A predictive control algorithm to optimize the operation of heat pumps in residential buildings in the context of smart grids

Philippe ANDRE and Elisabeth DAVIN,
BEMS, University of Liège, Arlon Campus Environnement

Jonathan MAUS, Master Student
University of Liège, Gembloux Agro-Biotech

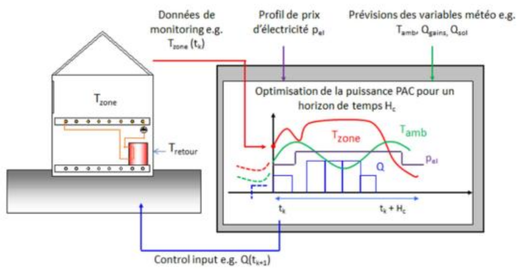
Belgium

Context of the Flexipac project

- Flexipac: research project funded by the walloon region of Belgium between 2013 and 2015
- Reasons for the research:
  - Increasing share of renewable (intermittent) electricity souces
  - Need for grid development and reinforcement for balancing loads on the grid and on the market
  - Increasing use of heat pumps as a substitute to fossil fuel boilers
  - Heat Pumps have the potential to shift electricity demands by means of short term thermal storage

Objective of the Flexipac project

- Development and test of an intelligent controller for a heat pump, based upon the « Model Predictive Control » paradigm, to be applied to residential buildings

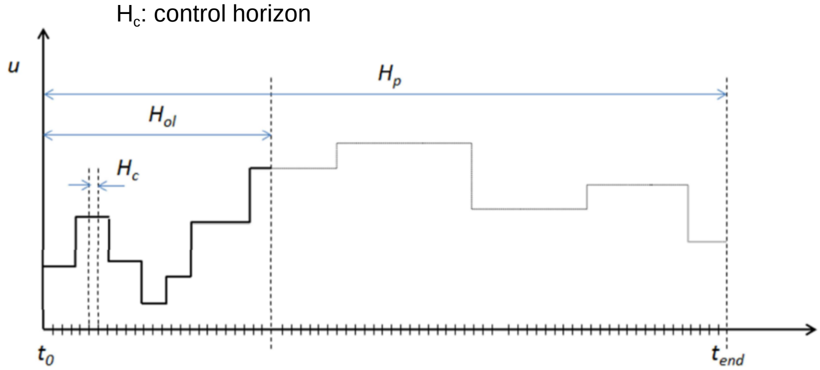


House + water storage + floor heating systems

Controller

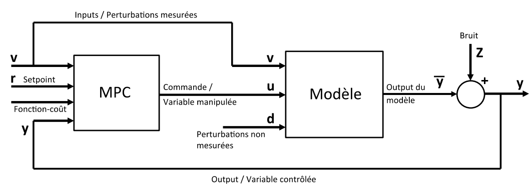
Model Predictive Control principle

H_p: prediction horizon
H_{ol}: optimization horizon
H_c: control horizon



Components of the Model Predictive Control

- State-space model of the system
- Disturbances forecasting
  - Weather
  - Occupancy of the house
- Optimisation algorithm



Methodology

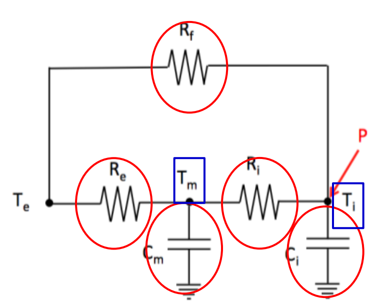
- Development of the model
- Identification of the parameters
- Selection of the optimisation algorithm
- Experimentation:
  - In simulation
  - In laboratory building

Development of the model

- Building modelling approaches:
  - White box (physical, knowledge)
    - Detailed
    - Many parameters
    - Not suitable for optimization
  - Black box (statistical, representation)
    - Simplified
    - Reduced number of parameters
    - Suitable for optimization

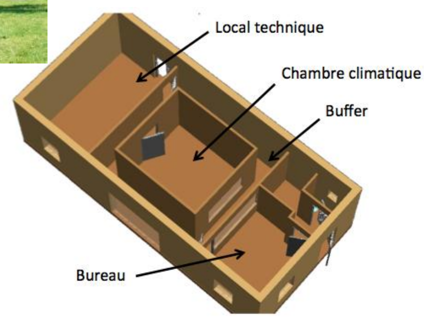
Development of the model

- Grey-box approach
  - Stil « simplified »
  - Reasonable number of parameters
  - Suitable for optimization
- Electrical analogy is very often used for a compact representation of model
  - Parameters
  - States



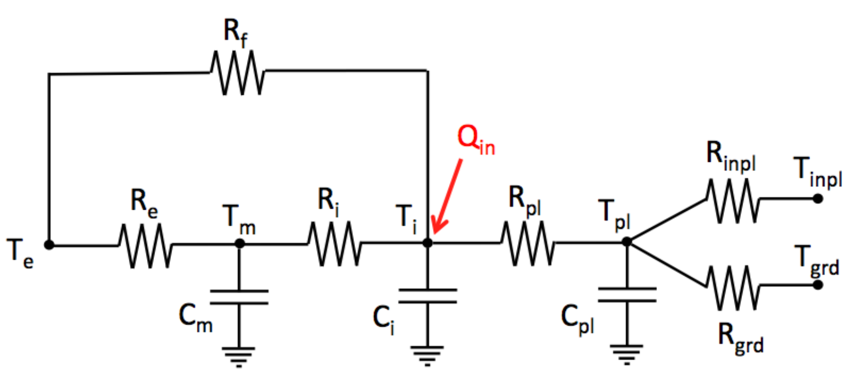
Testing environment: laboratory house

Energy systems laboratory on the Arlon campus



Heating system: floor heating

Modelling of the house



3 state variables; 4 inputs

Modeling of the house: equations

$$\frac{dT_m}{dt} = -\frac{(R_e + R_i)}{C_m R_e R_i} T_m + \frac{1}{C_m R_e} T_e + \frac{1}{C_m R_i} T_i$$

$$\frac{dT_i}{dt} = \frac{1}{C_i R_i} T_m - \frac{(R_i R_{pl} + R_i R_f + R_{pl} R_f)}{C_i R_i R_{pl} R_f} T_i + \frac{1}{C_i R_{pl}} T_{pl} + \frac{1}{C_i R_f} T_e + \frac{1}{C_i} Q_{in}$$

$$\frac{dT_{pl}}{dt} = \frac{1}{C_{pl} R_{pl}} T_i - \frac{(R_{pl} R_{inpl} + R_{pl} R_{grd} + R_{inpl} R_{grd})}{C_{pl} R_{pl} R_{inpl} R_{grd}} T_{pl} + \frac{1}{C_{pl} R_{inpl}} T_{inpl} + \frac{1}{C_i R_{grd}} T_{grd}$$

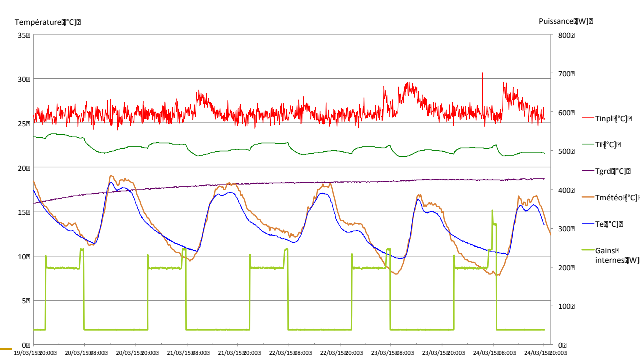
State-space formulation with

$$A = \begin{bmatrix} -\frac{(R_e + R_i)}{C_m R_e R_i} & \frac{1}{C_m R_i} & 0 \\ \frac{1}{C_i R_i} & -\frac{(R_i R_{pl} + R_i R_f + R_{pl} R_f)}{C_i R_i R_{pl} R_f} & \frac{1}{C_i R_{pl}} \\ 0 & \frac{1}{C_{pl} R_{pl}} & -\frac{(R_{pl} R_{inpl} + R_{pl} R_{grd} + R_{inpl} R_{grd})}{C_{pl} R_{pl} R_{inpl} R_{grd}} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{C_m R_e} & 0 & 0 & 0 \\ \frac{1}{C_i R_f} & 0 & 0 & \frac{1}{C_i} \\ 0 & \frac{1}{C_{pl} R_{inpl}} & \frac{1}{C_{pl} R_{grd}} & 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

Parameters identification

- Use of a test sequence
  - 5 days
  - 5 minutes sampling time

$$fit = 100\,(1 - \frac{\|y - \hat{y}\|}{\|y - moy(y)\|})$$



Optimisation algorithm

- Model-based Predictive Control (MPC)
- Variables:
  - Controlled variable: indoor temperature
  - Control variable: supply temperature of the floor heating system
  - Disturbances:
    - Measured:
      - « Outside » temperature
      - Internal gains
    - Non measured: none

Optimisation algorithm

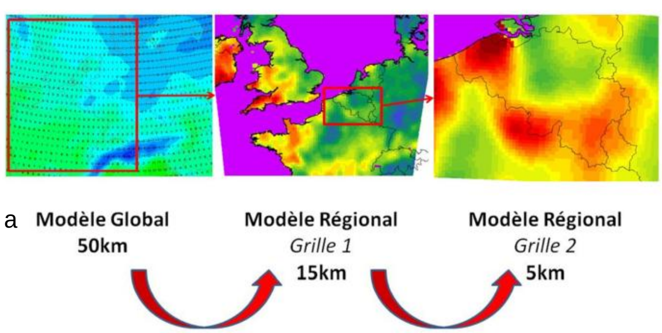
- Time step: 15 minutes
- Horizons:
  - Prediction horizon: 48 hours
  - Optimization horizon: 6 hours
  - Control horizon:
    - Receeding: 15 minutes (the next time step)
    - Non receeding
- Algorithm: « mpc » command of MatLab®

Cost function

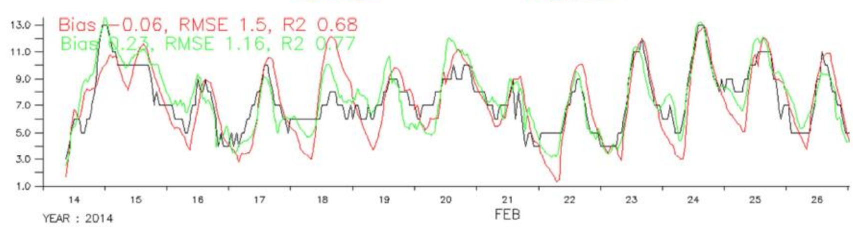
$$\min_{\Delta u(k|k),\ldots,\Delta u(m-1+k|k),\varepsilon} \left\{ \sum_{i=0}^{p-1} \left(\sum_{j=1}^{n_y} \left| w^{y}_{i+1,j}\left(y_j(k+i+1|k) - r_j(k+i+1)\right) \right|^2 + \sum_{j=1}^{n_u} \left| w^{\Delta u}_{i,j} \Delta u_j(k+i|k) \right|^2 + \sum_{j=1}^{n_u} \left| w^{u}_{i,j}\left(u_j(k+i|k) - u_{j\mathrm{target}}(k+i)\right) \right|^2 \right) + \rho_\varepsilon \varepsilon^2 \right\}$$

- Includes 3 terms:
  - Setpoint deviation (comfort) + hard constraints
  - Control variations (wear of equipment)
  - Control cost, including variable electricity price (cost, reflecting load on the network)
- Each term is weighted

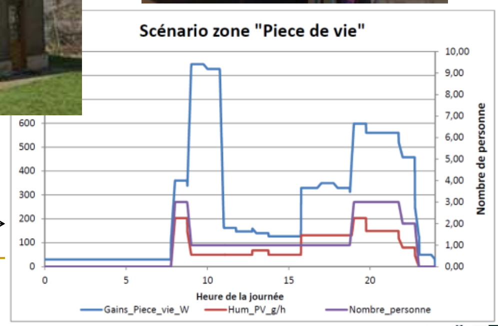
Weather forecasting



Connection to a weather model



Internal disturbances are artificially generated in the lab



Emulation of internal gains →

Testing

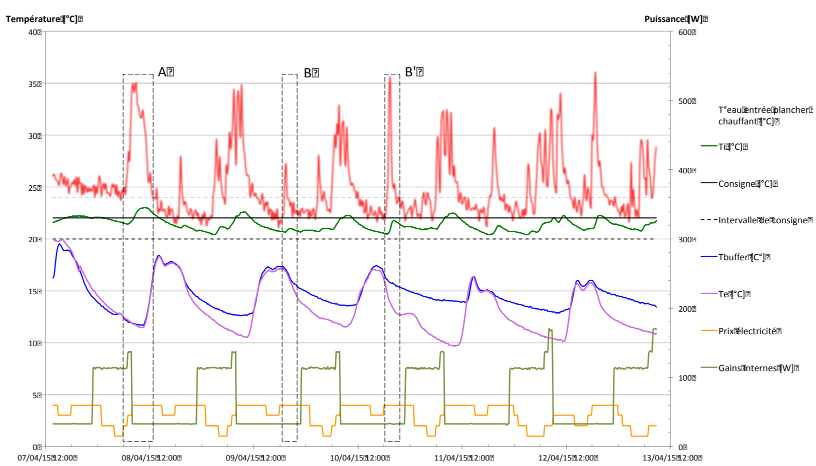
- In laboratory building:
  - Realistic
  - Controlled and replicable
- Objective
  - To assess, on site, the behaviour of the controller
  - To measure the impact of the Demand-Side Management on the thermal comfort of the occupant

Testing conditions and limitations

- Test 1
  - Average weighting factors
  - Ideal weather forecasts
  - Receeding horizon
- Test 2
  - Weighting factors:
    - First phase: energy cost priority
    - Second phase: comfort priority
  - Real weather forecasts
  - No longer receeding horizon
- Test 3
  - Weighting factors: average
  - Variable setpoint
  - Real weather forecasts
  - No receeding horizon

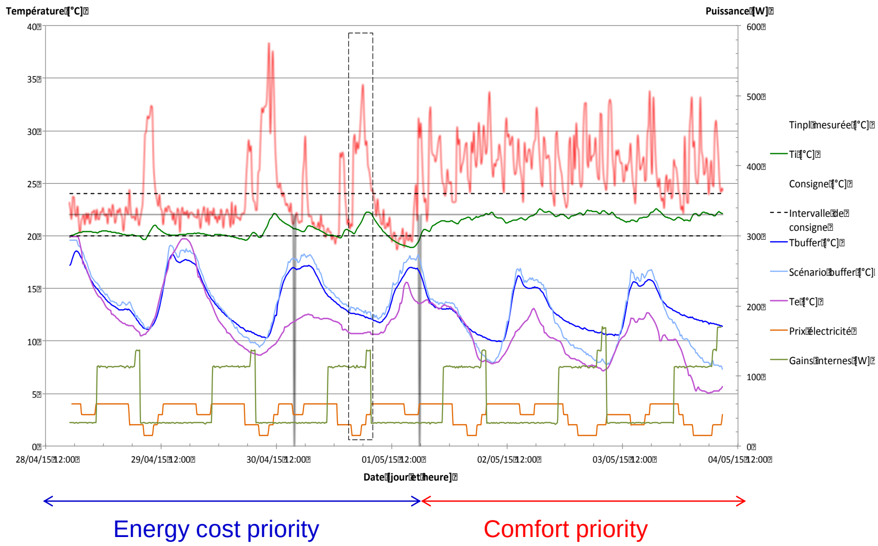
- Limitations
  - Energy cost is expressed by the supply temperature
  - Heat storage is limited (low inertia floor heating system)
  - Water storage not included in the optimisation
  - Load on the grid is supposed to be translated by the electricity price

Results: test 1

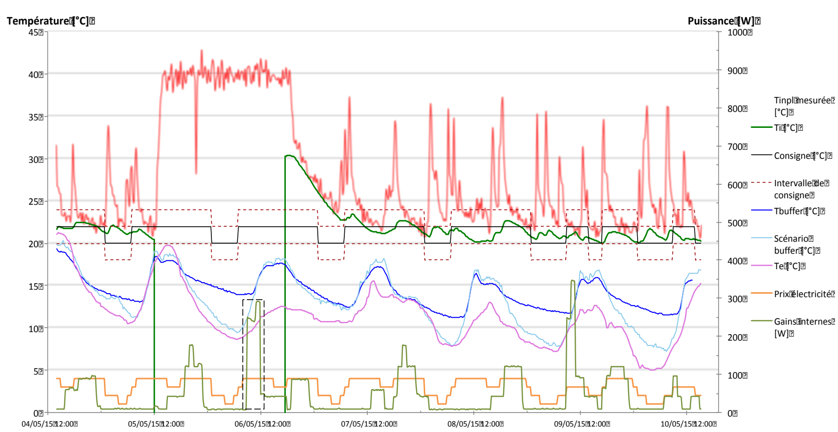


6 days; comfort is maintained; heat pump operation is imposed by a combination of factors

Results: test 2



Results: test 3



6 days; average weighting factors; variable setpoint; much more fluctuating internal gains
No longer receeding horizon

Conclusions and perspectives

- Experimental testing, in conditions close to reality, demonstrate the ability of a predictive controller to optimize the heat pump operation strategy

- Next steps:
  - Inclusion of the storage in the optimisation
  - Application to real houses
  - Application to larger number of houses -> global optimisation problem
  - Integration of local renewable electricity production (prosumers)

Thank you for your attention

This research was conducted with the support of the walloon region of Belgium