Tractable Predictive Control Strategies for Heating Systems in Buildings

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IBPSA Building Simulation Conference,
Chambéry, 25-28 August 2013

Summary

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- Energy Context
- “Sustainable Building and Innovation” Project

Energy context

- Non-residential building sector is one of the most energy-consuming sectors
- Needs to reduce consumption have led to new low-consumption non-residential buildings

$\Rightarrow$ Then heating and cooling can be significantly reduced

- But:
  - Low consumption buildings have limited heat power and high inertia
  - Non-residential buildings have known intermittent occupation
- $\Rightarrow$ Therefore important thermal discomfort and energy waste can appear:
  - Thermal comfort takes too long to be good after a none-occupancy period
  - Internal heat gain can cause energy waste and overheating
  - Energy consumption until the end of occupancy is not always required

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"Sustainable Building and Innovation" Project

- Financial support and partnerships
  - Research chair on "Sustainable Building and Innovation"
  - Financial support of Bouygues Construction
  - Partnership between research laboratories of Supelec (French graduate school of engineering) and the CSTB (French Scientific and Technical Center for Building)

BOUYGUES CONSTRUCTION

CSTB le futur en construction

Supélec

- Objectives
  - Develop a simulation model of a low-energy non-residential building using Simbad
  - Evaluate the impact of intermittent occupation on both the thermal comfort of the occupants and energy consumption
  - Propose predictive control algorithms to manage heating efficiently, taking into account intermittency
  - Propose solutions which are computationally tractable in order to been implanted in industrial embedded system

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PI-control struture for the heating system

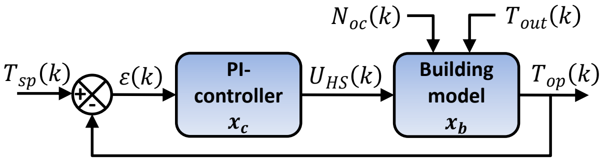
- Linear thermal model of the building

$$\begin{cases} \mathbf{x_b}(k+1) = \mathbf{A_b}\mathbf{x_b}(k) + \mathbf{B_b}\begin{bmatrix} U_{HS}(k) \\ T_{out}(k) \\ N_{oc}(k) \end{bmatrix} \\ T_{op}(k) = \mathbf{C_b}\mathbf{x_b}(k) \end{cases} \quad (1)$$

- PI-control of the heating system

$$\begin{cases} \mathbf{x_c}(k+1) = \mathbf{A_c}\mathbf{x_c}(k) + \mathbf{B_c}\varepsilon(k) \\ U_{HS}(k) = \mathbf{C_c}\mathbf{x_c}(k) + \mathbf{D_c}\varepsilon(k) \end{cases} \quad (2)$$

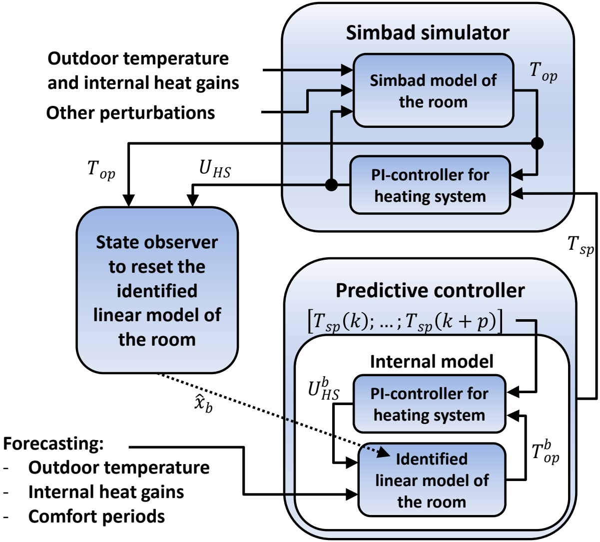
- Closed loop of the PI-control



Physical variables

T_{sp} → set-point temperature
T_{op} → operative temperature
T_{out} → outdoor temperature
U_{HS} → heat power
N_{oc} → number of occupants

MPC-control struture for the heating system



1^{st} predictive controller (with linear optimization)

- On-line linear optimization problem

Problem

At a time k, given $\mathbf{x_b}(k)$, $\mathbf{x_c}(k)$, the optimization problem is:

$$\min_{\mathbf{T_{SP}}(k:k+N_h-1)} \sum_{j=0}^{N_h-1} U_{HS}(k+j), \qquad (3)$$

s.t. $\forall j = 1..N_h \backslash N_{oc}(k+j) \neq 0$

$$T_{op,min} \leq T_{op}(k+j) \leq T_{op,max} \qquad (4)$$

$$0 \leq U_{HS}(k+j) \leq U_{HS}^{max} \qquad (5)$$

T_{op} and U_{HS} are computed according to linear models of the room and PI-controller with the prediction of:

- $\mathbf{T_{SP}}(k : k + N_h - 1)$ *(output of the MPC controller),*
- $\mathbf{T_{out}}(k : k + N_h - 1)$ *(flat prediction)*
- $\mathbf{N_{oc}}(k : k + N_h - 1)$ *(supposed known)*

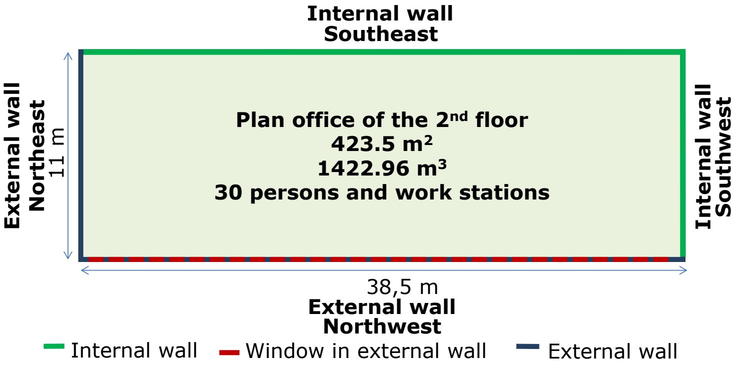
2nd predictive controller (without on-line optimization)

- Logical decision based on the prediction model
- No optimization toolbox needed
- The controller answers two questions:
  - Case 1: During inoccupancy, when switching the heating system on to ensure the thermal comfort for the next working hours, now or later ? (later if possible)
  - Case 2: During occupancy, when switching the heating system off to ensure the thermal comfort until the last occupancy hour, now or later ? (now if possible)
- Algorithms to solve these problems:
  - Case 1 : One simulation with input: $\mathbf{T_{SP}}(k : k + N_h) = [0, T_{SP}, T_{SP}, \ldots, T_{SP}]^T$
    $\Rightarrow$ `if` $T_{op}(k : k + N_h) \geq T_{op,min}(k + N_h)$ `then apply:` $T_{SP}(k) = 0$
    `else apply:` $T_{SP}(k) = T_{SP}$
  - Case 2 : One simulation with input: $\mathbf{T_{SP}}(k : k + N_h) = [0, T_{SP}, T_{SP}, \ldots, T_{SP}]^T$
    $\Rightarrow$ `if` $\forall i = 1, \ldots, N_h, T_{op}(k + i) \geq T_{op,min}(k + i)$ `then apply:` $T_{SP}(k) = 0$
    `else apply:` $T_{SP}(k) = T_{SP}$

Summary

Geometry of the building and window parameters

- One room in a low-consumption energy building used for office work
- Second floor of the 4-floor building
- Two external walls and two internal walls
- 28 windows on the Northwest side



Thermal parameters for walls and windows

THERMAL PARAMETERS FOR WALLS					
Wall	**Layer**	**Thickness** m	**Density** $kg{\cdot}m^{-3}$	**Capacity** $J{\cdot}kg^{-1}{\cdot}K^{-1}$	**Conductivity** $W{\cdot}m^{-1}{\cdot}K^{-1}$
External	Reinforced concrete	0.2	2150	1008	1.650
	Rockwool “Rockfaçade®”	0.12	39	1030	0.036
	Unventilated air gap	0.02	1	1000	0.130
	Ventilated air gap	0.022	1	1000	0.192
	Terra cotta “Terreal Zéphir®”	0.014	2286	1008	0.98
Internal	Drywall “BA13”	0.0125	825	1008	0.25
	Unventilated air gap	0.025	1	1000	0.155
	Drywall “BA13”	0.0125	825	1008	0.25
Floor	Concrete	0.31	2350	880	2.3

THERMAL PARAMETERS FOR WINDOWS	
Parameters	**Value**
Thermal diffusivity ($W{\cdot}m^{-2}{\cdot}K^{-1}$)	1.8
Solar absorption	0.095
g factor	0.42
Light transmission	0.71
Emissivity of exterior side	0.095
Emissivity of interior side	0.095

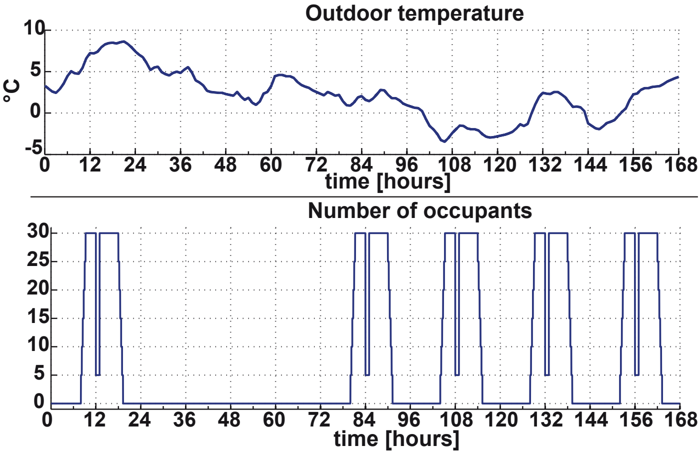
Systems for lighting and HVAC

- Lighting system

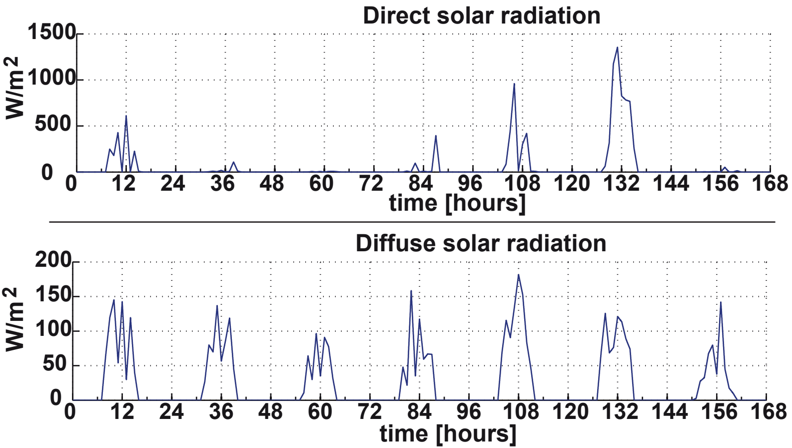
PARAMETERS OF THE LIGHTING SYSTEM		
Name	**Unit**	**Value**
Total lighting power	W	40
Illuminance efficiency	lm/W	88
Luminaire mean efficiency	–	0.8
Luminaire maintenance factor	–	1.11
Lighting heat gain	–	0.25

- HVAC system
  - Mechanical ventilation with heat recovery ($\varepsilon = 84\%$)
  - Air flow during occupancy : 0.3454 $\mathrm{kg{\cdot}s^{-1}}$
  - Air flow during inoccupancy : 0.034 54 $\mathrm{kg{\cdot}s^{-1}}$
  - Heat power : 0 to 12.588 kW (8.8 $\mathrm{W{\cdot}m^3}$)

Outdoor temperature and number of occupants



Solar radiation



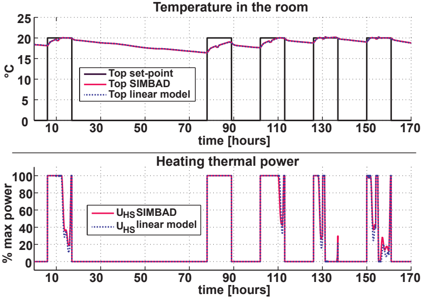
Summary

Identification of a linear model

- Identification of a 4-order linear model of the room (open loop), using the numerical algorithm for subspace state-space systems, based on dataset generated with Simbad
- Validation of the closed-loop model (with the PI-controller) considering 2 scenarios
  - V1: heating control always switched on
  - V2: heating control works during occupancy periods

VALIDATION OF THE CLOSED-LOOP MODEL

Criterion	Unit	V1	V2
FIT of T_{op}	%	95.6	96.7
FIT of U_{HS}	%	80.1	95.8
Total energy difference	%	−0.62	0.26



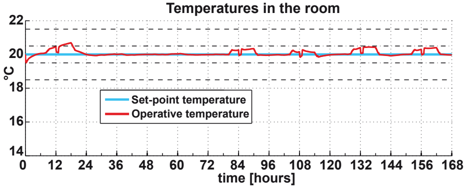
Evaluation of thermal comfort

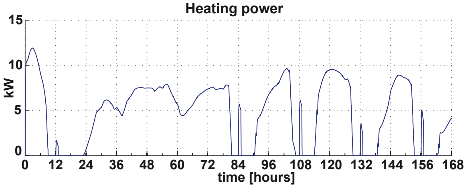
- Thermal comfort is evaluated according to % of time in three comfort domains for the operative temperature T_{op}
  - D_1: the optimal comfort domain (a 1 °C width temperature band, centered around the set-point).
  - D_2: the low discomfort domain.
  - D_3: the high discomfort domain, when the occupants feel an important thermal discomfort.

THERMAL COMFORT DOMAINS	
Name	**Conditions**
D_1	$\{T_{sp} + 0.5 > T_{op} > T_{sp} - 0.5\}$
D_2	$\{T_{sp} + 1.5 > T_{op} > T_{sp} + 0.5\}$ $\cup \{T_{sp} - 0.5 > T_{op} > T_{sp} - 1.5\}$
D_3	$\{T_{op} > T_{sp} + 1.5\}$ $\cup \{T_{op} < T_{sp} - 1.5\}$

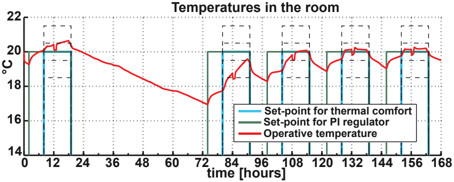
Results of PI-controller strategies

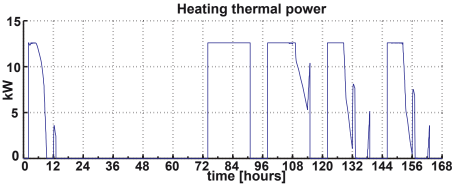
- PI-S1: Heating switched on 24/7
- Energy consumed: 797 kWh
- % of time with an optimal comfort: 91.1%





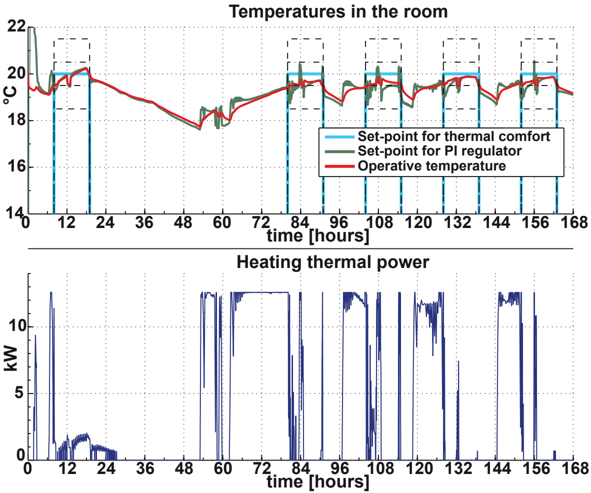
- PI-S2: 6-hour anticipation
- Energy consumed: 700 kWh
- % of time with an optimal comfort: 70.33%





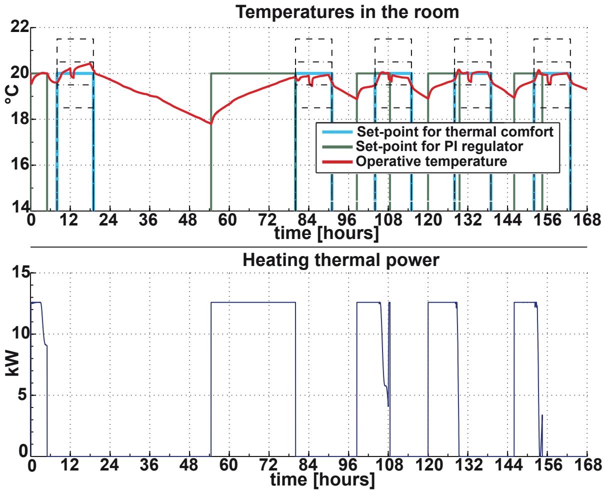
Results of the 1st Predictive Controller (MPC 1)

- Energy consumed: 670 kWh (-15.9% than PI-S1, -4.2% than PI-S2)
- % of time with an optimal comfort: 95.2% (+4.5% than PI-S1 +35.4% than PI-S2)



Results of the 2nd Predictive Controller (MPC 2)

- Energy consumed: 700 kWh (-12.2% than PI-S1, equal than PI-S2)
- % of time with an optimal comfort: 99.3% (+9% than PI-S1, +41.2% than PI-S2)



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Conclusion and outlook

- Conclusions
  - Development of a simple but intelligent predictive strategy
  - Preservation of local controllers
  - Computationally tractable algorithms
    - on-line linear optimization (MPC 1)
    - no-online optimization (MPC 2)
  - Significant reduction of energy use and better comfort level
- Future works
  - Estimation of operative temperature without any radiant measurement
  - Use of PMV instead of operative temperature
  - Generalization for multi-zone buildings
  - Control of multiple systems (blinding system. . .)
  - Integration of variable cost of energy
  - Experimental validation in a real building

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Thank you for your attention

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