How Can Smart Buildings Be Price-Responsive?

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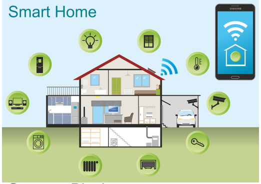
OASYS
Optimization and Analytics for Sustainable energY Systems

Motivation

- Increasing demand-side participation in current and future electricity systems
- Advances on home automation and a growing penetration of smart meters in distribution networks
- **Smart buildings** can play a key role in providing flexibility!

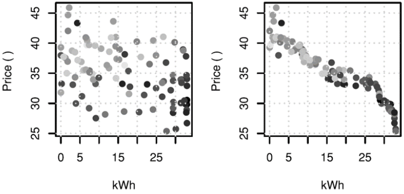


Source: *Pixabay.*

Motivation

- **Lack of real-life data** from price-responsive buildings 

Pool of non-flexible consumers ⟹



⟸ Pool of flexible consumers

Source: *Saez-Gallego and Morales 2018.*

- Existing works in the technical literature
  - Precise modelling of a single element of the smart building
  - Most of the works consider thermostatically-controlled loads

Compact Formulation

We use **economic model predictive control** to model the heat dynamics of a smart building as the minimization of its electricity costs plus the penalty cost due to discomfort:

$$\min_{\boldsymbol{u},\boldsymbol{v},\boldsymbol{x},\boldsymbol{y}} \quad h(\boldsymbol{u}, \underset{\substack{\downarrow \\ \text{Slack variables}}}{\boldsymbol{v}})$$

1) The state-space model of the building heat dynamics:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{E}\underset{\substack{\downarrow \\ \text{Disturbances}}}{\boldsymbol{z}}$$

$$\boldsymbol{y} = \underset{\substack{\downarrow \\ \text{Identity matrix}}}{\boldsymbol{C}}\boldsymbol{x} + \underset{\substack{\downarrow \\ \text{Null matrix}}}{\boldsymbol{D}}\boldsymbol{u}$$

2) User-defined comfort constraints: $\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{y} \in \mathcal{C}$

3) Technical constraints: $\boldsymbol{u} \in \mathcal{T}$ (continuous + binary variables)

Model is characterized as an **MILP** once it is discretized

Formulation

We assume a **single-zone household**:

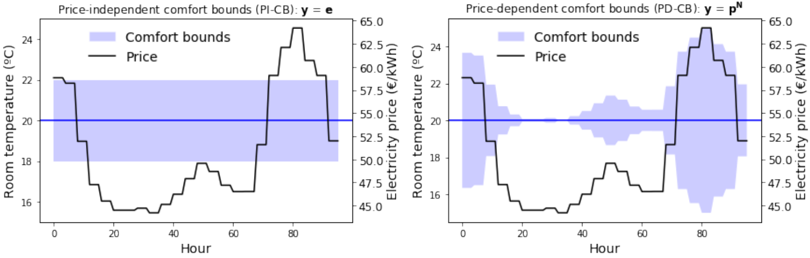
- State-space model:
  - Space heaters: water-based floor heater (3 states) and HVAC (1 state)
  - Thermal loads: residential refrigerator and water heater
  - Disturbances: ambient temperature, room occupancy, hot water demand
- Comfort constraints (e.g. indoor temperature or light levels)
- Technical constraints:
  - Bounds on each appliance's power
  - Precise modelling of the operation of the uninterruptible loads (cycle time, cycle power for each phase)
  - Building electricity consumption (u^b) = the contribution of each appliance

Comfort bounds

Let us assume that the comfort bounds can be set as:

$$\underline{\mathbf{x}}^r = \mathbf{x}^{r,set} - \alpha\mathbf{y}$$
$$\overline{\mathbf{x}}^r = \mathbf{x}^{r,set} + \alpha\mathbf{y}$$

$\overline{\mathbf{x}}^r$ and $\underline{\mathbf{x}}^r$	maximum and minimum bounds on the indoor air temperature
$\mathbf{x}^{r,set}$	set point indoor air temperature
α	maximum temperature difference w.r.t $\mathbf{x}^{r,set}$ that the user is able to withstand
$\mathbf{y}$	vector of continuous parameters varying between 0 and 1



- Parameter α defines the flexibility of the occupants.

Data

- Single-zone household (30 m^2 with 1-m^2 window)
- Electricity prices (ENTSOe), ambient temperature (AEMET + Energyplus)
- Solar radiation, outdoor illuminance, occupancy schedules
- Thermal loads:
  - Water-based floor heater (FH) and HVAC system: 1 kW
  - 30-l water heater (outside): 0.35 kW
  - Residential refrigerator: 1.26 kW
- Indoor artificial lighting: 60 W
- Uninterruptable loads: oven, washing machine, tumble dryer, and dishwasher

	$\mathcal{T}_i$
Washing machine	06:00-14:00
Dishwasher (first)	06:00-14:00
Dishwasher (second)	16:00-00:00
Tumble dryer	15:00-00:00
Oven	10:00-15:00

Simulation setup

- Daily simulations are run with 15-min time steps for one year
- A look-ahead window of one day is used
- PI-CB vs. PD-CB
- Comfort bounds for cases *noflex*, *flex*, and *extraflex*

	noflex	**flex**	**extraflex**
$x_t^{r,set}$ [°C]	20	20	20
α [°C]	0	2	5
$\{\underline{x}^{wh}, \overline{x}^{wh}\}$ [°C]	{54, 56}	{50, 60}	{45, 65}
$\{\underline{x}^{rf}, \overline{x}^{rf}\}$ [°C]	{4.9, 5.1}	{4, 5}	{3, 6}

- CPLEX 12.6.3 under Pyomo 5.2
- Computing times < 1 hour

Results: Effect of comfort settings

Type	Comfort bounds	Case	Annual cost [€]	Violations [°C · h]	Freq. at 20°C [%][a]	Freq. [18,20)–(20,22] °C [%][a]	Freq. [15,18)–(22,25]°C [%][a]	u^b [%][b]
FH	PI-CB	*noflex*	103.5	862.5	37.5	62.5	0.0	54.5
		flex	78.9	0.0	1.5	98.5	0.0	62.7
		extraflex	68.4	0.0	0.0	0.3	99.7	63.5
	PD-CB	*noflex*	103.5	862.5	37.5	62.5	0.0	54.5
		flex	93.2	55.9	22.2	77.8	0.0	61.9
		extraflex	87.0	35.2	21.7	78.3	0.0	64.1
HVAC	PI-CB	*noflex*	107.0	0.0	100.0	0.0	0.0	57.2
		flex	89.9	0.0	1.1	98.9	0.0	63.5
		extraflex	76.1	0.0	0.5	19.6	79.9	64.7
	PD-CB	*noflex*	107.0	0.0	100.0	0.0	0.0	57.2
		flex	94.5	0.0	11.1	88.9	0.0	62.3
		extraflex	84.2	0.0	8.0	61.6	30.4	64.4

[a] Columns 6–8: percentage of 15-min time intervals lying within the given temperature intervals throughout the year.
[b] Column 9 represents the share of power lying within low-price periods.

- HVAC system leads to costlier solutions but provides in general less discomfort

Results: Effect of comfort settings

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- In the *noflex* case, HVAC is able to keep the air temperature within comfort bounds compared to the FH because of its faster dynamics

Results: Effect of comfort settings

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[a] Columns 6–8: percentage of 15-min time intervals lying within the given temperature intervals throughout the year.
[b] Column 9 represents the share of power lying within low-price periods.

- Annual costs decrease when increasing the degree of flexibility at expense of a higher degree of discomfort

Results: Effect of comfort settings

Type	Comfort bounds	Case	Annual cost [€]		Violations [°C · h]	Freq. at 20°C [%][a]	Freq. [18,20)–(20,22] °C [%][a]	Freq. [15,18)–(22,25]°C [%][a]	u^b [%][b]
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[a] Columns 6–8: percentage of 15-min time intervals lying within the given temperature intervals throughout the year.
[b] Column 9 represents the share of power lying within low-price periods.

- PI-CB lead to higher cost reductions than PD-CB when increasing the degree of flexibility regardless of the space heater

Results: Effect of comfort settings

Type	Comfort bounds	Case	Annual cost [€]		Violations [°C · h]	Freq. at 20°C [%][a]	Freq. [18,20)–(20,22] °C [%][a]	Freq. [15,18)–(22,25]°C [%][a]	u^b [%][b]
FH	PI-CB	*noflex*	103.5		862.5	37.5	62.5	0.0	54.5
		flex	78.9	↓ 34%	0.0	1.5	98.5	0.0	62.7
		extraflex	68.4		0.0	0.0	0.3	99.7	63.5
	PD-CB	*noflex*	103.5		862.5	37.5	62.5	0.0	54.5
		flex	93.2	↓ 16%	55.9	22.2	77.8	0.0	61.9
		extraflex	87.0		35.2	21.7	78.3	0.0	64.1
HVAC	PI-CB	*noflex*	107.0		0.0	100.0	0.0	0.0	57.2
		flex	89.9	↓ 29%	0.0	1.1	98.9	0.0	63.5
		extraflex	76.1		0.0	0.5	19.6	79.9	64.7
	PD-CB	*noflex*	107.0		0.0	100.0	0.0	0.0	57.2
		flex	94.5	↓ 21%	0.0	11.1	88.9	0.0	62.3
		extraflex	84.2		0.0	8.0	61.6	30.4	64.4

[a] Columns 6–8: percentage of 15-min time intervals lying within the given temperature intervals throughout the year.
[b] Column 9 represents the share of power lying within low-price periods.

- PD-CB lead to higher costs due to the time-varying comfort bounds, however it leads to less discomfort than the PI-CB

Results: Effect of comfort settings

Type	Comfort bounds	Case	Annual cost [€]	Violations [°C · h]	Freq. at 20°C [%][a]	Freq. [18,20)–(20,22] °C [%][a]	Freq. [15,18)–(22,25]°C [%][a]	u^b [%][b]	
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		flex	78.9	0.0	1.5	98.5	0.0	62.7	↓ 9.0%
		extraflex	68.4	0.0	0.0	0.3	99.7	63.5	
	PD-CB	*noflex*	103.5	862.5	37.5	62.5	0.0	54.5	
		flex	93.2	55.9	22.2	77.8	0.0	61.9	↓ 9.6%
		extraflex	87.0	35.2	21.7	78.3	0.0	64.1	
HVAC	PI-CB	*noflex*	107.0	0.0	100.0	0.0	0.0	57.2	
		flex	89.9	0.0	1.1	98.9	0.0	63.5	↓ 7.2%
		extraflex	76.1	0.0	0.5	19.6	79.9	64.7	
	PD-CB	*noflex*	107.0	0.0	100.0	0.0	0.0	57.2	
		flex	94.5	0.0	11.1	88.9	0.0	62.3	↓ 7.5%
		extraflex	84.2	0.0	8.0	61.6	30.4	64.4	

[a] Columns 6–8: percentage of 15-min time intervals lying within the given temperature intervals throughout the year.

[b] Column 9 represents the share of power lying within low-price periods.

- Both space heaters shift energy to low-price periods when increasing the user-defined flexibility

Both systems can be price-responsive

To wrap up...

From a modelling perspective:

- Detailed formulation for a smart building with smart appliances (including 5 states to capture thermal dynamics)
- Precise modelling of variable power cycles for uninterruptible loads
- Development of a simulation tool to generate synthetic data of price-responsive loads

To wrap up...

From the numerical results:

- Substantial cost savings can be achieved when increasing the comfort bounds
- The more-price responsive the household is, the higher discomfort the occupants experience
- Price-dependent comfort bounds may help reduce the occupants' discomfort

Future Work

- Extension to a smart multi-zone building
- Inclusion of battery energy storage system and local renewable generation to increase flexibility

Contacts

Any questions?

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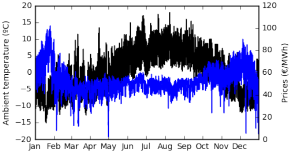
Data

- Single-zone household (30 m^2 with 1-m^2 window)
- Electricity prices (ENTSOe) and ambient temperature (AEMET + Energyplus weather data)



- Solar radiation, outdoor illuminance, occupancy schedules
- Thermal loads: water-based floor heater (FH) and HVAC system
  - FH: mass of water = 400 kg, nominal power = 1 kW, COP = 3
  - HVAC: COP = 1.67(3.67) for heating(cooling), nominal power = 1 kW

Data

- Thermal loads: 30-l water heater (outside) and a residential refrigerator

	Refrigerator	Water heater
Nominal power capacity [kW]	0.35	1.26
COP	0.76	0.92
Thermal capacity [Wh/$^\circ$C]	6.65	34.85
Heat transfer coefficient [W/$^\circ$C]	0.678	0.5

- Indoor artificial lighting: 60 W, indoor luminous efficacy = 90 lumen/W
- Uninterruptable loads: oven, washing machine, tumble dryer, and dishwasher

	$\mathcal{T}_i$
Washing machine	06:00-14:00
Dishwasher (first)	06:00-14:00
Dishwasher (second)	16:00-00:00
Tumble dryer	15:00-00:00
Oven	10:00-15:00

Results: Effect of structural parameters

- $UA^{r,a}$: heat transfer coefficient = heat conductivity x surface area
- The higher $UA^{r,a}$, the less insulated the household is
- We consider no windows and *flex* case
- Value of $UA^{r,a}$ is multiplied by factors: 0.5, 1, 2, 4

Type	Cost and metrics	Factor			
		0.5	**1**	**2**	**4**
FH	Cost [€]	76.6	86	105.8	149.8
	Violations [°C · h]	0	0	1.1	93.4
	Freq. at 20°C [%]	0	0	2.9	4.2
	Freq. [18,20)–(20,22]°C [%]	100	100	97	95.4
	Freq. [15,18)–(22,25]°C [%]	0	0	0.1	0.2
HVAC	Cost [€]	87	106.5	146	225
	Violations [°C · h]	0	0	0	0
	Freq. at 20°C [%]	0.9	0.6	0.3	0.2
	Freq. [18,20)–(20,22]°C [%]	99.1	99.4	99.7	99.8
	Freq. [15,18)–(22,25]°C [%]	0	0	0	0

- Annual costs increase when the household is less insulated at the expense of slightly increasing the occupants' discomfort

Results: Effect of structural parameters

- Effect of $UA^{r,a}$ on the share of building power consumption lying within low-price periods in %

	FH			HVAC		
Factor	**noflex**	**flex**	**extraflex**	**noflex**	**flex**	**extraflex**
0.5	54.9	64.2	65.5	56.1	63.0	65.2
1.0	54.0	67.2	68.1	55.9	62.3	64.6
2.0	53.1	71.0	71.7	55.7	60.2	62.2
4.0	51.7	72.5	73.4	55.6	57.8	58.6

- FH is more price-responsive when increasing the household is less isolated
- Opposite behaviour can be observed for the HVAC
- HVAC system has faster dynamics than the water-based FH