Integrated planning of biomass inventory and energy production

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Outline

1. Production planning and investment evaluation
   - Changing fuel: From coal to wood pellets
2. Mathematical model
   - Mixed integer linear programming model
3. Benders decomposition
   - Benders optimality cuts
   - Handling multiple scenarios
4. Results

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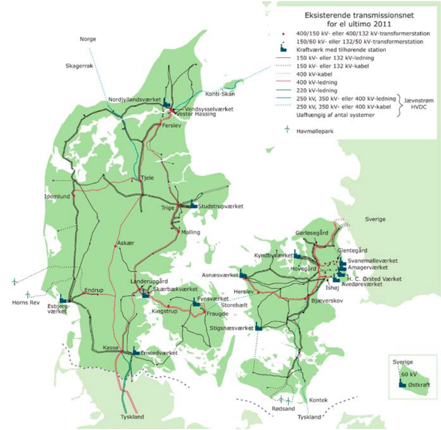
Danish energy system

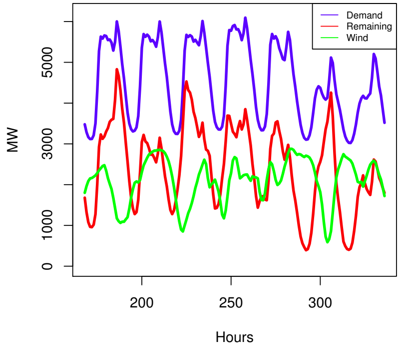
(source Energinet.dk)

Danish energy system



(source Energinet.dk)

Weekly demand profile



Energy production

- Uncontrollable:
  - Wind power
  - Solar power
- Controllable
  - Thermal units:
    Providing heat to the local heating area
  - Connections to neighboring countries
- Other sources:
  - SmartGrid
  - Electric cars

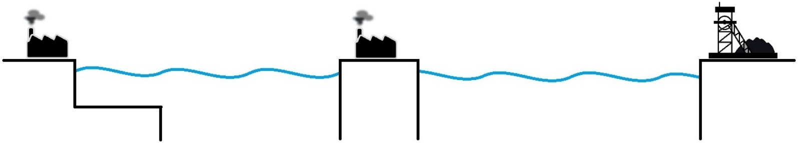
Overview of Avedøre power plant

Wood pellet storage at Avedøre

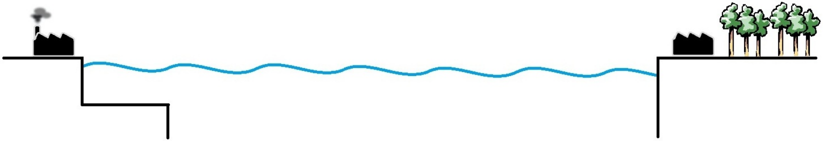
Fuel delivery processes

Logistics differences

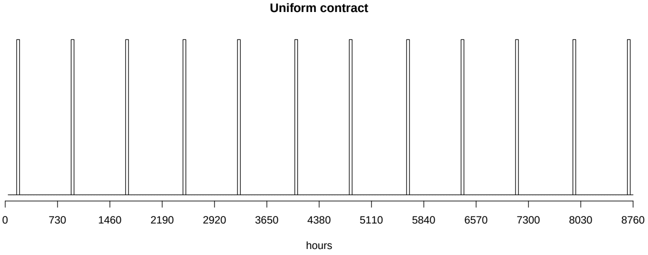
Coal logistics

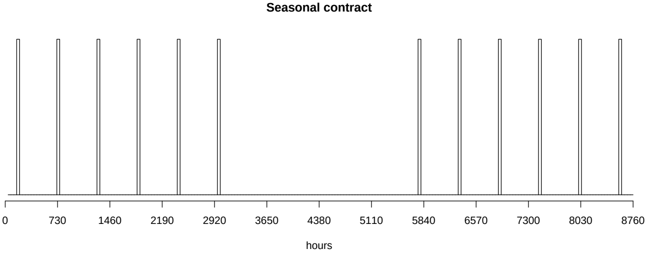


Wood pellets logistics



Biomass contracts





Two stage stochastic approach

- Biomass contracts must be decided a year ahead.
- But future demand, prices and exact delivery times are unknown $\rightsquigarrow$ uncertainty.

Two stage stochastic approach (look-ahead policy):

- **First stage**: long term decisions on biomass contracts might yield:
  - Running out of fuel (underflow)
  - Running out of storage space (overflow)
- **Second stage**: optimize when uncertainty is revealed
  - Production of electricity and heat.
  - Foreign trade (only electricity).
  - Using an alternative (fossil) fuel
  - Redirection of deliveries.

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Mixed integer linear programming model

Several scenarios for future uncertainty

Objective function (minimize):

- Cost of biomass contracts
- Use of fossil fuel
- Foreign trade
- Over/under production (slack/surplus demand)

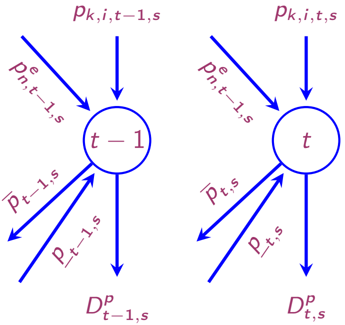
Constraints:

- Electricity and heat demand
- Power plant production (including trade with neighboring countries)
- Biomass fuel levels and redirection of deliveries

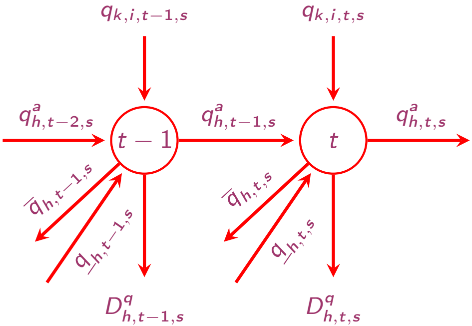
Constraints

Electricity and heat balance

Electricity

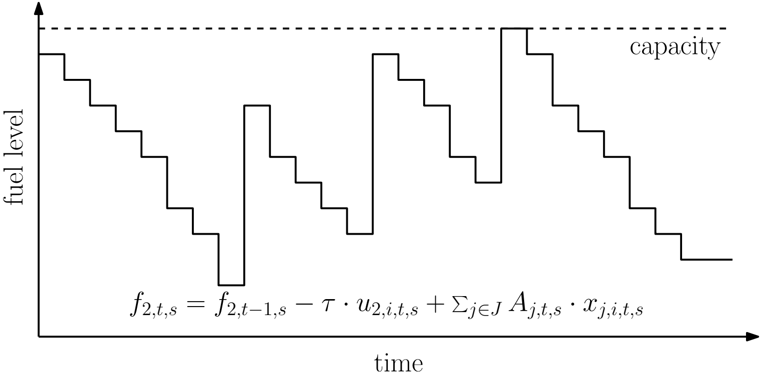


Heat



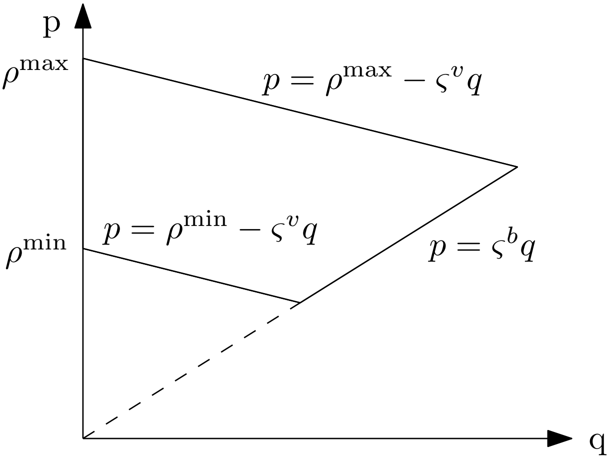
Constraints

Biomass fuel level constraints



Constraints
Modeling power plant production

Cogeneration power plant



The full model

min

$$\sum_{j \in J} C^w_j \cdot w_j + \qquad \text{biomass purchase costs} \tag{1a}$$

$$\frac{1}{|S|}\left(\sum_{i \in I}\sum_{t \in T}\sum_{s \in S} C^y_i \cdot y_{i,t,s}\right) + \qquad \text{unit starting costs} \tag{1b}$$

$$\frac{1}{|S|}\left(\sum_{i \in I}\sum_{t \in T}\sum_{s \in S} \tau \cdot C^u_{t,s} \cdot u_{1,i,t,s}\right) + \qquad \text{fossil fuel utilization costs} \tag{1c}$$

$$\frac{1}{|S|}\left(\sum_{i \in I}\sum_{t \in T}\sum_{s \in S} \tau \cdot C^q \cdot q_{1,i,t,s}\right) + \qquad \text{heating production tax costs} \tag{1d}$$

$$\frac{1}{|S|}\left(\sum_{t \in T}\sum_{s \in S}\left(C^{\overline{p}} \cdot \overline{p}_{t,s} + C^{\underline{p}} \cdot \underline{p}_{t,s}\right)\right) + \qquad \text{under/over power costs} \tag{1e}$$

$$\frac{1}{|S|}\left(\sum_{h \in H}\sum_{t \in T}\sum_{s \in S}\left(C^{\overline{q}} \cdot \overline{q}_{h,t,s} + C^{\underline{q}} \cdot \underline{q}_{h,t,s}\right)\right) + \qquad \text{under/over heat costs} \tag{1f}$$

$$\frac{1}{|S|}\left(\sum_{n \in N}\sum_{t \in T}\sum_{s \in S} \tau \cdot C^e_{n,t,s} \cdot p^e_{n,t,s}\right) \qquad \text{power exchange value} \tag{1g}$$

s.t.

$$\tau \cdot D^p_{t,s} = \sum_{k \in K}\sum_{i \in I} \tau \cdot p_{k,i,t,s} + \sum_{n \in N} \tau \cdot p^e_{n,t,s} - \overline{p}_{t,s} + \underline{p}_{t,s} \qquad \forall t \in T, \forall s \in S \qquad \text{power demand} \tag{1h}$$

$$\tau \cdot D^q_{h,t,s} + q^a_{h,t,s} = \sum_{k \in K}\sum_{i \in I_h} \tau \cdot q_{k,i,t,s} - \overline{q}_{h,t,s} + \underline{q}_{h,t,s} + q^a_{h,t-1,s} \qquad \forall h \in H, \forall t \in T, \forall s \in S \qquad \text{heat demand} \tag{1i}$$

$$q^a_{h,t,s} \le B^q_h \qquad \forall h \in H, \forall t \in T, \forall s \in S \qquad \text{heat accumulator} \tag{1j}$$

$$p_{k,i,t,s} + \varsigma^v_i \cdot q_{k,i,t,s} \le \rho^{\max}_i \cdot v_{k,i,t,s} \qquad \forall k \in K, \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{maximum effect} \tag{1k}$$

$$p_{k,i,t,s} + \varsigma^v_i \cdot q_{k,i,t,s} \ge \rho^{\min}_i \cdot v_{k,i,t,s} \qquad \forall k \in K, \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{minimum effect} \tag{1l}$$

$$p_{k,i,t,s} \ge \varsigma^b_i \cdot q_{k,i,t,s} \qquad \forall k \in K, \forall i \in I_e, \forall t \in T, \forall s \in S \qquad \text{extraction units} \tag{1m}$$

$$p_{k,i,t,s} = \varsigma^b_i \cdot q_{k,i,t,s} \qquad \forall k \in K, \forall i \in I_b, \forall t \in T, \forall s \in S \qquad \text{back pressure units} \tag{1n}$$

$$q_{k,i,t,s} = 0 \qquad \forall k \in K, \forall i \in I_c, \forall t \in T, \forall s \in S \qquad \text{condensing units} \tag{1o}$$

$$\epsilon_k \cdot u_{k,i,t,s} = \frac{3.6}{\eta_i}\left(p_{k,i,t,s} + \varsigma^v_i \cdot q_{k,i,t,s}\right) \qquad \forall k \in K, \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{energy production} \tag{1p}$$

$$f_{i,t,s} = f_{i,t-1,s} - \tau \cdot u_{2,i,t,s} + \sum_{j \in J} A_{j,t,s} \cdot x_{j,i,t,s} \qquad \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{biomass level} \tag{1q}$$

$$f_{i,t,s} \le B^f_i \qquad \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{biomass capacity} \tag{1r}$$

$$p^e_{n,t,s} \le E^{\max}_n \qquad \forall n \in N, \forall t \in T, \forall s \in S \qquad \text{power purchase} \tag{1s}$$

$$p^e_{n,t,s} \ge E^{\min}_n \qquad \forall n \in N, \forall t \in T, \forall s \in S \qquad \text{power sale} \tag{1t}$$

$$z_{i,t,s} = \sum_{k \in K} v_{k,i,t,s} \qquad \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{fuel type} \tag{1u}$$

$$y_{i,t,s} \ge z_{i,t,s} - z_{i,t-1,s} \qquad \forall i \in I, \forall t \in T, \forall s \in S \qquad \text{plant operation} \tag{1v}$$

$$\sum_{i \in I} x_{j,i,t,s} \le w_j \qquad \forall j \in J, \forall t \in T, \forall s \in S \qquad \text{redirection} \tag{1w}$$

$$p, \overline{p}, \overline{q}, q^a, \underline{p}, \underline{q}, u, f \in \mathbb{R}^+ \tag{1x}$$

$$p^e \in \mathbb{R} \tag{1y}$$

$$w, x, y, z, v \in \mathbb{B} \tag{1z}$$

Outline

Benders Decomposition

We consider the MILP with *complicating* y-variables, which are the biomass contracts:

$$
\begin{aligned}
\min_{x,y} \quad & z = c^T x + f^T y \\
& Ax + By \geq b \\
& y \in Y \\
& x \geq 0
\end{aligned}
$$

Benders Decomposition

We consider the MILP with *complicating* y-variables, which are the biomass contracts:

$$\begin{aligned} \min_{x,y} \quad & z = c^T x + f^T y \\ & Ax + By \geq b \\ & y \in Y \\ & x \geq 0 \end{aligned}$$

or emphasizing the two stage approach:

$$\min_{y \in Y} \left[f^T y + \min_{x \geq 0} \left(c^T x | Ax \geq b - By \right) \right]$$

Benders optimality cuts

Given a specific set of biomass contracts $\overline{y}$ the dual of the inner problem is:

$$\max_{u} \quad f^T \overline{y} + (b - B\overline{y})^T u$$
$$A^T u \leq c$$
$$u \geq 0$$

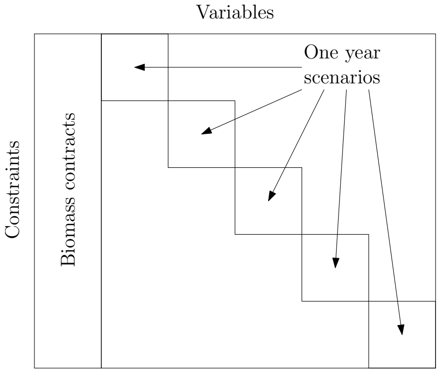
The solution $\overline{u}$ to the dual problem gives a lower bound to the original problem.
The lower bound is valid for all biomass contracts y and the generalization gives:

Benders optimality cut

$$z \geq f^T y + (b - By)^T \overline{u}.$$

Handling multiple scenarios

Block angular structure



Benders optimality cuts for multiple scenarios

$$\min_{y \in Y} \quad f^T y + \frac{1}{|S|} \sum_{s \in S} z_s$$

$$\text{s.t. } z_s \geq (b^s - B^s y)^T u_k^s$$

$$\forall s \in S, k = 1 \ldots K$$

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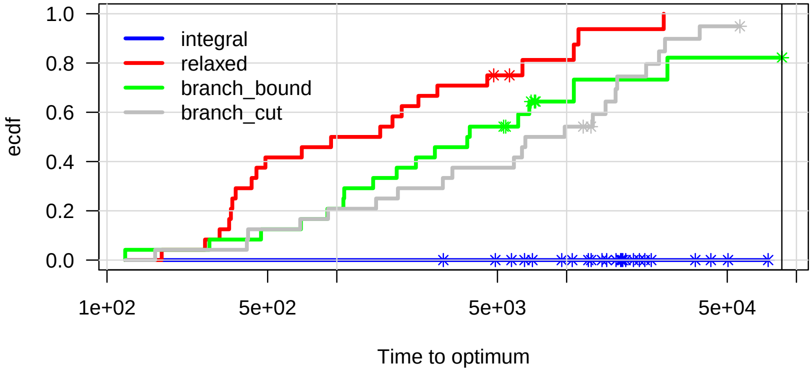
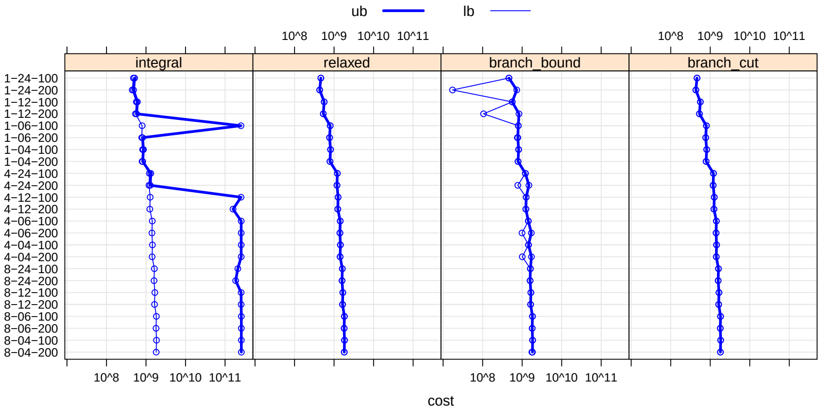
Time to optimality

Empirical cumulative distribution function of the time to completion of the run for the four models

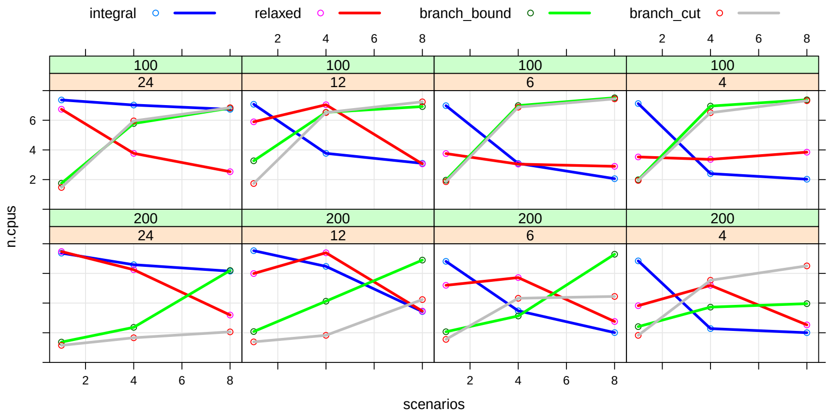


Optimality gap



Exploitation of computational resources

Average number of CPUs used during a run for varying number of scenarios (x-axis) and number of contracts and step size (strip text in the panels).



Conclusions

- Biomass logistics complicates long term planning
- Relaxing some of the binary variables does not impact significantly the total cost assessment
- It is important to consider several scenarios and flexible contracts
- Benders relaxation does not improve solution times
  but it is able to exploit computational resources
  ⇝ potential improvement by primal heuristics + more aggressive cuts (future work)

Thank you for your attention!