An Approximation Scheme for Risk Averse Stochastic Equilibrium Problems

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(visiting researcher IMPA)

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Limoges, Terry Fest, May 18th, 2015

joint work with J.P. Luna (UFRJ) and M. Solodov (IMPA)

What this talk is about?

- Large-scale variational inequalities

  VI$(F, C) : \langle F(\bar{q}), q - \bar{q} \rangle \geq 0 \ \forall$ **feasible** $q = (q^0, \ldots, q^N)$

  – with VI operator $F(q) = \prod_{i=0}^{N} F^i(q)$

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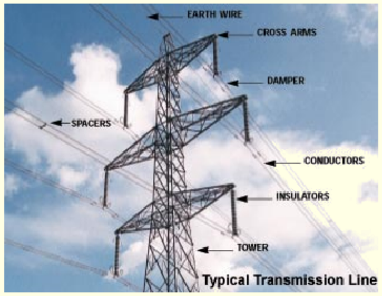
  - with VI feasible set $C = \prod_{i=0}^{N} Q^i \bigcap \{q : MC(q) = 0\}$ almost decomposable
- arising in equilibrium models for energy markets
- Create stochastic versions for VIs that tackle risk aversion
- Solve such models.

Context: the industry of electricity


Generation



Transmission

Distribution

>90's business model: competitive G + regulated TD

Rationale: fierce G competition of G provides incentive (- costs, + innovation)

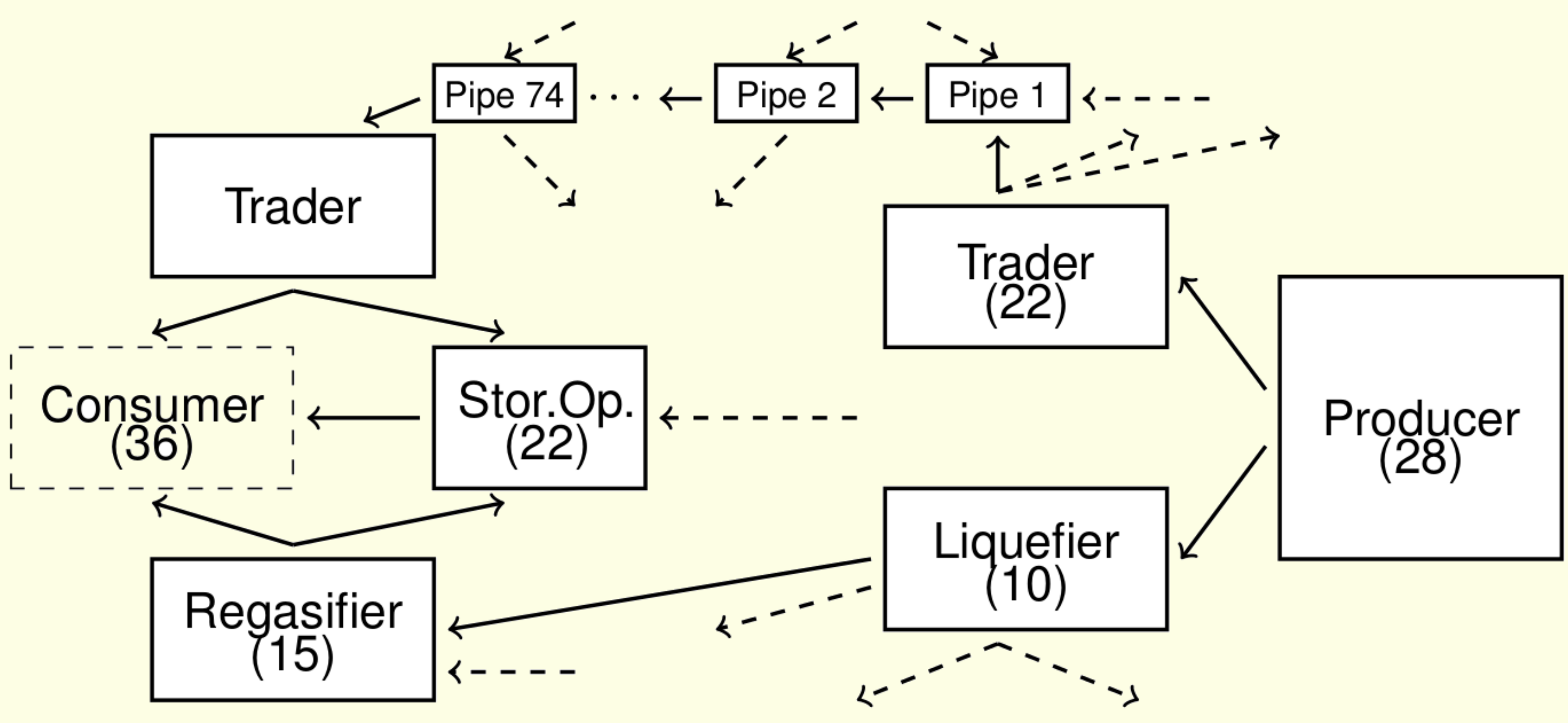
Criticism: it is not clear how fierce competition is …

This makes important to understand competitive interaction between several G firms seeking to maximize profit, taking into account unique aspects of electricity: not storable, yet supply needs to meet demand, energy needs to be transmitted from G plants to consumers, etc

European NG network

R. Egging, S. A. Gabriel, F. Holtz and J. Zhuang

A complementarity model for the European natural gas market**Energy Policy**, **36:2385–2414, 2008.**



Market: Premises

- Agents (producers, traders, logistics)
  - -take unilateral decisions
  - -behave competitively
- A representative of the consumers (the ISO)
  - -focuses on the benefits of consumption
  - -seeking a price that matches supply and demand
  - -while keeping prices “low”
- Agents’ actions coupled by some relations, clearing the market.

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Typically, models from game theory or complementarity leading to VIs

Market as a generalized Nash model

- Agents (producers, traders, logistics)

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i\text{th producer problem} \left\{ \begin{array}{ll} \min & c^i(q^i) \\ \text{s.t.} & q^i \in Q^i \\ & q^i + \sum_{j \neq i} \tilde{q}^j = DEM \iff \text{MC}(q^i, \tilde{q}^{-i}) = 0 \end{array} \right.
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\text{Agent } 0 \text{ problem} \left\{ \begin{array}{ll} \min & c^0(\tilde{q}^{-0}) \qquad\qquad (\equiv \text{max welfare}) \\ \text{s.t.} & q^0 = \text{DEM} - \sum_{j \neq 0} \tilde{q}^j \in Q^0 \end{array} \right.
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Market: Equilibrium price: $\bar{\pi}$

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A Variational Equilibrium of the game is a Generalized Nash Equilibrium satisfying $\bar{\pi}^i = \bar{\pi}$

Market: Variational Equilibrium price: same $\bar{\pi}$

+ Agents (producers, traders, logistics)

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Variational Inequality follows from optimality conditions

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$$\boxed{\begin{array}{c} \text{1st order OC} \\ \text{(primal form)} \\ \left\langle \nabla_{q^i} c^i(\bar{q}), q^i - \bar{q}^i \right\rangle \geq 0 \\ \forall q^i \in Q^i \cap \textsc{mc} \end{array}}$$

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Variational Inequality follows from optimality conditions

In $\mathrm{VI}(F, C) : \left\langle F(\bar{q}), q - \bar{q} \right\rangle \geq 0 \; \forall$ feasible q

- the VI operator $F(q) = \prod_{i=0}^{N} F^i(q)$ for $F^i(q) = \nabla_{q^i} c^i(q)$
- the VI feasible set $C = \prod_{i=0}^{N} Q^i \bigcap \{q : \textsc{mc}(q) = 0\}$

NOTE: $\textsc{mc}$ does not depend on i: constraint is **shared**

Application to symmetric electricity market

An ISO wants to design a market, by splitting a set of

$N_T = 100$ thermal power plants into

$N = \{1, 2, 3, 4, 5, 10, 25, 50, 75, 100\}$ firms.

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π	**20.5**	**20.5**	**20.5**	**20**	**20**	**20**	**20**	**20**
Deficit	**5**	**5**	**5**	**0**	**0**	**0**	**0**	**0**

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If less than 4 firms share the market

it behaves like a monopoly,

with bad consequences for consumers: **+ price, - quality**

What about uncertainty?

Suppose there are $k = 1, \ldots, K$ uncertain scenarios (demand, costs, etc)

Production variables depend on realizations: $q_k = (q_k^i, i = 0, \ldots, N)$

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\text{ith problem for scenario } k \quad \left\{
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\min & c_k^i(q_k^i, q_k^{-i}) \\
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For one scenario k, a VI(F_k, C_k) with $F_k^i(q_k) = \nabla_{q_k^i} c_k^i(q_k)$

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For one scenario k, a $\mathrm{VI}(F_k, C_k)$ with $F_k^i(q_k) = \nabla_{q_k^i} c_k^i(q_k)$

VI literature treats uncertainty in $\mathrm{VI}(F_k, C_k)$ using a gap function, or taking expectation in F: $\mathrm{VI}(\mathbb{E}\left[(F_k)_{k=1}^K\right], C_{\cancel{k}})$ same C

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We can do better (VI origin is known)

1st handle uncertainty in agents problems

2nd derive the VI

Stochastic VI for risk-averse agents

Use $\mathtt{CVaR}$ risk measure, and derive VI from

$$\text{ith problem with risk aversion} \quad \begin{cases} \min & \mathtt{CVaR}\left[(c_k^i(q_k))_{k=1}^K\right] \\ \text{s.t.} & q_k^i \in Q_k^i \text{ for } k = 1:K \\ & \mathrm{MC}_k(q_k) = 0 \text{ for } k = 1:K \end{cases}$$

Difficulties arise:

- As written, $\mathtt{CVaR}$ nonsmoothness makes the VI operator $\partial_{\mathbf{q}^i_{1:K}} \mathtt{CVaR}\left[c^i(q)\right]$, **multivalued**

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Difficulties arise:

- As written, $\mathtt{CVaR}$ nonsmoothness makes the VI operator $\partial_{\mathbf{q}^i_{1:K}} \mathtt{CVaR}\left[c^i(q)\right]$, **multivalued**
- Reformulating the agents problem by means of $\mathtt{CVaR}_\varepsilon[\mathcal{Z}] = \min_u \left\{u + \frac{1}{1-\varepsilon}\mathbb{E}\left[[\mathcal{Z}_k - u]^+\right]\right\}$ **couples all scenarios**.

$\texttt{CVaR}$ reformulation

FROM $\left\{ \begin{array}{ll} \min & \texttt{CVaR}\left[(c_k^i(q_k))_{k=1}^K\right] \\ \text{s.t.} & q_k^i \in Q_k^i \text{ for } k = 1:K \\ & \text{MC}_k(q_k) = 0 \text{ for } k = 1:K, \end{array} \right.$ using

$\texttt{CVaR}[\mathcal{Z}] := \min_u \left\{ u + \frac{1}{1-\varepsilon}\mathbb{E}\left[[\mathcal{Z}_k - u]^+\right] \right\}$ and writing $[]^+$ by means of new variables and constraints

TO: $\left\{ \begin{array}{ll} \min & \mathbf{u^i} + \frac{1}{1-\varepsilon}\mathbb{E}\left[(\mathbf{T_k^i})_{\mathbf{k=1}}^{\mathbf{K}}\right] \\ \text{s.t.} & q_k \in Q_k \text{ for } k = 1:K \\ & \text{MC}_k(q_k) = 0 \text{ for } k = 1:K \\ & T_k^i \geq c_k^i(q_k) - u^i, T_k^i \geq 0 \text{ for } k = 1:K, \mathbf{u^i} \in \mathbb{R} \end{array} \right.$

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NOTE: new constraint is **NOT shared**

no longer a generalized Nash game, but a bilinear CP ($\exists$?).

Dealing with multivalued Risk-Averse VIs

The risk measure $\rho(\mathcal{Z}) := \mathtt{CVaR}_\varepsilon[\mathcal{Z}] = \min_u \left\{ u + \frac{1}{1-\varepsilon} \mathbb{E}\left[[\mathcal{Z}_k - u]^+ \right] \right\}$
is nonsmooth because it is a value-function and $[\cdot]^+$ is nonsmooth

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We use smooth approximations ρ^ℓ

$$\rho^\ell(\boldsymbol{\mathcal{Z}}) := \min_u \left\{u + \frac{1}{1-\varepsilon}\mathbb{E}\left[\sigma_\ell(\boldsymbol{\mathcal{Z}}_k - u)\right]\right\},$$

for smoothing $\sigma_\ell \to [\cdot]^+$ uniformly as $\tau_\ell \to 0$. For instance,

$$\sigma_\ell(t) = (t + \sqrt{t^2 + 4\tau_\ell^2})/2$$

Since ρ^ℓ is smooth, $\mathbf{VI}(F^\ell, C)$ has a a single-valued VI operator involving $\nabla_{q^i}\rho^\ell\left[(c_k^i(q_k))_{k=1}^K\right]$

Theorems

- like CVaR, ρ^ℓ is a risk-measure
  - convex, monotone, and translation equi-variant,
  - but not positively homogeneous (only coherent in the limit).
- ρ^ℓ is C^2 for strictly convex smoothings such as $(t + \sqrt{t^2 + 4\tau_\ell^2})/2$
- Any accumulation point of the smoothed problems solves the original risk-averse (non-smooth) problem as $\ell \to \infty$.

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  existence result

Reference: An approximation scheme for a class of risk-averse stochastic equilibrium problems. Luna, Sagastizábal, Solodov

Assessing both options

- Smoothed `CVaR`
  - Keeps feasible set separable by scenarios: easier VI
  - Needs to drive smoothing parameter to ∞: repeated VI solving
- Reformulated `CVaR`
  - eliminates nonsmoothness
  - Non-separable feasible set

Smoothed versus Reformulated CVaR

Random toy problems solved with PATH S. Dirkse, M. C. Ferris, and T. Munson

- Time (averaged for 5 instances)

  With $K = 20$ both formulations take 13 s

  With $K = 100$, reformulated CVaR takes **100** times longer

  (smoothing 33 s, reformulation 55 min!)

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- Solution quality (20 runs, $K = 50$): comparing equilibrium prices and production variables obtained with $\tau \in \{10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 0.2, 0.4, 0.6, 0.8, 1., 10, 50, 75, 100\}$ and with reformulation gives practically identical results for $\tau^{\ell} < 1$.

Final Comments

- When in the agents' problems objective function depends on actions of other agents', writing down the stochastic VI can be tricky: which selection mechanism in a 2-stage setting?
- Handling `CVaR` nonsmoothness via reformulation seems inadequate for large instances
- Smoothing solves satisfactorily the original risk-averse nonsmooth problem for moderate τ (no need to make $\tau \to 0$)
- Smoothing preserves separability; it is possible to combine
  - Benders' techniques (along scenarios) with
  - Dantzig-Wolfe decomposition (along agents)
- Decomposition matters: for European Natural Gas network
  - Solving VI directly with PATH solver S. Dirkse, M. C. Ferris, and T. Munson
  - Using DW-decomposition **saves 2/3 of solution time**

From April to June 2016 IMPA will host

http://svan2016.sciencesconf.org, a thematic trimestre

Stochastic Variational Analysis

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Stochastic Variational Analysis

- Workshop on Analysis and Applications of Stochastic Systems
  - stochastic networks and games;
  - energy markets and financial mathematics, and
  - the optimal control and optimization of systems s. t. uncertainty.
- Basic course on Stochastic Programming and minicourses on
  - Scenario generation and sampling methods
  - Randomized Methods, Machine Learning, Big Data
  - Equilibrium Routing under Uncertainty
  - Stochastic VIs
- ICSP 2016

Plenary talks in

http://icsp2016.sciencesconf.org

- Designing the uncertainty models (J. Royset)
- Risk measures (A. Ruszczynski)
- Mixed integer stochastic programming (S. Ahmed)
- Stochastic programming for energy planning (M. Pereira)

Minisymposia (=1 semiplenary + 3 talks)

- Data-driven methods (G. Bayraksan)
- Stochastic dynamic programming (D. Brown)
- Machine learning and stochastic optimization (W. Powell)
- Stochastic equilibrium and variational inequalities (H. Xu)
- Finance (M. Kopa)
- Applications in natural resources (D. Woodruff)

Tutorials on the weekend before the conference

SAVE THE DATES! June 25th-July 1st, 2016

Submission deadlines

Thematic Sessions: June, July, August, 2015

Individual Contributions: September 2015 - January 2016