Optimization Challenges in Smart Grid Operations

Miguel F. Anjos

Canada Research Chair in
Discrete Nonlinear Optimization in Engineering

GERAD

ÉCOLE POLYTECHNIQUE MONTRÉAL

NSERC CRSNG

Various parts are joint work with
G. T. Costanzo (formerly EPM; now at DTU),
J. Ostrowski (formerly U. Waterloo; now at U. Tennessee-Knoxville),
G. Savard and G. Zhu (EPM),
and
A. Vannelli (U. Guelph)

Thanks to T. Creemers, L.-M. Rousseau, W. van Hoeve

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What is a/the "Smart Grid"?

"A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies."

– Schneider Electric (2010)

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Smart Grid: Challenges and Opportunities

- The concept of a smart grid has its origins in the development of advanced metering infrastructure for
  - better demand-side management;
  - greater energy efficiency; and
  - improved supply reliability.
- Other developments have expanded the scope of smart grids:
  - renewable energy generation (wind and solar, among others);
  - maximizing the utilisation of generating assets; and
  - increased customer choice.
- New technologies will continue to expand the scope:
  - electric vehicles;
  - energy storage (batteries); and
  - smart appliances.

Optimization in Smart Grid Research

1. Unit Commitment
2. Demand Response
3. Integration of Renewable Energy Sources
4. Integration of Energy Storage
5. Integration of Electric Vehicles
6. Autonomous Load Management

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Demand Response

Demand-response programs offered by SCE (Southern California):

Operating Months	May 1 - October 31
Curtailment Window	Weekdays from 11:00 a.m. - 7:00 p.m., excluding holidays
Limits to Frequency of Events	No more than 1 event per day, and a maximum of 24 hours per month.
Event Notification (SCE to Aggregator)	***Day-Ahead Event:*** By 3:00 p.m. the day before an event. ***Day-Of Event:*** Approximately 3 hours before the start of a day-of event (up to 30 minutes prior to the close of the CAISO hour-ahead market). Participants are notified of an event via the CBP Web site (as a courtesy, phone, pager or email notifications may also be arranged).

Company	Day-Ahead	Day-Of	Curtailment Window
Constellation Energy	Yes	May – October	11:00 a.m. – 7:00 p.m.
Energy Connect, Inc.	Yes	No	10:00 a.m. – 5:00 p.m.
EnerNOC	No	Yes	11:00 a.m. – 7:00 p.m.
North American Power Partners	Yes	Yes	10:00 a.m. – 6:00 p.m.

(Joint work with F. Gilbert and J.A.G. Herrera)

Integration of Energy Storage & Renewables

China claims 'world's largest battery storage station'

POSTED ON **JANUARY 3, 2012** · POSTED IN **SUPER BATTERIES**

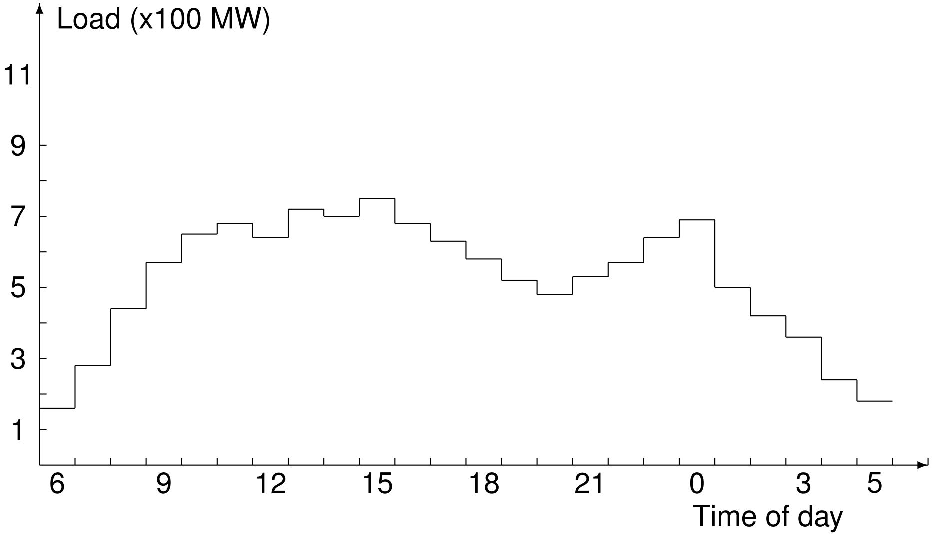
China has earned first-place status in the energy world yet again, this time by completing what it says is the "world's largest battery energy storage station."

Built in conjunction with a 140-megawatt wind- and solar-energy project in Zhangbei, Hebei Province, the station — with arrays of batteries larger than a football field — will provide up to 36 megawatt-hours of energy storage, along with a smart power transmission system. The $500-million phase-one project is designed to help stabilize the electricity grid by storing renewably generated power to manage the ups and downs of intermittent wind and solar sources.

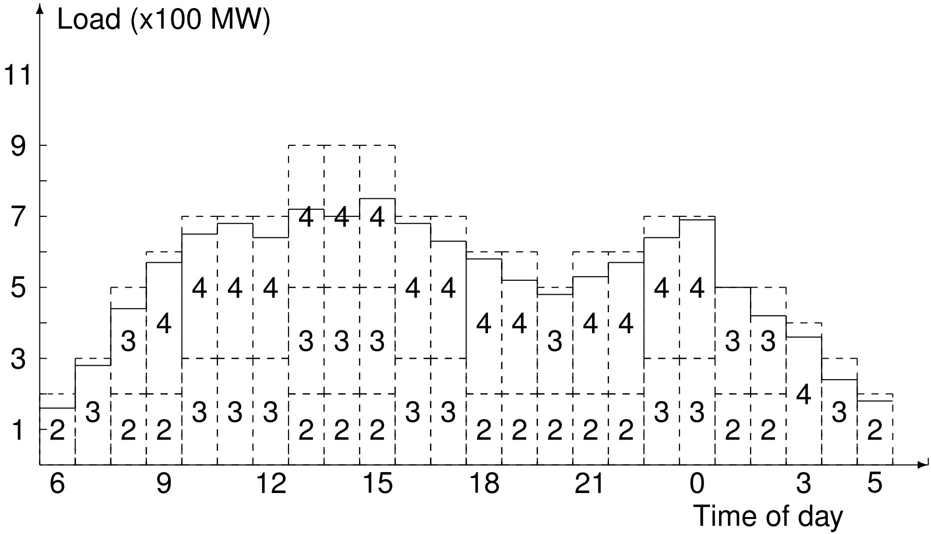
(Joint work with X. Xu)

Unit Commitment (UC)

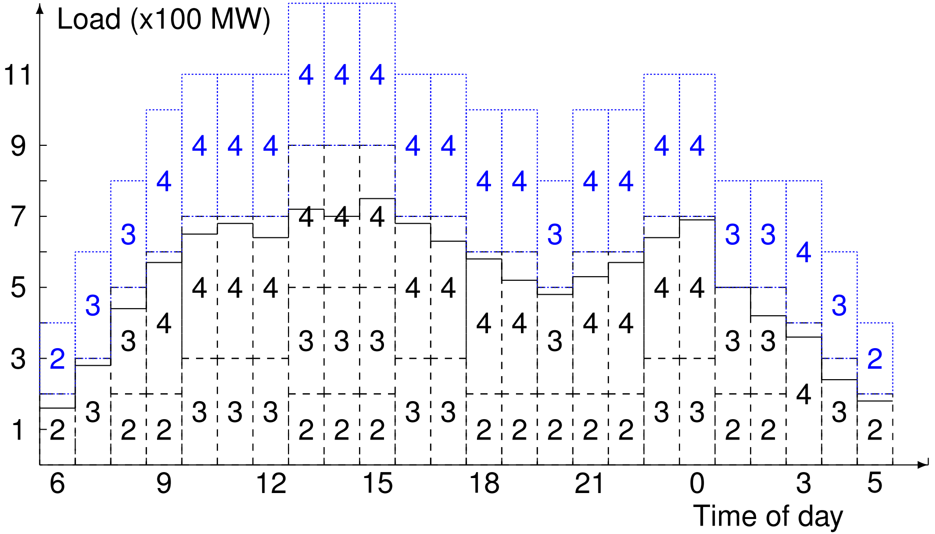
Unit Commitment



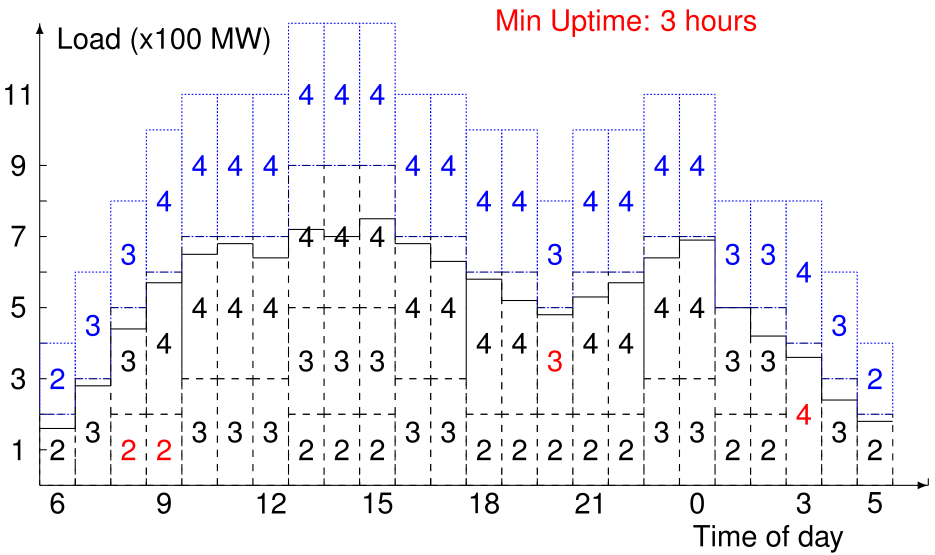
Unit Commitment



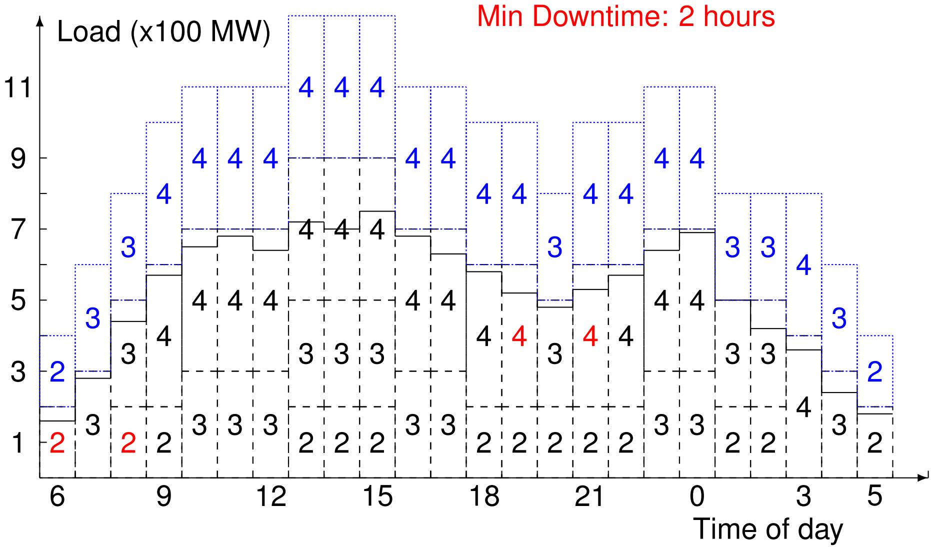
Unit Commitment



Unit Commitment



Unit Commitment



Unit Commitment (UC)

The purpose of UC is:

- to minimize the system-wide cost of power generation
- while ensuring that demand is met, and
- that the system operates safely and reliably.

Small improvements in the solution quality $\Rightarrow$ substantial cost savings.

There is a vast literature on solution techniques for UC:

- Lagrangian relaxation
- Mixed-integer linear optimization
- CP: Huang-Yang-Huang (1998)
- Stochastic optimization, robust optimization, etc.
- *The Next Generation of Electric Power Unit Commitment Models*, Hobbs et al. (eds), 2001.

Formulating the UC Problem

Basic Structure

$$\begin{aligned} \min \quad & \sum_{t \in T} \sum_{j \in J} c_j(p_j(t)) \\ \text{s.t.} \quad & \sum_{j \in J} p_j(t) \geq D(t), \quad \forall t \in T \\ & p_j \in \Pi_j, \quad \forall j \in J \end{aligned}$$

- $c_j(p_j(t))$ gives the cost for generator j of producing $p(t)$ units of electricity at time t.
  - Generally assumed to be a quadratic function.
  - Can be modeled as a piecewise linear function.
- Demand must be met.
- The production schedule p_j for generator j must be feasible.

A 3-binary variable formulation for Π

A common way to formulate Π requires the use of 3 different types of binary variable (and one type of continuous):

- $v_j(t) = 1$ if generator j is producing at time t.
- $y_j(t) = 1$ if generator j is switched on at time t.
- $z_j(t) = 1$ if generator j is switched off at time t.
- $p_j(t) =$ the quantity of power generated by generator j at time t.

Note the close relationship between the v, y, and z variables. If we know all the v values, we also know all the y and z values.

Maximum and Minimum Power Limits

If a generator is switched, it must produce a least $\underline{P}$ units of power, but no more than $\overline{P}$:

$$\underline{P}_j v_j(t) \leq p_j(t) \leq \overline{P}_j v_j(t) \; \forall t \in T \; \forall j \in J$$

Ramping Constraints

A generator cannot change its output too fast:

$$p_j(t) - p_j(t-1) \le RU_j v_j(t-1) + SU_j y_j(t) \;\; \forall t \in T \forall j \in J$$

$$p_j(t-1) - p_j(t) \le RD_j v_j(t) + SD_j z_j(t) \;\; \forall t \in T \forall j \in J$$

- RU_j and RD_j represent the maximum change in output a generator can handle between time periods (assuming the generator is on at both time periods).
- If the generator was off at time $t-1$ and turns on at time t, it can produce at most SU_j units.
- Similarly, if the unit shut down at time t, then in the previous time period it can produce no more than SD_j units.

Minimum Up / Downtime Constraints

We also need constraints on when generators can be switched on or off.

If a generator is switched on at time k, it must stay on for at least UT time periods:

$$\sum_{i=k}^{k+UT_j-1} v_j(i) \geq UT_j y_j(k) \ \ \forall k = 1, \ \ldots, \ T$$

Similarly, if it was switched off at k, it must stay off for DT time periods:

$$\sum_{i=k}^{k+DT_j-1} (1 - v_j(i)) \geq DT_j z_j(k) \ \ \forall k = 1, \ \ldots, \ T$$

Tighter Minimum Up / Downtime Constraints

- An alternative to the minimum up/downtime constraints mentioned above are based on Rajan & Takriti (2005).
- They claim that the constraints (1) and (2) are facets of the minimum up and downtime polytope.

$$\sum_{k=t-UT_j+1,\ k\geq 1}^{t} y_j(k) \leq v_j(t)\ \forall t \in T. \tag{1}$$

$$v_j(t) + \sum_{k=t-DT_j+1,\ k\geq 1}^{t} z_j(k) \leq 1\ \forall t \in T. \tag{2}$$

- In fact, along with some trivial inequalities, (1) and (2) completely describe the minimum up/downtime polytope.

Alternative formulation for Π

- As noted earlier, the v, y, and z variables are closely related.
- We can describe Π without using the y and z variables.
- This is the efficient formulation of Carrión & Arroyo (2006).

A Comparison of Formulations

We performed computational tests comparing 3 different formulations:

- The “efficient” formulation of Carrión & Arroyo (only one set of binary variables);
- The “original” formulation (3 sets of binary variables); and
- The original formulation with the convex hull of the “up/downtime” polytope.

Instances were randomly generated based on generator data provided by Carrión & Arroyo.

Problems were solved to 0.5% optimality using CPLEX 12.1 with a cutoff of 2 hours (7200 sec).

Computational Results

Problem	Efficient		Original		Up/Downtime	
Size	Time	Nodes	Time	Nodes	Time	Nodes
27	7200.0	5212	1485.0	531	1107.6	513
34	7200.4	3790	3320.6	561	2034.5	616
43	7200.1	3355	5312.9	557	3849.4	568
44	7200.1	2713	5340.4	528	3587.6	545
48	7200.1	2006	5973.7	557	2222.6	352
48	7200.0	2721	5460.0	526	3584.0	541
50	7200.2	2274	6711.0	511	4210.8	541
50	7200.4	1351	6672.9	550	3724.8	539
50	7200.1	1259	6530.9	560	4948.8	527
53	7200.4	1633	6446.5	494	4002.2	552

Conclusions Regarding Formulations

- Using the original formulation with the minimum up/downtime constraints of Rajan and Takriti seem to generate the best results.
- Explanation:
  Yes, the “original” and “up/downtime” formulations have 3 times the number of variables of the “efficient” formulation,
  but these additional variables allow for a tighter linear optimization relaxation.
- Adding tight inequalities for the minimum up/downtime constraints was very beneficial.

Can we improve times further by looking at the other constraints?

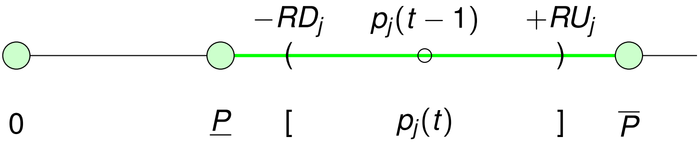
Ostrowski-Anjos-Vannelli (2012)

- We show how to strengthen the upper bound constraints on $p_j(t)$.
- We also show how to strengthen the ramping constraints by taking into consideration when the generator is switched on/off.
- We prove that the resulting inequalitites are facets of suitable projections of the feasible region.

The Meaning of a Strengthened Ramp-Down Inequality

Consider the original ramp down inequality:

$$p_j(t-1) - p_j(t) \leq RD_j v_j(t) + SD_j z_j(t)$$

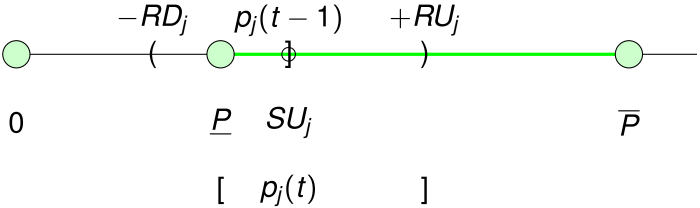


What if $y_j(t-1) = 1$?

The Meaning of a Ramp-Down Inequality (ctd)

If $y_j(t-1) = 1$ then

$$p(t-1) - p(t) \leq RDv(t) + SDz(t) - (RD - SU + \underline{P})y(t-1) - (RD + \underline{P})y(t)$$



Stronger Inequalities

Overall we have 5 additional constraints per time unit per generator.

Advantages:

- The linear optimization relaxation with the additional constraints gives a better lower bound for production cost.
- This can lead to smaller branch-and-bound trees and faster solutions.

Disadvantages:

- These additional constraints can make the linear optimization relaxation more difficult to solve.
- Even though fewer relaxations may have to be solved, the overall computational cost may increase.

For efficiency: Only constraints dealing with fractional variables need to be added to the formulation.

Computational Results

Solved to 0.5% of Optimality

	Root Node (%)			Solution			
	Gap (%)	Gap (%)	% Gap	Time (s)		Nodes	
Size	UD	Tight	Closed	UD	Tight	UD	Tight
27	1.97	1.82	7.39	1107.6	1487.6	513	517
34	2.86	2.58	9.77	2034.5	1835.5	616	483
43	2.29	2.08	8.92	3849.4	3060.8	568	532
44	1.82	1.67	8.27	3587.6	3445.1	545	510
48	1.97	1.78	9.28	3584.0	3382.0	541	512
49	1.61	1.50	6.86	2222.6	3169.1	352	410
50	2.07	1.86	10.07	4210.8	3253.8	541	313
50	2.71	2.47	8.81	4948.8	4094.9	527	548
51	2.15	1.97	8.58	3724.8	3201.6	539	559
53	1.96	1.80	7.95	4002.2	3484.0	552	507

Computational Results - Larger Instances

Solved to 1.0% of Optimality

	Root Node (%)			Solution			
	Gap (%)	Gap (%)	% Gap	Time (s)		Nodes	
Size	UD	Tight	Closed	UD	Tight	UD	Tight
131	2.32	2.07	10.68	7187.8	1465.6	543	0
155	2.09	1.92	7.92	7200.4	5920.8	541	44
155	2.25	2.09	7.32	7200.1	2144.6	207	0
164	3.25	3.10	4.70	7200.6	5477.0	139	20
166	1.82	1.68	8.09	5514.1	2556.0	371	0
171	2.38	2.21	7.32	7200.2	4964.0	278	10
181	2.03	1.87	7.91	7200.1	3788.0	212	0
181	2.07	1.92	7.35	7200.6	3529.0	92	0
182	2.26	2.10	7.20	7200.4	3796.0	284	0
186	1.97	1.82	7.56	7200.4	3556.7	346	0

Conclusions

- Reducing the number of binary variables does not necessarily improve the efficiency of branch-and-bound for the IP formulation of UC.

- Adding the proposed set of (facet-defining) inequalities can significantly increase the quality of the linear optimization relaxation, and hence the efficiency of branch-and-bound.

Research Questions

- It is possible for there to be multiple generators of the same type (same costs, rampup rate, etc.)
  - The presence of multiple generators adds symmetry to the problem.
  - We have studied, and continue to study, the use of symmetry-handling techniques for UC.
- UC with AC description of the power network $\Rightarrow$ large-scale nonlinear mixed-integer problem
- Incorporating renewables in UC $\Rightarrow$ large-scale stochastic mixed-integer linear/non-linear problem

Autonomous Load Management

Autonomous Load Management

The objective is to coordinate large numbers of appliances, many with low power consumption.

Obviously, it is unrealistic to connect all the appliances directly to the network.

One alternative is to decentralize control on the side of the consumer.

Autonomous Load Management (ctd)

We consider the energy consumption of a given building (home, hospital, factory, etc.).

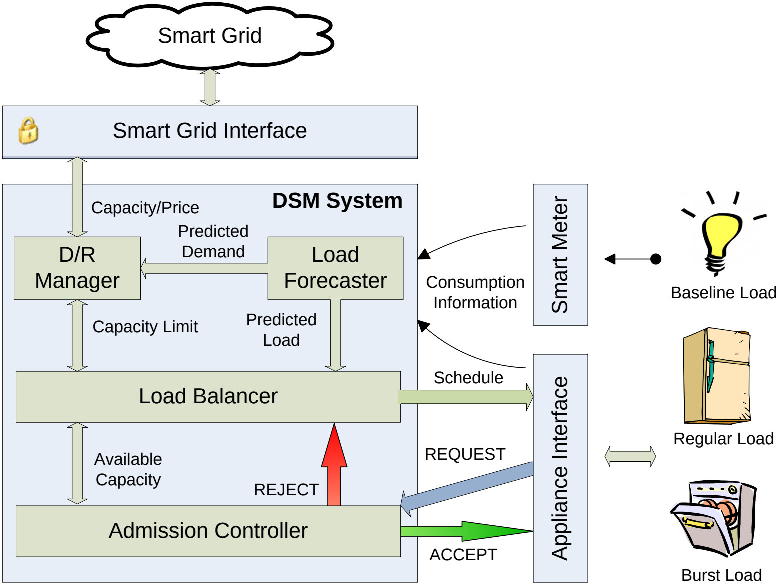
Concept:

- The load control is handled locally by the consumer
- whereas the utility influences the consumer's decision on power consumption by changing energy price in real-time (according to the energy market, network load, etc.).
- With an appropriate architecture, only limited information exchange should be needed.

Challenge: Different time scales:

- Appliance control is carried out in a real-time, while
- price and other system signals mostly arrive on a longer time-scale.

Layered Home Energy Manager



Optimization problem for LB

$$
\begin{aligned}
\min \quad & \sum_{i,j} P_i K_j x_{ij} + \sum_{i,j} G_{ij} d_{ij} \\
\text{s.t.} \quad & \sum_i P_i x_{ij} \le C_j, \ \ \forall j \in \mathcal{M} \\
& d_{ij} \le x_{it} \\
& \quad t = j, j+1, \cdots j + \tau_i - 1, \ \ \forall j \in \mathcal{M} \\
& \sum_j d_{ij} = 1, \ \ \forall i \in \mathcal{N} \\
& x_{ij} = 0, \ \ \forall i \in \mathcal{N}, \ \ \forall j \notin (T_i^{earliest}, T_i^{latest}) \\
& d_{ij} \in \{0, 1\}, \ \ \forall i \in \mathcal{N}, \ \ \forall j \in \mathcal{M} \\
& x_{ij} \in \{0, 1\}, \ \ \forall i \in \mathcal{N}, \ \ \forall j \in \mathcal{M}
\end{aligned}
$$

where $\mathcal{N}$ is the set of appliances and $\mathcal{M}$ is the set of time frames.

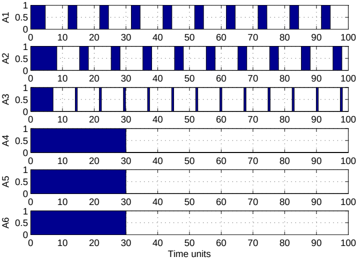
Case Study

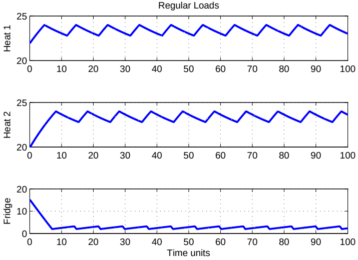
Simulation studies carried out using Matlab/Simulink©.

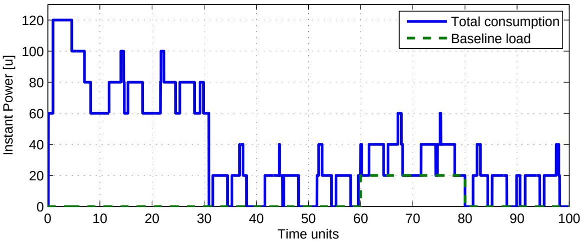
For the results presented here:

- all the requests arrive at the same time and burst loads deadlines are 40, 40 and 70 time units;
- each appliance has a power consumption of 20 power units;
- the external temperature is constant and equal to 20^0C;
- the comfort zone for rooms 1,2 is 22^0C-24^0C and for the refrigerator is 2^0C-5^0C;
- the internal temperatures are initialized at 22^0C, 20^0C and 15^0C for rooms 1,2 and refrigerator respectively.

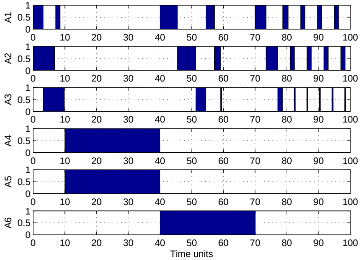
Without Load Management

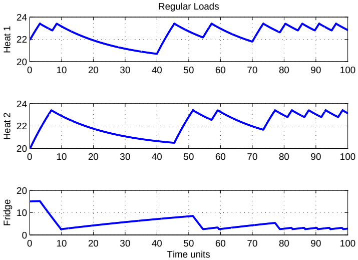


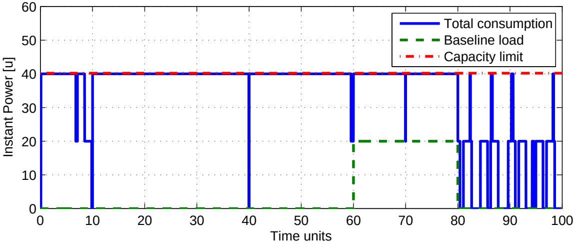




Load management via AC + LB

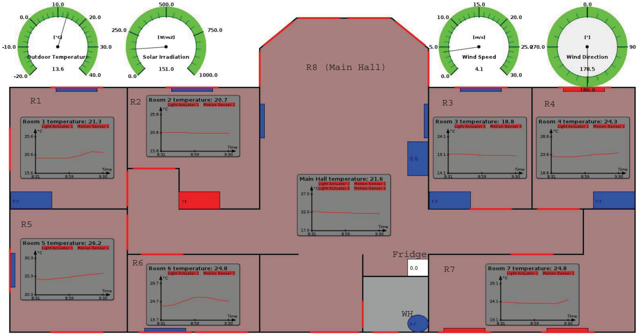






Results validated at the Energy FlexHouse of DTU

- Eight rooms electrically heated/cooled, motion sensors, dimmable lights, light/temp sensors, automated windows
- Tested regular loads management with AC



Conclusions and Current Research

Conclusions:

- The simulations confirm that the proposed system can, if it is possible, schedule loads so as to stay within the capacity limit while meeting deadlines.
- When it is not possible, the system minimizes the amount of time during which it operates above the capacity limit.

Current research:

- Further validation of the results at the Energy FlexHouse of DTU (already done for baseline & regular loads, only with AC).
- Implementation of the upper layer & testing with time-of-use pricing.

References

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Take-Home Message

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For papers, references, questions, you are welcome to contact me:

`miguel-f.anjos@polymtl.ca`

Thank you for your attention.