**Thermal control in building using MPC under air quality constraints**

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This work is supported by TOPAs H2020 project, GA nb 676760 (https://www.topas-eeb.eu/).

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**Context**

- 40% of energy consumed by buildings worldwide
- Strategies for
  - Energy conservation
  - Energy savings
- Better coordination among Building Automation Systems (FP7 SCUBA project)

- One of TOPAs objectives: **advanced control techniques**
  - Ventilation
  - Heating
  - Energy savings
  - Take into account “user comfort”, at least bounds on Temp. & CO2
Objectives

- Develop a generic (D)MPC framework to support control design
- Deploy, Test and Validate
  - Post-grad room in NIMBUS
  - Improve thermal comfort and air quality
  - Energy savings
  - Peak demand management / energy cost

- Post-grad room: open office in NIMBUS building
  - CIT Campus, Cork, Ireland
  - Climate zone: temperate maritime (mild winter, cool summer, regular rains)

Outline

- Context and objectives
- “System” under study
- Modelling
  - Thermal: white-box lumped capacitance (2RC)
  - CO2 concentration: mass balance
- Model Predictive Control for thermal and CO2 regulation
- Implementation in real field
  - Model tuning with real field data
  - Modelling for control?
- Next steps
“System” under study

- **NIMBUS – Proof of Concept**
  - Post-grad area split in 3 zones
  - **White box model**
    - CO2 concentration, thermal RC equivalent model
  - **Coupling** between zones (CO2 and temp.)
  - **Natural ventilation, controlled openings (windows)**
  - Outdoor conditions
  - Modular → “extendable”

- **Modelling - Thermal**

  - For each zone:
    - Simplified Lumped capacitance model (2RC)
      - **Coupling** between zones (natural convective heat transfer)
      - Influence of occupants \( \phi \)
      - Influence of heaters \( r \)
      - Influence of openings (natural leak, windows opening) (outdoor temperature)

    - For zone 1: 6 ODEs:
      - \( T_1, T_{sw}, T_{ww}, T_f, T_c, T_r \)

    - Similar approach for other zones
Modelling – CO2 concentration

• For each zone:
  Mass balance
  – **Coupling** between zone (diffusion via Fick’s law)
  – Influence of **openings** (natural leak, windows opening) (outdoor CO2)
  – Influence of **#occupants**
    • Uniform distribution over the room
  – 1 ODE per zone

*Continuous time linear model*

For both parts of the model: parameters fixed thanks to **basic knowledge** on building materials, building geometry, mean CO2 production and heat per occupant

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Application of Model Predictive Control to NIMBUS

(D)MPC framework

Control objectives
Indoor air quality
Thermal Comfort
Energy price

Constraints
Maximum heating power
Windows opening

Measurements per zone:
- temperature
- heating power
- windows opening

Measurements for the room:
- #occupants

Objectives
- Thermal Comfort
- Energy price

Constraints
- Maximum heating power
- Windows opening

Information exchange between zones: possibly, #occupants, heating power, windows opening

Results in simulation

<table>
<thead>
<tr>
<th>Power Consumption (kWh)</th>
<th>Conventional Control (on/off)</th>
<th>Centralized Control (CMPC)</th>
<th>Decentralized Control (DeMPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>181</td>
<td>127.85</td>
<td>138.59</td>
</tr>
<tr>
<td>Gain compared with conventional controller</td>
<td>0%</td>
<td>30%</td>
<td>23.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of states</th>
<th>Number of inequalities</th>
<th>Average optimization time per sampling time (normalized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPMC</td>
<td>21</td>
<td>660</td>
</tr>
<tr>
<td>DeMPC</td>
<td>7</td>
<td>220</td>
</tr>
</tbody>
</table>
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Implementation of control in real-field using (D)MPC framework

• Have a realistic comportemental model
  – Parameter identification \( \hat{\theta} \) for model tuning
    • Instead of \( R \) and \( C \), identify time constants \( \tau = RC \)
    • Building geometry known

  – Non-linear optimisation pb with constraints (+ODE integration)
    \[
    \hat{\theta} = \arg\min\{\|x(t, \theta) - \text{measures}(t)\|_2^2\}
    \]
    s.t. \( \theta \in [\theta_{\min}, \theta_{\max}] \)
    where \( \frac{dx}{dt} = f(x, u, t, \theta) \)
Model tuning

- Data extracted from TOPAs oBMS
- Parameter identification and model validation for the white-box continuous-time non-linear model

Modelling for Model Predictive Control

- White box model \(\rightarrow\) state space model for MPC
  - Linearisation
  - Exact discretisation: matrix exponential
  - Sparse matrix \(\rightarrow\) Full matrix

- Use directly identification techniques (Output Error + constraints)?
  - directly estimate discrete-time state-space model
  - Take advantage of knowledge from white-box model
  - Multiple Inputs Single Output (MISO) models
  - Transfer functions \(\rightarrow\) state-space representation

Initial model
Measurements
Model tuned

#occupants? Windows opening?
• As for many industrial systems: **availability & reliability of data?**
  – Data losses (wireless, wired)
  – Data accuracy: e.g. #occupants
  – Noise
  – Synchronisation
  – Occupancy per zone
    - Badge
    - Several persons
    - No information on the zone: uniform distribution, periodic reset
  – Power delivered by heaters
    - Coarse estimation (inlet/outlet temperature for the whole floor)
  – Windows opening
    - Manual ones!
    - Controlled ones but also partly non-functioning

2 days of trustful data record
→ Identification
→ Validation

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Modelling for Model Predictive Control

- **Model Inputs:**
  - Windows opening per zone: $w_1$ (N.U.), $w_2$ (N.U.), $w_3$ (N.U.)
  - Heaters: $P_1$ (kW), $P_2$ (kW), $P_3$ (kW)
  - $T_{out}$ (°C)
  - #occupants: $Nb_1$ (N.U.), $Nb_2$ (N.U.), $Nb_3$ (N.U.)

- **Model Output:** $T_1$ (°C) = $y$

\[
[x]_{k+1} = [A][x]_k + [B_1 \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} + B_2 \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} + B_3[T_{out}] + B_4 \begin{bmatrix} Nb_1 \\ Nb_2 \\ Nb_3 \end{bmatrix}
\]

\[
T_1 = y_k = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} x_k + D[u]_k
\]

For zone 1
• **Model selection**: standard deviation, pole/zero simplification, goodness of fit ...

![Model validation with another set of data](image)

Model validation with another set of data

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**Modeling for Model Predictive Control**

- **Model Inputs**:
  - Nb1 (N.U.), Nb2 (N.U.), Nb3 (N.U.)
  - windowZ1 (N.U.), windowZ2 (N.U.), windowZ3 (N.U.)

- **Model Output**: CO2\(_{z2}\) (ppm) = \( y \)

\[
[x]_{k+1} = [A][x]_k + B_1 \begin{bmatrix} Nb_1 \\ Nb_2 \\ Nb_3 \end{bmatrix} + B_2 \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}
\]

Measured “disturbances”

Control inputs

\[
CO2_{z1} = y_k = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} x_k + D[u]_k
\]

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Sustainable Places 2017
S. Leseq 17
Modelling for Model Predictive Control

- **Model selection**: standard deviation, pole/zero simplification, goodness of fit ...

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Next steps

• Currently under implementation on NIMBUS
  – (D)MPC framework developed by CIT
  – through LINC middleware (M. Louvel, presentation on Wednesday)

• Model improvement
  – Take solar irradiance into account
  – Longer period of time for identification / validation

• TOPAs: “GAP reduction”
  – Model re-adaptation when the “gap” (prediction / measure) is too large