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Bilevel Modelling of Energy Pricing Problem

Sezin Afşar, Luce Brotcorne, Patrice Marcotte, Gilles Savard

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1-4 November 2015
Outline

Demand Side Management

Bilevel Programming

Heuristic Methods

Conclusion
Demand Side Management

Motivation

- Demand for energy is largely uncontrollable and varies with time of day and season.
  - In UK, given the average demand across the year, the average utilization of the generation capacity is \( \leq 55\% \).
  - Minimum demand in summer nights \( \approx 30\% \) of the winter peak
- Energy is difficult to store in large quantities.
- Supply-demand balance failure \( \rightarrow \) system instability
- Total capacity of installed generation must be \( \geq \) max demand to ensure the security of supply.
Demand Side Management

Why Necessary?

- DSM: control and manipulate the demand to meet capacity constraints.
- DSM’s role: To improve the efficiency of operation and investment in the system.

Demand Side Management

Major DSM Techniques

- Direct load control, load limiters, load switching
- Commercial/industrial programmes
- Demand bidding
- Time-of-use pricing
- Smart metering and appliances

New Challenge

"Commitment to market based operation and deregulation of the electricity industry places consumers of electricity in the center of the decision-making process regarding the operation and future development of the system" - G. Strbac, 2008
Demand Side Management

Residential Electricity Use

- Air Conditioning: 23%
- Water Heating: 9%
- Refrigerators: 7%
- Space Heating: 6%
- All Other Appliances and Lighting: 55%
Bilevel Programming

Classical Mathematical Program

\[
\max_x f(x) \\
\text{s.t.} \quad x \in X
\]

Bilevel Program

\[
\max_x f(x, y) \\
\text{s.t.} \quad (x, y) \in X \\
y \text{ solves } \min_y g(x, y) \\
\text{s.t.} \quad (x, y) \in Y
\]

Luce Brotcorne

A Bilevel Approach to Energy Pricing Problem using Smart Grids
Bilevel Programming

Classical Mathematical Program

\[ \max_x f(x) \]
\[ \text{s.t.} \]
\[ x \in X \]

Bilevel Program

\[ \max_x f(x, y) \]
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\[ y \text{ solves } \min_y g(x, y) \]
\[ \text{s.t.} \]
\[ (x, y) \in Y \]

Consumer Behavior

Demand Response
Energy Pricing Problem

Smart Grid Technology

- Every customer is equipped with a device that can receive, process and transfer data: smart meter
- Smart meters communicate with each other → smart grid
- Meters are programmable according to the needs of the customer
- Smart grid receives prices from the supplier(s), demand from the customers and schedules the consumption
Energy Pricing Problem

Bilevel Approach

Supplier(s)

Maximize Revenue
Minimize Peak
Minimize Deviations

Maximize Utility Function

Schedule

Hourly Prices
Incentives
Capacity

Smart Grid

Demand
Time Windows

Customer1
Customer2
Customer n

A Bilevel Approach to Energy Pricing Problem using Smart Grids
Bilevel Model

Properties

- Stackelberg game / Bilevel programming
- The supplier (upper level) and a group of customers connected to a smart grid (lower level).
- Prices from supplier and demand with time windows from customers are received by the smart grid.
- Time-of-use price control to minimize peak demand and maximize revenue.
- Demand-response to hourly changing prices to minimize cost and waiting time.
Bilevel Model

Objectives

- Leader maximizes \((\text{revenue} - \text{peak cost})\) by deciding on prices.
- Follower minimizes \((\text{billing cost} + \text{waiting cost})\) by deciding on the schedule of consumption.

Assumptions

- A fixed upper bound for prices.
- Demand is fixed.
- All operations are preemptive.
- Every customer has a set of appliances and certain time windows.
- All appliances have power consumption limits.
- One cycle has 24 time slots (hours) in total.
Bilevel Model - Preemptive

\[
\begin{align*}
\max_{p, \Gamma} & \quad \sum_{n \in N} \sum_{a \in A_n} \sum_{h \in H_{n,a}} p^h x^h_{n,a} - \kappa \Gamma & \quad \text{Revenue - Peak Cost} \\
\text{s.t.} & \quad \Gamma \geq \sum_{n \in N} x^h_{n,a} \quad \forall h \in H & \quad \text{Peak Definition} \\
& \quad p^h \leq p^h_{\max} \quad \forall h \in H & \quad \text{Price Limit} \\
\min_{\chi} & \quad \sum_{n \in N} \sum_{a \in A_n} \sum_{h \in H_{n,a}} p^h x^h_{n,a} + \sum_{n \in N} \sum_{a \in A_n} \sum_{h \in H_{n,a}} C^h_{n,a} x^h_{n,a} & \quad \text{Billing Cost + Waiting Cost} \\
\text{s.t.} & \quad x^h_{n,a} \leq \gamma^\max_{n,a} \quad \forall n \in N, \forall a \in A_n, \forall h \in H_{n,a} & \quad \text{Device Limit} \\
& \quad \sum_{h \in H_{n,a}} x^h_{n,a} = E_{n,a} \quad \forall n \in N, \forall a \in A_n & \quad \text{Demand Satisfaction} \\
& \quad x^h_{n,a} \geq 0 \quad \forall n \in N, \forall a \in A_n, \forall h \in H_{n,a}
\end{align*}
\]
Bilevel Model

Exact Solution Method

- Optimality conditions (primal, dual and complementarity constraints) of the follower are added to the upper level.
- Complementary slackness constraints $\rightarrow$ linearized with binary variables.
- Objective function is linearized using the follower’s dual objective function.
- Single level MIP is solved with CPLEX.
Bilevel Model

Load Distribution Under Different Peak Parameters

Price Change Under Different Peak Parameters
Price Heuristic

Idea

- Modify the price vector
- Observe the corresponding schedule and peak
- Compute the optimal prices corresponding to this schedule with Inverse Optimization (IO)
Price Heuristic

Initialization

- Set all prices to maximum
- Find the peak, assume it happens at 13:00
- Keep the prices before 13:00 at maximum and randomly generate the rest
- Solve the lower level problem with this price vector
- Solve IO problem to find the optimal corresponding prices
- Compute the net revenue
- Repeat this procedure 50 times, pick the solution pair with best net revenue
Price Heuristic

**Iteration**

- Find the peak
- Decrease the prices of 4 time slots that come after peak
- Solve the lower level problem with this price vector
- Solve IO problem to find the optimal corresponding prices
- Compute the net revenue
- Repeat this procedure until there is no improvement
## Idea

- Based on a binary search on the peak value
- Fix a peak value
- Find a feasible schedule with respect to the peak value
- Compute the corresponding prices using Inverse Optimization
- Compute the objective function value
Peak Search Heuristic

Initialization

- UB on peak: assign all jobs to the first preferred hour
- LB on peak: minimize peak under scheduling constraints
- Combing: divide the [LB, UB] interval into 20 subintervals, and follow the previous procedure
- Pick the two best objective values and update LB and UB with corresponding peak values
Peak Search Heuristic

Iteration

- Define \((UB-LB)/2\) as the new peak limit
- Compute the objective function
- Take its left (L) and right (R) neighbors
- If one of them is better, pick that side, else, STOP

Stopping Criteria

- \(|UB - LB| < \epsilon\)
- It cannot improve the incumbent solution
Experiments

Details

- For the experiments, CPLEX version 12.3 is used on a computer with 2.66 GHz Intel 283 Xeon CPU and 4 GB RAM, running under the Windows 7 operating system.
- There are 10 randomly generated instances which consist of 10 customers, each owns 3 preemptive appliances. Since it is a system optimal model, we can say that there are 30 jobs.
- Peak weight $\kappa$ takes 5 values: 200, 400, 600, 800 and 1000.
### Table: Comparison of Optimality Gap of Heuristics

<table>
<thead>
<tr>
<th>Kappa</th>
<th>% Gap of PSH</th>
<th>% Gap of PrH</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>400</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>600</td>
<td>0.12</td>
<td>0.00</td>
</tr>
<tr>
<td>800</td>
<td>0.00</td>
<td>0.13</td>
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<tr>
<td>1000</td>
<td>1.38</td>
<td>0.12</td>
</tr>
<tr>
<td>Avg</td>
<td>0.16</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Comparisons

Experiments

**Table**: Computation Time of Classical Exact Method and Heuristics (sec)

<table>
<thead>
<tr>
<th>( \kappa )</th>
<th>CEM</th>
<th>PSH</th>
<th>PrH</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>31.90</td>
<td>21.70</td>
<td>13.50</td>
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<tr>
<td>400</td>
<td>410.40</td>
<td>102.90</td>
<td>74.70</td>
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<tr>
<td>600</td>
<td>2022.70</td>
<td>141.90</td>
<td>122.10</td>
</tr>
<tr>
<td>800</td>
<td>4244.20</td>
<td>154.00</td>
<td>152.20</td>
</tr>
<tr>
<td>1000</td>
<td>8717.70</td>
<td>153.60</td>
<td>154.00</td>
</tr>
</tbody>
</table>
Load and Price Curves of Exact Solution

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Luce Brotcorne
Load and Price Comparison for Low Peak Weight
Peak Cost Comparison of All Methods

The chart shows a comparison of peak costs for different methods across various time periods, ranging from 200 to 1000 units. The methods include:

- Peak Cost of BC
- Peak Cost of Exact
- Peak Cost of Price Heu
- Peak Cost of Peak Heu

The x-axis represents time periods from 200 to 1000, while the y-axis indicates the peak cost values, ranging up to 70,000.
## Conclusion

### Our Work

- Innovative approach for DSM
- Explicitly integrated customer response into the optimization process of the supplier
- Efficient heuristic approach to provide good solutions

### What else is Possible?

- Stochastic approach (prices, demand)
- More efficient heuristics
- Robust modelling
THANK YOU FOR LISTENING

Q & A
Bibliography


