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Thermal control in building using MPC under air quality constraints

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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

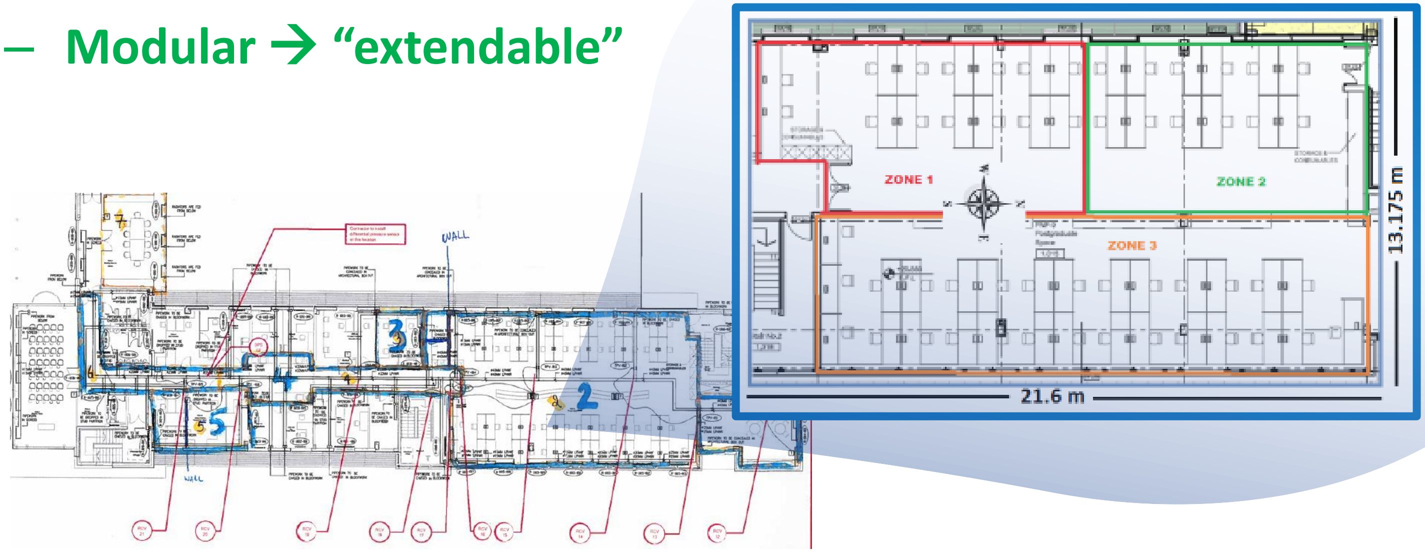
- Model Predictive Control for thermal and CO2 regulation
- Implementation in real field
  - Model tuning with real field data
  - Modelling for control?

- Next steps

"System" under study

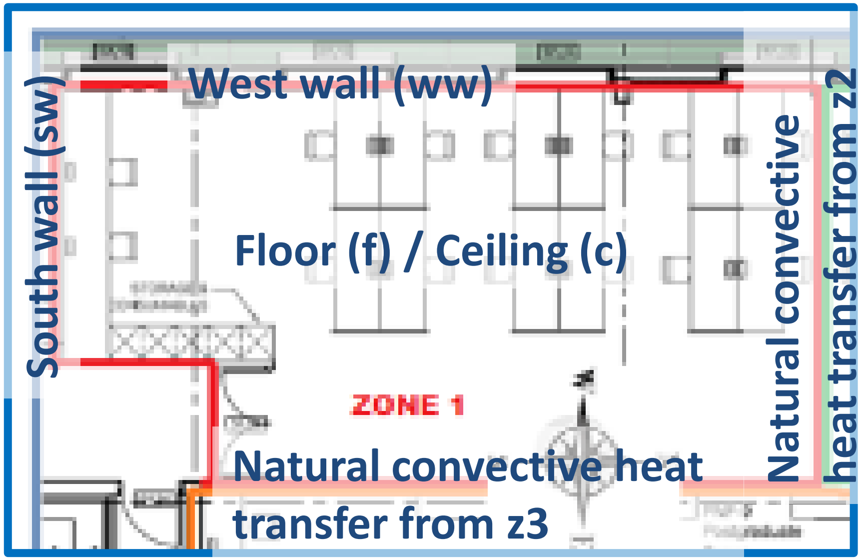
- NIMBUS – Proof of Concept
  - Post-grad area split in 3 zones
  - White box model
    - CO2 concentration, thermal RC equivalent model
  - **Coupling** between zones (CO2 and temp.)
  - **Natural ventilation, controlled openings (windows)**
  - Outdoor conditions

  - **Modular → "extendable"**



3 virtual zones
single space

Modelling - Thermal

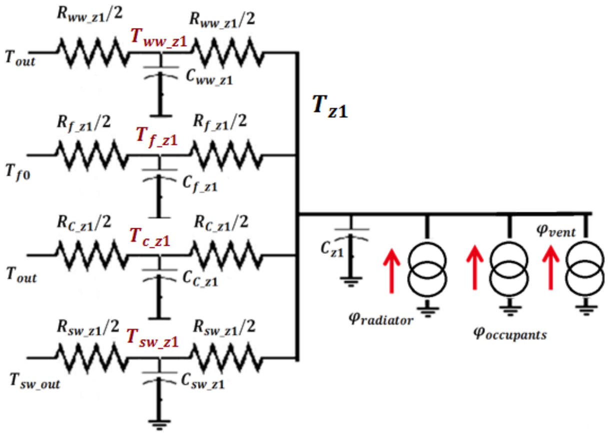


- For each zone:

  Simplified Lumped capacitance model (2RC)
  - **Coupling** between zones (natural convective heat transfer)
  - Influence of **#occupants** φ
  - Influence of heaters (r)
  - Influence of **openings** (natural leak, windows opening) (outdoor temperature)
  - For zone 1: 6 ODEs:

    T1, Tsw, Tww, Tf, Tc, Tr
  - Similar approach for other zones

Continuous time non-linear model



S. Walker et al., IFAC WC 2017

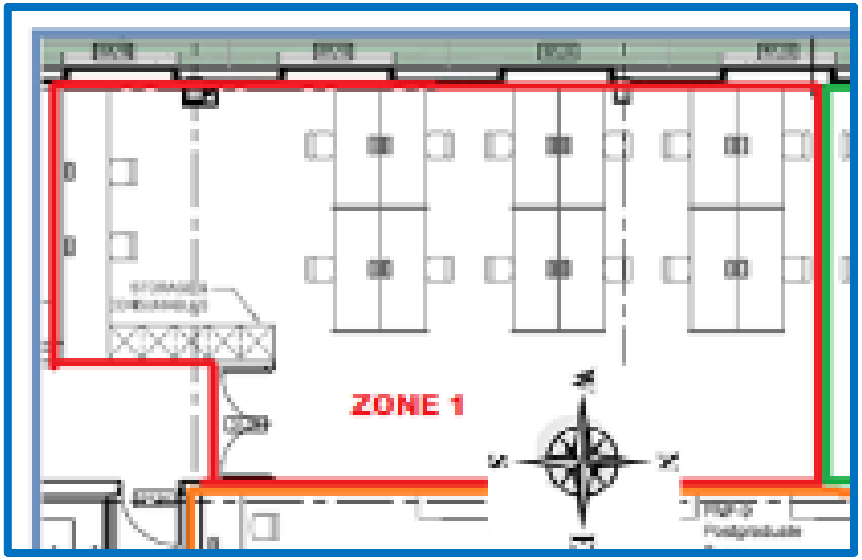
Modelling – CO2 concentration

- 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

S. Walker et al., IFAC WC 2017

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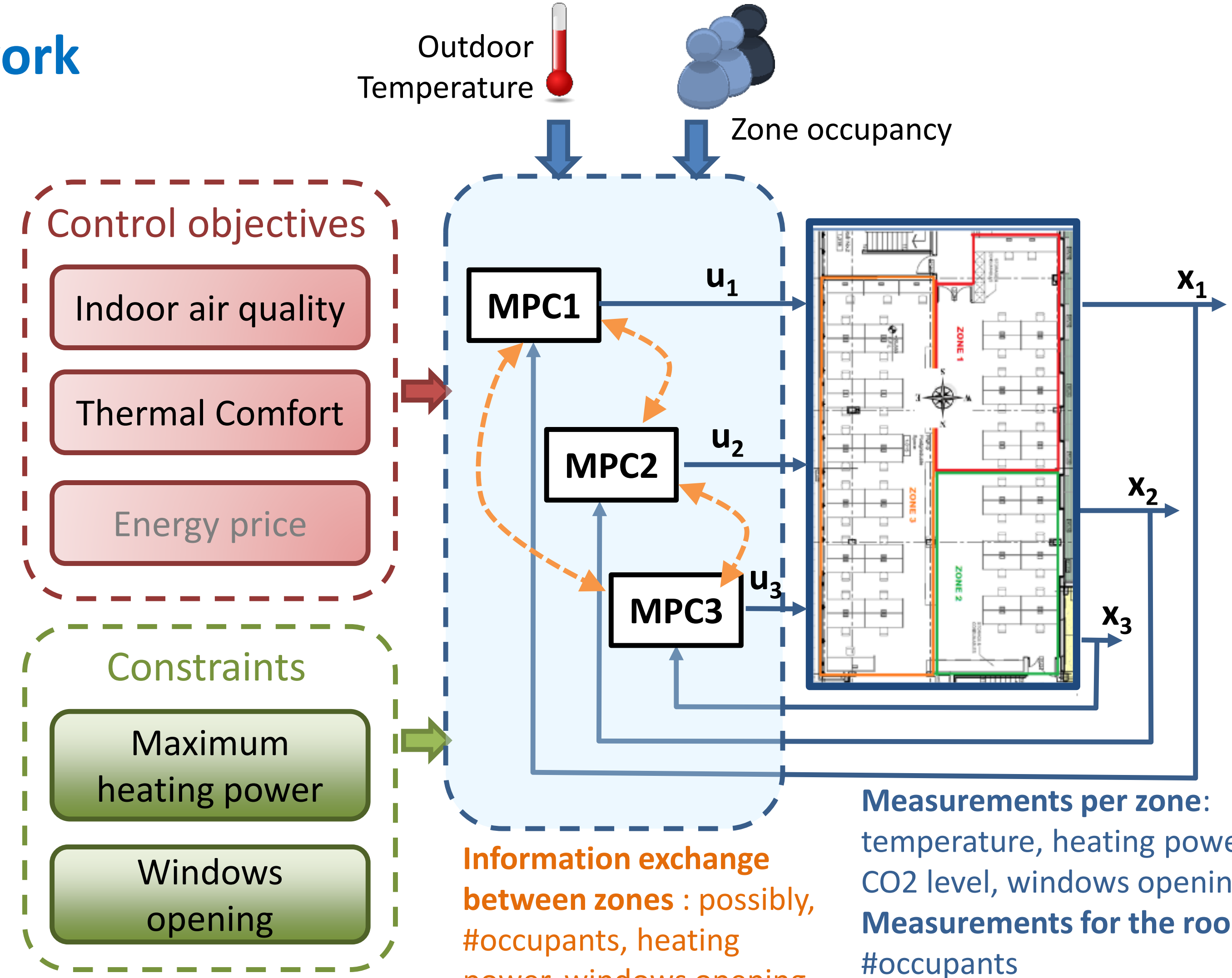
Application of Model Predictive Control to NIMBUS

(D)MPC framework



Control objectives

- Indoor air quality
- Thermal Comfort
- Energy price

Constraints

- Maximum heating power
- Windows opening

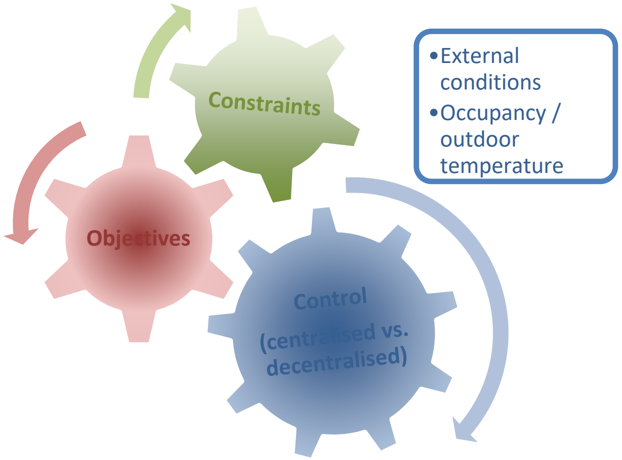
Information exchange between zones : possibly, #occupants, heating power, windows opening

Measurements per zone: temperature, heating power, CO2 level, windows opening

Measurements for the room: #occupants

$$J=\sum_{j=1}^{N}\{\underbrace{\|(y-y_{ref})(k+j)\|_Q^2}_{\text{Comfort}}+\underbrace{\|\Delta u(k+j)\|_R^2}_{\text{Energy}}\}$$

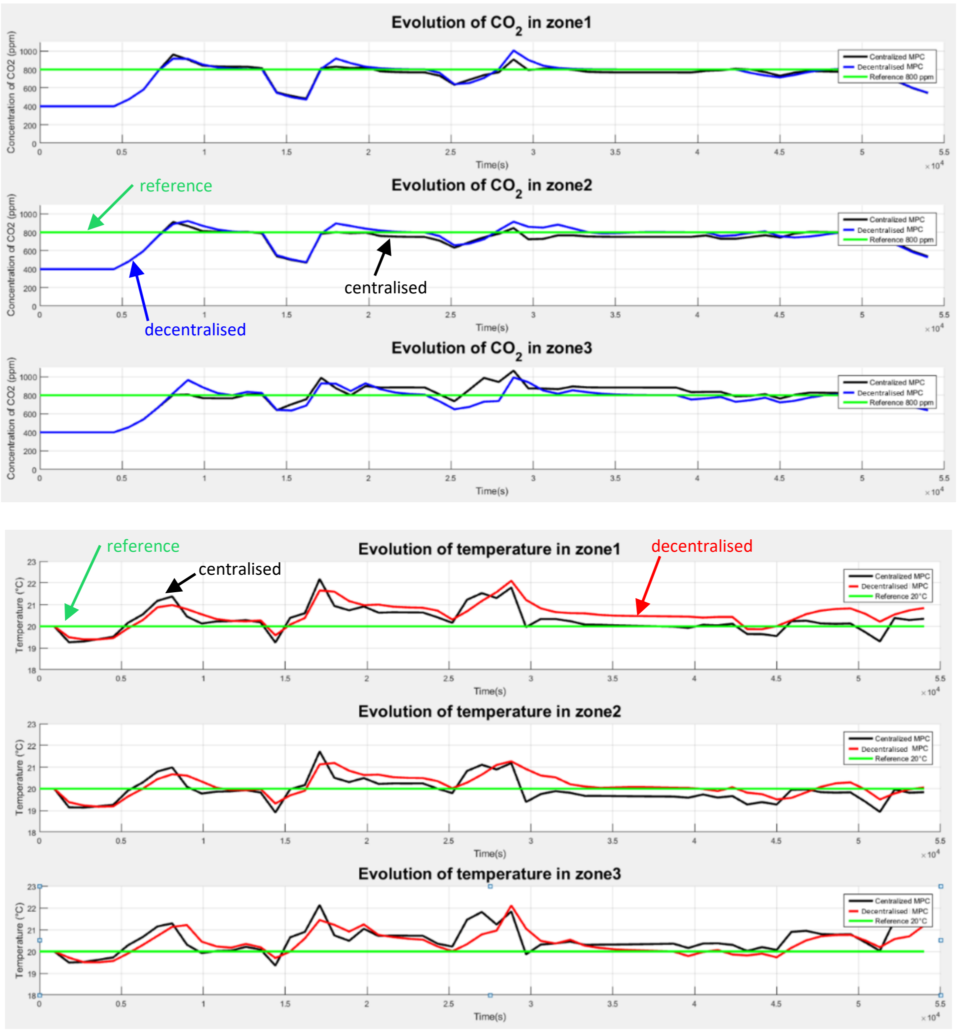
Results in simulation



- External conditions
- Occupancy / outdoor temperature

Power Consumption (kWh)	Conventional Control (on/off)	Centralized Control (CMPC)	Decentralized Control (DeMPC)
Total	181	127,83	138,59
Gain compared with conventional controller	0%	30%	23,5%

	Number of states	Number of inequalities /equalities	Average optimi. time per sampling time (normalized)
CPMC	21	660	4.7
DeMPC	7	220	1



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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)

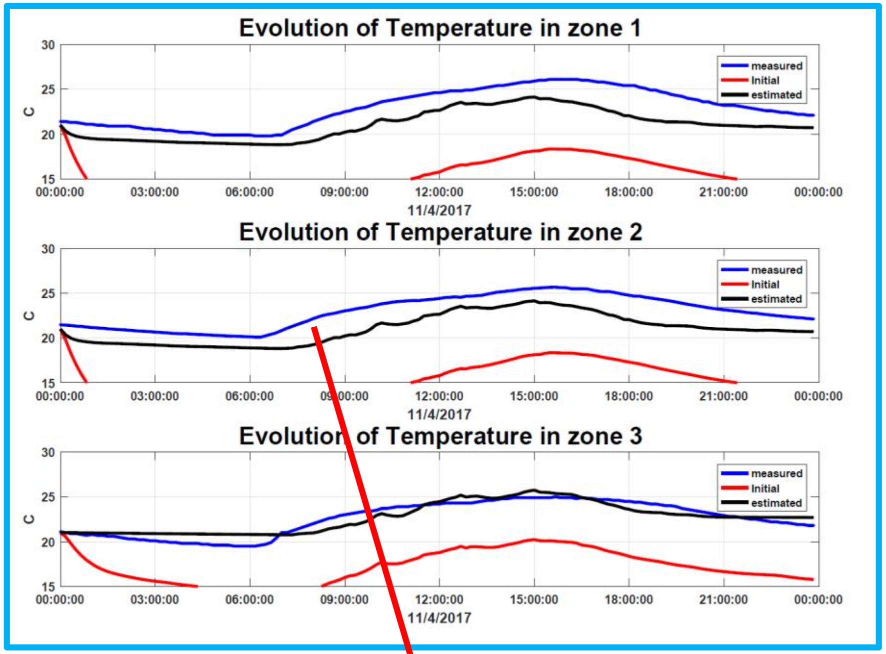
$$\hat{\theta} = argmin\{\|x(t,\theta) - measures(t)\|_2^2\}$$

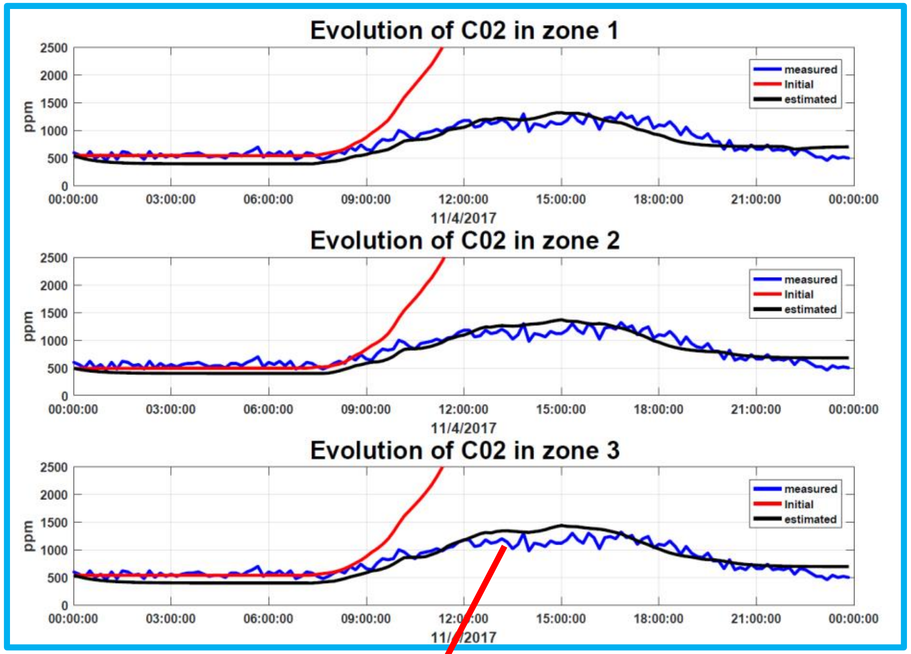
$$\text{s.t.} \quad \theta \in [\theta_{min}, \theta_{max}]$$

$$\text{where } \frac{dx}{dt} = f(x,u,t,\theta)$$

Model tuning

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



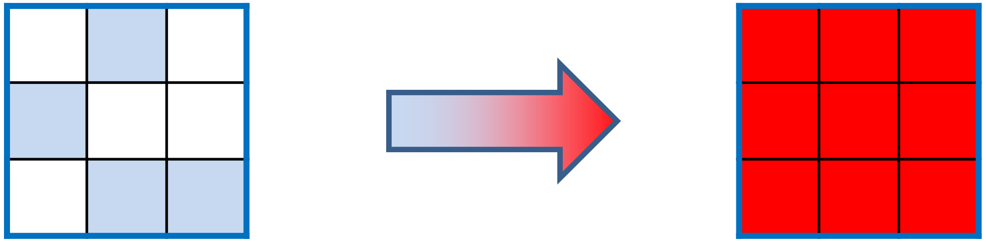


#occupants? Windows opening?

Initial model
Measurements
Model tuned

Modelling for Model Predictive Control

- White box model → state space model for MPC
  - Linearisation
  - Exact discretisation: matrix exponential



Sparse matrix

Full matrix

No more **physical meaning** for the parameters

- **Use directly identification techniques (Output Error + constraints)?**

→ directly estimate discrete-time state-space model

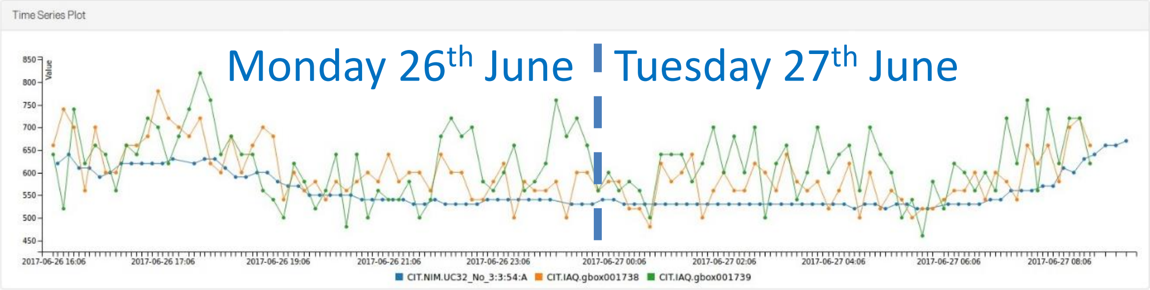
→ Take advantage of **knowledge** from **white-box model**

→ Multiple Inputs Single Output (MISO) models

→ Transfer functions → state-space representation

Modelling for Model Predictive Control

- 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

Modelling for Model Predictive Control

For zone 1

- Model Inputs:

$[u]$

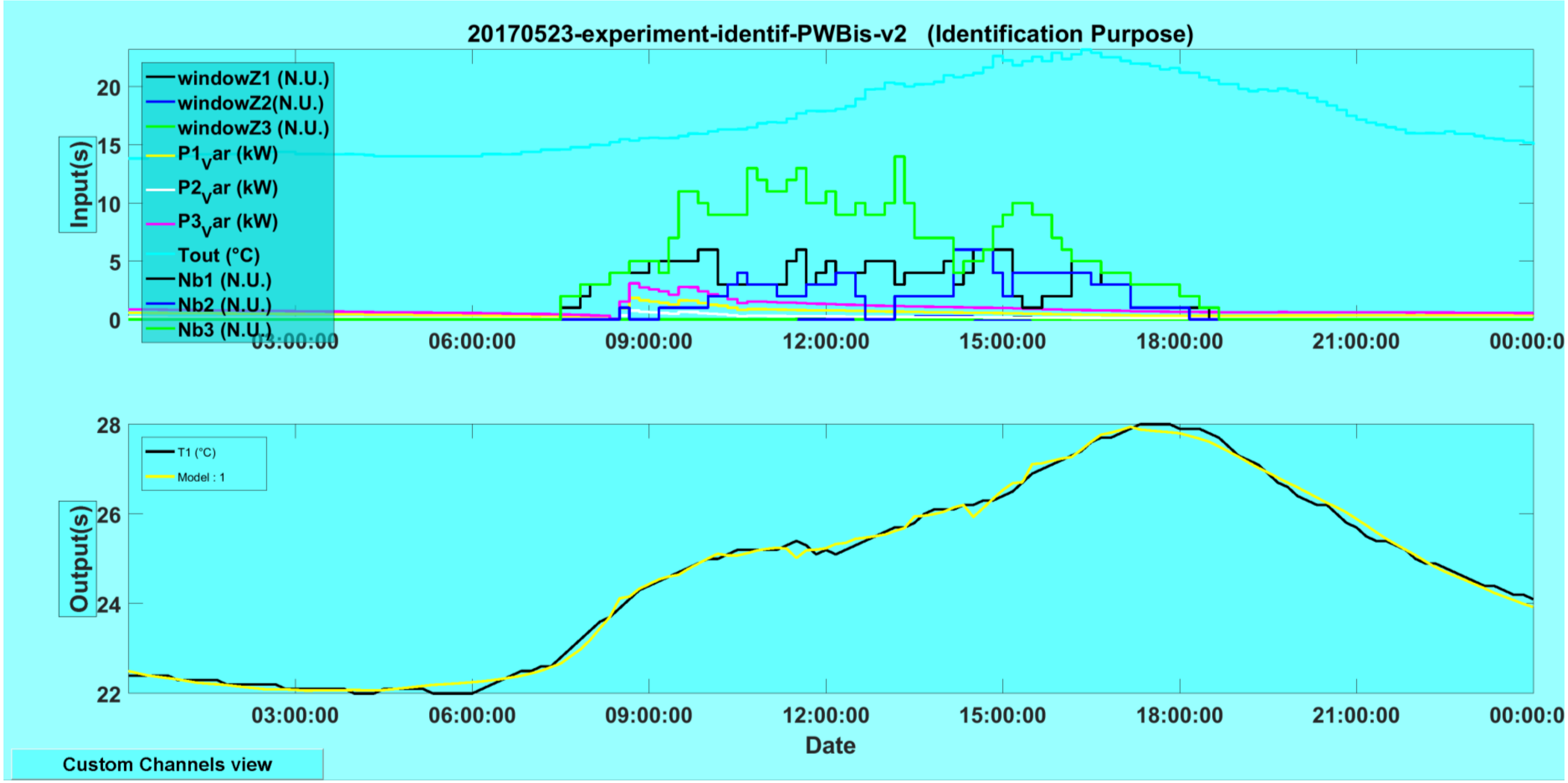
  - Windows opening per zone: w_1 (N.U.), w_2(N.U.), w_3 (N.U.)
  - Heaters: P_1 (kW), P_2 (kW), P_3 (kW)
  - T_{out} (°C)
  - #occupants: Nb_1 (N.U.), Nb_2 (N.U.), Nb_3 (N.U.)
- Model Output: T_1 (°C) $= y$

$$[x]_{k+1} = [A][x]_k + \underbrace{B_1 \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} + B_2 \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix}}_{\text{Control inputs}} + \underbrace{B_3[T_{out}] + B_4 \begin{bmatrix} Nb_1 \\ Nb_2 \\ Nb_3 \end{bmatrix}}_{\text{Measured “disturbances”}}$$

$$T_1 = y_k = [1 \quad 1 \quad 1]x_k + D[u]_k$$

Modelling for Model Predictive Control

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



Model validation with another set of data

Modelling for Model Predictive Control

For zone 1

- Model Inputs:

$[u]$

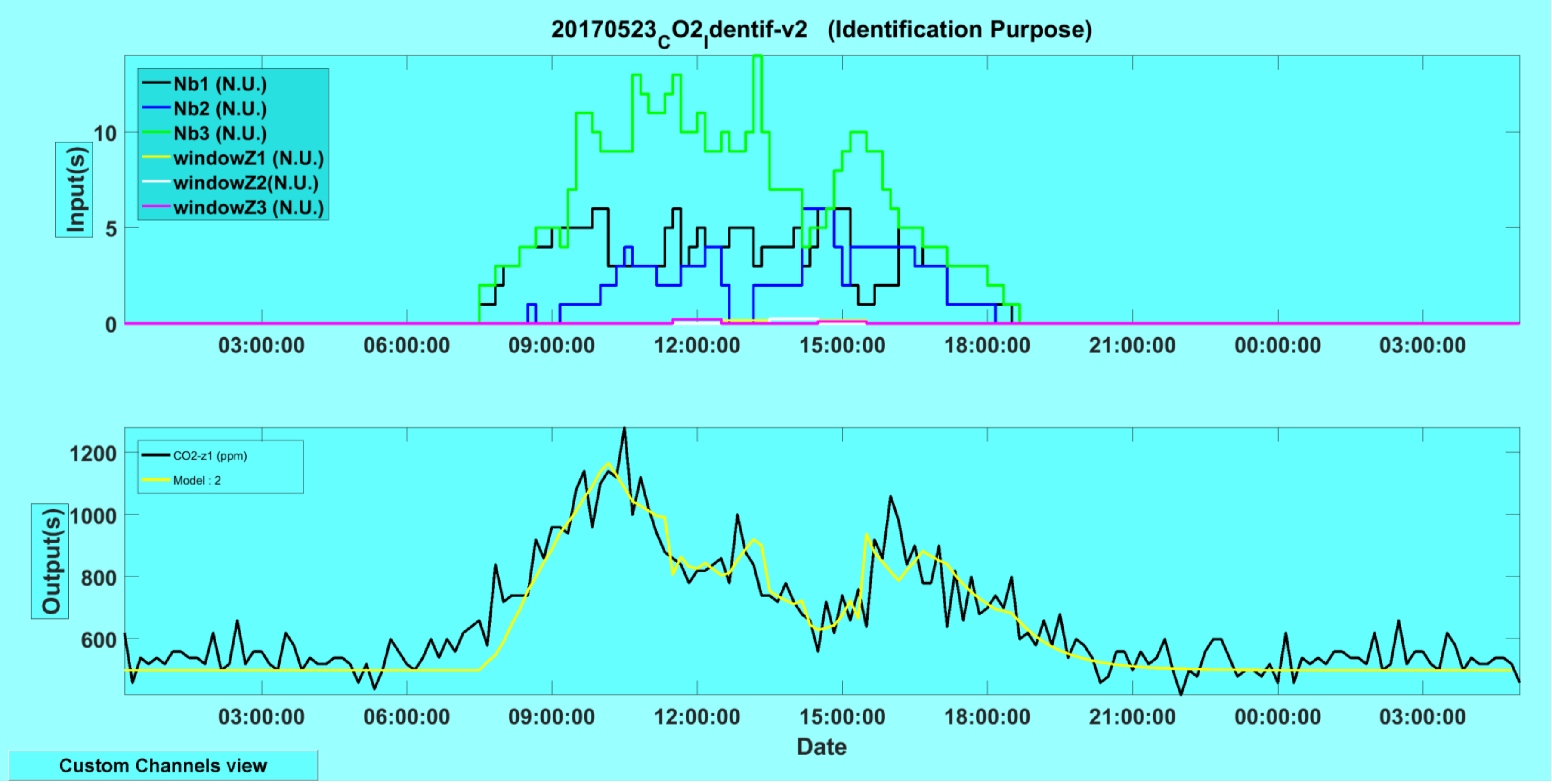
  - Nb1 (N.U.), Nb2 (N.U.), Nb3 (N.U.)
  - windowZ1 (N.U.), windowZ2(N.U.), windowZ3 (N.U.),
- Model Output: $CO2_{z2}$ (ppm) $= y$

$$[x]_{k+1} = [A][x]_k + B_1 \underbrace{\begin{bmatrix} Nb_1 \\ Nb_2 \\ Nb_3 \end{bmatrix}}_{\text{Measured “disturbances”}} + B_2 \underbrace{\begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}}_{\text{Control inputs}}$$

$$CO2_{z1} = y_k = [1 \quad 0 \quad 0]x_k + D[u]_k$$

Modelling for Model Predictive Control

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



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- 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