Situated Mathematics:
Agent-Based Test Beds for Mathematics in Practice

Mathematics for New Economic Thinking
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The issue:

Systemic risk effects?

Unknown system-wide effects of locally used mathematical routines
Explore system-wide effects via an agent-based test bed.
Presentation Outline

- Complexity of Critical Infrastructure Systems (CIS)

- Agent-based test beds for exploring system-wide effects of locally used CIS decision support tools

- **Illustration:** System-wide effects from local use of DP and MIP optimization routines for electric power system operations are being tested via the

  Integrated *Retail & Wholesale (IRW)* Power System Test Bed

  [http://www.econ.iastate.edu/tesfatsi/irwprojecthome.htm](http://www.econ.iastate.edu/tesfatsi/irwprojecthome.htm)
Complexity of Critical Infrastructure Systems (CIS)

- Modern societies depend on CIS for essential goods & services (electric power, credit, health services, …)

- CIS are large complex systems encompassing
  - Human decision-makers
  - Physical constraints
  - Institutional arrangements

- Difficult to judge ex ante the system-wide effects of locally used CIS decision support tools
Can Agent-Based Modeling (ABM) help?

- **Classical Approach (Top Down):** Represent a system by means of parameterized differential equations
  
  - *Example:* Archimedes, a large-scale system of ODEs modeling pathways of disease spread under alternative possible health care response systems

- **ABM Approach (Bottom Up):** Represent a system as a virtual world of interacting agents
  
  - Each agent is an entity encapsulating data together with methods that act on this data.
  
  - Starting from user-specified initial conditions, world events are driven entirely by agent interactions.
Agent-Based Test Bed

- ABM computational lab that permits controlled computational experiments and visualization of outcomes

Example:
An agent-based test bed implementing an extended Schelling model of urban segregation

Meaning of “agent” in ABM

**Agent** = Encapsulated bundle of data and methods acting within a computationally constructed world

- Agents can represent:
  - Individuals (consumers, traders, entrepreneurs,…)
  - Social groupings (households, communities,…)
  - Institutions (markets, corporations, gov’t agencies,…)
  - Biological entities (crops, livestock, forests,…)
  - Physical entities (weather, landscape, electric grids,…)

[Image of the page]
Meaning of “agent” in ABM … Continued

**Decision-making agents (DMAgents)** are capable (in different degrees) of

- 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 internal* data and methods as well as on external data streams (including from real world)
Partial depiction of agents for a macroeconomic ABM with “is a” ↑ and “has a” ↓ relations
Agent-based 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) Scenario discussion/role-playing games
3) Incorporate findings into agent-based test bed
4) Generate hypotheses through intensive computational experiments.
System-wide performance criteria for CIS decision support tools

- **For Users:**
  - Provides benefits that sustain voluntary use

- **For Regulators:**
  - Sustains/improves reliability of operations
  - Robust against gaming for unfair advantage

- **For Society as a Whole:**
  - Reduces inefficiency (wastage of resources)
Key Issue:
Does the local use of a CIS decision support tool enhance system-wide performance?

ABM Approach:
- Represent the CIS as an ABM “virtual world”.
- Let one or more virtual-world agents use the decision support tool in their decision-making.
- Let the virtual world evolve over time, starting from systematically varied initial conditions.
- Check resulting virtual-world outcomes to see if system-wide performance criteria are met.
Performance testing of CIS decision support tools for practical implementation

- Must cross “valley of death” between theory & practice
- Valley of Death ➔ Technology Readiness Levels 4–6
  
  TRL 4: Analytical/computational verification that the CIS decision support tool performs “locally” as expected

  TRL 5: Performance testing of the CIS decision support tool in a reasonably realistic CIS simulation

  TRL 6: Performance testing of the CIS decision support tool in a high-fidelity CIS simulation

https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view
**TRL-5 Example:** The Integrated Retail & Wholesale (IRW) Power System Test Bed

5-Bus 1-Feeder Example

**AMES Test Bed**

- Wholesale
- Retail
- net energy demands
- bulk energy & prices

Distribution Test Feeders
IRW Test Bed: An Agent-Based Test Bed for the TRL-5 Study of U.S. Electric Power Systems

Bilateral Contracts

Wholesale

AMES

Retail

Distribution

Test Feeders

Market Processes

Data Flows

Power Flows

Generation Companies

ISO

HV Transmission Grid

T/D Utilities

D-Substation & Grid

LSEs

Contracts

Contracts

Contracts

Prices

Meter Data

Resources (DER)

Consumer-Owned DER

Retail Consumers
Independent System Operator (ISO) activities during a typical day D-1

<table>
<thead>
<tr>
<th>Time</th>
<th>Real-Time Market</th>
<th>Day-Ahead Market</th>
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</thead>
<tbody>
<tr>
<td>00:00</td>
<td>ISO collects energy bids &amp; offers from buyers &amp; sellers.</td>
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<tr>
<td>11:00</td>
<td>ISO conducts SCUC/SCED to determine commitment, dispatch, &amp; price schedule for each hour of next day D.</td>
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<td>16:00</td>
<td>ISO posts schedule for each hour of next day D.</td>
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<tr>
<td>23:00</td>
<td>Day-ahead settlement</td>
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Economic Incentives for Retail & Wholesale Traders

- Generation Companies (GenCos)
- Load Serving Entities (LSEs)
- DAM/RTM Prices Received
- DAM/RTM Prices Paid
- Supply Offers
- Demand Bids
- Actual Supplies
- Actual Demands
- Production/UC Costs Paid
- Retail Prices Received
- Retail Prices Paid
- Retail Consumers

Day-Ahead Market (DAM)
Real-Time Market (RTM)
ISO
Wholesale Level
Retail Level
Application 1 (EPRC/PNNL Project): System-wide performance when retail consumers use smart Air Conditioning (A/C) controllers

- A smart A/C controller for households has been developed by project members that implements a **stochastic dynamic programming (DP) algorithm**

- On each day D-1, finds optimal 24-hour comfort/cost trade-offs (energy usages) for day D, given expected retail prices & environmental conditions for day D

- IRW Test Bed is being used to study IRW effects when some households use this smart A/C controller
Application 1: Air-Conditioning (A/C) control via stochastic dynamic programming

Comfort  Cost

Prices

Household Preferences

Forecast of environmental conditions
Retail price sequence

Scheduling (on remote or local server)

House Thermal Dynamics (ETP model)

Environmental conditions

(to A/C motor)  On/Off  Air Temp.

Control Map  Estimator for Mass Temp.

User-defined preferences (entered via a user-friendly graphical interface)

Wall Control Unit
**Application 2 (ARPAe/DOE project):**

System-wide performance when ISO uses stochastic optimization for electric power generation scheduling

**Project Goal:**

Develop/test a *stochastic mixed-integer programming (MIP) algorithm* for generation unit commitment under uncertainty

- **Phase 1:** Uncertainty arises from
  - variable conventional loads (washers, refrigerators, …)
  - wind generation

- **Phase 2:** Additional uncertainty arises from
  - price-sensitive retail demand (smart A/C, …)
  - strategic trading by learning traders
Application 2: Deterministic vs. stochastic MIP for Generation Security-Constrained Unit Commitment (SCUC)

Deterministic SCUC

- Expected Load (EL)
- Unit commitment vector: $u_k^D$
- Power dispatch: $P_k^D$
- SCED
- Calculate Total Cost

Stochastic SCUC

- Load Scenarios: $S_1, S_2, S_3, ..., S_n$
- Unit commitment vector: $u_k^S$
- Power dispatch: $P_k^S$
- SCED
- Calculate Total Cost

RL: Real-time Load
System-wide testing of stochastic DP & MIP optimization algorithms via IRW Test Bed

Weather conditions → A/C energy usage via stochastic DP → RTM load
Retail prices
Retail contract form
DAM prices via stochastic MIP

Background (BG) load: Not price responsive
DAM buyer demand forecasts
DAM buyer demand bids
DAM seller supply offers
Illustrative System Outcomes for Application 1:
Retail A/C Energy Usage Determined via Stochastic DP
RTM price at feeder bus (peak hour 18) under different forcing-term & retail-price conditions

Wholesale price fluctuations arise due to price-responsive retail demand even *without* any variation in forcing terms.
RTM price at feeder bus (peak hour 18)
RTM price at feeder bus (peak hour 18)

* Variation in weather and BG load
Illustrative System Outcomes for Application 2:
Deterministic vs. Stochastic MIP Optimization for Generation Unit Commitment

<table>
<thead>
<tr>
<th>Start-Up &amp; Shut-Down Cost Scaling Factor</th>
<th>No-Load Cost Scaling Factor</th>
<th>Deterministic Cost ($)</th>
<th>Stochastic Cost ($)</th>
<th>Total Cost Saving (%)</th>
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* Outcomes for Base Test Case: Uncertainty arises from conventional load variation only, with 5% average load forecast error
Agent-based test beds for math in practice:

Agent-Based System Model

system agents use math routine

System

Explore system-wide effects via an agent-based test bed

Projected system-wide effects

Actual system-wide effects
On-Line Resources

- **IRW Project Homepage**
  
  www.econ.iastate.edu/tesfatsi/IRWProjectHome.htm

- **AMES Test Bed Homepage (Code/Manuals/Publications)**
  
  www.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- **Agent-Based Electricity Market Research**
  
  www.econ.iastate.edu/tesfatsi/aelect.htm

- **Open Source Software for Electricity Market Research, Teaching, and Training**
  
  www.econ.iastate.edu/tesfatsi/electricoss.htm