents its hourly utilization level.

6. SMART II+

SMART II+ is a Swarm-based [2-3] extension to SMART II. SMART II is the Swarm Development Group 2000 Conference (SwarmFest 2000) Best Presentation winner. SMART II itself builds on several other models [4-5].

SMART II+ includes an integrated set of agents and interconnections representing each of the following:

- The electric power marketing and transmission infrastructure.
- The natural gas marketing and distribution infrastructure.
- The interconnections between the two infrastructures in the form of natural gas fired electric generators.

Both of the infrastructures modeled in SMART II+ include many features:

- Two different kinds of agents, producers and consumers, represent the market participants.
- Interconnections represent transmission or distribution systems with capacities on each line or pipe and complex routing.
- Important economic issues are considered such as investment capital, demand growth for successful consumers, new generation capacity for profitable producers, and bankruptcy for noncompetitive organizations.
- Components can be disabled in real time to simulate failures.

The electric power infrastructure includes the added feature of natural gas fired electric generators. These generators buy fuel from the natural gas market. The resulting electricity is then sold in the electric power market.

6.1 SMART II+ Time Management

SMART II+ is implemented in Swarm [1]. This focuses the model on a time-stepped approach to time management. Furthermore, SMART II+ models use a cyclic bidding process during market clearing. This further focuses it on time-stepped simulation.

6.1. SMART II+ Producer Agents

SMART II+ producers determine their production level based on the potential profit to be made. Each producer has investment capital that is increased by profits and reduced by losses. If a producer reaches a predetermined level of investment capital it can purchase additional production capacity in the form of new electric generators or new natural gas sources. New producers are similar to their owner and can connect to the distribution network in either the same location or a new one. Producers that run out of investment capital go bankrupt and no longer participate in the market. Producers choose whether or not to sell energy based on either their cost curves or natural gas prices.

Standard producers derive their costs and capacities from cost curves with maximum generation limits as shown in Figure 6. Both costs and capacities are exogenous. SMART II+ producer agents obey the same basic rules as SMART II generation agents with the exception of natural gas-fired electric generator agents.

Natural gas-fired electric generation agents derive their costs and capacities from the natural gas market. These agents are consumers in the natural gas marketplace. Their costs are based on the price they pay for natural gas. Their capacities are based on both the amount of natural gas they can purchase and their design limits.

The rules for natural gas-fired electric generation agents are as follows:

- If the agent made a profit in the last hour, then attempt to increase natural gas purchases and offer more electrical generation capacity.
- If the agent posted a loss in the last hour, then attempt to decrease natural gas purchases and offer more electrical generation capacity.
- If the total profit has risen above the investment level for a new unit, then purchase a new generator. Select the new generator type based on a combination of the parent's fuel source and the availability of natural gas.
- If the total profit has fallen to zero, then go bankrupt.

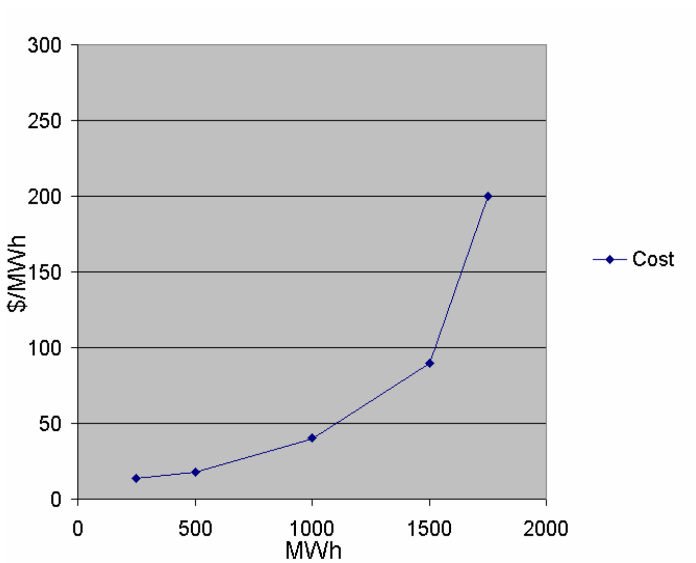


Figure 6: An example producer cost curve

Producer simulation display appearance depends on current profit levels (Figure 7).

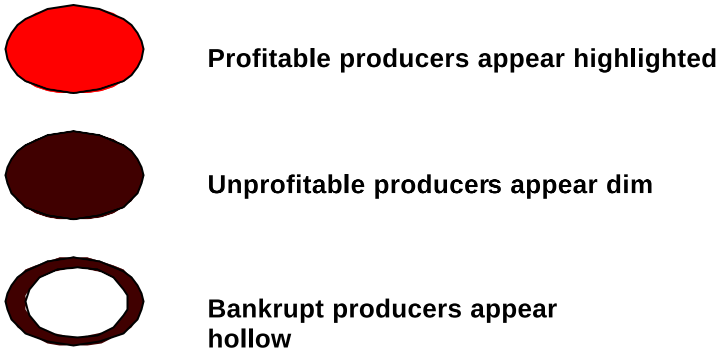


Figure 7: Producer Appearance

6.2. SMART II+ Consumer Agents

SMART II+ consumer agents buy energy for their own use. Businesses buy fixed amounts of energy to remain in business. Populations buy fixed amounts of energy to live their lives. Natural gas fired electric generators buy natural gas to produce salable electric power.

Each consumer has investment capital that is increased by profits and reduced by losses. If a consumer reaches a predetermined level of investment capital it can grow in the form of new consumers. Consumers that run out of investment capital go bankrupt and no longer participate in the market.

Consumer simulation display appearance depends on current profit levels (Figure 8).

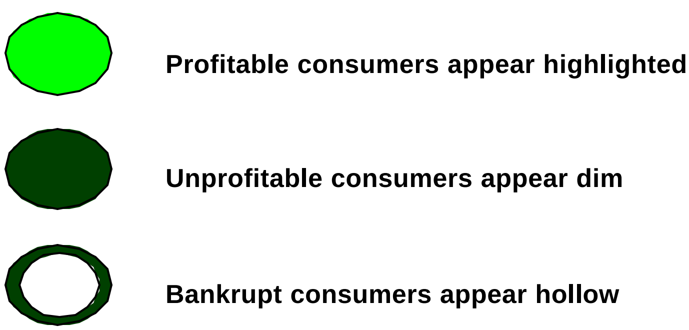


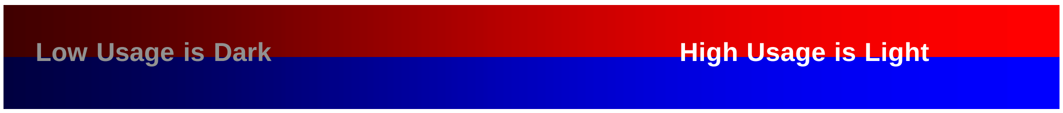
Figure 8: Consumer Appearance

Investment capital represents several things. For industrial users it is their total financial capital. For individuals it is the employment and personal opportunities that keep them in an area or encourage them to leave.

6.3. SMART II+ Interconnections

Interconnections represent transmission lines or distribution pipes each with an individual capacity limit. Individual capacity limits vary by interconnection type. Central transmission lines or main distribution pipes have high capacity limits and are drawn with thick marks. Outlying transmission lines or secondary distribution pipes have moderate capacity limits and are drawn with medium marks. Feeder lines or pipes have low capacity limits and are drawn with thin marks. Interconnection color represents contents and usage as shown in Figure 9.

Electrical lines appear red



Natural gas pipes appear blue

Figure 9: Interconnection Appearance

6.4. SMART II+ Market Indicators

The key SMART II+ market indicators are market prices, unserved energy and natural gas fired electrical generator market share. All key SMART II+ indicators are represented by graphs updated in real time.

Market price is the per unit purchase price of the given energy resource. Electric power prices are given in tenths of a cent per kilowatt-hour (Mills/KWh). Natural gas prices are given in dollars per thousand cubic feet ($/1,000 cubic feet). The SMART II+ price graphs are shown in Figure 10.

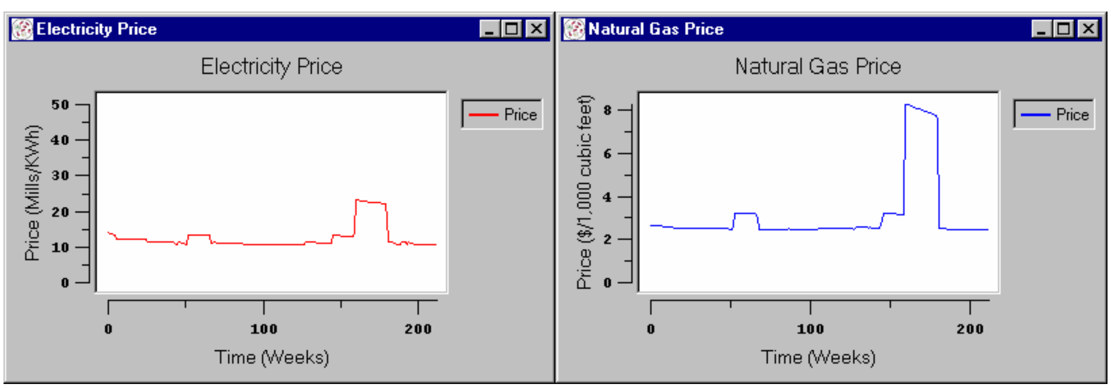


Figure 10: Price Graphs

Unserved energy (UE) is the energy demand that was not met by the market. UE represents a form of market failure. UE is given as a percentage of total energy demand. The SMART II+ UE graph is shown in Figure 11.

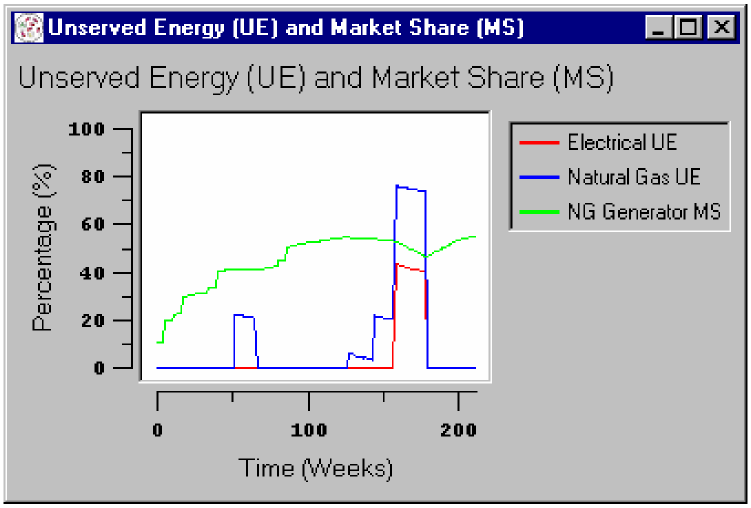


Figure 11: UE and NG Generator MS Graph

Natural gas fired electric generator market share (NG Generator MS) is a measure of the electric generation capacity that is supplied by natural gas units. NG Generator MS is key to infrastructure interdependency. NG Generator MS is given as a percentage of total capacity. The SMART II+ NG Generator MS graph is also shown in Figure 11.

6.5. SMART II+ Network Display

The geographical SMART II+ display is based on an equivalenced network. An example notional SMART II+ network is shown in Figure 12.

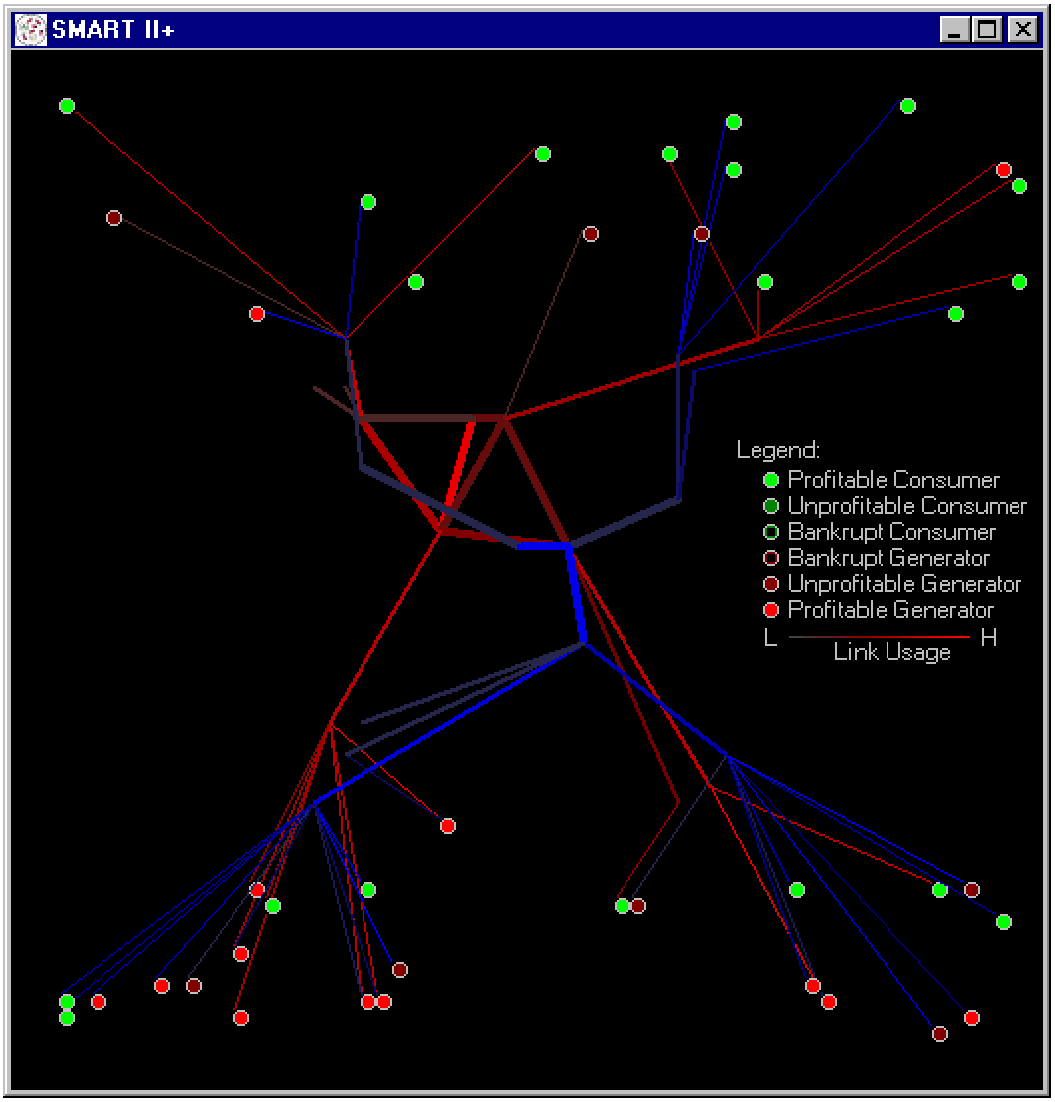


Figure 12: Example Notional SMART II+ Network

SMART II+ seeks to apply CAS techniques to investigate system reliability in the face of cascading failures. As such, the focus is on modeling a large number of infrastructures with properties approximating those of real equivalenced electrical systems.

To achieve the goal of modeling a large number of electrical infrastructures, SMART uses probability distributions to create example networks. These distributions are carefully chosen to approximate real equivalenced electrical systems. This approach allows many networks to be rapidly created and simulated. The result is a broad understanding of the economic issues that surround general electrical infrastructures. It is possible to fix the SMART distributions to particular values to model specific, real world networks. However, to provide more detail on individual electrical infrastructures, the approach followed by FAST is recommended.

6.6. SMART II+ Validation and Calibration

As with SMART II, SMART II+ has undergone initial qualitative validation by matching its outputs to basic analytic predictions:

- Markets with a single superior producer among a large number of higher cost competitors have been tested.
- Markets with many identical participants have been tested.

SMART II + has undergone initial qualitative calibration by comparing the model's natural gas-fired electric generator market share trends to those found in real systems.

Much more work is clearly required to quantitatively validate and quantitatively calibrate SMART II+ therefore only limited qualitative insights are currently being derived.

6.7. SMART II+ Insights

As originally presented to our research sponsors in May 2000, preliminary insights from SMART II+ indicate that:

- Rising natural gas-fired electrical generator market share radically increases market interdependence.
- Increasing market interdependence can pit the electric power and natural gas markets against one another during simultaneous failures since both markets are fighting for the same underlying resource, natural gas.

This interdependency insight was borne out in the aftermath of the recent El Paso natural gas pipeline explosion.

What is the state of the world today? Nationwide natural gas-fired electrical generator market share is roughly 15% to 20%. Nationwide natural gas-fired electrical generator market share is expected to radically increase over the next five years. J.P. Morgan analysts predict that there is expected to be a 31% increase in generation capacity [7]. These analysts predict that roughly 95% of new electrical generation capacity will come from natural gas-fired units [7]. An example is the midwestern region dominated by Commonwealth Edison (ComEd).

ComEd presently gets less than 10% of its current 20,000 MW generation capacity from natural gas-fired generators. Permits are being issued for the construction of 8,000 MW of new capacity, over 95% of which will be natural gas-fired.

The interdependency between the electric power and natural gas markets implies that when natural gas-fired electrical generator market share becomes high enough a single energy resource, "virtual natural gas," is being traded in both markets. Viewing energy systems from the perspective of virtual natural gas suggests that future electrical system capacity expansion planning should explicitly feature the natural gas distribution infrastructure as a key component. Power Systems Engineers should note that electrical models might be substantially incomplete without explicitly including the natural gas infrastructure. Highly distributed electrical generation plans including local load servicing schemes may especially benefit from this view since they rely heavily on the existence of other energy sources such as natural gas.

7. FAST

FAST is an integrated infrastructure model based on SMART II+. FAST includes many of the features of SMART II+ along with improvements in modeling infrastructure, detail and fidelity. FAST is currently under construction. FAST has three components:

- FAST:Run is the runtime infrastructure that will be merged with RePast [8].
- FAST:E is the electric power system model.
- FAST:G is the natural gas system model.

FAST:Run is designed to be a lightweight large-scale system with the following major features:

- FAST:Run is written entirely in Java.
- FAST:Run is fully distributed.
- FAST:Run has a multithreaded scheduler that focuses on maximizing parallel execution.

7.1. FAST Time Management

The underlying design paradigm of FAST is that of a time continuum ranging from decades to seconds. On the scale of decades, the focus is long-term human decisions constrained by economics:

- Radical technology changes are possible.
- Radical legal/regulatory environmental changes are possible.
- Radical market structure changes are possible.
- Radical demand change is possible.
- Radical capacity expansion is possible.
- Radical business model changes are possible.

On the scale of years the focus is short-term human economic decisions constrained by economics:

- Radical legal/regulatory environmental changes are possible.
- Radical market structure changes are possible.
- Substantial demand change is possible.
- Substantial capacity expansion is possible.
- Substantial business model changes are possible.

On the scale of months and days the focus is short-term human economic decisions constrained by economics and physical laws:

- Substantial price change (e.g. fuels, power) is possible.
- Substantial demand change is possible.
- Small business models changes are possible.
- Substantial component failures are possible.

On the scale of hours, the focus is short-term human economic decisions constrained by physical laws and economics:

- Moderate demand change is possible.
- Substantial component failures are possible.

On the scale of minutes or less, the focus is on physical laws that govern distribution systems:

- Small demand changes are possible.
- Substantial component failures are possible.

Over longer time scales, human economic decisions are emphasized. Over shorter time scales, physical laws dominate. FAST includes a large number of different agents to model these varying time scales. Modeling over the full range of time scales is necessary to understand the complex infrastructure interdependencies between the electric power and natural gas markets.

Many agents representing real-world entities have a set of basic functions that are activated on a periodic basis during each model run. Typically, these activations will occur at hourly, daily, weekly, monthly and yearly intervals during runs. The agents also occasionally will be activated at irregular intervals for special tasks. A combination of regular periodic activation combined with occasional irregular activation forms the core structure of the FAST agent-based simulation approach. The FAST classes that implement these concepts follow.

The new classes that implement the core structure of the FAST agent-based simulation focus on activities. Activities can either be specific tasks or collections of subtasks. The subtasks may either be sequential or concurrent. In all cases, tasks may begin and end at specific times. These ideas are embodied in the specific FAST interfaces.

Interfaces in OOP reflect a general contract for functionality without a specific implementation [1]. The contract details the names and parameters of the available functions without saying how those functions are actually coded. This allows interface users to write working programs that are independent of any particular interface implementation. Users are free to choose any implementation that is available. At the same time, interface writers maintain maximum implementation flexibility. They can even use completely different implementation approaches without affecting users.

For example, one interface implementation might be local and sequential. It would provide the type of code most people imagine when they think of a simple computer program. A second implementation might use Java Remote Method Invocation (RMI) to distribute the computation across a Beowulf cluster. Both the standard and RMI approaches could use the same interfaces so no user code changes would be required to switch implementations. In fact this is exactly what FAST does. All of the classes in the FAST hierarchy use interfaces to maximize internal and external flexibility.

7.2. FAST Agents

Many FAST agents are relatively "thick" compared to typical agents. FAST agents are highly specialized to perform diverse tasks ranging from acting as Independent System Operators to being transmission lines. To support specialization, FAST agents include large numbers of highly specific rules.

Over twenty unique FAST agents are being created to model the electrical and natural gas infrastructures in detail. An example is the electric generator agent with the following basic considerations:

- Electric generator agents simulate the physical characteristics of an individual electric generator.
- There will be many different types of generator agents including the following:
    - Thermal generators will be included.
    - Hydroelectric generators will be included.
    - Renewable generation systems will be included.
    - Combined heat and power generators will be included.
    - Others types of electrical generators will be included as well.
- Generators themselves do not adapt; all decisions on their operation are made by Generation Company Agents.
- Random events can affect electric generator operations (e.g., unplanned outages).
- Multiple generators may be physically connected to a single node in the network.
- A generator may be the only supply owned by a given Generation Company Agent or it could be one of several owned by a given Generation Company Agent.
- A generator may have shared ownership with several Generation Company Agents.

Overall, the electric generator agents have limited ability to adapt to their environment. They must operate within their physical limits. If these limits are exceeded or are about to be exceeded the electric generator will trip out. If it does, it must follow its physical rules for restarting before becoming available again.

The generation company that owns the unit makes operating decisions that address issues other than the physical limits. Examples of such issues include economic decisions on whether or not to operate the plant and, if so, at what level.

A simplified set of example steps for generator agents working in the hourly market is as follows:

- Receive the committed capacity for the next 24 hours.
- For each hour:
  - Calculate the available capacity for the next hour.
  - Distribute the available capacity to the committed generation categories.
  - Send the results to the Real-time Dispatch Agent.
  - Receive feedback from the Real-time Dispatch Agent.
  - Determine if the generator has tripped as a result of the dispatch.
  - Calculate generator results.

Detailed rules are provided for each step. For example, the rule to determine if a generator has tripped is as follows:

- If the dispatched capacity received from the Real-time Dispatch Agent for the given generator in the specific hour is less than the generator's minimum capacity, then trip out the generator.
- If the dispatched capacity received from the Real-time Dispatch Agent for the given generator in the specific hour is greater than the generator's maximum capacity, then trip out the generator.
- If generator has instantaneously failed, then trip out the generator.

7.3. FAST Networks

FAST will use specific data from actual equivalenced electrical and natural gas systems. These data will be created manually by power systems and natural gas systems experts in close coordination with agent-based modeling experts. The close coordination will be necessary due to the emergent behavior of CAS.

The emergent behavior of CAS implies that many model results cannot be predicted until the simulation is actually run. The presence of emergent behavior means that modelers should develop simulations in an iterative manner much like that of the spiral software engineering model [9].

The FAST system and its component agents will be subjected to rigorous quantitative validation and calibration. This process will include matching the outputs from FAST under the following scenarios:

- Basic analytic predictions such as markets with a single superior producer among a large number of higher cost competitors and markets with many identical participants will be tested.
- Existing test cases from recognized organizations such as those created by Institute of Electrical and Electronics Engineers will be used [10-11].
- Known events such as the California electricity price spikes and the El Paso natural gas pipeline explosion will be tested.
- A variety of special purpose cases will be created and investigated.

8. Conclusion

Developing the initial capability to create CAS models requires substantial organizational investment as demonstrated by the SMART and FAST efforts. Once this initial investment has been made models can be created that allow innovate studies. ANL has made this investment by creating both SMART and FAST and applying SMART.

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