An optimization algorithm for load-shifting of large sets of electric hot water tanks

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Introduction : Goals

Uses	TWh	Share
Heating	46	29.9%
Hot water	20.2	13.1%
Cooking	11.6	7.5%
Others	76.2	49.5%
All	154	100%

Table: French electric consumption in primary residence
(Sources : CEREN, 2011)

Pools of electric hot water tanks (EHWT) appear as promising for load shifting applications.

- Dimension
- Flexibility
- Geographically distributed

Introduction : Goals

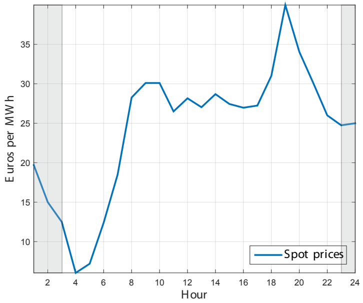

Figure: Day-ahead market prices (Sources : EPEX Spot)

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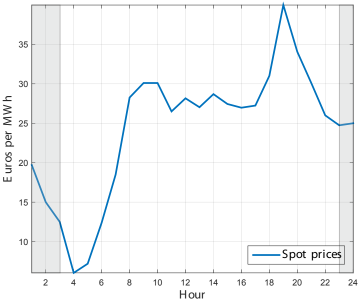

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Home automation: more cost reduction with other load curves.

⇒ How to schedule the heating times to obtain an objective load?

Outline of the presentation

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2. Formulation of the problem
   - Electric water heating
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3. Resolution heuristic and simulations [Contribution]
   - Stochastic heuristic
   - Simulation results

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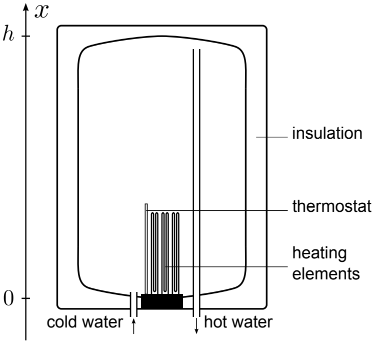

Figure: Schematic EHWT

- Phenomena: Forced convection, natural convection, thermal diffusion, heat loss
- To minimize thermo-hydraulic hazards: heating time undivided

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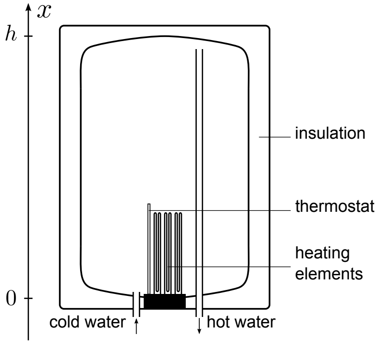
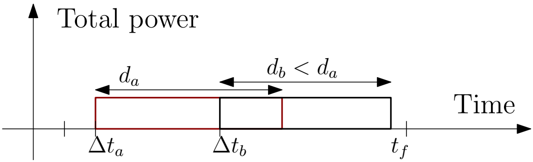


Figure: Schematic EHWT

- Phenomena: Forced convection, natural convection, thermal diffusion, heat loss
- To minimize thermo-hydraulic hazards: heating time undivided
- Each tank i is defined by power p^i, heat loss k^i and start time Δt^i
- Energy: $e_0^i \to e_f^i$

Duration modification due to heat loss

Duration of heating depends on the moment it begins



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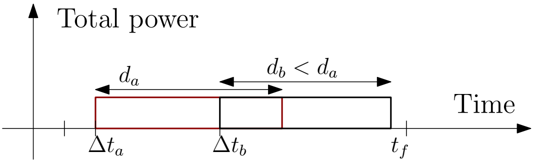

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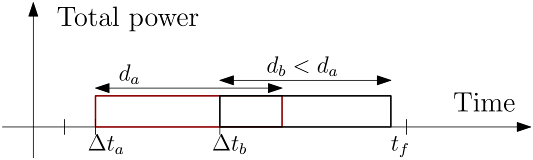

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$$\frac{\mathrm{d}e^i}{\mathrm{d}t} = -k^i e^i + u^i - c^i,$$

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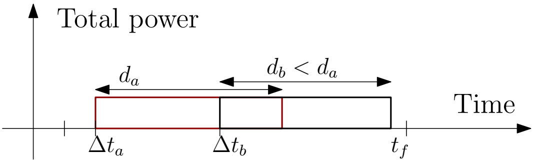


Basically, $\Delta t^i_b > \Delta t^i_a \Rightarrow d^i_b < d^i_a$

Energy balance

$$\frac{\mathrm{d}e^i}{\mathrm{d}t} = -k^i e^i + u^i - c^i,$$

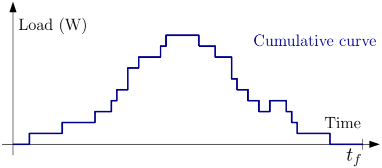
yields

$$d^i(\Delta t^i) = d^i_a + \frac{1}{k^i} \ln(\mathrm{e}^{(k^i(\Delta t^i - d^i_a))} + \mathrm{e}^{(k^i \Delta t^i_a)} - \mathrm{e}^{(k^i(\Delta t^i_a - d^i_a))}) - \Delta t^i.$$

Formulation of the problem

The load curve is then defined

$$f(t) = \sum_{i=1}^{n} p^i \mathbf{1}_{[\Delta t^i, \Delta t^i + d^i]}$$



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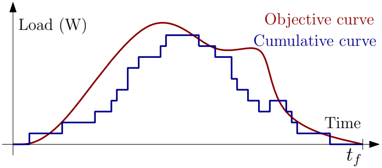

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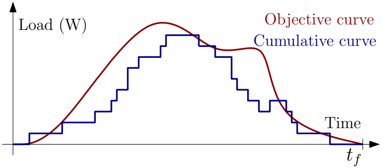

We desire to solve

$$\min_{\color{red}{\Delta t^1, \dots, \Delta t^n}} \int_0^{t_f} (f(t) - P(t))^2 dt \qquad \text{s.t. } \forall i \ \Delta t^i + d^i(\Delta t^i) \leq t_f$$

Some inequality constraints can be added to represent time-of-use policies

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Stochastic heuristic

- In discrete time, this problem is not easy and is equivalent to the "exact cover problem" (NP-complete [Karp,1972])
- We propose a heuristic tailored for the objective curves

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- We propose a heuristic tailored for the objective curves
- We use the flexibility of small durations, scheduling each tank one-by-one from the longest duration to the shortest
- We generate diversity by introducing stochasticity

Stochastic heuristic: principle

The longest durations are the less flexible

- We sort the tanks decreasingly by duration as if they all start at $\Delta t^i = 0$
- We schedule each tank one-by-one

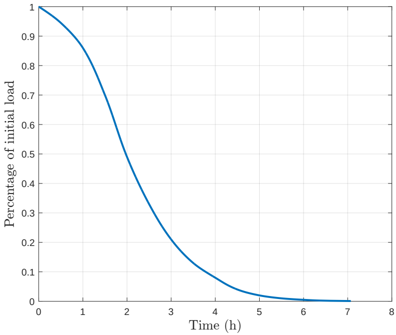

Figure: Distribution of the durations

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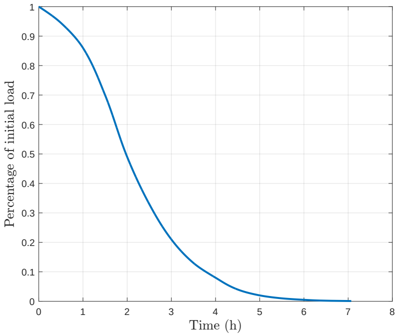
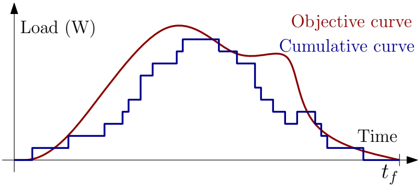


Figure: Distribution of the durations

Stochastic heuristic: steps and distributions



Use of residual load curve (initialized $f_r^0(t) = f_o(t)$)

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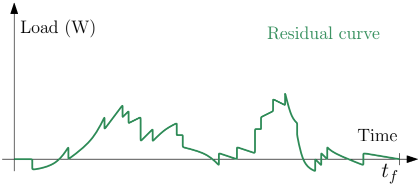

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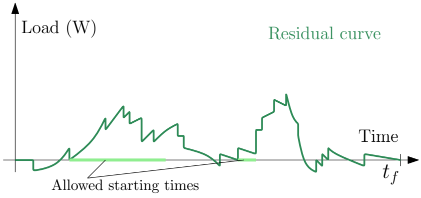

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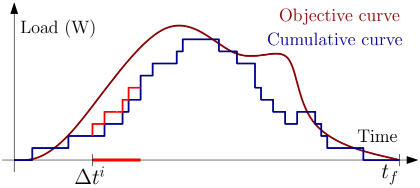

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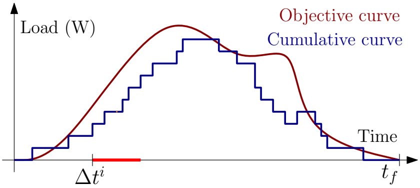

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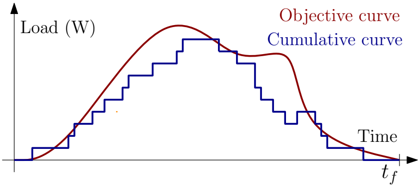

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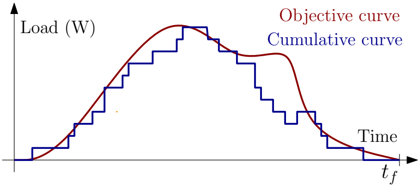

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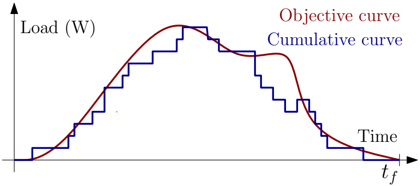

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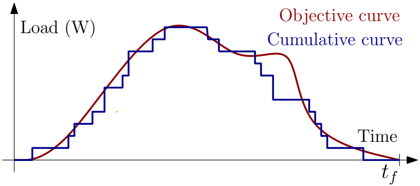

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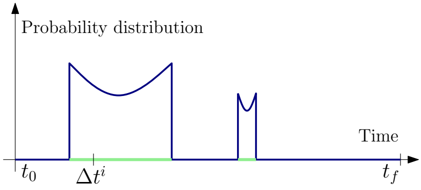

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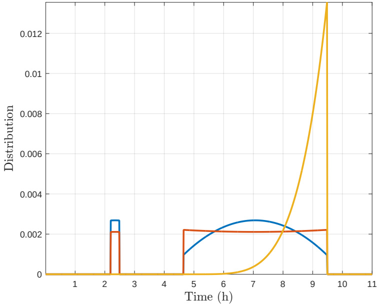

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Simulation: examples

Distribution: real household measurement
Objective curves: 8 objectives, for each season week+weekends

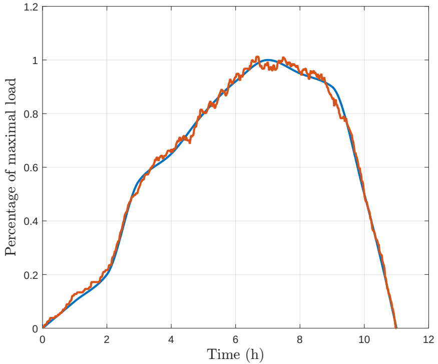

Figure: 500 tanks, 100 timesteps

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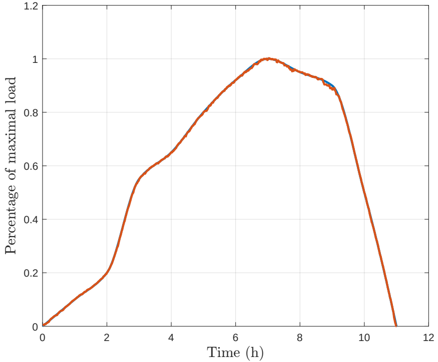

Figure: 5000 tanks, 1000 timesteps

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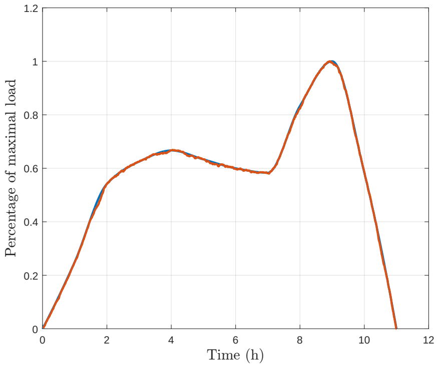

Figure: 5000 tanks, 1000 timesteps

Simulation: quantification

Quadratic quality index:

$$q_2 = \frac{\int_{t_0}^{t_f} (f_b(s) - f_o(s))^2 ds}{\int_{t_0}^{t_f} (f_o(s))^2 ds}$$

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Objective load curve	q_2	Computation time
1	0.29%	22.3s
2	0.41%	18.6s
3	0.42%	18.5s
4	0.44%	17.9s
5	0.30%	25.6s
6	2.45%	20.3s
7	0.42%	15.4s
8	0.65%	17.2s

Table: Objective load curves 1 to 8 (5000 tanks, 1000 timesteps).

Conclusion and perspectives

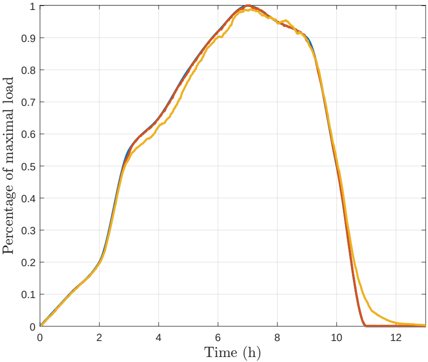
For load-shifting of large pools of electric hot water tanks:

- Formulation of an optimization problem.
- Resolution in the form of a stochastic heuristic.
- Satisfying results with less than 1% of optimality loss.

Perspectives

- Formulation with uncertainty.
- Load balance for several days.

Introduction of uncertainty



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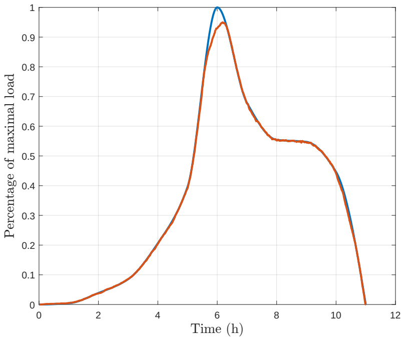

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