A proposal for the practice of optimization in the Institute for energy transition Efficacity

Michel DE LARA
CERMICS, École des Ponts ParisTech, France

CERMICS, France

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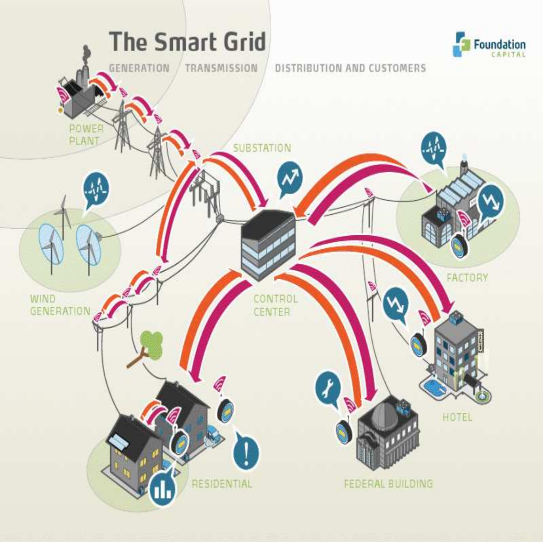
Challenges ahead for optimization in energy



Optimizing is obtaining the best compromise between needs and resources

Marcel Boiteux (président d'honneur d'Électricité de France)

Outline of the talk

- In 2000, the *Optimization and Systems* group was created at École des Ponts ParisTech and, since then, we have *trained PhD students* in stochastic optimization, mostly with Électricité de France Research and Development
- Since 2011, we witness a growing demand from energy firms for stochastic optimization, fueled by a *deep and fast transformation of power systems*
- We will sketch *mathematical optimization*
  and cast a glow on optimization methods relevant for *smart grid* issues

Outline of the presentation

1. How we cooperate between academy and industry
2. What is happening to power systems?
3. How we frame energy issues as mathematical optimization problems
4. What practices for optimization in Efficacity?

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Outline of the presentation

1. How we cooperate between academy and industry
   - École des Ponts ParisTech–Cermics–Optimization and Systems
   - Industry partners of the Optimization and Systems Group
2. What is happening to power systems?
3. How we frame energy issues as mathematical optimization problems
   - What is “mathematical optimization”?
   - How do we deal with multi-criteria?
   - What is stochastic optimization?
   - What optimization methods are suited for smart grids?
4. What practices for optimization in Efficacity?

Let's open the Russian dolls... one by one

University Paris-Est

- École des Ponts ParisTech
  is one of the world's oldest engineering institutes
  and hosts a substantial research activity
  - CERMICS
    is the applied mathematics and scientific computing research center
    - The Optimization and Systems Group
      is one of the three groups harbored by the Cermics

Here is the flesh and blood of the Optimization and Systems Group

- Senior researchers
  - J.-P. CHANCELIER
  - M. DE LARA
  - V. LECLÈRE
  - F. MEUNIER
- Associated researcher
  - P. CARPENTIER (ENSTA ParisTech)
- PhD students

The Optimization and Systems Group specializes in... optimization!

- Methods
  - Stochastic optimal control (discrete-time)
    - Large-scale systems
    - Discretization and numerical methods
    - Probability constraints
  - System control theory, viability and stochastic viability
  - Discrete mathematics; combinatorial optimization; operations research
- Applications
  - Optimized management of energy systems under uncertainty (production scheduling, power grid operations, risk management)
  - Transport modelling and management
  - Natural resources management (fisheries, mining, epidemiology)
- Softwares
  - Scicoslab, NSP
  - Oadlibsim

We teach at master and engineering levels

- Masters
  - *Master Parisien de Recherche Opérationnelle*
  - *Optimisation & Théorie des Jeux. Modélisation en Economie*
  - *Mathématiques, Informatique et Applications*
  - *Économie du Développement Durable, de l'Environnement et de l'Énergie*
  - *Renewable Energy Science and Technology Master ParisTech*
- École des Ponts ParisTech
  - Introduction à la recherche opérationnelle (F. MEUNIER)
  - Optimisation et contrôle (J.-P. CHANCELIER)
  - Modéliser l'aléa (J.-P. CHANCELIER)
  - Modélisation pour la gestion durable des ressources naturelles (M. DE LARA)

Our industrial contracts mostly deal with energy issues, whereas the public ones touch on biodiversity management

- Industrial contracts
  - Conseil français de l'énergie (CFE)
  - SETEC Energy Solutions
  - Électricité de France (EDF R&D)
  - Thales
  - Institut français de l'énergie (IFE)
  - Gaz de France (GDF)
  - PSA
- Public contracts
  - STIC-AmSud (CNRS-INRIA-Affaires étrangères)
  - Centre d'étude des tunnels
  - CNRS ACI Écologie quantitative
  - RTP CNRS

Outline of the presentation

We cooperate with industry partners, looking for longlasting research relations through training and capacity building

- As academics, we cooperate with industry partners, looking for longlasting close relations
- We are not consultants working for clients, but focus en capacity building
- Our job consists mainly in
  - training Master and PhD students, working within the company and interacting with us, on subjects designed jointly
  - developing methods, algorithms
  - contributing to computer codes developed within the company
  - training professional engineers in the company

Électricité de France R & D / Département OSIRIS

- Électricité de France is the French electricity main producer
  - 159 000 collaborateurs dans le monde
  - 37 millions de clients dans le monde
  - 65,2 milliards d'euros de chiffre d'affaire
  - 630,4 TWh produits dans le monde
- Électricité de France Research & Development
  - 486 millions d'euros de budget
  - 2 000 personnes
- Département OSIRIS
  Optimisation, simulation, risques et statistiques pour les marchés de l'énergie
  Optimization, simulation, risks and statistics for the energy markets
  - 145 salariés (dont 10 doctorants)
  - 25 millions d'euros de budget

Recently, contacts have expanded with small companies

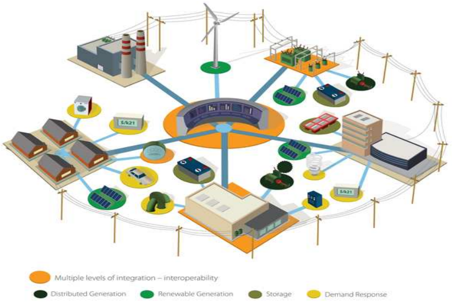
- ARTELYS is a company specializing in optimization, decision-making and modeling. Relying on their high level of expertise in quantitative methods, the consultants deliver efficient solutions to complex business problems. They provide services to diversified industries: Energy & Environment, Logistics & Transportation, Telecommunications, Finance and Defense.
- Créée en 2011, SETEC Energy Solutions est la filiale du groupe SETEC spécialisée dans les domaines de la production et de la maîtrise de l'énergie en France et à l'étranger. SETEC Energy Solutions apporte à ses clients la maîtrise des principaux process énergétiques pour la mise en œuvre de solutions innovantes depuis les phases initiales de définition d'un projet jusqu'à son exploitation.
- SUN'R Smart Energy is a Paris based company with a focus on building smarter solutions for distributed energy resources in the context of emerging deregulated energy markets and a solid political will towards the development of both renewables and energy storage. The company is part of a larger group founded in 2007 and is a growing, well-funded early stage business.

French Energy Council, member of the World Energy Council, contracted the Optimization and Systems group to report on Optimization methods for smart grids

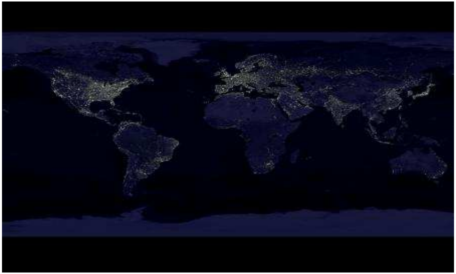
- Formed in 1923, the World Energy Council (WEC) is the UN-accredited global energy body, representing the entire energy spectrum
- WEC informs global, regional and national energy strategies
- In 2012, the French Energy Council contracted the Optimization and Systems group to produce a report on Optimization methods for smart grids, freely available on October 2014
  - Power Systems Undergo a Deep Remolding
  - Energy Actors Express Renewed Demands towards Optimization
  - Uncertainty in Decision-Making Can Be Handled in Many Ways
  - Displaying Stochastic Optimization Resolution Methods
  - Relating Ongoing Works and Practices

Outline of the presentation

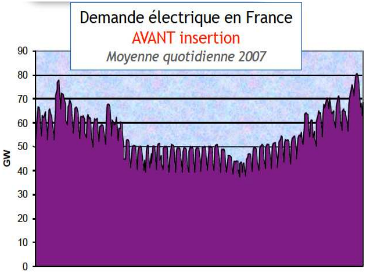
Three key drivers are remolding power systems

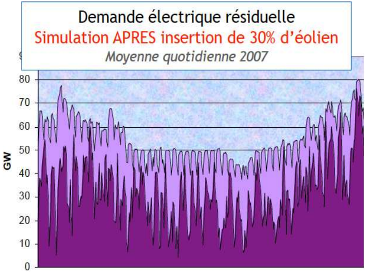


- Environment
- Markets
- Technology



Key driver: environmental concern





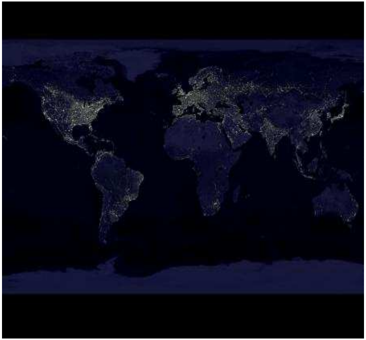
The European Union climate and energy package materializes an environmental concern with three 20-20-20 objectives for 2020

- a 20% improvement in the EU's energy efficiency
- a 20% reduction in EU greenhouse gas emissions from 1990 levels
- raising the share of EU energy consumption produced from renewable resources to 20%

$\Downarrow$

Successfully integrating renewable energy sources has become critical, and made especially difficult because they are unpredictable and highly variable, hence triggering the use of local storage

Key driver: economic deregulation



- A power system (generation/transmission/distribution)
  - less and less vertical (deregulation of energy markets)
  - hence with many players with their own goals
- with some new players
  - industry (electric vehicle)
  - regional public authorities (autonomy, efficiency)
- with a network in horizontal expansion
- with more and more exchanges (trade of commodities)

$\Downarrow$

A change of paradigm for management
from centralized to more and more decentralized

Key driver: telecommunication technology

Linky

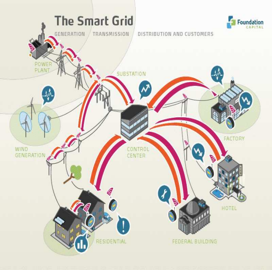
A power system with more and more technology due to evolutions in the fields of metering, computing and telecoms

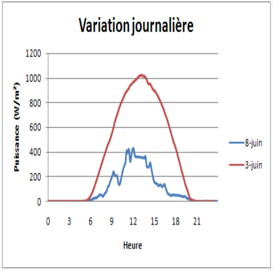
- smart meters
- sensors
- controllers
- grid communication devices. . .

⇓

A huge amount of data which, one day, will be a new potential for optimized management

The "smart grid"? An infrastructure project with promises to be fulfilled by a "smart power system"





- Hardware / infrastructures / smart technologies
  - Renewable energies technologies
  - Smart metering
  - Storage
- Promises
  - Quality, tariffs
  - More safety
  - More renewables (environmentally friendly)
- Software / smart management
  (energy supply being less flexible,
  make the demand more flexible)

smart management, smart operation, smart meter management, smart distributed generation, load management, advanced distribution management systems, active demand management, diffuse effacement, distribution management systems, storage management, smart home, demand side management. . .

Outline of the presentation

What is “optimization”?

Optimizing is obtaining the best compromise between needs and resources

Marcel Boiteux (président d’honneur d’Électricité de France)

- Resources: portfolio of assets
  - production units
    - costly/not costly: thermal/hydropower
    - stock/flow, predictable/unpredictable: thermal/wind
  - tariffs options, contracts
- Needs: energy, safety, environment
  - energy uses
  - safety, quality, resilience (breakdowns, blackout)
  - environment protection (pollution) and alternative uses (dam water)
- Best compromise: minimize socio-economic costs (including externalities)

When one speaks of optimization, it may refer to
optimizing investment *or* optimizing operations/control

Outline of the presentation

Let us have a look at economic dispatch (static) as a cost-minimization problem under supply-demand balance

Consider energy production units $i = 1, \ldots, N$, like coal, gas, nuclear...

$$\underbrace{\min_{(u_1,\ldots,u_N)} \sum_{i=1}^{N} J_i(u_i)}_{\text{costs minimization}} \quad \text{under} \quad \underbrace{\sum_{i=1}^{N} \Theta_i(u_i) = D}_{\text{supply = demand}}$$

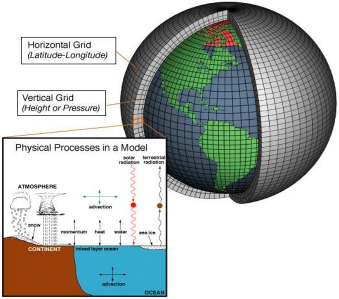
where

- u_i is the decision (production level) made for each unit i
- $J_i(u_i)$ is the cost of making decision u_i for unit i
- $\Theta_i(u_i)$ is the production induced by making decision u_i for unit i
- D is the demand

In practice, we first have to contend with a modeling issue

- What are the decision variables?
  (the ones with respect to which we will optimize)
  - Investment: battery capacity? number of solar panels?
  - Operations: battery energy delivery (how much and when?), online dispatch
- What is the timing of decision-making? What is the horizon?
- What are the other variables: stocks? energy demand? market exchanges? fatal energy production (wind, solar)?
- Which variables enjoy known values? (parameters, demand chronicles)
  Which variables are unknown or, possibly, display a statistical description? (demand, fatal energy production)
- What (physical) relations relate and constrain all variables?
  (static, dynamic)

Then, we embark on fabricating models: knowledge/simulation models *versus* decision models



Knowledge models:
1/1 000 000 → 1/1 000 → 1/1 maps
to support numerical simulations

Office of Oceanic and Atmospheric Research (OAR) climate model

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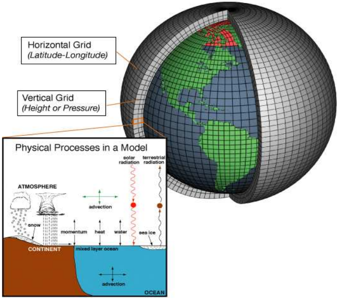

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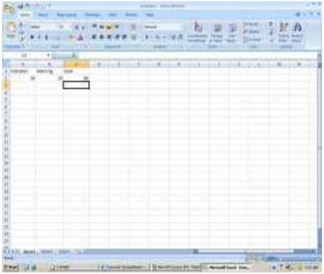

Action/decision models:
to design (optimal) strategies

William Nordhaus
economic-climate model

In practice, we first have to contend with a modeling issue (follow up)

- What are the (multiple) objectives?
  How can we formulate them as criteria exceeding thresholds?
- What are the costs? And how can we build up a criterion to optimize?
  (cost to minimize, value to maximize)

Second, we formulate optimization problems

- Decision variables u, belonging to a decision space $\mathcal{U}$

$$u \in \mathcal{U}$$

  - $\mathcal{U}$ may include scalar, vectorial, integer variables
  - u_i may be possibly indexed by agents/units/nodes
  - u_t may be possibly indexed by time
  - u_ω may be possibly indexed by randomness/uncertainty
- Constraints restrict the wiggle room of decision variables

$$u \in \mathcal{U}^{ad} \subset \mathcal{U}$$

  - bound constraints (capacities)
  - relations between agents/units/nodes
  - static or dynamic relations between successive times
  - information relations (who knows what)

Second, we formulate optimization problems (follow up)

- Criteria are indicators, that make possible to materialize objectives
  - functions attaching a value to a decision
  - in optimization, one specific function J is selected,
  - whereas the other criteria enter into “target” constraints (with achievable thresholds)
- Finally, we arrive at a mathematical optimization problem

$$\min_{u \in \mathcal{U}^{ad}} J(u)$$

Third, we mobilize optimization methods and algorithms, and develop proper ones

- numerical methods (with decision models)
- algorithms
- softwares
- simulations (on simulation models)

Outline of the presentation

How do we deal with multi-criteria?

- Different agents/viewpoints $a \in A$
- Multiple indicators/criteria (with different units)

$$u \mapsto J_a(u) \; , \quad a \in A$$

- Multiple objectives = criteria + threshold/target

$$J_a(u) \leq \theta_a \; , \quad a \in A$$

- We distinguish one indicator

$$J_A(u) = \Phi\big(J_a(u) \; , \quad a \in A\big)$$

- Finally, we arrive at a mathematical optimization problem

$$\begin{array}{l} \min_{u \in \mathcal{U}^{ad}} J_A(u) \\ J_a(u) \leq \theta_a \; , \quad a \in A \end{array}$$

We distinguish ex post from ex ante multi-criteria formulations

- Ex ante multi-criteria formulation

$$J_A(u) = \sum_{a \in A} \lambda_a J_a(u)$$

  where the weights λ_a are fixed ex ante
- Ex post multi-criteria formulation
  - starts with a focal agent $\overline{a}$ (whatever)
  - pays attention to the optimum

$$J^{\star}_{\overline{a}}(\theta_a, a \neq \overline{a}) = \begin{array}{l} \min_{u \in \mathcal{U}^{ad}} J_{\overline{a}}(u) \\ J_a(u) \leq \theta_a \ , \ \ a \neq \overline{a} \end{array}$$

  - studies the sensitivity of the optimum with respect to marginal changes $\theta_a \to \theta_a + \epsilon_a$ in the objectives

We recommend ex post multi-criteria formulation rather than ex ante

- The sensitivity of the optimum $J^\star_{\overline{a}}(\theta_a, a \neq \overline{a})$ with respect to relaxing/strengthening objective a is materialized by μ_a

$$\mu_a = \frac{\partial J^\star_{\overline{a}}(\theta_a, a \neq \overline{a})}{\partial \theta_a}$$

(provided as a constraint multiplier by the numerical optimization process)

- and we obtain an ex post multi-criteria formulation

$$J_A(u) = 1 \times J_{\overline{a}}(u) + \sum_{a \neq \overline{a}} \mu_a J_a(u)$$

where the weights $1, \mu_a, a \neq \overline{a}$ are determined ex post

Outline of the presentation

Inviting in uncertainty gives economic dispatch new suits of clothes

$$\underbrace{\min_{(u_1,\ldots,u_N)} \mathbb{E}\Big[\sum_{i=1}^{N} J_i(u_i, \overbrace{p_i}^{\text{price}})\Big]}_{\text{expected costs minimization}} \quad \text{under} \quad \underbrace{\sum_{i=1}^{N} \Theta_i(u_i, \overbrace{w_i}^{\text{weather}}) = \overbrace{D}^{\text{demand}}}_{\text{almost-surely supply = demand}}$$

- Mathematical description of sources of uncertainties (prices p_i, weather w_i, demand D, failures...): statistics? bounds?
- Mathematical formulation of the criterion under uncertainty: in expectation ($\mathbb{E}$)? worst case (max)?
- Mathematical formulation of the constraints under uncertainty: in expectation? in probability? almost surely? robust? by penalization?

With uncertainty come stages, hence a dynamics

- In electricity, the *supply matches demand* equation "is like gravity, you cannot negociate" (who claimed that?)
- One way or another, we are driven to add a new instantaneous source u_{N+1}

$$\sum_{i=1}^{N} \Theta_i(u_i, \overbrace{w_i}^{\text{weather}}) + \underbrace{u_{N+1}}_{\text{new source}} = \overbrace{D}^{\text{demand}}$$

- The control $u_{N+1} = D - \sum_{i=1}^{N} \Theta_i(u_i, w_i)$ depends on the uncertain variables D and $w_1, \ldots, w_N$
- Whereas $u_1, \ldots, u_N$ are decisions made before knowing their realizations
- To cut to the point, we now have two stages

$$\Downarrow$$

Piecing things together, we started from static economic dispatch and we arrive at dynamic economic dispatch under risk

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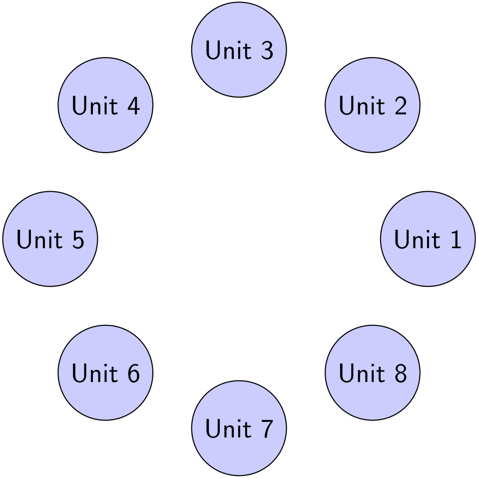
3. How we frame energy issues as mathematical optimization problems
   - What is "mathematical optimization"?
   - How do we deal with multi-criteria?
   - What is stochastic optimization?
   - What optimization methods are suited for smart grids?
4. What practices for optimization in Efficacity?

We have a nice decomposed problem but. . .

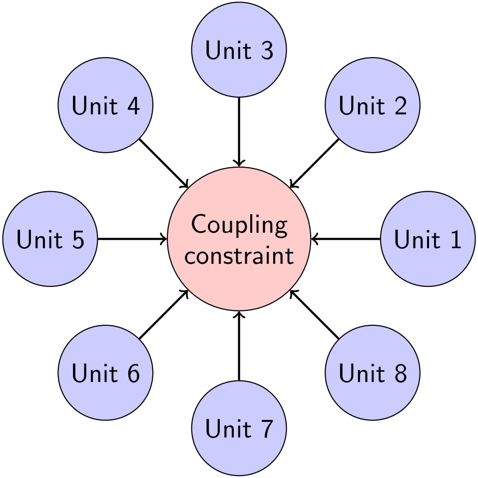
Flower structure



We are almost in the case where units could be driven independently one from another

We have a nice decomposed problem but. . .

Flower structure



Unfortunately...

The associated optimization problem can be written as

$$\underbrace{\min_{(u_1,\ldots,u_N)} \sum_{i=1}^{N} J_i(u_i)}_{\text{costs minimization}} \quad \text{under} \quad \underbrace{\sum_{i=1}^{N} \Theta_i(u_i) = D}_{\text{supply = demand}}$$

where

- u_i is the decision of each unit i
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Under appropriate duality assumptions, the associated optimization problem can be written without constraints

- For a proper Lagrange multiplier λ

$$\min_{(u_1,\ldots,u_N)} \sum_{i=1}^{N} J_i(u_i) + \lambda \underbrace{\Big(\sum_{i=1}^{N} \Theta_i(u_i) - D \Big)}_{\text{constraint}}$$

- We distribute the coupling constraint to each unit i

$$\min_{(u_1,\ldots,u_N)} \Big(\sum_{i=1}^{N} J_i(u_i) + \lambda \Theta_i(u_i) \Big) - \lambda D$$

- The problems splits into N optimization problems

$$\min_{u_i} \big(J_i(u_i) + \lambda \Theta_i(u_i) \big) , \quad \forall i = 1, \ldots, N$$

Proper prices allow decentralization of the optimum

$$\min_{(u_1,\ldots,u_N)} \sum_{i=1}^{N} J_i(u_i) \quad \text{under} \quad \sum_{i=1}^{N} \Theta_i(u_i) = D$$

The simplest decomposition/coordination scheme consists in

- buying the production of each unit at a price $\lambda^{(k)}$ at iteration k
- and letting each unit minimize its modified costs

$$\min_{u_i} J_i(u_i) + \underbrace{\lambda^{(k)}}_{\text{price}} \Theta_i(u_i)$$

- then, updating the price depending on the coupling constraint

$$\lambda^{(k+1)} = \lambda^{(k)} + \rho\Big(\sum_{i=1}^{N} \Theta_i(u_i) - D\Big)$$

(like in the "tâtonnement de Walras" in Economics)

Take advantage of decentralizing the computation

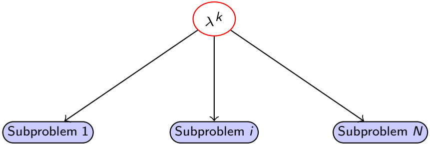
Samples/scenarios of
dual variable
at iteration k

λ^k

Take advantage of decentralizing the computation

Samples/scenarios of
dual variable
at iteration k

We solve subproblems
using $\mathbb{E}(\lambda^k|\mathbf{y})$
by Dynamic Programming



Take advantage of decentralizing the computation

Samples/scenarios of
dual variable
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We solve subproblems
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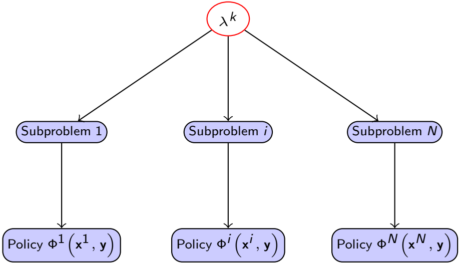
by Dynamic Programming

We obtain policies



Take advantage of decentralizing the computation

Samples/scenarios of
dual variable
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We solve subproblems
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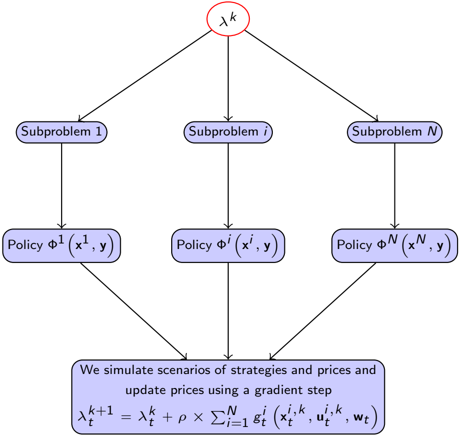
We obtain policies

We update prices
using a gradient step



Take advantage of decentralizing the computation

At iteration $k + 1$

We solve subproblems
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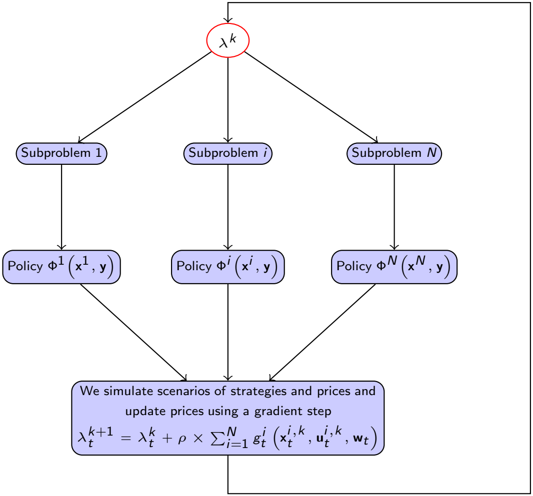
by Dynamic Programming

We obtain policies

We update prices
using a gradient step



Outline of the presentation

Agenda between Optimization and Systems Group and Efficacity researchers

Agree on shared vocabulary and concepts, and

- Work out (rough) decision models
- Formulate mathematical optimization problems
- Look for optimization methods and algorithms
- Develop software
- Try the algorithms on (detailed) simulation models
- ... Go back to first item ;-)