Generating models for Model Predictive Control in buildings

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Context

- **40%** of energy consumed by buildings worldwide
- Focus on **new strategies** for
  - Energy conservation
  - Energy savings

- One of TOPAs objectives: advanced control techniques
  - Ventilation
  - Heating

→ *Energy savings*
→ *Take into account "user comfort", at least bounds on Temp. & CO2*

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TOPAs
advanced control objective

MPC => **Model-based** control approach

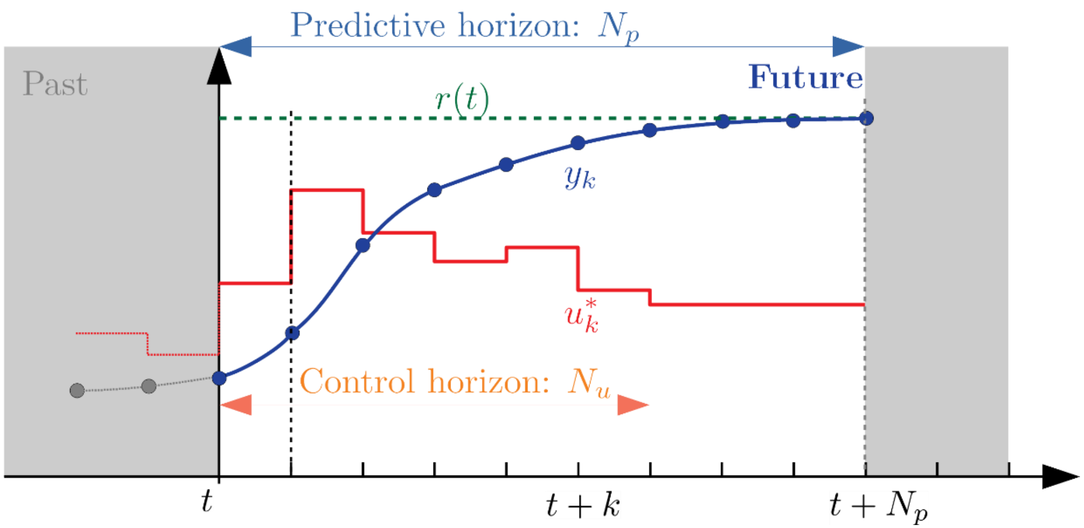
- Develop a **generic modelling framework**
- **Deploy, Test and Validate**
  - Post-grad room in NIMBUS
  - Improve thermal comfort and air quality
  - Energy savings

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

Outline

- Model Predictive Control **philosophy**
  - Model-based strategy (*state-space*, transfer function)
  - Receding horizon to *predict future behavior*
  - Compute *optimal control* sequence

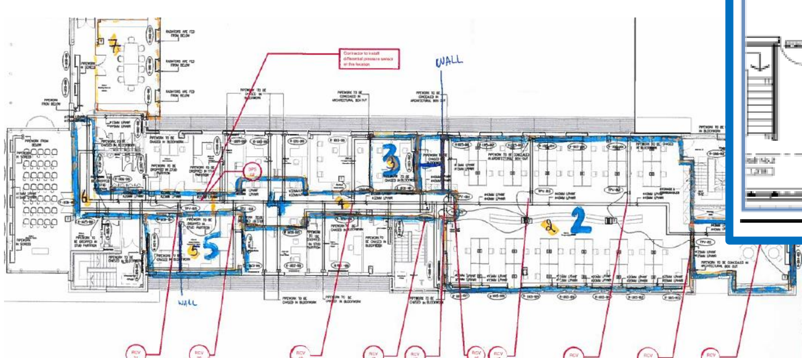
- **Why** MPC for building ?
  - Coordinate multiple inputs / outputs systems
  - Economic vs performance *tradeoff*
  - Constraint handling

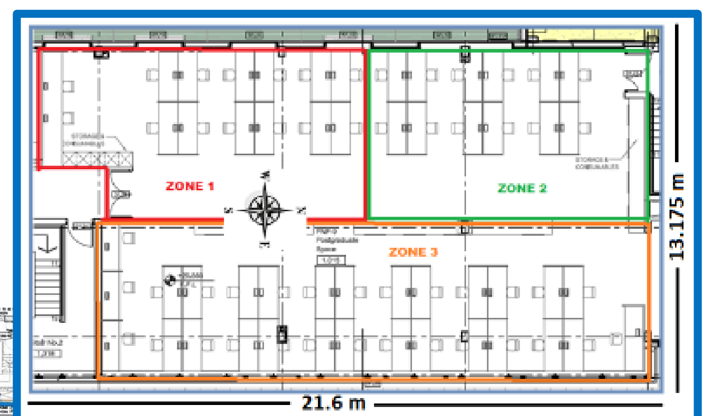


Rely on a (sampled) dynamic model

- Considering a **multiple zones** building
  - *Coupling* between zones
  - Controlled *ventilation and heating*
  - Outdoor conditions

- How to generate a **numerical model** (≠ simulation model)
  - *Suitable for MPC* control design
  - Accurate
  - *Modular*





Definition:

model = a mathematical representation of a system, which describes the relationships between an entrie u and an output y subject to exogenous signals w

State of arts:

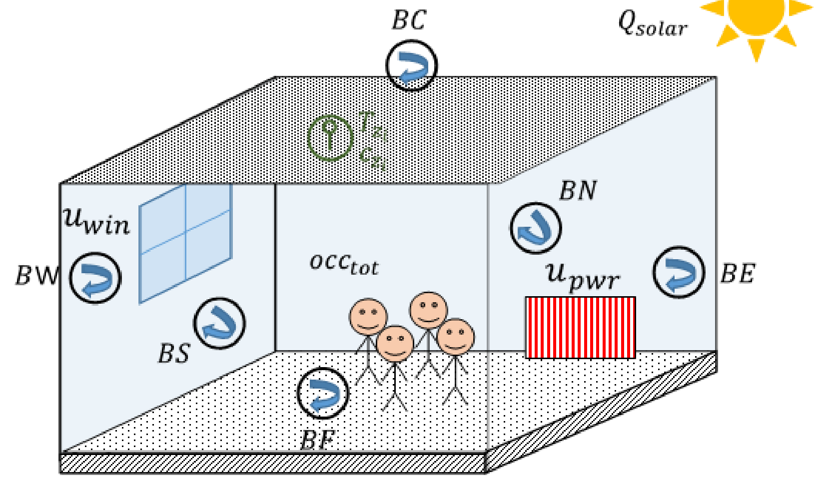
	White box	Grey box[1]	Black box
Modelling principle	Physical	Behaviour	Identification
Source of knowledge	LoN	A, LoN, DC	DC
Advantage	Physical meaning	Easy to extend	Hand on the model structure
Disadvantage	- Expertise in the domain - Complex	- Difficult to calibrate	- Sensitivity to data quality

LoN: Law of Nature; A: Analogy; DC: Data Collection

[1] : [SP 2017, IFAC-2017]

1. Context and objectives
   a. Context
   b. Objective
2. Problem statement
   a. MPC basics
   b. Problem definition
   c. Modelling types
3. Generating models for MPC
   a. Acquiring data for modelling
      i. General system description
      ii. Capturing zone behavior
   b. Modelling and identification
      i. Model structure
      ii. Parameter optimization problem
      iii. Validation process
4. Application
   a. Distributive Model Predictive Control for thermal comfort
   b. TOPAs control architecture
   c. Results

- Find a proper **description** that:
  - Defines the *input & output* variables
  - Is *common* to any zone



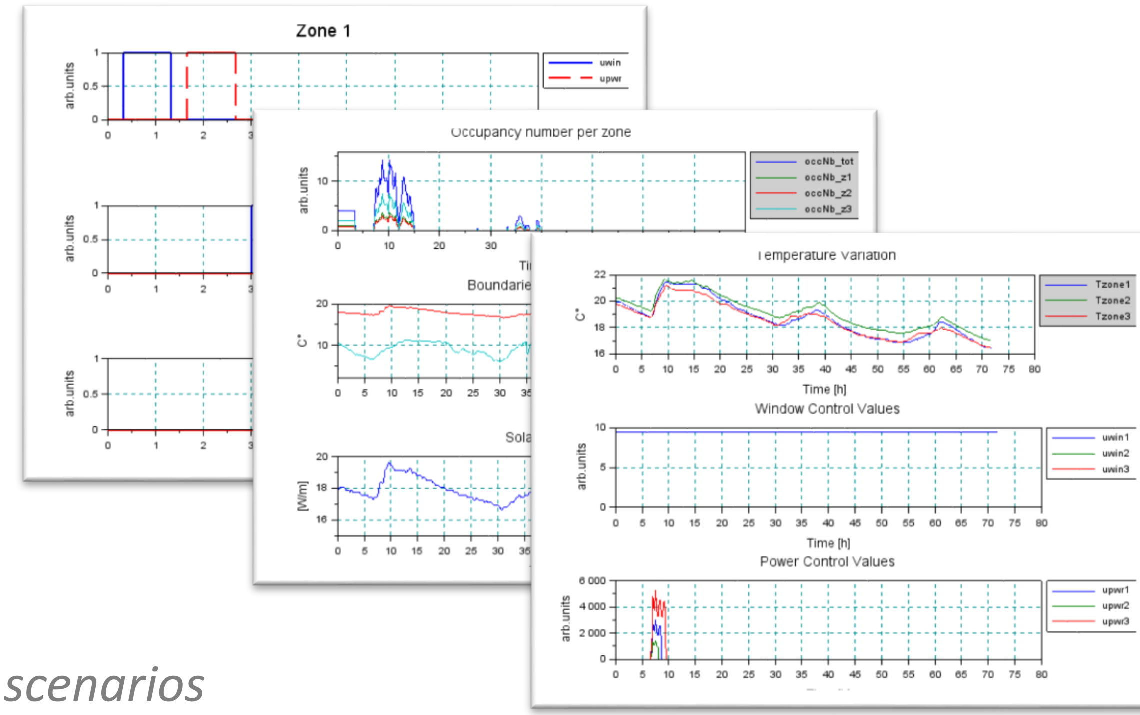
- **Four types** of variable

Regulated	*Boundaries*	*Exogenous*	*Control*
T_{z_i}: Temperature (°C) c_{z_i}: CO_2 (ppm)	North face: T_{bn}, c_{bn} East face: T_{be}, c_{be} South face: T_{bs}, c_{bs} West face: T_{bw}, c_{bw} Ceiling: T_{bc}, c_{bc} Floor: T_{bf}, c_{bf}	occ_{tot}: total occupancy Q_{solar}: heat input generated by solar radiation (W)	u_{win}: air flow / window position (%) u_{pwr}: heating power (W)

Capturing zone behavior

<u>Main idea:</u> *Stimulate the system along its whole frequency spectrum*

- **Challenging** because of:
  - Highly coupled interactions
  - Occupancy & weather conditions



- **Three types** of data set
  - Working day;
  - Weekend day;
  - *Experiments day: PRBS or scenarios on the manipulated variables*

Training data = a weighted sum of the three types

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The model structure is **defined by the designer**

- We propose the **Brunowski** state-space form
  - Naturally sparse => *ease the process* of identification
  - State matrices => cope with early *MPC algorithms*
  - Partitioned matrix => ready for *distributive / decentralized* application

$$n_1 = 3 \quad n_2 = 2 \quad n_3 = 1$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ 0 & 0 & 0 & 0 & 1 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \end{bmatrix}, \qquad B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{31} & b_{32} \\ b_{41} & b_{42} \\ b_{51} & b_{52} \\ b_{61} & b_{62} \end{bmatrix}$$

n_i: design parameters
a_{ij}, b_{ij}: model parameters => **to identify**

Parameters optimization problem (1)

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Find the model parameters by solving an optimization problem

- Denote $z_t = [T_{z_i}, c_{z_i}]$, $\mathrm{u_t} = [u_{win}, u_{pwr}]$, $\theta = [\mathrm{a_{ij}}, \mathrm{b_{ij}}, x_0 \in \mathbb{R}^{n_x}, \beta \in \mathbb{R}^{n_y}]$

  (Vector of parameters to identify)

- Cost function

$$F(\theta) = \sum_{t=1}^{N} [y_t(\theta) - z_t]^2$$

- Optimisation problem

$$\theta^* = arg \min_{\Theta \in D} F(\theta)$$

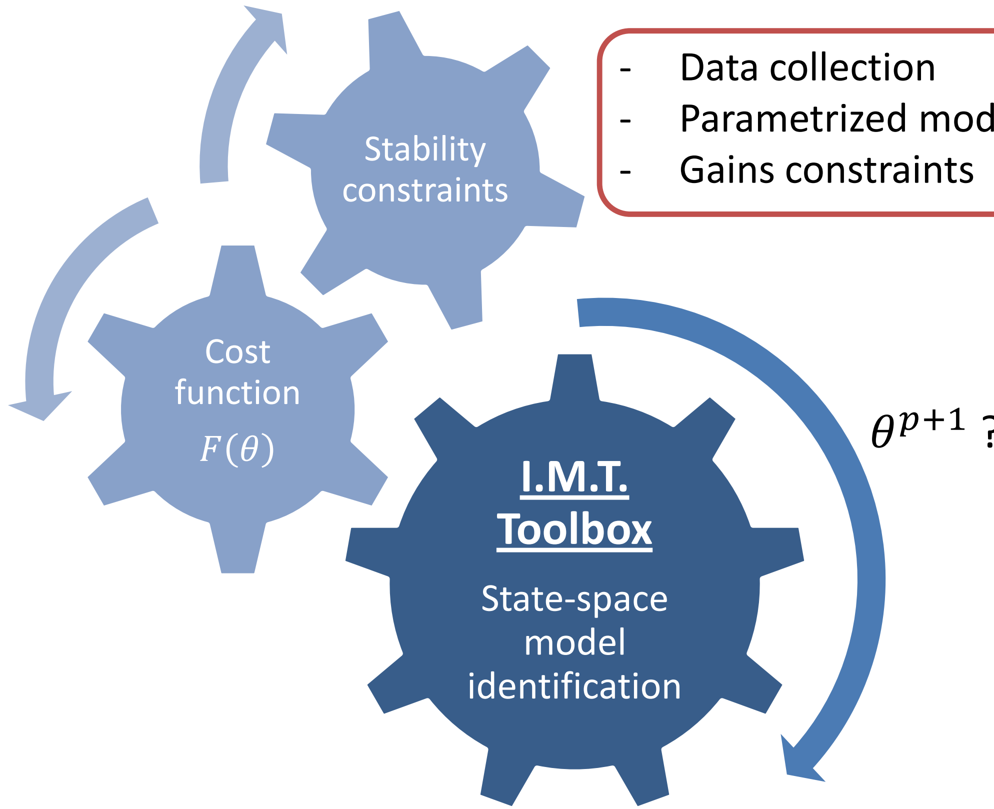
$$\begin{cases} x_{t+1} = A(\theta)x_t + B(\theta)u_t, \quad x_0(\theta) \\ y_t = Cx_t + Du_t + \beta(\theta) \end{cases}$$

Parametrized model (Governing equation)

Find the model parameters by **resolving an optimization problem**

Identification & Modelling Tool:

- Includes natural robustness to model uncertainties
- Deals with Brunowski form.
- Allow static gains constraints.

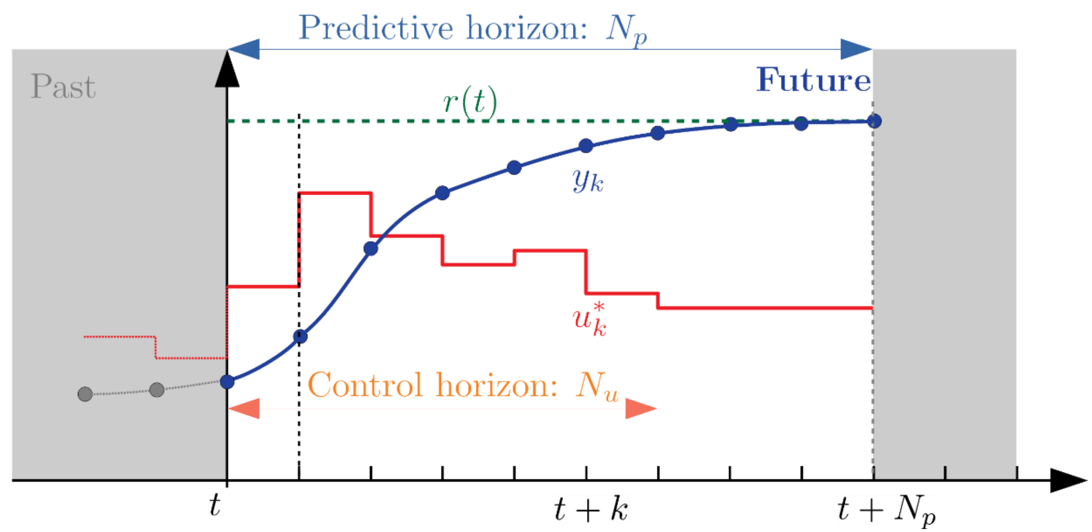


- Data collection
- Parametrized model
- Gains constraints

How to **validate** the model for MPC purpose?

- Model Predictive Control **philosophy**

*Use **the dynamic model** to **predict future** behavior and compute the optimal control sequence*

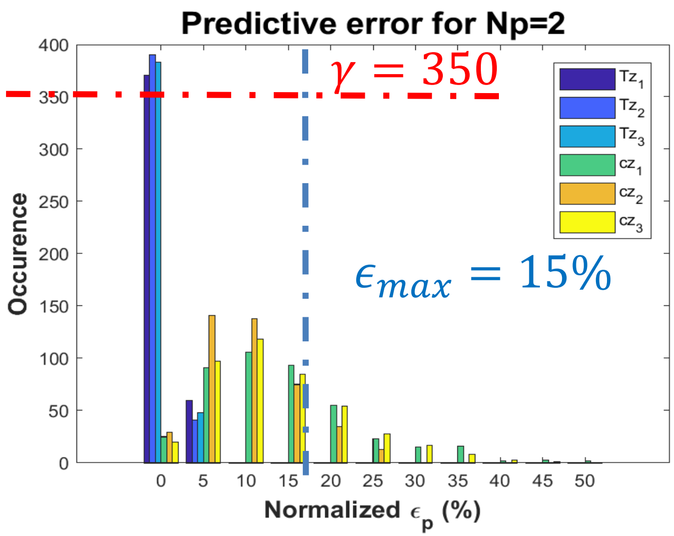


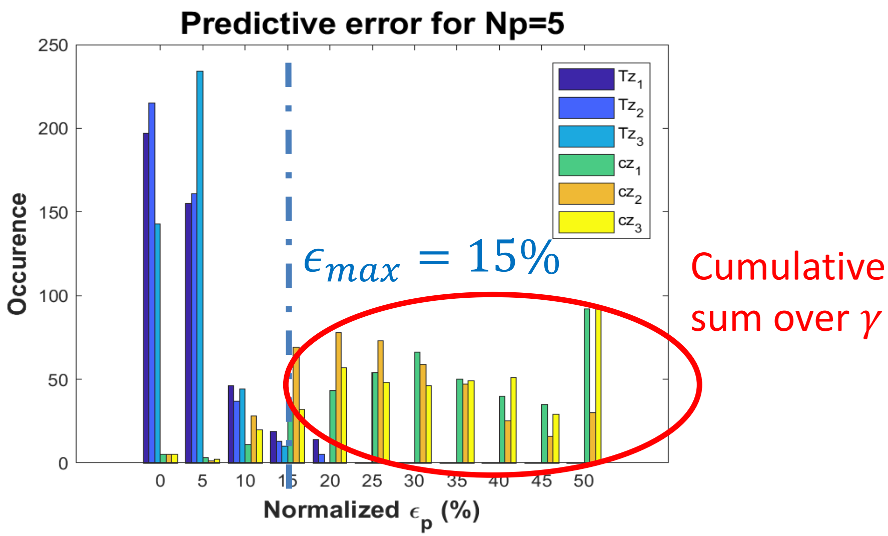
- **Idea:** compute at sample k the relative error **on receding horizon** N_p

$$\epsilon_p(k) = \sum_{k=t}^{t+N_p} \left\| \frac{y_t(k) - z_t(k)}{z_t(k)} \right\|^2$$

- For a defined N_p **analyse** the results
  - Measure occurrence
  - Fix a tolerance γ

$$\epsilon_p(k) = \sum_{k=t}^{t+N_p} \left\| \frac{y_t(k) - z_t(k)}{z_t(k)} \right\|^2$$





- **Example** with 432 sampling (3 days) ($\gamma = 350, \epsilon_{max} = 15\%$)
  - Thermal model validated for $N_p \leq 5$
  - CO2 model validated for $N_p \leq 2$

$$\sum_{\epsilon_p > \epsilon_{p_{max}}} occ(\epsilon_p)\Big|_{Np_{min}} > \gamma$$

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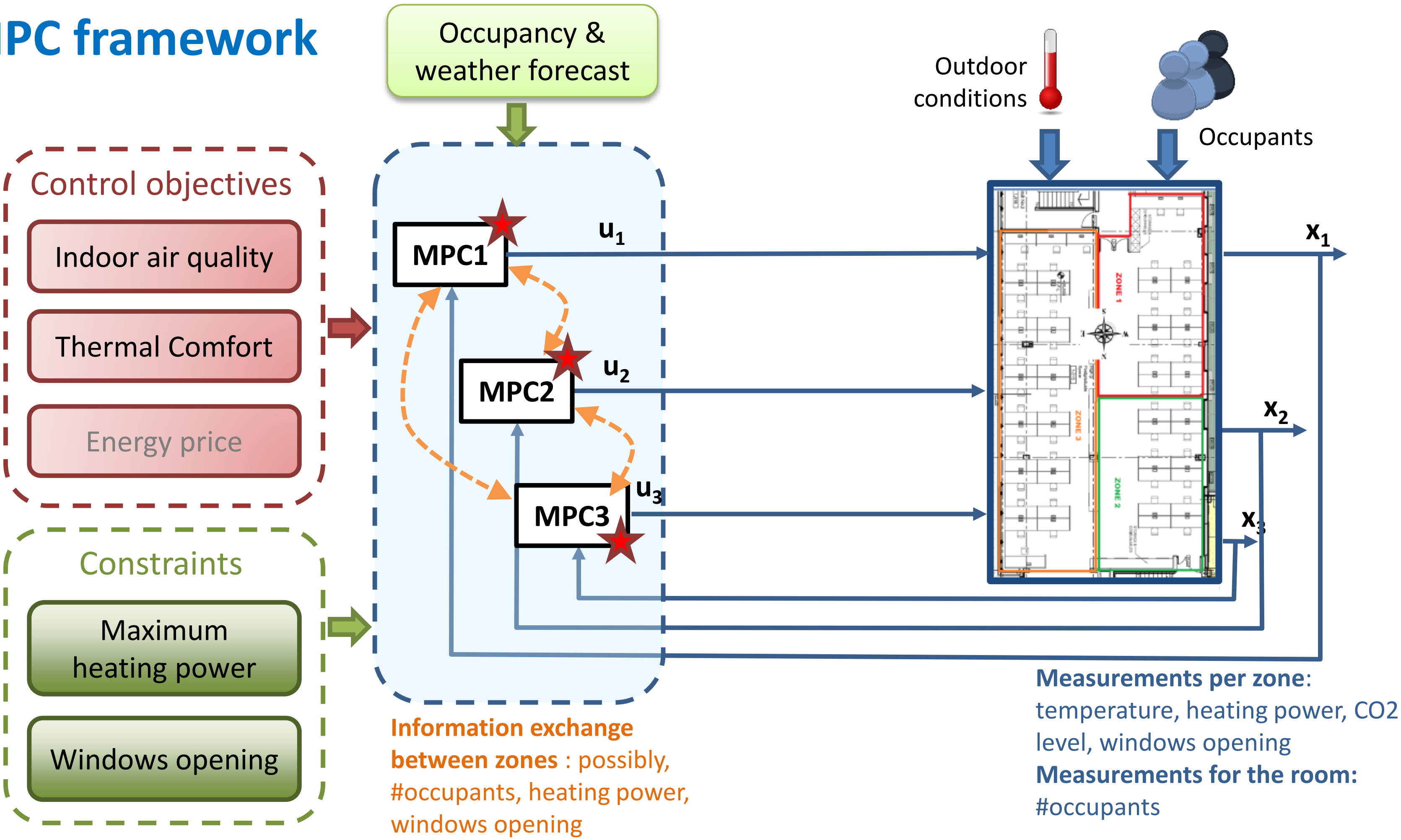
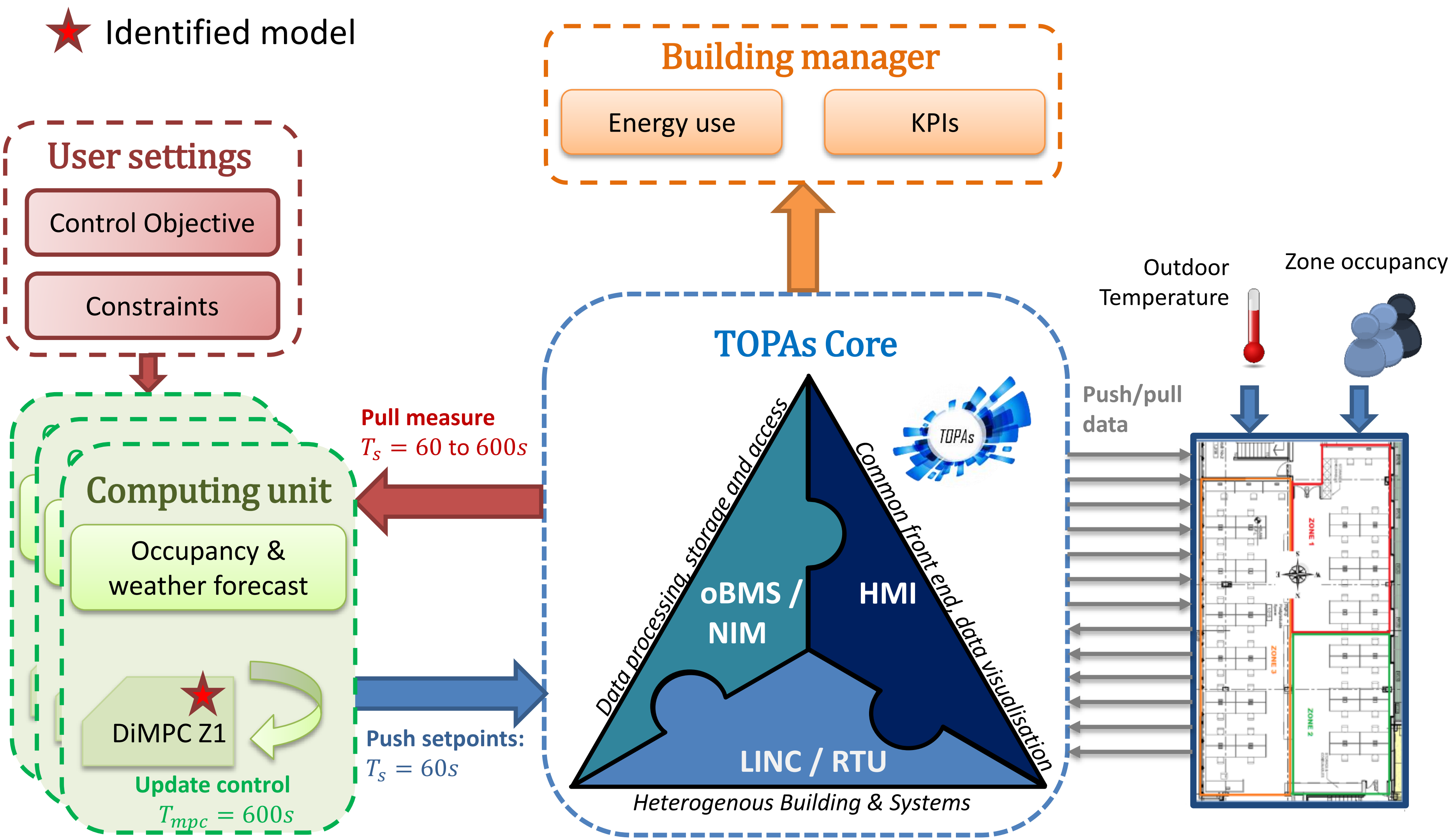
DiMPC framework



$$J = \sum_{k=1}^{N_p} \left(\mathrm{T}_{\mathrm{i}}^{\mathrm{ref}} - \mathrm{T}_{\mathrm{i}}(\mathrm{k})\right)^{\mathrm{t}} \mathrm{Q}_{\mathrm{i}} \left(\mathrm{T}_{\mathrm{i}}^{\mathrm{ref}} - \mathrm{T}_{\mathrm{i}}(\mathrm{k})\right) + \mathrm{u}_{\mathrm{i}}^{\mathrm{t}}(\mathrm{k})\mathrm{R}\mathrm{u}_{\mathrm{i}}(\mathrm{k})\mathrm{dt}$$

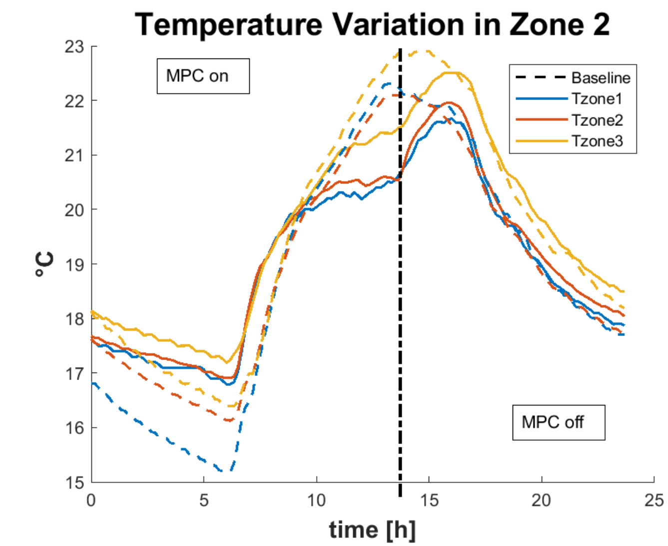
★ Identified model

TOPAs control architecture

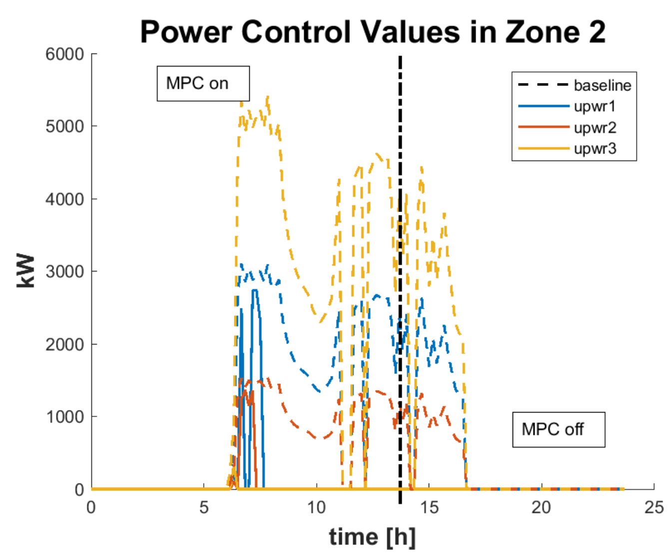


Experimental results (winter)

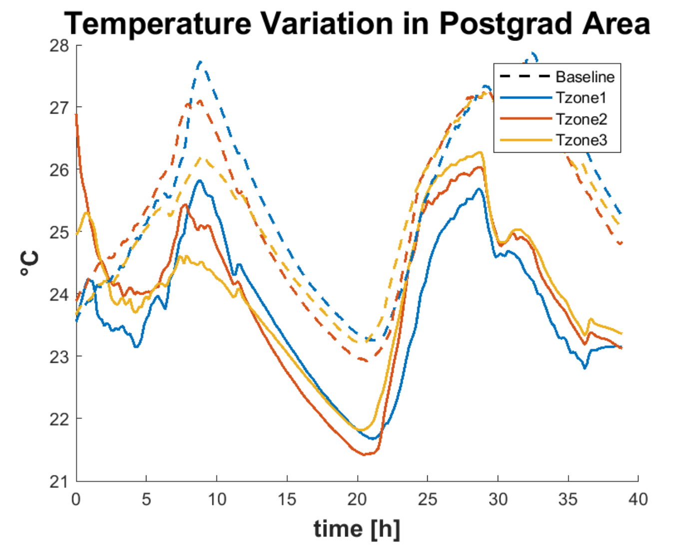
- **Scenarios**
  - Two consecutive days
  - *Similar* occupancy and solar irradiation profile
  - Winter conditions
  - $T_{ref} = 22°C$



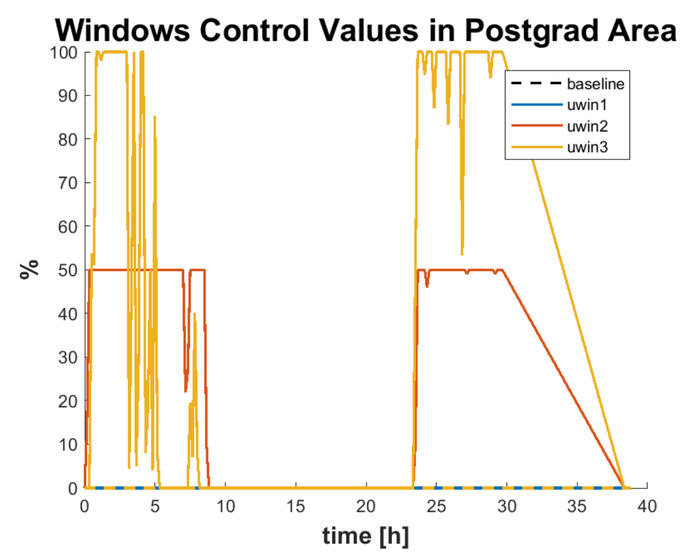
- **Outcome**
  - Lower use of heater (energy saving)
  - Enhance thermal comfort



- **Scenarios**
  - Two *consecutive & similar* days
  - $T_{ref} = 22°C$
  - Spring conditions



- **Outcome**
  - Enhance thermal comfort



Conclusion & Perspectives

- The presented **modelling approach**
  - Deals with multizone building and is extensible to new zones
  - Copes with MPC controller design
  - Is validated on receding horizons

- Successfully **applied to** TOPAs demonstration site
  - Allowed to reduce (heat) energy consumption
  - Handled comfort constraints

- **Future work** will concentrate on:
  - Pursue execution until end-of-project
  - Replicate the modelling on a second demo-site
  - Adaptive algorithm to re-identify model according to seasonal changes

Thank you

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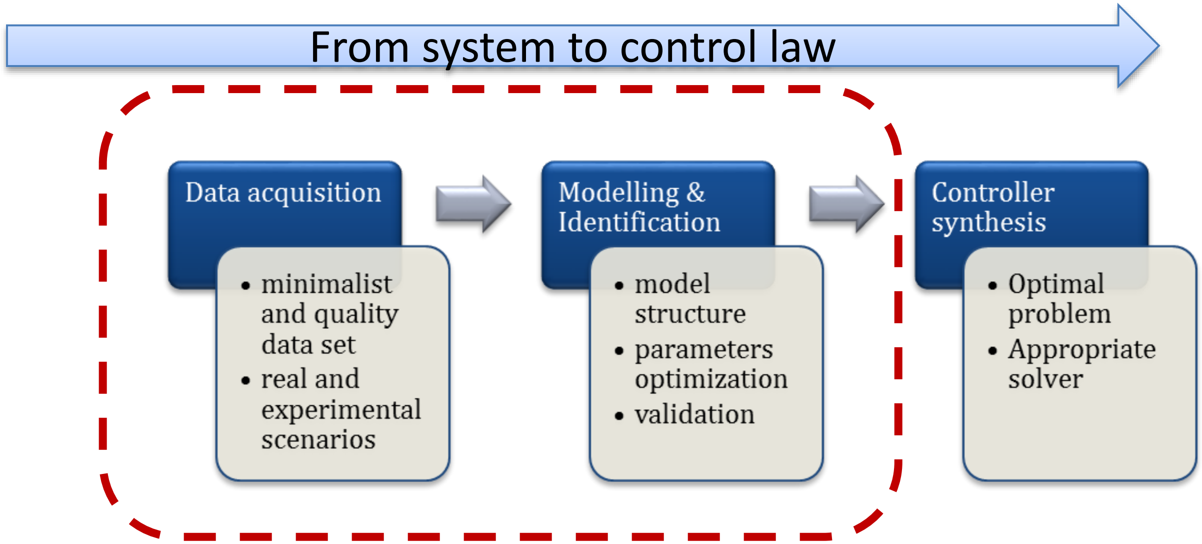
From system to control law
Data acquisition
• minimalist and quality data set
• real and experimental scenarios
Modelling & Identification
• model structure
• parameters optimization
• validation
Controller synthesis
• Optimal problem
• Appropriate solver