Testing Institutional Arrangements via Agent-Based Modeling

A U.S. Electricity Market Example

Leigh Tesfatsion
Professor of Economics
 Courtesy Professor of Mathematics
 and Electrical & Computer Engineering
 Iowa State University, Ames, Iowa

https://www2.econ.iastate.edu/tesfatsi/
tesfatsi@iastate.edu

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Complexity of large-scale institutional systems

*Agent-Based* Modeling (*ABM*) test beds for institutional design

**Example: AMES Test Bed.** An ABM test bed enabling study of the reliability, efficiency, and welfare implications of proposed or implemented designs for grid-supported centrally-managed wholesale electric power markets.

Illustrative AMES findings for U.S. markets:

- Incentives for price manipulation
- Incentives for congestion inducement
Modern societies depend strongly on large-scale institutions for production & distribution of critical goods and services (e.g., electric power, financial assets, health care, ...)

Institutional outcomes depend in complicated ways on
- Physical constraints restricting feasible actions
- Rules governing participation, operation & oversight
- Behavioral dispositions of participants
- Interaction patterns of participants

To be useful and informative, institutional studies need to take proper account of all four elements.
Mathematical Modeling of Institutional Systems
Classical Mathematics vs. Agent-Based Modeling (ABM)

◆ **Classical Approach (Top Down):** Model the system by means of parameterized difference or differential equations
  
  — **Example:** *Archimedes*, a large-scale system of ordinary differential equations modeling pathways of disease spread under alternative possible health-care response systems

◆ **ABM Approach (Bottom Up):** Model the system as a collection of interacting “agents”

  — Each agent is a software program encapsulating data, attributes, and/or methods.

  — Agents can contain other agents as member data. These “has a” relations among agents permit hierarchical agent constructions.
Meaning of “Agent” in ABM

**Agent** =: Encapsulated bundle of data, attributes, and/or methods able to act within a computationally constructed world.

- **Agents can represent:**
  - **Individuals** (consumers, traders, entrepreneurs,...)
  - **Social groupings** (households, communities,...)
  - **Institutions** (markets, corporations, government agencies,...)
  - **Biological entities** (crops, livestock, forests,...)
  - **Physical entities** (weather, landscape, electric grids,...)
Potential Capabilities of Cognitive Agents ("CogAgents") in ABM

CogAgents can exhibit:

- Behavioral adaptation
- Goal-directed learning
- Social communication (talking with each other!)
- Endogenous formation of interaction networks

**Autonomy:**
Self-activation and self-determination based on *private or protected internal data, attributes, and/or methods* (including internalized data streams from the real world), starting from modeler-specified initial conditions.
UML Diagram Illustrating “is a” ↑ and “has a” ↓ Agent Relations for a Macroeconomic ABM
**ABM vs. Object-Oriented Programming (OOP)**

- Key distinction is ABM CogAgents are typically able to exhibit greater degrees of autonomy than OOP objects, since the latter have traditionally been designed as tools to carry out top-down modeler-specified tasks.

- OOP objects encapsulate data, attributes, and/or methods, but these encapsulated functionalities typically do not permit self-activation and local choice to achieve local goals.

- ABMs permit distributed agent control, not simply distributed agent action.
Importance of Encapsulation

• In the real world, all calculations must be done by entities that are actual residents of this world.

• ABM forces modelers to respect this constraint.

• An intended action of an ABM agent at a specific instant is determined by the data, attributes, and/or methods of this agent at this specific instant.

• This encapsulation of agent functionality achieves a more transparent and realistic representation of real-world systems composed of interacting distributed entities with limited information and computational capabilities.
Constructive Replacement

Encapsulation of agent functionality permits “constructive replacement” in the following sense:

任何形式的agent within an ABM able to interact with other agents in the ABM by means of its input-output public interface can be replaced by a real person that uses this same public interface to interact with other agents in the ABM.

• Since the data, attributes, and/or methods of the original ABM agent can differ from the data, attributes, and/or methods of the human replacement, this replacement could surely affect subsequent outcomes for the ABM.

• The only claim here is the feasibility of physical replacement due to the encapsulation of functionality for agents comprising an ABM.
Role of Equations in ABMs

◆ The state (data, attributes, and/or methods) of an agent in an ABM can include or be based on equations.

◆ The intended action of an agent in an ABM world at a given instant is determined by the agent’s state at this instant. The expressed action of an agent within an ABM world at a given instant is determined by the ensemble of agent states at this instant.

◆ ABM events (changes in agent states) at a given instant are determined by agent interactions at this instant.

◆ Thus, ABM events can depend on equations. However, ABM events cannot depend on free-floating equations that exist outside of the states of the agents that comprise this ABM. For example, ABM states cannot depend on external constraints (“sky hooks”) such as modeler-imposed equilibrium conditions.
ABM and Institutional Design

Key Issues:
- Will a proposed or implemented institutional design promote efficient, fair, and orderly social outcomes over time?
- Will the design give rise to adverse unintended consequences?

ABM Culture-Dish Approach:
- Develop an ABM “computational laboratory” embodying the institutional design of interest.
- Configure and set initial conditions (agent states) for this ABM.
- Let the ABM evolve with no further external intervention, and observe and evaluate the resulting outcomes.
ABM Test Bed Development via Iterative Participatory Modeling (IPM)

- Stakeholders and researchers from multiple disciplines join together in a **repeated looping through four stages of analysis**:

1. Field work and data collection
2. Role-playing games/human-subject experiments
3. Incorporate findings into agent-based test bed
4. Generate hypotheses through intensive computational experiments.
Illustrative Institutional Design Project*
Integrated Retail & Wholesale (IRW) Power System Operation with Smart-Grid Functionality

Project Directors: Leigh Tesfatsion (Professor of Economics, Courtesy Professor of Mathematics & ECpE, ISU)
Dionysios Aliprantis (Assistant Prof. of ECpE, ISU)
David Chassin (Staff Scientist, PNNL/DOE)

Research Assoc’s: Dr. Junjie Sun (Financial Economist, OCC, U.S. Treasury, Wash, D.C.)
Dr. Hongyan Li (Consulting Eng., ABB Inc., Raleigh, NC)

Research Assistants:
Qun Zhou & Nanpeng Yu (ECpE PhD/Econ M.S. Candidates, ISU);
Abhishek Somani & Huan Zhao (Econ PhD Candidates, ISU);
Chengrui Cai (ECpE PhD Candidate, ISU).

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IRW Power System: Basic Structure

Source: http://www.nerc.com/page.php?cid=1|15

Basic Structure of the Electric System

Generation  Transmission  Distribution

Wholesale  Retail
IRW Power System: Dynamic Operation

[Diagram showing market processes, data & signal flows, and power flows involving wholesale generation and storage, transmission utilities, independent system operator, high voltage transmission grid, distribution grid, grid-edge resource aggregators, distributed consumers and prosumers, and external bilateral contracts.]
Illustrative Institutional Design Study: 
Restructuring of U.S. Wholesale Power Markets

- In an April 2003 White Paper, the U.S. Federal Energy Regulatory Commission (FERC) proposed a wholesale power market design based on a two-settlement system: namely, centrally-managed day-ahead and real-time markets settled by Locational Marginal Pricing (LMP).

- The following regions serving over 60% of U.S. generation now operate under this FERC market design:
  - New York (NY-ISO)
  - mid-Atlantic states (PJM)
  - New England (ISO-NE)
  - Midcontinent (MISO)
  - Texas (ERCOT)
  - Southwest (SPP)
  - California (CAISO)

**Note:** ERCOT (by deliberate within-state design) is not under FERC jurisdiction; however, it chose to implement the core element of the FERC market design – a two-settlement system -- in 2010. Ontario (IESO), Alberta (AESO), and other Canadian provinces operate under variants of the FERC market design.
North-American Regions Operating Under Variants of the FERC Market Design as of Nov 2015

FERC Market Design: Key Features in Greater Detail

- Market to be managed by an *Independent System Operator (ISO)* having no ownership or financial stake in market operations.

- Concurrent daily operation of a *day-ahead market* plus a “*real-time market*” consisting of multiple *intra-day market processes*.

- Transmission grid congestion managed via *Locational Marginal Prices (LMPs)*, where LMP(k,T) ($/MWh) at grid bus k for operating period T (measured in hours) is the least cost of supplying one additional *maintained* MW of power at bus k during T.

- *Oversight & market power mitigation* by outside agency.

Has led in practice to complicated systems *difficult to analyze by standard analytical & statistical tools*!
Example: Complex MISO Market Organization
Business Practices Manual 001-r1 (1/6/09)

Exhibit 2-3: DART Components Overview

LMP Two-Settlement System Core Element of the FERC Market Design
AMES (V2.06) Computational Test Bed

- Development and open-source release of AMES (Agent-based Modeling of Electricity Systems)

- AMES =: Computational test bed incorporating core features of the FERC wholesale power market design

- Used to test FERC design performance for grid-supported wholesale power markets under systematically varied initial conditions.

- Used to test performance of proposed FERC design modifications.

The latest OSS-released version of AMES is V5.0 (2020). Documentation and code for all versions of AMES released to date can be found at the following AMES homepage: https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm
AMES (V2.06) Architecture:
Based on business practices manuals for MISO/ISO-NE

➢ Two-settlement system
  ▪ Day-ahead market (double auction, financial contracts)
  ▪ Real-time market (collection of intra-day markets to ensure balancing)

➢ Nodal settlements to handle potential transmission grid congestion
  ▪ Generation Companies (GenCos) & Load-Serving Entities (LSEs) located at user-specified transmission-grid buses
  ▪ Settlements determined via Locational Marginal Prices (LMPs)
  ▪ \( \text{LMP}(k,T) \) (\$/MWh) at bus \( k \) for operating period \( T \) =: Least cost of maintaining one additional MW of power generation at bus \( k \) \textbf{during} \( T \).

➢ Traders
  ▪ GenCos (sellers)
  ▪ LSEs (buyers)
  ▪ Learning capabilities

➢ Independent System Operator (ISO)
  ▪ System reliability assessments
  ▪ Day-ahead scheduling via bid/offer-based DC optimal power flow (DC-OPF)
  ▪ Real-time dispatch
AMES (V2.06) Architecture is Modular & Extensible

◆ Market protocols & AC transmission grid structure
  — Graphical user interface (GUI) & modular class structure (Java) permit easy experimentation with alternative parameter settings, alternative market rules, and alternative forms of system constraints.

◆ Learning representations for traders
  — Java Reinforcement Learning Module (JReLM)
  — “Tool-box” permitting experimentation with a wide variety of learning methods (Reinforcement, Temporal Difference/Q-learning, ...)

◆ Bid/offer-based optimal power flow formulation
  — Java DC Optimal Power Flow Module (DCOPFJ)
  — Permits experimentation with various DC OPF formulations

◆ Output displays and dynamic test cases
  — Customizable chart/table displays, inclusion of 5-bus/30-bus test cases
Focus on Incentive Alignment: Does the market design align the incentives of market participants with system objectives: reliability; efficiency (non-wastage of resources); & welfare (max total net benefit for participants)

AMES-run experiments reported in following slides:
Incentive alignment under FERC wholesale power market design is studied for a range of experimental treatments:

- **GenCo learning capabilities** [intensive parameter sweep]
- **Price-sensitivity of LSE demand bids** [0 to 100%]

Grid Configuration
Based on a 5-bus test-case developed by John Lally (ISO-NE) that is now used in many RTO/ISO business practice and training manuals

Five Generation Company (GenCo) suppliers G1,…,G5
and three Load-Serving Entity (LSE) buyers LSE 1, LSE 2, LSE 3
ISO Activities During a Typical Day D
ISO market-management activities during a typical day D include planning ahead for day D+1

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td><strong>Day-Ahead Market (DAM)</strong> held on day D for day D+1&lt;br&gt;ISO collects LSE demand bids and GenCo supply offers</td>
</tr>
<tr>
<td>11:00</td>
<td>ISO solves bid/offer-based DC Optimal Power Flow (DC-OPF) for day D+1</td>
</tr>
<tr>
<td>16:00</td>
<td>ISO posts optimal dispatch and LMP schedule for day D+1</td>
</tr>
<tr>
<td>23:00</td>
<td>Day-ahead settlement</td>
</tr>
</tbody>
</table>
Independent System Operator (ISO) Agent

Public Access:

// Public Methods
getWorldEventSchedule( clock time,... );
getMarketProtocols( bid/offer reporting, settlement,... );
Methods for receiving data;
Methods for retrieving stored ISO data;

Private Access:

// Private Methods
Methods for gathering, storing, posting, & sending data;
Method for solving hourly DC optimal power flow;
Methods for posting schedules and carrying out settlements;
Methods for implementing market power mitigation;

// Private Data
Historical data (e.g., cleared bids/offers, market prices,...);
Address book (communication links);
Generation Company (GenCo)
True Cost & Capacity Attributes

GenCo True Marginal Cost Functions

Price ($/MWh)

Power (MWs)

GenCo1
GenCo2
GenCo3
GenCo4
GenCo5
GenCos are **learning** agents who report **strategic** supply offers to the ISO for the Day-Ahead Market (DAM)

Hourly supply offer for each GenCo $i = \text{ Reported linear marginal cost function over a reported operating capacity interval for real power } p_{Gi} \text{ (in MWs)}:

$$MC^R_i(p_{Gi}) = a^R_i + 2b^R_i p_{Gi}$$

$$Cap_{iL} \leq p_{Gi} \leq Cap^R_{iU}$$

GenCos can learn to report **higher-than-true** marginal costs and/or to report **lower-than-true** maximum capacity.
Each GenCo maintains action choice propensities, $q$, normalized to form choice probabilities, $Prob$, that are used to choose actions (supply offers). A good (bad) reward $r_k$ resulting from an action $a_k$ increases (decreases) both $q_k$ and $Prob_k$. 

GenCos use VRE-RRL Learning

(Variant of Roth-Erev Reactive Reinforcement Learning)
Generation Company (GenCo) Agent

Public Access:

// Public Methods
getWorldEventSchedule( clock time,... );
getMarketProtocols( ISO market power mitigation,... );
Methods for receiving data;
Methods for retrieving GenCo data;

Private Access:

// Private Methods
Methods for gathering, storing, and sending data;
Methods for calculating own expected & actual net earnings;
Method for updating own supply offers \textbf{(learning)};

// Private Data
Own capacity, grid location, cost function, current wealth... ;
Data recorded about external world (prices, dispatch,...);
Address book \textbf{(communication links)} ;
Load-Serving Entity (LSE)  
Hourly Demand-Bid Formulation

◆ Hourly demand bid for each LSE j

**Fixed + Price-Sensitive** Demand Bids:

- **Fixed** demand bid =: $p^F_{Lj}$ (MW)
- **Price-sensitive** demand bid
  
  =: Inverse demand function $F_j$ mapping real power $p^S_{Lj}$ (MW) over a purchase capacity interval into a per-unit price ($/MWh) for some designated hour $H$:

  \[ F_j(p^S_{Lj}) = c_j - 2d_j p^S_{Lj} \]

  \[ 0 \leq p^S_{Lj} \leq SLMax_j \]
R Measure for Price Sensitivity of LSE Demand Bids
Permits price sensitivity to be systematically varied across experiments

For LSE j in Hour H:

\[ \text{p}_{F\text{L}_j} = \text{Fixed demand for real power (MWs)} \]

\[ \text{SL}_{\text{Max}_j} = \text{Maximum potential price-sensitive demand (MWs)} \]

\[ R = \frac{\text{SL}_{\text{Max}_j}}{\text{p}_{F\text{L}_j} + \text{SL}_{\text{Max}_j}} \]

- $/\text{MWh}$
- \( \text{p}_{L_j} \)
- \( \text{p}_{F\text{L}_j} \)
- \( \text{SL}_{\text{Max}_j} \)

\[ R = 0.0 \] (100% Fixed Demand)

\[ R = 0.5 \] (100% Price-Sensitive Demand)

\[ R = 1.0 \]
# Load-Serving Entity (LSE) Agent

## Public Access:

// **Public Methods**
- `getMarketProtocols(posting, trade, settlement);`
- `getMarketProtocols(ISO market power mitigation);`
- Methods for receiving data;
- Methods for retrieving LSE data;

## Private Access:

// **Private Methods**
- Methods for gathering, storing, and sending data;
- Methods for calculating own expected & actual net earnings;

// **Private Data**
- Own downstream demand, grid location, current wealth...;
- Data recorded about external world (prices, dispatch,...);
- Address book *(communication links)* ;
ISO Solves Hourly DC Optimal Power Flow (DC-OPF)

GenCos report hourly supply offers and LSEs report fixed & price-sensitive hourly demand bids to ISO on day D for Day-Ahead Market (DAM)

Minimize

\[
\sum_{i=1}^{I} [a_i P_{Gi}^R + b_i P_{Gi}^2] - \sum_{j=1}^{J} [c_j p_{Lj}^S - d_j p_{Lj}^S]^2 + \pi \left[ \sum_{km \in BR} [\delta_k - \delta_m]^2 \right]
\]

w.r.t. \( p_{Gi}, \ i = 1, \ldots, I; \ p_{Lj}^S, \ j = 1, \ldots, J; \ \delta_k, \ k = 1, \ldots, K \)

subject to

\[
\sum_{i \in I_k} p_{Gi} - \sum_{j \in J_k} (p_{Lj}^F + p_{Lj}^S) - \sum_{km \in BR} B_{km} [\delta_k - \delta_m] = 0
\]

Fixed and price-sensitive demand bids for LSE j

GenCo-reported total avoidable cost

LSE total buyer surplus (benefit)

ISO Choice Variables

Operating capacity interval constraint for GenCo i

Dual variable for this bus-k power balance constraint gives the LMP ($/MWh) for bus k

Purchase capacity interval constraint for LSE j

\( P_{km}^U \) = Thermal limit for branch km
Maintained Experimental Fixed Demand Configuration for R=0.0

LSE Total Fixed Demand at Buses 2, 3, and 4
for Hours 1 – 24 on Operating Day D, given R=0.0

17 = Peak demand hour
First Experiments: Avg GenCo net earnings (Day 1000) for R=0 under varied settings for VRE-RRL learning parameters (α, β)

Small beta ≅ “zero-intelligence” budget-constrained trading.

Learning matters!

= Sweet-spot region

★ = Sweet-spot setting for learning parameters (α, β) set in subsequent experiments
Lerner Index (LI): Measure of “Market Power”

- The LI for any GenCo $i$ supplying a positive amount of power $P_{Gi}$ is defined as follows:

$$LI_i(P_{Gi}) = \frac{[LMP_{k(i)} - MC_i(P_{Gi})]}{LMP_{k(i)}}$$

- Typically, LI measures are calculated on an hourly basis.

- LI is commonly used as a measure of Market Power, defined for a GenCo as ability to affect market price in its own favor.

A binding capacity constraint on GenCo $i$ can cause $LI_i > 0$ even if GenCo $i$ submits a true supply offer reflecting its true marginal cost curve & supply-capacity conditions.
Second Experiments: Avg LMP with and without GenCo VRE-RRL learning as demand varies from R=0 (100% fixed) to R=1 (100% price sensitive)

**Note:** “No Learning” = GenCos report their true marginal cost curves & capacity constraints.
Single-Run Illustration of LMP Findings for R=0.0 (100% Fixed Demand)

W/O Gen Learning (Day 1000)

With Gen Learning (Day 1000)

Learning has big effects on price!
Summary of Findings from First Two Sets Experiments

★ BOTTOM LINE:

Even with 100% price-sensitive demand bids (R=1.0), prices (LMPs) are much higher under GenCo VRE-RRL learning due to GenCo strategic supply offers, primarily under-reported supply capacities.

★ NEEDED:

**Countervailing power** = Price-sensitive LSE demand bidding plus more numerous GenCo suppliers competing for profits to support more competitive pricing at wholesale.

★ POSSIBLE MEANS:

*Integrated retail and wholesale (IRW) operations* that permit: (i) more active participation of distribution-level power resources in wholesale power markets; and (ii) increased opportunities for distribution-level consumers with price-sensitive demands to preferentially select their LSE intermediary suppliers.
**Third Set of Experiments:**
Net surplus extraction by ISOs in day-ahead energy markets under Locational Marginal Pricing (LMP)

Day-ahead market activities on a typical operating day D:

https://www2.econ.iastate.edu/tesfatsi/ISONetSurplus.WP09015.pdf
ISO goal is to maximize Total Net Surplus (TNS) subject to system constraints: A Two-Bus Example
(Adapted from Harold Salazar, ISU ECpE M.S. Thesis, 2008)

Given the line capacity limit $M$, the cleared LSE load at bus 2 is $p_F^L$. The LSE receives price $r$ ($/\text{MWh}$) for the resale of $p_F^L$ at the retail level. $M$ units of $p_F^L$ are supplied by GenCo G1 at bus 1 at price $LMP_1$ ($/\text{MWh}$); the line capacity limit $M$ prevents G1 from supplying any additional units. Remaining $[p_F^L – M]$ units are supplied by GenCo 2 at bus 2 at the higher price $LMP_2$ ($/\text{MWh}$). The LSE at bus 2 pays $LMP_2$ for each unit of $p_F^L$.

As a result of these transactions, the ISO collects “ISO Net Surplus” defined as follows:

**ISO Net Surplus**

$$= [ \text{LSE Payments} - \text{GenCo Revenues} ]$$

$$= LMP_2 \times p_F^L - M \times LMP_1 - [p_F^L - M] \times LMP_2$$

$$= M \times [ LMP_2 - LMP_1 ] = [\text{Shaded Figure Area}]$$
Two-Bus Example ... Continued

ISO Net Surplus:
Area INS =: M \times [LMP_2 - LMP_1]

GenCo Net Surplus:
Area S1 + Area S2

LSE Net Surplus:
Area B =: p_L^F \times [r - LMP_2]

Total Net Surplus:
TNS = [INS + S1 + S2 + B]

ISO Optimization Objective:
Maximize TNS subject to system constraints.
Third Experiments: 5-Bus Test Case Results Without GenCo VRE-RRL Learning
Mean LSE, GenCo, and ISO net surplus extractions on day 1000 as LSE demand varies from R=0.0 (100% fixed) to R=1.0 (100% price sensitive)
Third Experiments: 5-Bus Test Case Results With GenCo VRE-RRL Learning
Mean LSE, GenCo, and ISO net surplus extractions on Day 1000 as LSE demand varies from R=0.0 (100% fixed) to R=1.0 (100% price sensitive)
Third Experiments: Summary of ISO Net Surplus Findings

- ISO net surplus extractions *not well aligned with market efficiency*

- Treatments resulting in *greater* GenCo economic capacity withholding (hence higher & more volatile LMPs) also result in *greater* ISO & GenCo net surplus

- ISO net surplus collections *should be allocated ex ante* for remedy of structural/behavioral problems that encourage GenCo economic capacity withholding.

- ISO net surplus collections *should not be used ex post* for LMP payment offsets and LMP risk hedge support (current practice)
ISO Net Surplus Extraction: Empirical Comparisons

- From PJM 2008 report:
  ISO net surplus from day-ahead market: $2.66 billion

- From MISO 2008 report:
  ISO net surplus from day-ahead market: $500 million

- From CAISO 2008 report:
  ISO net surplus from day-ahead inter-zonal congestion charges: $176 million

- From ISO-NE 2008 report:
  Combined ISO net surplus for real-time and day-ahead markets: $121 million
Conclusions

* Restructured wholesale power markets are complex large-scale institutions encompassing physical constraints, administered rules of operation, and strategic human participants.

* Agent-based test beds permit the systematic dynamic study of such institutions through intensive computational experiments.

➢ For increased empirical validity, test beds should be iteratively developed with ongoing input from actual market participants.

➢ To increase usefulness for research/teaching/training and to aid knowledge accumulation, test beds should be open source.
On-Line Resources

- Presentation Slides
  https://www2.econ.iastate.edu/tesfatsi/TestInstViaABM.Waterloo2010.pdf

- Agent-Based Computational Economics Homepage
  https://www2.econ.iastate.edu/tesfatsi/ace.htm

- AMES Test Bed Homepage (Code/Manual/Publications)
  https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- Agent-Based Electricity Market Research
  https://www2.econ.iastate.edu/tesfatsi/aelectric.htm

- Other Highly Active ABM Social Science Research
  https://www2.econ.iastate.edu/tesfatsi/aapplic.htm