Automation and wireless control for mining ventilation

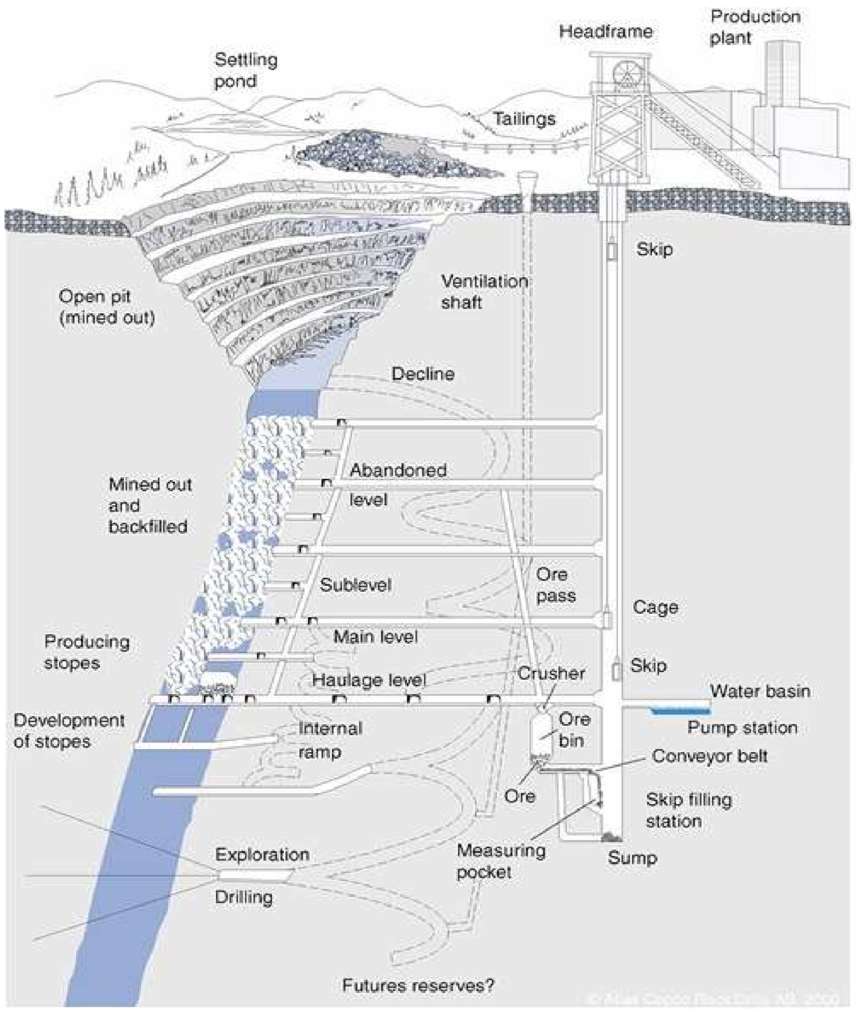
Emmanuel Witrant

GIPSA-lab, Control Systems dept.

In collaboration with
ABB – KTH – Boliden (Sweden)
UAQ – UNISI (Italy), GIPSA – Supélec (France)

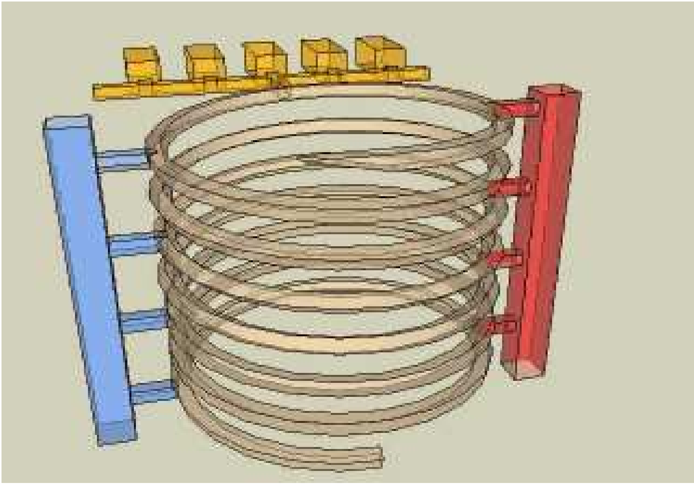
GdR – CPNL meeting, January 22nd, 2009

Mining



Components:

- Blasting and drilling
- Transport: trucks or hoist
- Ore crushing
- Ventilation: 50% of the energy consumption – Mining = 4 (US) to 6% (South Africa) of industrial electrical consumption



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NEW BOLIDEN

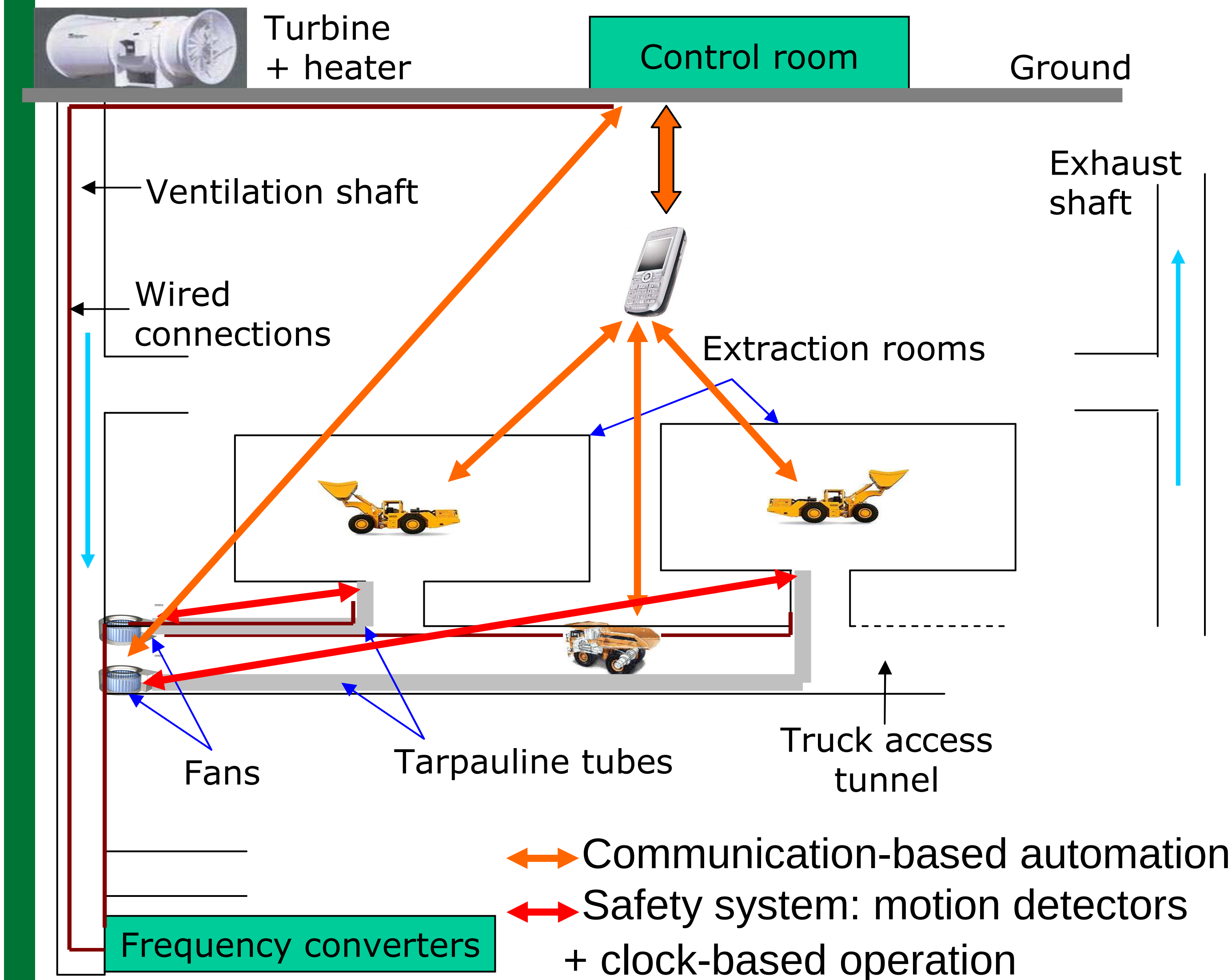
- Mining and smelting company
- 3 500 MEUR turnover
- 4 500 employees
- 3 Swedish and 1 Irish mine

Garpenberg mine

- Mining since 9th century
- 1000K ton ore/yr
  - 58K Zn, 21K Pb, 0.56K Cu, 0.1K Ag, 0.2 Au
- 1 100 m deep
- 280 employees

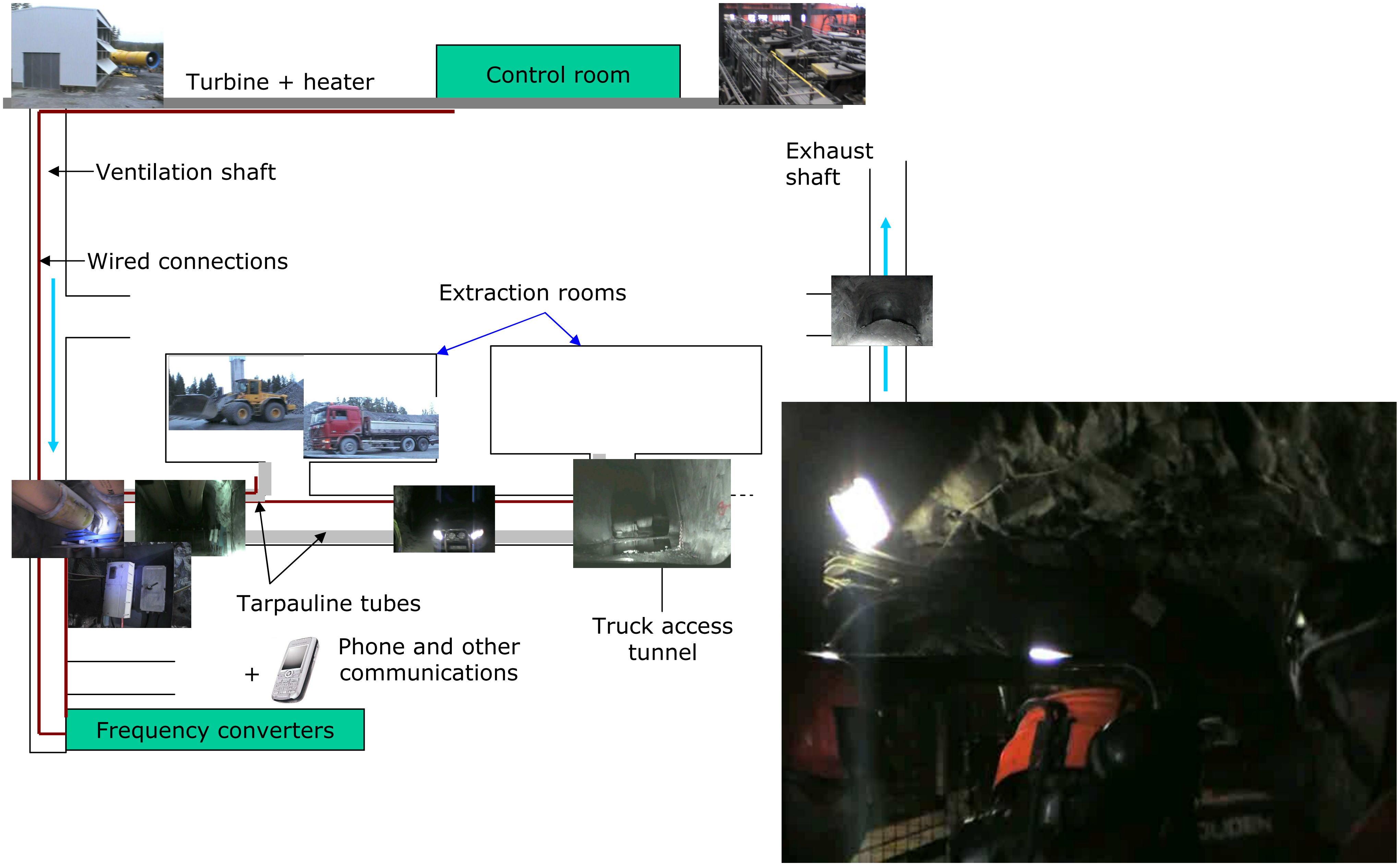
I. Mining ventilation control

actual architecture

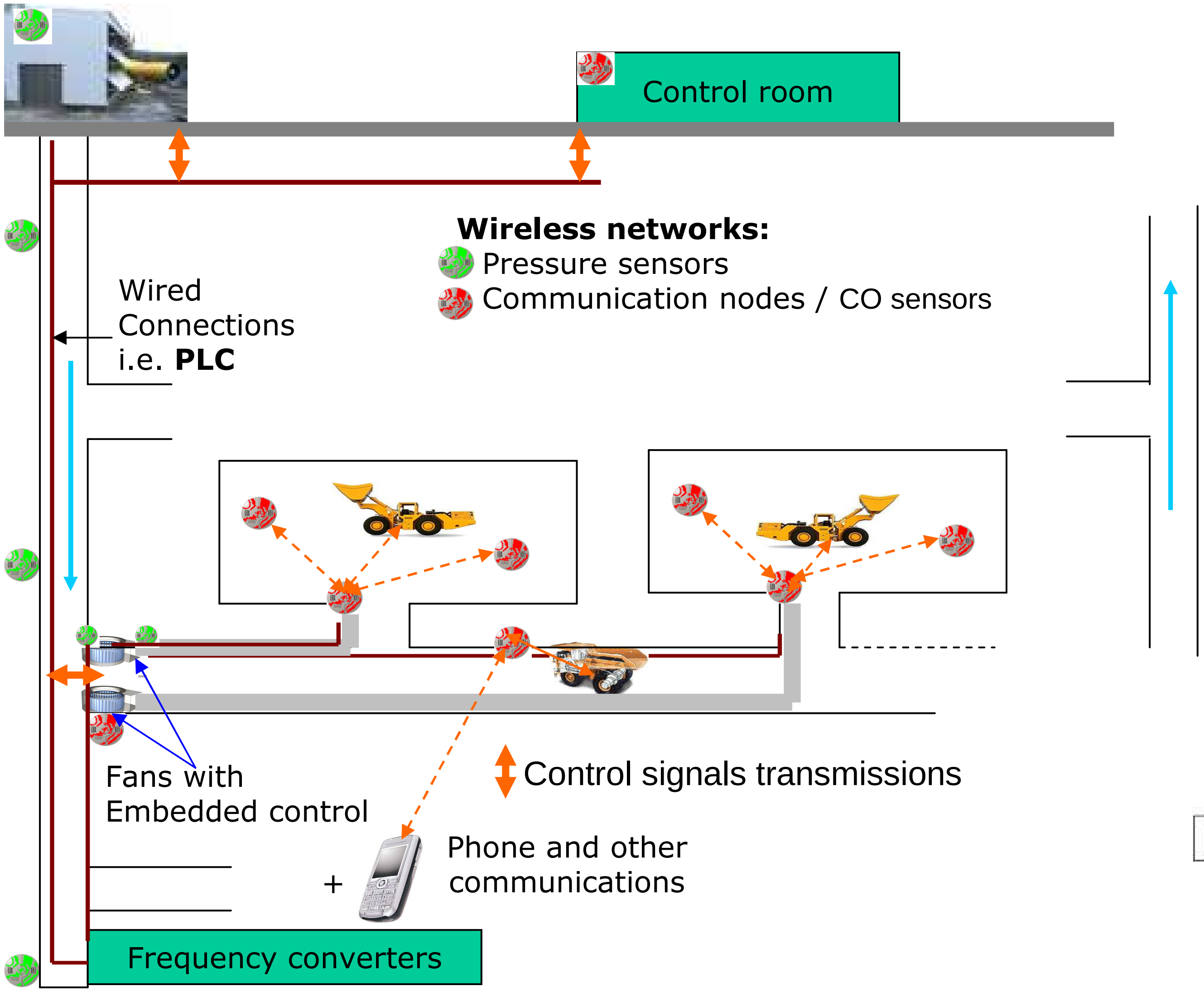


- Ventilation control = worst case ventilation design
- i.e. choice of the tunnels diameter / fans power depending on the trucks
- Operation at max power when extracting the ore
- No continuous air quality monitoring (scheduled)
- No WSN

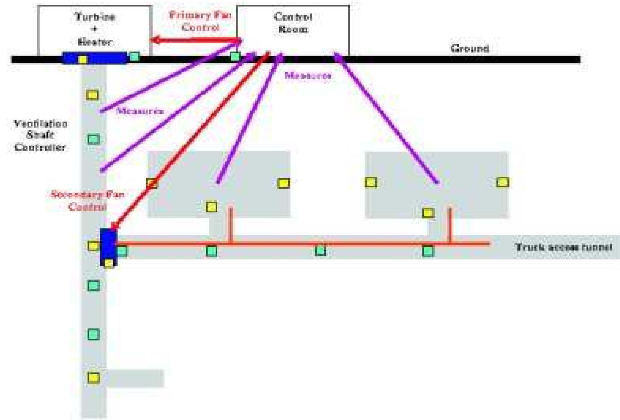
Garpenberg mine



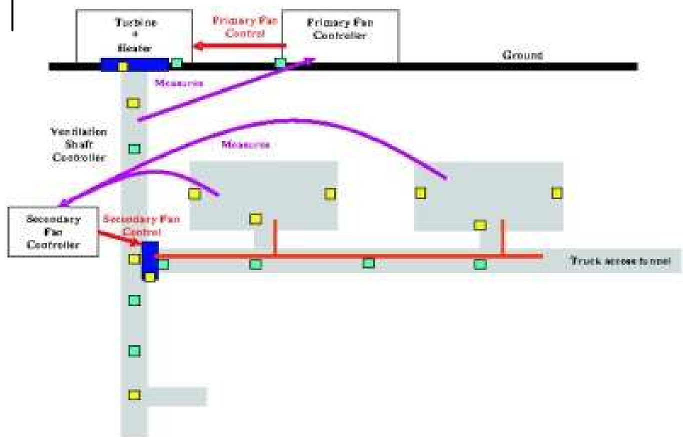
Potential wireless control architecture for mining ventilation



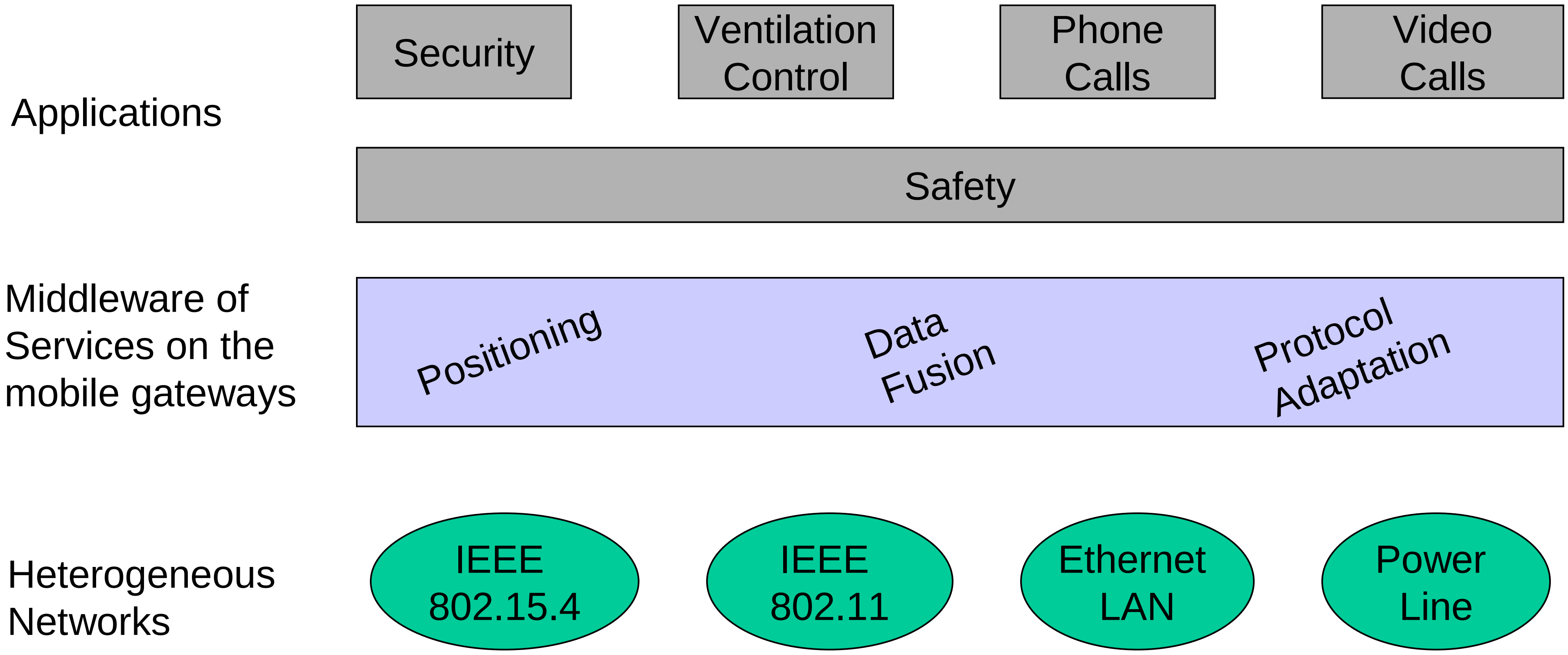
• Centralized



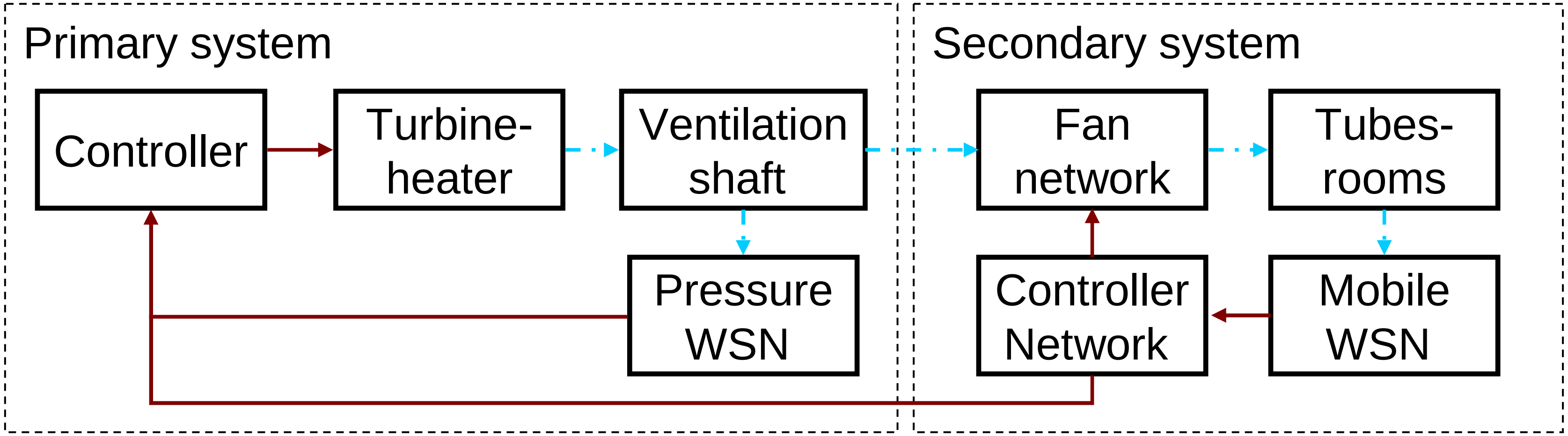
• Decentralized



Network Modeling: Platform of Services



Control architecture and objectives



Objectives:

- Control air quality (O_2, NOx and CO) in extraction rooms at suitable level
  - Regulate turbine and heater to provide suitable airflow pressure at ventilation fans
  - Regulate ventilation fans to ensure air quality in extraction rooms
- Safety through wireless networking for personal communication and localization

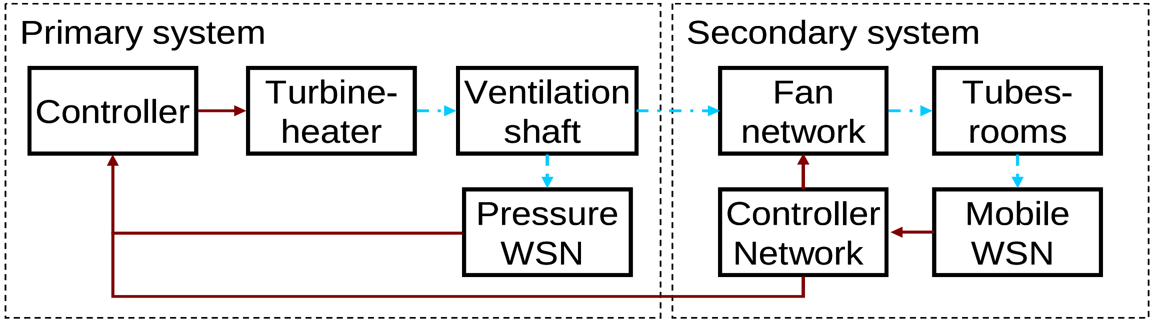
Design constraints:

- Physical interconnections, actuators limitations and networking capabilities
- Sensing capabilites: O_2, NOx, CO and pressure and temperature

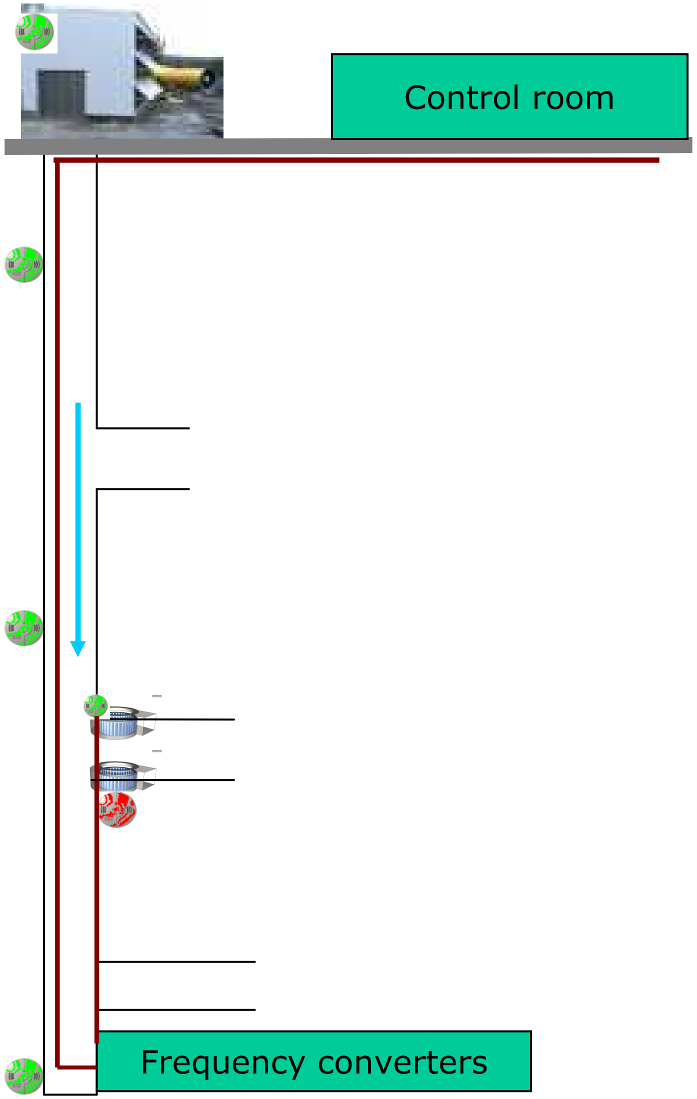
Plant models and control systems

- Primary system:
  - Flow model: compressible viscous flow (Navier-Stokes)
  - Regulated output: pressure at the fans locations
  - Actuation: turbine and heater
  - Sensing: pressure and temperature along vertical shaft
  - External inputs: fan boundary conditions, atmospheric conditions

- Secondary system:
  - Flow model: Incompressible, inviscid, adiabatic flow + empirical data
  - Regulated output: air quality
  - Actuation: fans
  - Sensing: air quality through WSN
  - External inputs: pressure in primary system, number of vehicles in the room

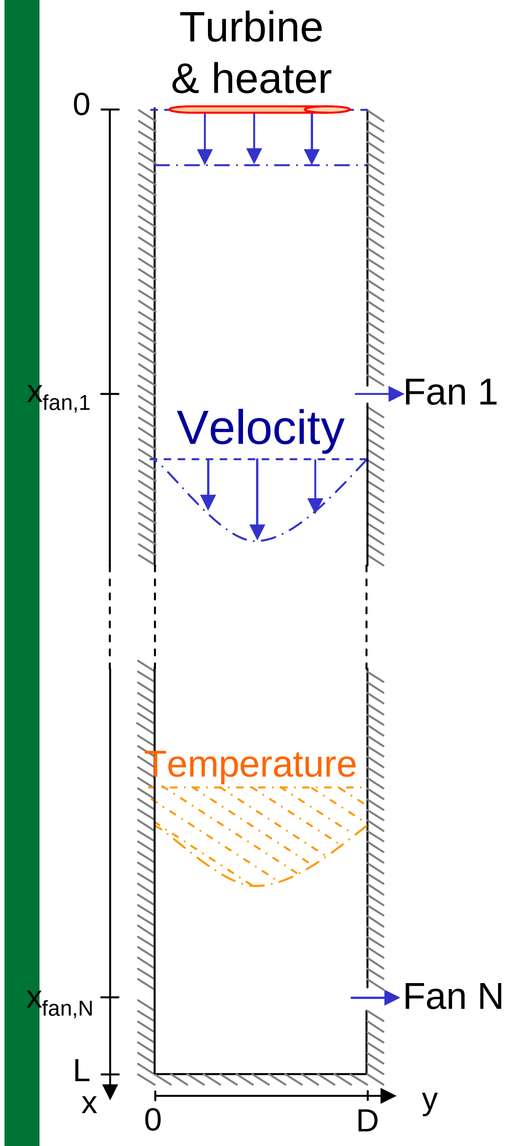


II. Primary System



- Turbine and heater (2nd and 1st order dynamics, respect.)
- Compressible viscous flow
- Estimation / observation based on pressure and/or temperature sensors
- Fans exhausts and regulated pressure
- Delayed measurements, bandwidth limitation

Physical model for the vertical shaft



- 2-D model:
  - conservation of mass, momentum and energy

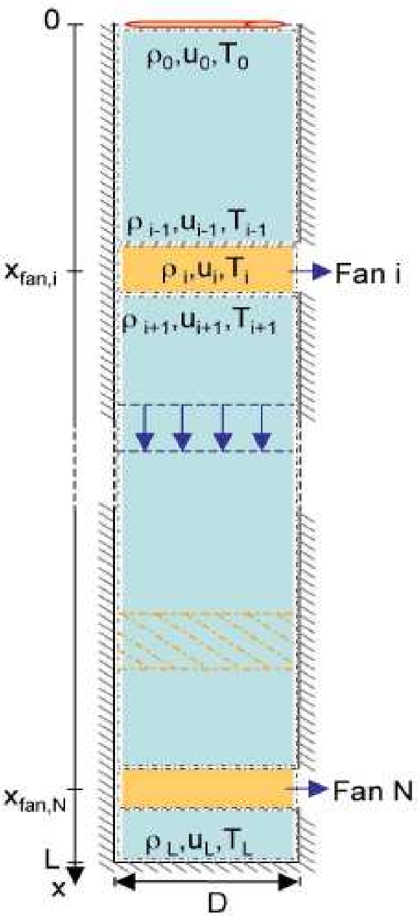
$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\mathbf{V}\\ \rho E\end{bmatrix}+\nabla\cdot\begin{bmatrix}\rho\mathbf{V}\\ \rho\mathbf{V}^T\otimes\mathbf{V}+p\mathbf{I}-\tau\\ \rho\mathbf{V}H-\tau\cdot\mathbf{V}-k\nabla T\end{bmatrix}=\begin{bmatrix}0\\0\\ \dot{q}\end{bmatrix}$$

  - state-space expression

$$\begin{aligned}
\frac{\partial\rho}{\partial t} &= -\nabla\cdot(\rho\mathbf{V})\\
\rho\frac{Du}{Dt} &= -\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}\\
\rho\frac{Dv}{Dt} &= -\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}\\
\rho\frac{D(e+\mathbf{V}^2/2)}{Dt} &= \rho\dot{q}+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)-\nabla\cdot(p\mathbf{V})\\
&\quad+\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}\\
p &= \rho RT\\
e &= c_vT
\end{aligned}$$

  - + discrete boundary conditions (potential numerical instabilities)

0D, bond graph model



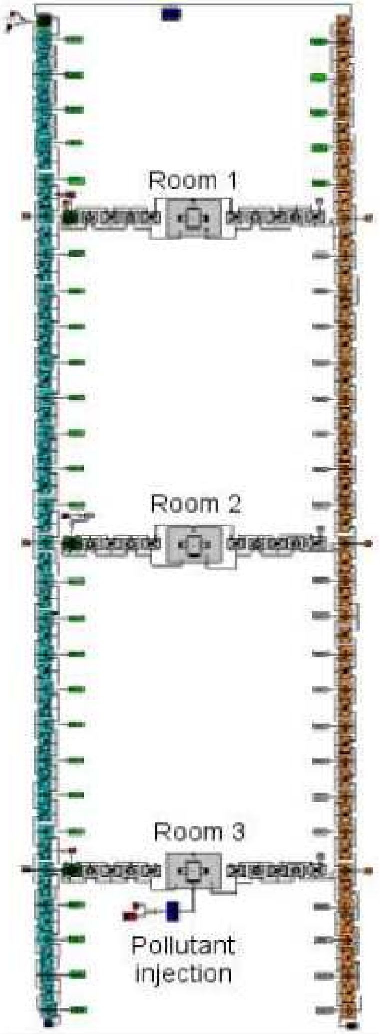
- Energy approach: equivalent to finite volume method → physically consistent averaging of the dynamics.

- Hypotheses:

  1. only static pressure considered in energy conservation;
  2. impulsive term negligible compared to pressure in momentum conservation;
  3. momentum dynamics simplified using Saint-Venant equations → algebraic relationship.

⇒ Algebro-differential model with numerically robust ODE description.

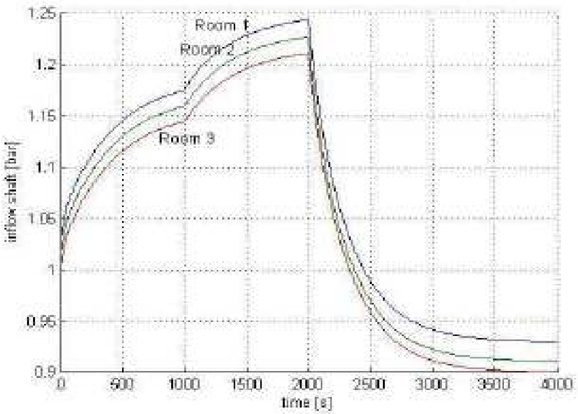
Resulting simulator



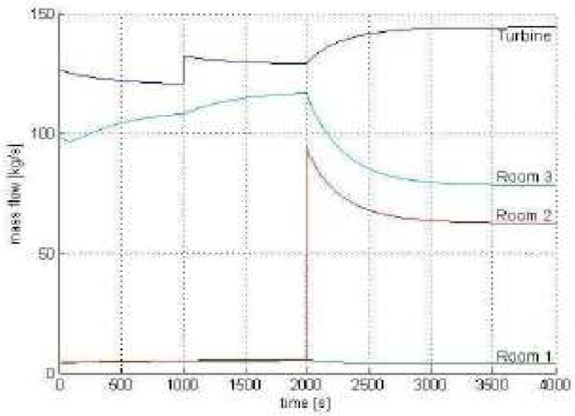
- Simulator properties:
  - ventilation shafts $\approx$ 28 control volumes (CV);
  - 3 extraction levels;
  - regulation of the turbine and fans;
  - flows, pressures and temperatures measured in each CV.

- Case study:
  - turbine rotational speed increased from 260 to 280 rpm at $t = 1000\ s$;
  - 1^{st} level fan not operated, 2^{nd} level fan goes from 0 to 150 rpm at $t = 2000\ s$ and 3^{rd} level fan operated at 200 rpm;
  - CO pollution injected at $t = 500\ s$ during $80\ s$ in 3^{rd} level;
  - measurement of flow speed, pressure, temperature and pollution at the surface and extraction levels.

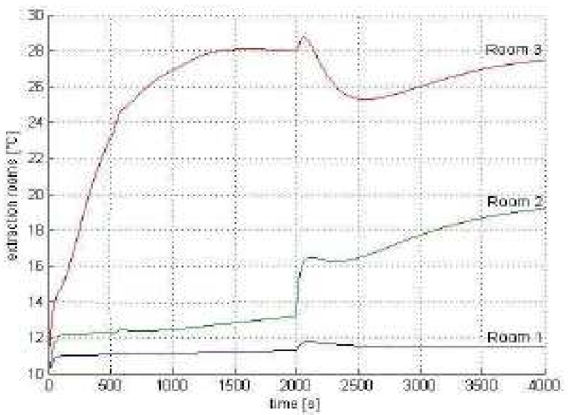
Simulation results



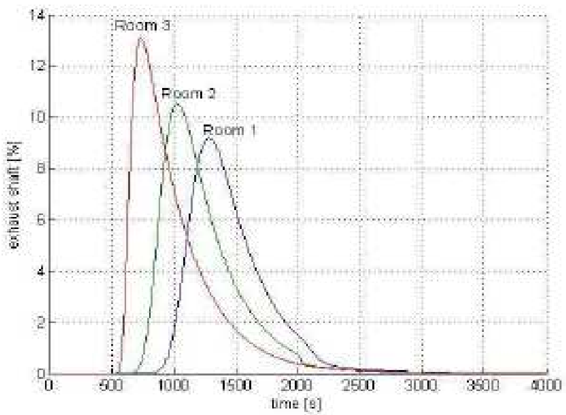
(a) Pressure losses in the inflow shaft



(b) Extraction rooms ventilation rate



(c) Extraction rooms temperature

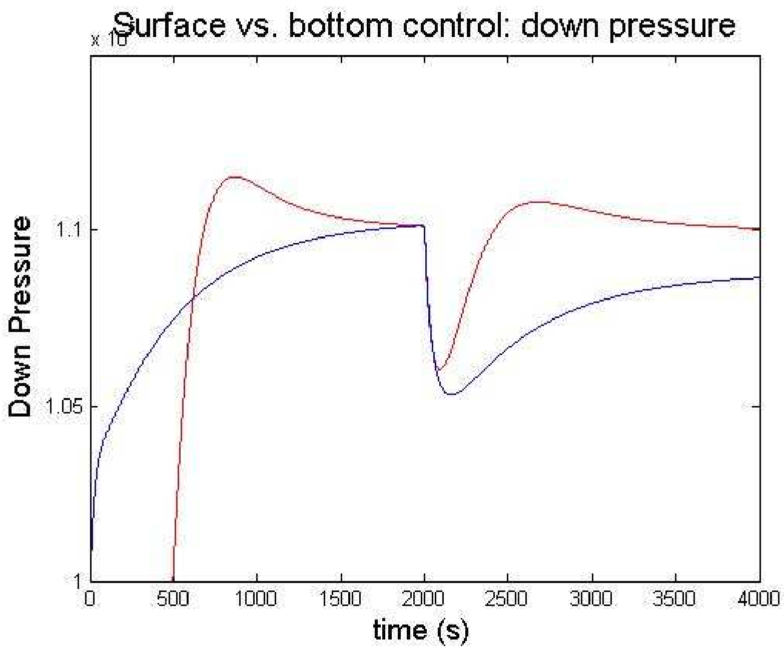


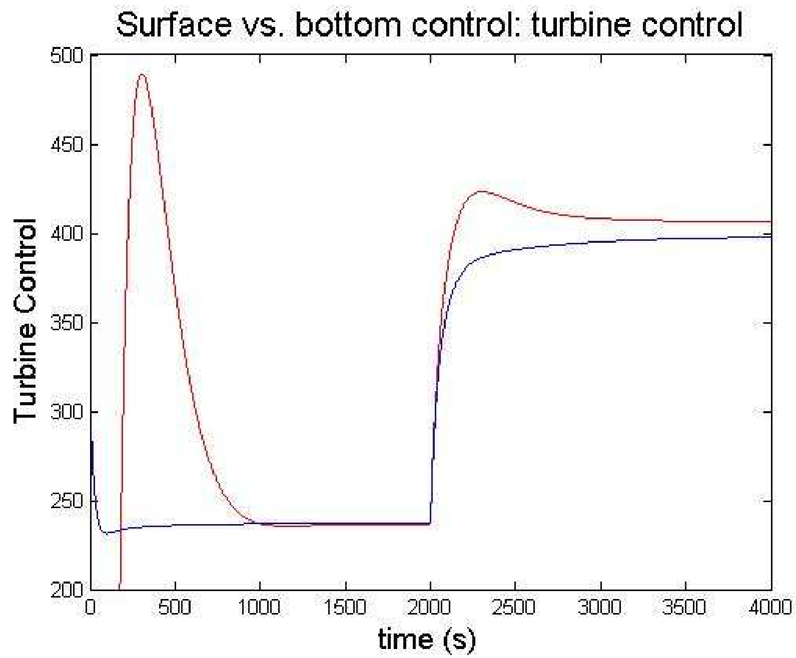
(d) CO pollutant concentrations in the exhaust shaft

- Physical and chemical airflow properties:
  - pressure losses = energy losses;
  - rooms ventilation rate = physical interconnections and importance of a global control strategy;
  - temperature: geothermal effect and fans compression;
  - pollutant transport: time-delay effect;
- Computation time 34× faster than real-time.

First results on feedback control

- (P)I control based on surface measurements (blue) vs. surface + bottom (red)
- Down pressure tracking (1.1*10^5 Pa)





- Promising improvements with down pressure measurements
- Sensitivity to initial conditions and destabilizing effect of P control motivate more advanced control methodologies

Model reduction: on-line parameter estimation & TdS

- General formulation:
  - estimate $c(t)$, $d(t)$, $r(t)$ and $s(t)$ in single variable 1-D model

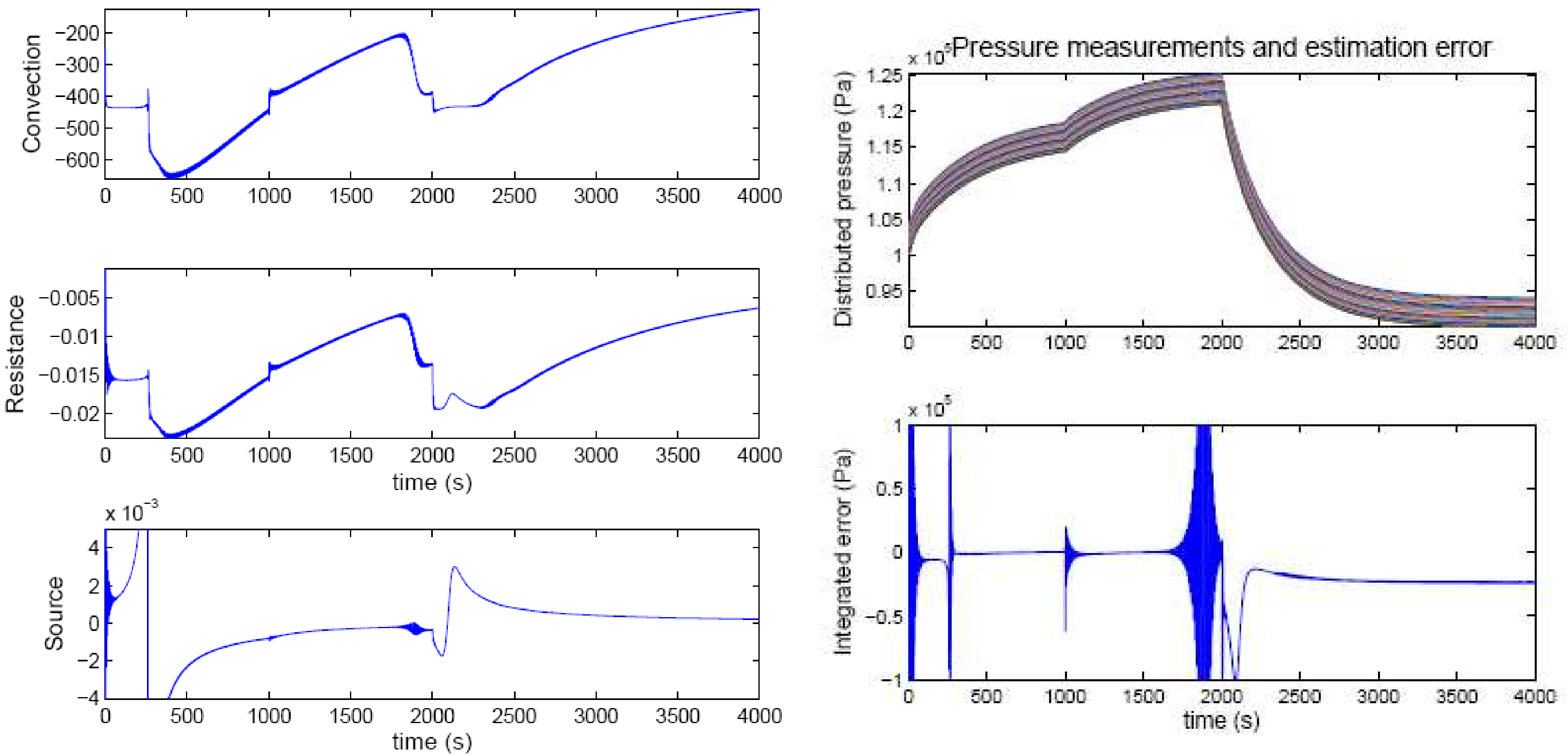
$$\frac{\partial \tilde{p}}{\partial t} = c(t)\frac{\partial \tilde{p}}{\partial x} + r(t)\tilde{p} + s(t)\varrho_x(x)\Delta p_{fan}(t)\eta_{fan}(t)$$

  from distributed pressure and perturbation measurements;
  - cost function

$$J(\vartheta, t) = \frac{1}{2}\int_0^x \|p_{meas}(\theta, t) - \tilde{p}(\vartheta, \theta, t)\|_2^2 \, d\theta.$$

  - minimized using stochastic gradient and Gauss-Newton method, with online sensitivity computation (ODE)

$$\frac{d}{dt}\left[\frac{\partial \tilde{p}}{\partial \vartheta}\right] = \frac{\partial}{\partial \tilde{p}}\left[c(t)\frac{\partial \tilde{p}}{\partial x} + r(t)\tilde{p}\right]\frac{\partial \tilde{p}}{\partial \vartheta} + \left[\frac{\partial \tilde{p}}{\partial x} \;\; \tilde{p} \;\; \varrho_x(x)\Delta p_{fan}(t)\eta_{fan}(t)\right].$$



⇨The proposed simplified model is promising for control purpose but the estimation algorithm needs to be robustified

Time-delay formulation

- The PDE model (homogeneous convective-resistive)

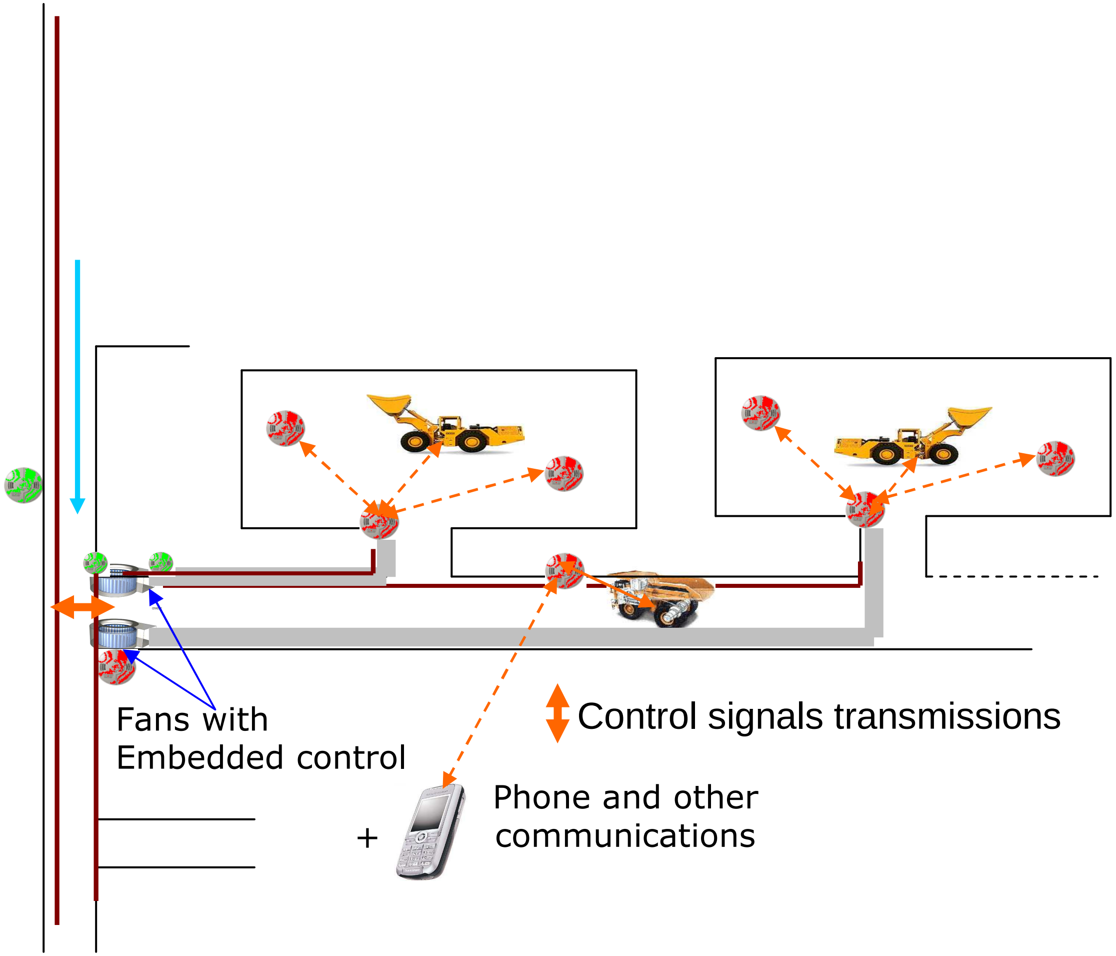
$$\frac{\partial}{\partial t}c(t,x) + v(t)\frac{\partial}{\partial x}c(t,x) = r(t,x)c(t,x) \qquad \begin{aligned} c(t,0) &:= u(t) \\ c(0,L) &:= \psi(L) \end{aligned}$$

Is equivalent to the delay differential equation

$$\dot{\xi}(t) = v(t)\left[u(t) - u(t-\theta_f)e^{r\theta_f}\right] + r\xi(t)$$

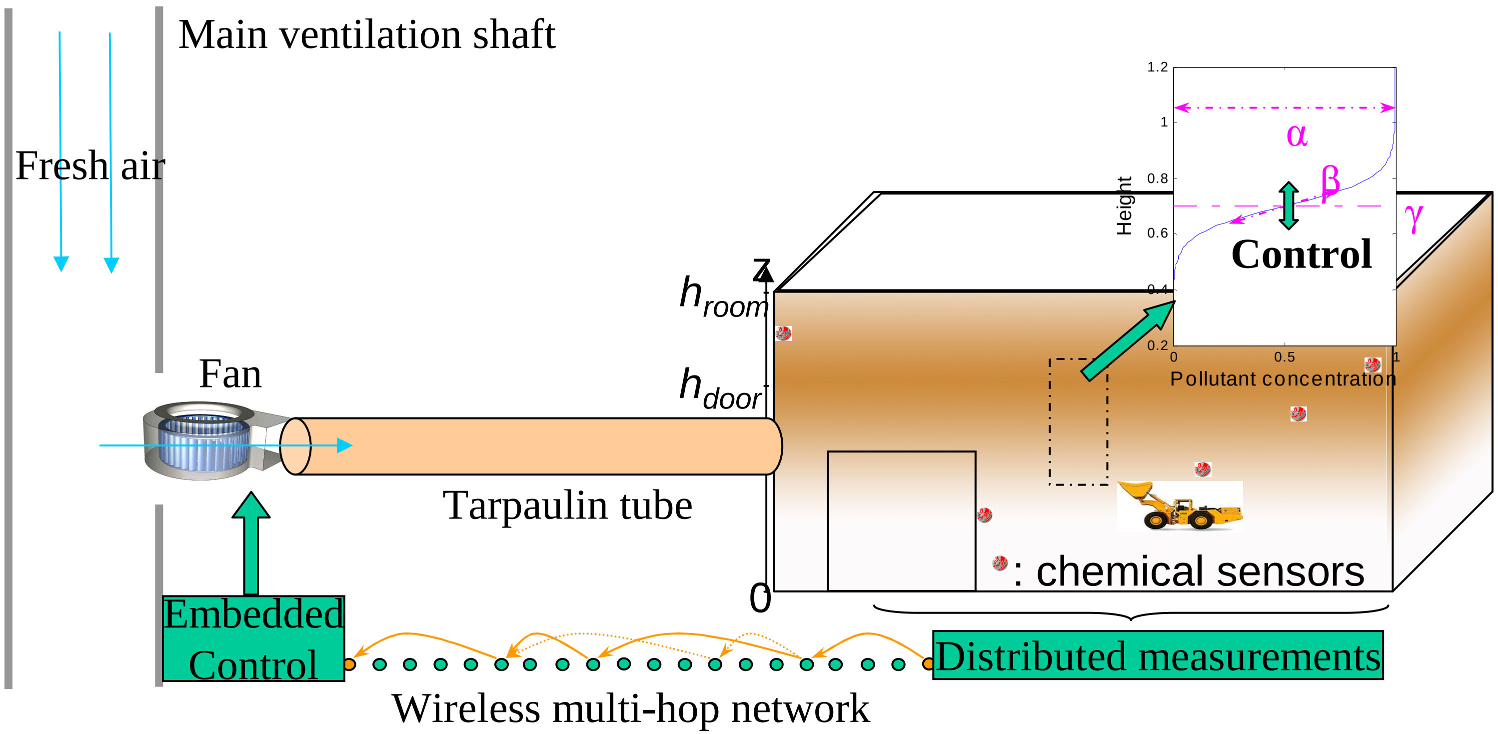
⇨ Reduced model equivalent to a time-varying delay system: significant and exact model reduction for control!

III. Secondary system



A. system and model

- System to be controlled



Tropical orchids growing: from plume to stratified flow

[movies]

- Model of the system
  - Physical delay in the tarpauline tube:

$$\tau_{tarp}(t) \approx \frac{L}{\overline{u}(t) + \sqrt{r\gamma \overline{T}(t)}}$$

  - Chemical concentration of pollutant *j*:

$$c_j(x,t) = \frac{\alpha_j(t)}{1 + \exp(-\beta_j(t)\cdot(z - \gamma_j(t)))}$$

  - Shape parameters dynamics:

$$\begin{bmatrix} \dot{\alpha}_j(t) \\ \dot{\beta}_j(t) \\ \dot{\gamma}_j(t) \end{bmatrix} = E^+[\dot{m}_{j,in}(t) - B_j u_{fan}(t - \tau_{tarp}) - D_{jk}]$$

  - Chemical reactions in mass conservation:

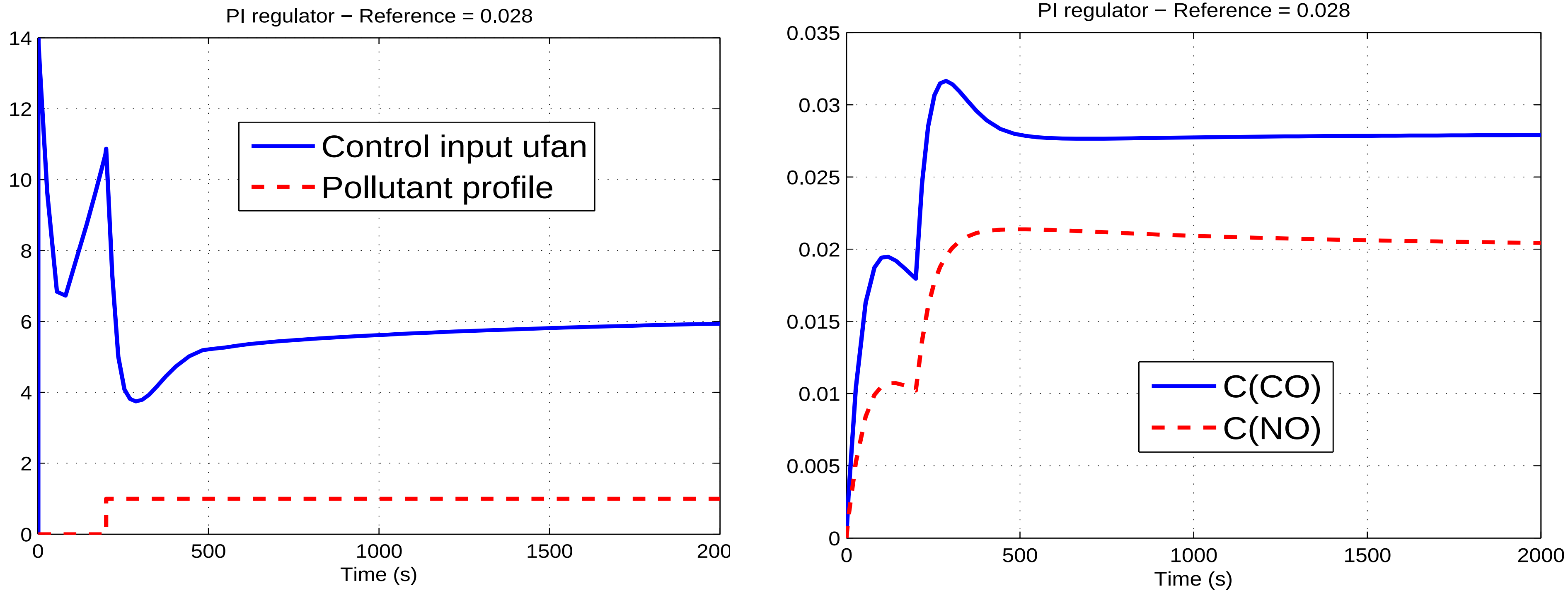
$$\dot{m}_j(t) = \dot{m}_{j,in}(t) - \dot{m}_{j,out}(t) - \dot{m}_{j,chem}(t)$$

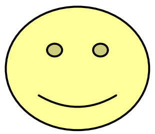
  - Experimental WSN multi-hop delay [Witrant & al., CCA'07]:

$$\tau_{wsn}(t) = h(t)F + \sum_{i=1}^{h(t)}(\alpha_i + \beta_i)$$

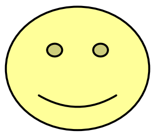
Using linear controllers ?

- Test of a linear controller: PI tuned to regulate CO at 0.028

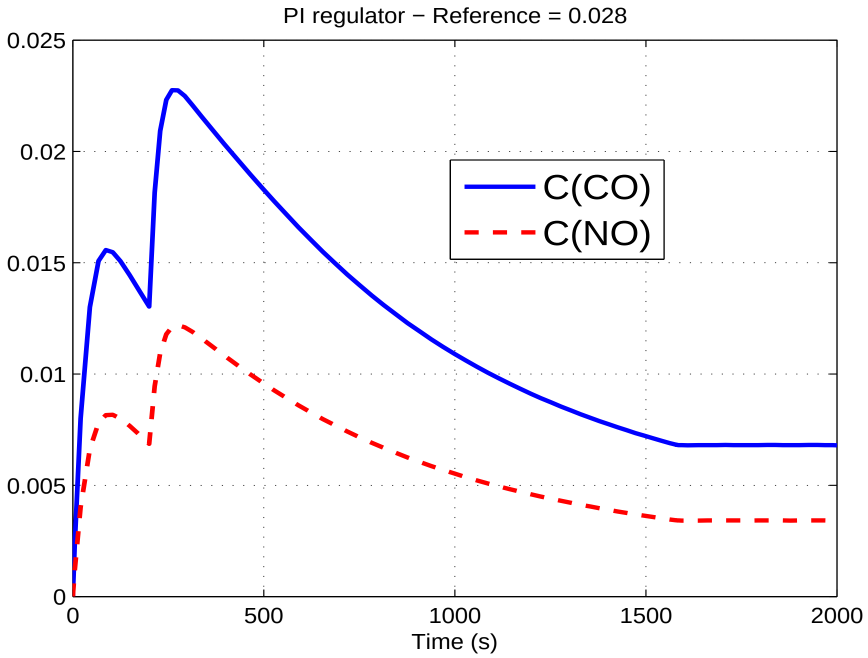


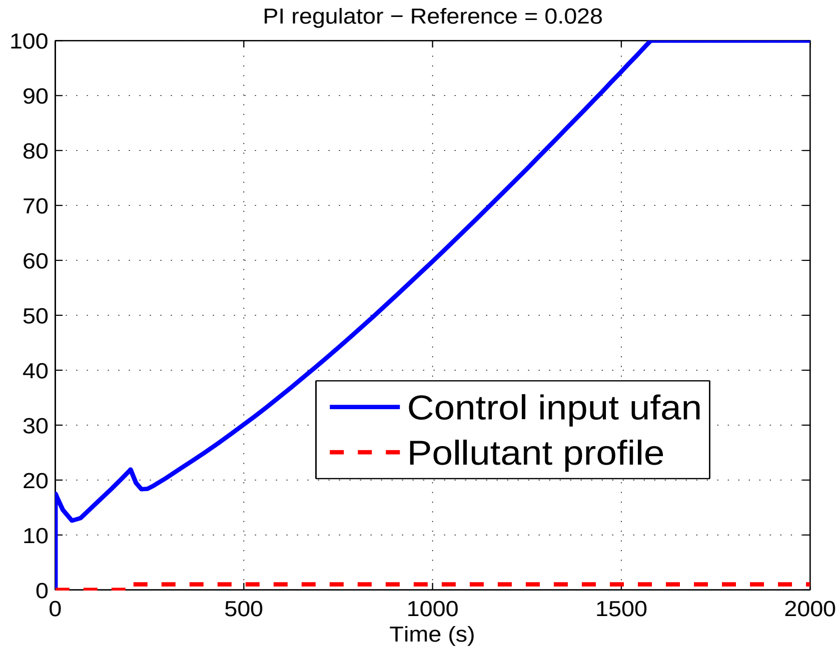


Very satisfactory !!
But….



- But, changing the reference to 0.035…





Non linearities of the system
have to be carefully taken into account

B. NLMPC: Receding horizon control

- Control objectives:
  - Regulate the level of pollutants $y_j(t) \to y_{j,des}$
- Constraints to be satisfied $\forall j, \quad \max_t \; y_j(t) \le \bar{y}_j$

Open loop: control

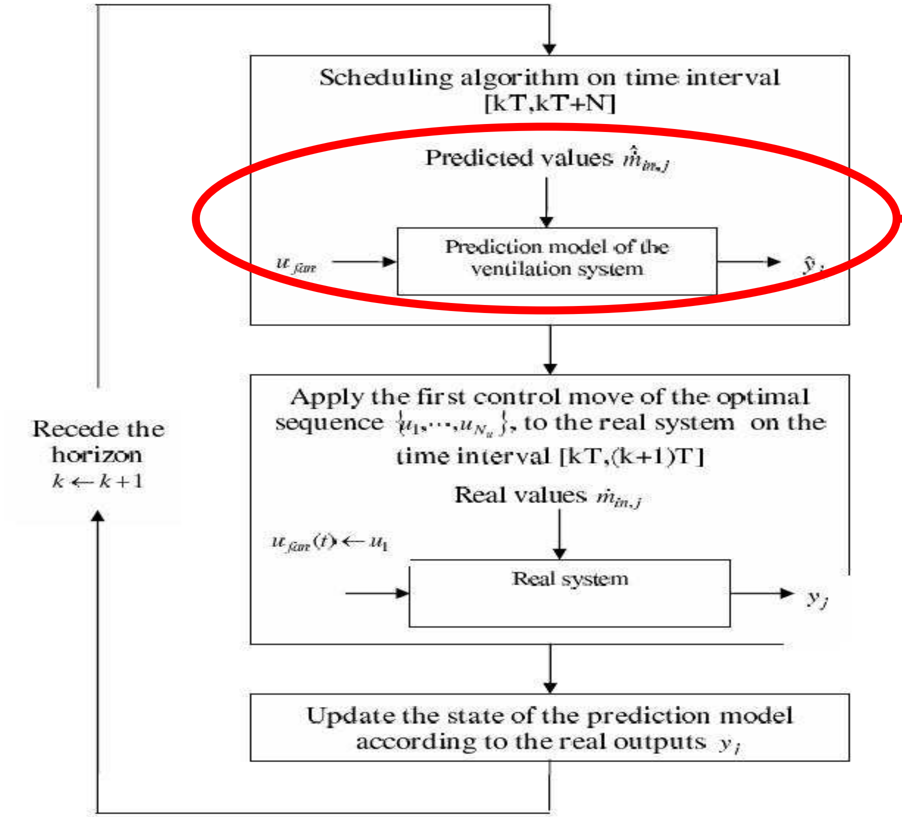
$$\min_{\{u_i, i=1,\ldots;N_u\}} \int_{\tau=kT}^{kT+N} ((\hat{y}_j(\tau) - y_{j,des}(\tau))^2 + \lambda u_{fan}^2(\tau)) d\tau$$

with $\quad u_{fan}(\tau) = u_i, \quad \tau \in \left[kT + (i-1)\frac{N_u}{N}, kT + i\frac{N_u}{N} \right[$

Computed from prediction model

- Control tuning parameters:
  - N: prediction horizon, long enough for transient behavior
  - Nu: number of degrees of freedom: precision vs. complexity
  - λ: weight control effort vs. tracking performances

- Problem: robustness against pollutant emissions predictions
  → Need of a closed loop structure



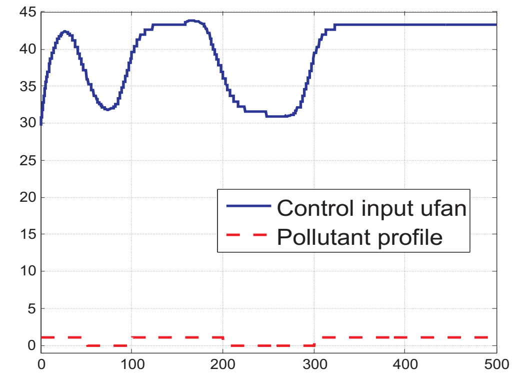
Scheduling algorithm based on prediction model (maximum value of the delay)

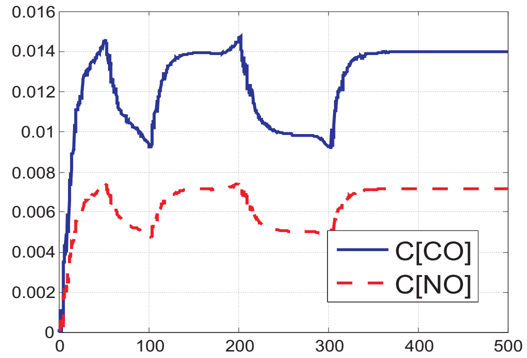
MPC with on-line solution of successive optimization problems

Simulation results

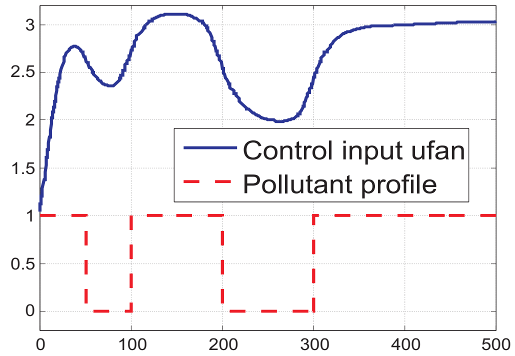
- Unconstrained case, tuning of the control law (1)

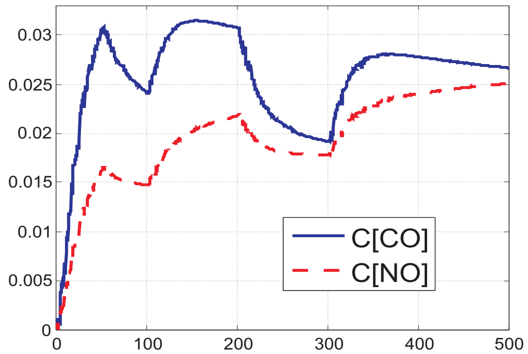
$N_u = 2, \quad \lambda = 10^{-7}$





$N_u = 2, \quad \lambda = 10^{-5}$

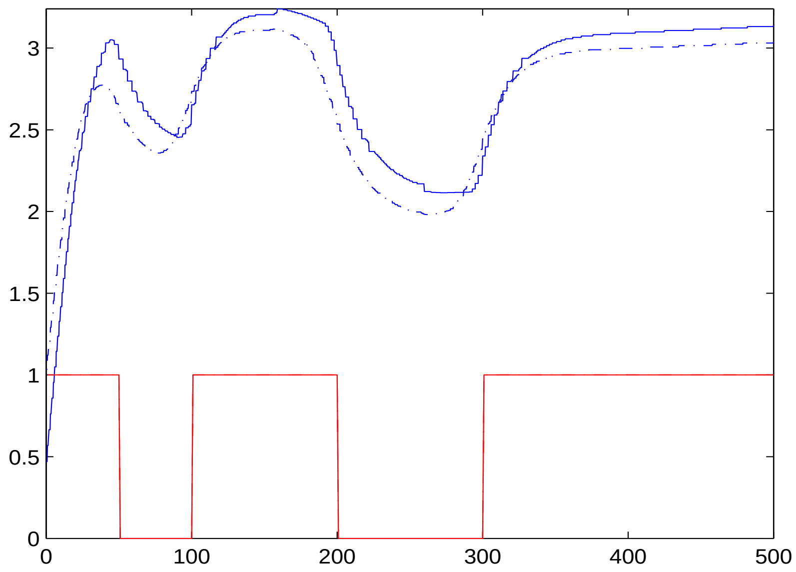




Increase in λ =
•decrease in fan power
•increase in pollutant

- Unconstrained case, tuning of the control law (2)

Nu = 2 (continuous line), Nu = 5 (dotted line)



Increase in Nu:
• more reactive control
• Increased computational effort (often untractable online)

Robustness against pollutant prediction error (50% underestimated):
if infeasibility then unconstrained and decrease λ

- Constrained case (1)
  - $y_{j,des} = 0.025$, with a bound constraint $y_j \leq 0.028$

Due to constraints, the successive solution of optimization problems may lead to infeasibility

Development of a « reaching feasibility again » strategy

Try to solve the constrained scheduling algorithm with $\lambda = 10^{-5}$ (strategy 1)

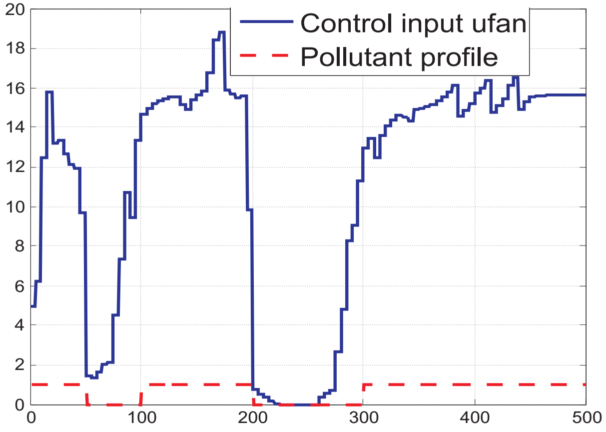
Try to satify constraints with low control efforts

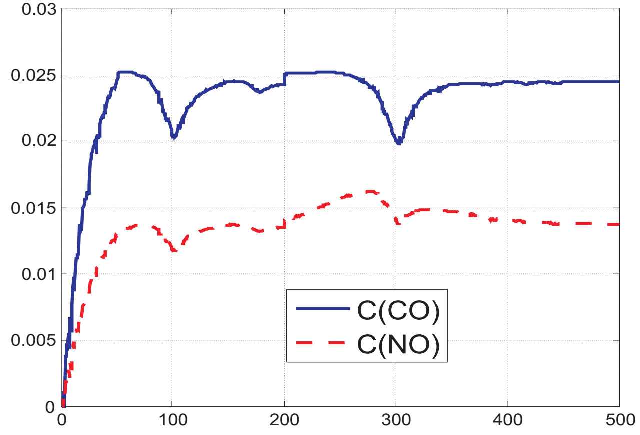
If unfeasible, solve the un constrained scheduling algorithm with $\lambda = 10^{-7}$ (strategy 2)

If impossible, allow high control efforts to reach feasibility again as soon as possible

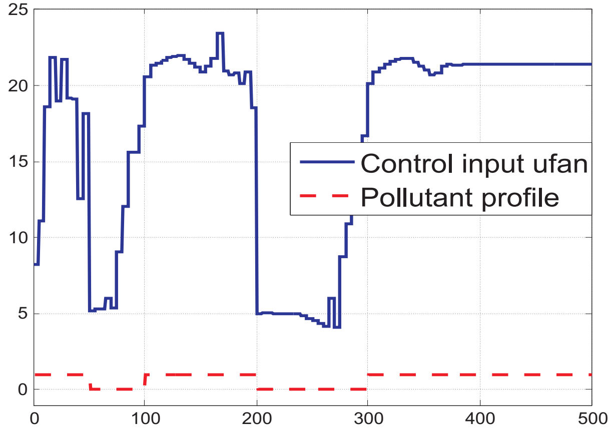
- Constrained case (2)
  - $y_{j,des} = 0.025$, with a bound constraint $y_j \leq 0.028$

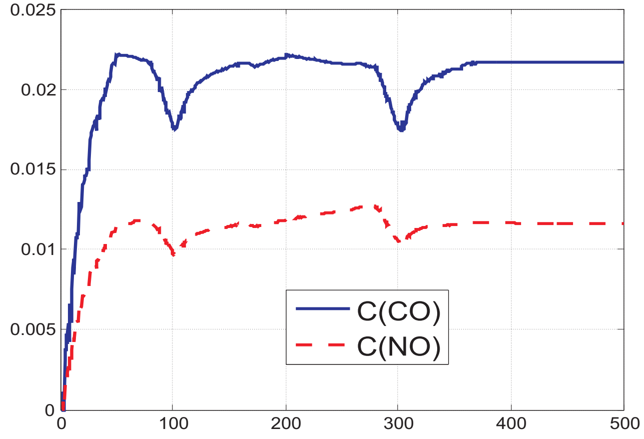
$N_u = 2, \quad \lambda = 10^{-7}$



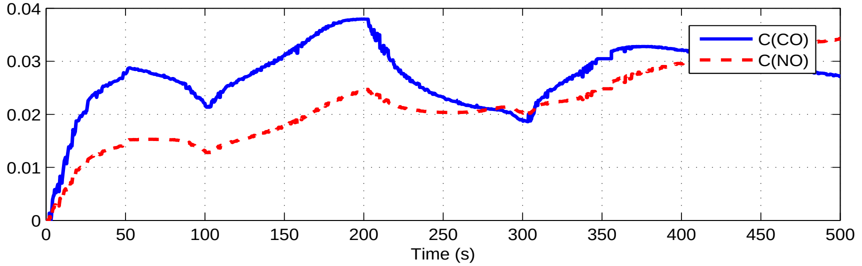


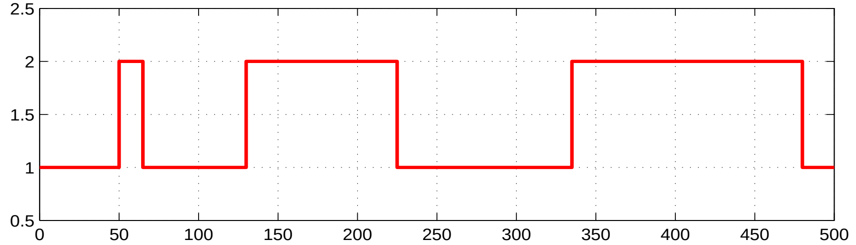
$N_u = 2, \quad \lambda = 10^{-5}$

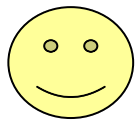




- Robustness of the control law
  - ➢ Worst case experiment: pollutant emissions 50% underestimated



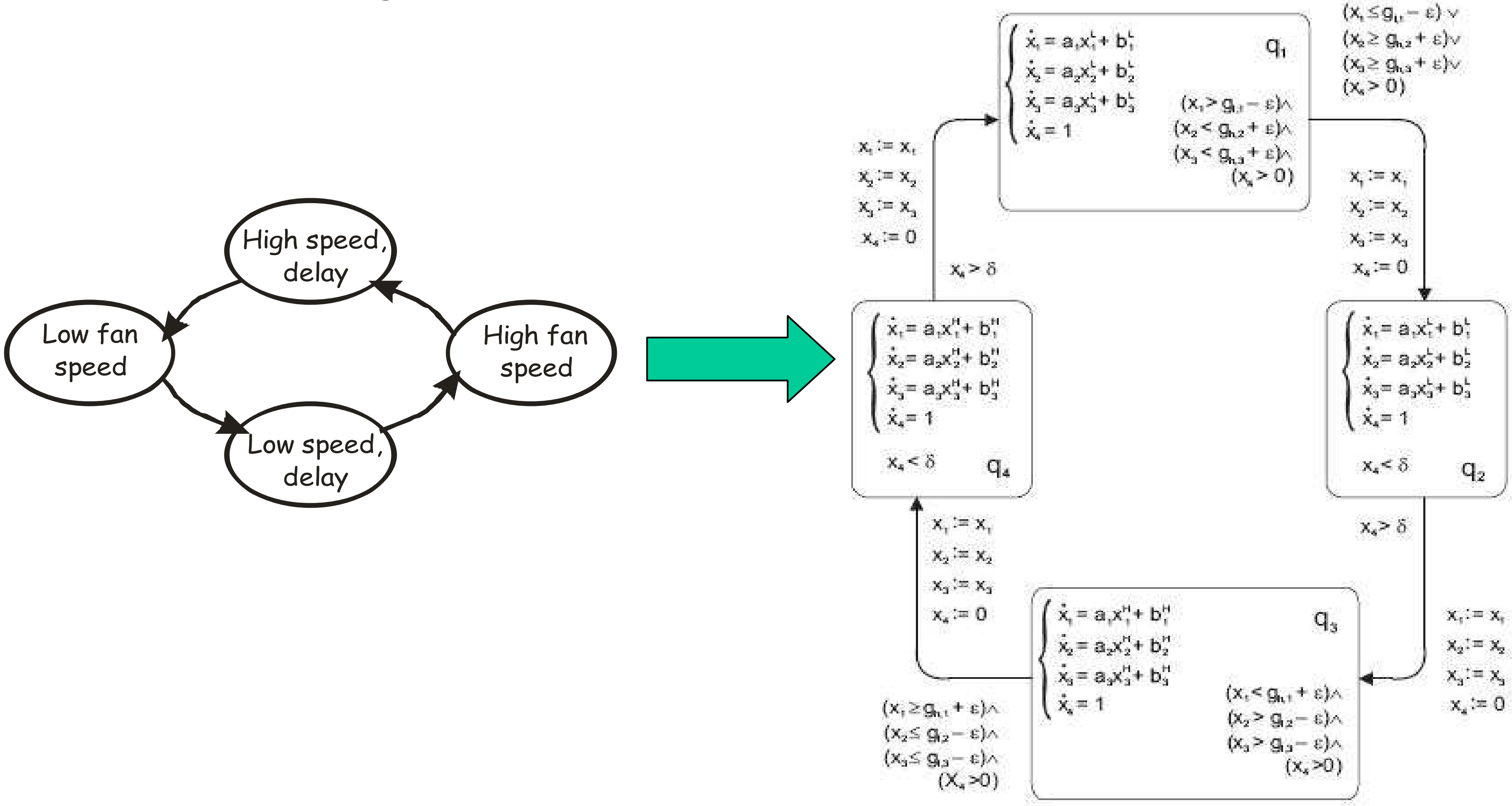




Very satisfactory,
thanks to the closed loop
and the « reaching feasibility again » strategy

C. Hybrid Control Strategy

- Affine hybrid model



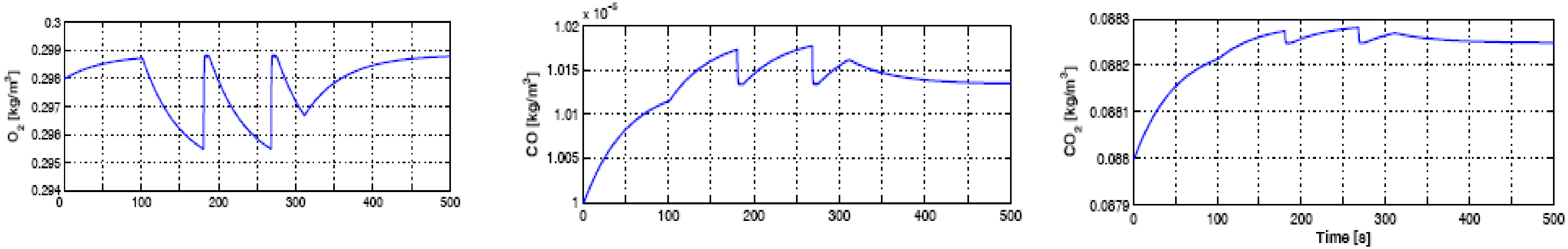
Safety Control

- Automatically verify if *for a given control strategy* the hybrid automaton satisfies Safety and Comfort properties
  - Unfortunately, model checking is in general undecidable even for affine hybrid automata

    ⇨ construct an abstraction of a hybrid automaton with affine dynamics, which preserves temporal properties expressed by CTL and TCTL formulae (temporal logics constraints)

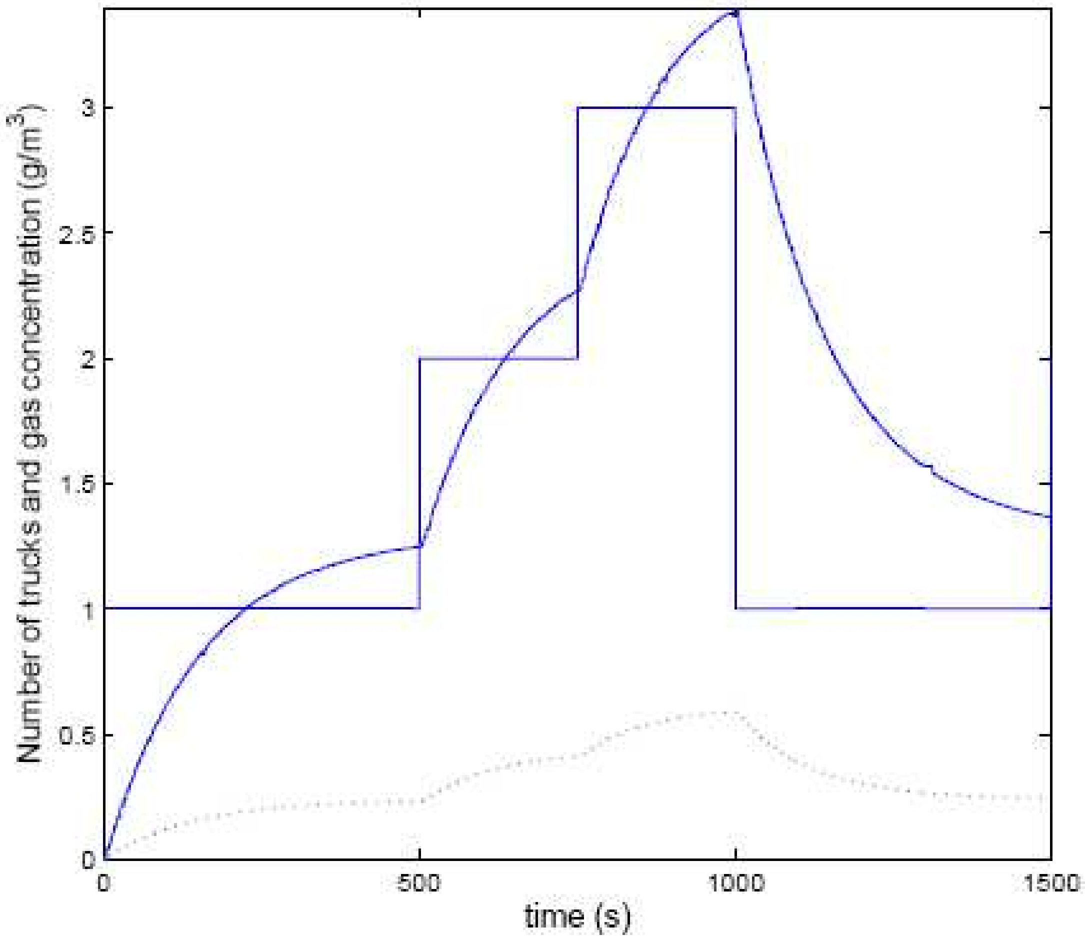
    - The abstract model belongs to a subclass of timed automata, called *durational graph*

- Example
  - Automatic verification procedure on the hybrid model using the following set of thresholds
    - *gl*1 = 0,2955, *gl*2 = 0,5 $*10^{-3}$, *gl*3 = 0,0885 [Kg/m^3]
    - *gh*1 = 0,2975, *gh*2 = 2,5$*10^{-3}$, *gh*3 = 0,091 [Kg/m^3]
  - the original hybrid system is safe and the maximum time of uncomfortable air quality is bounded by 62 s

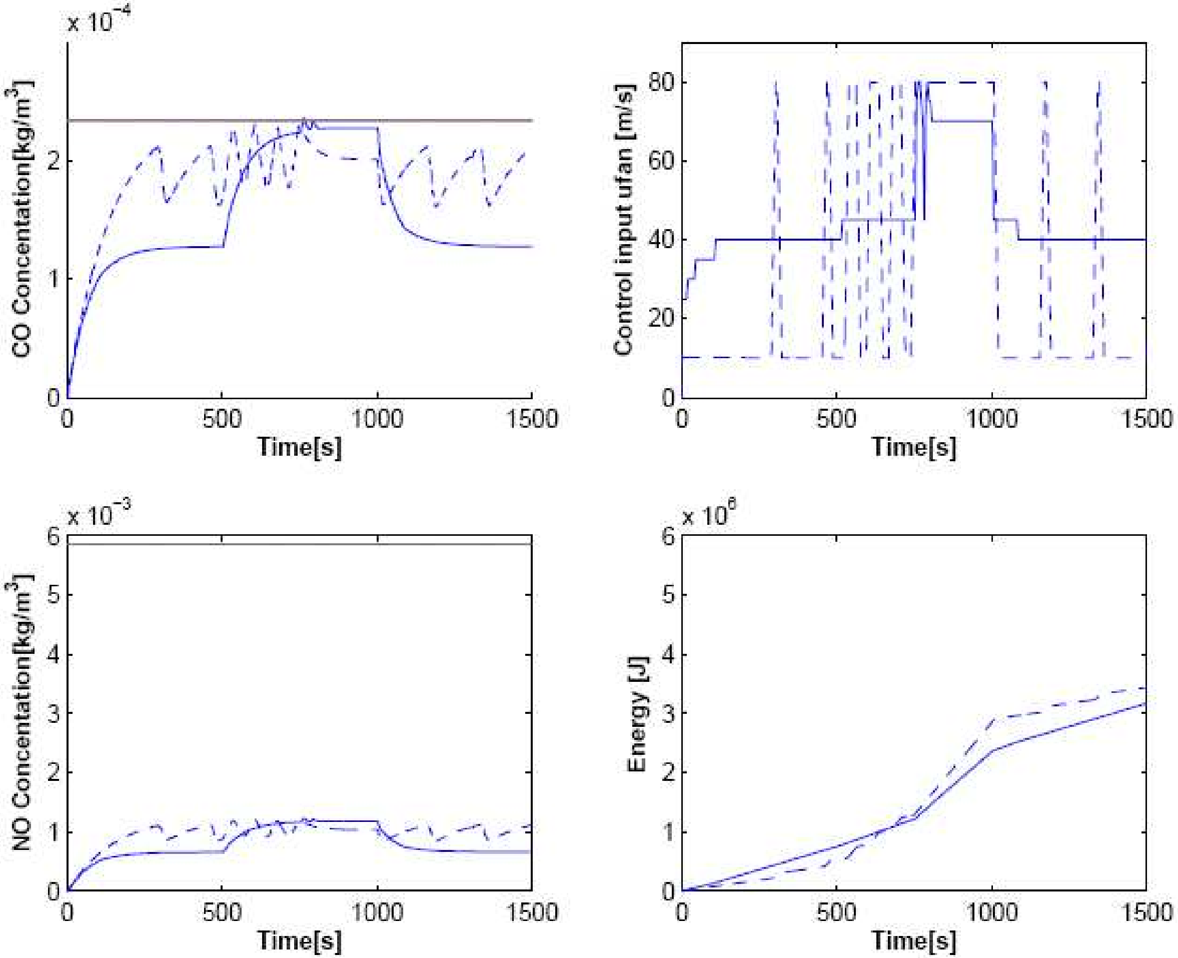


D. Comparison between the two approaches

- Test case



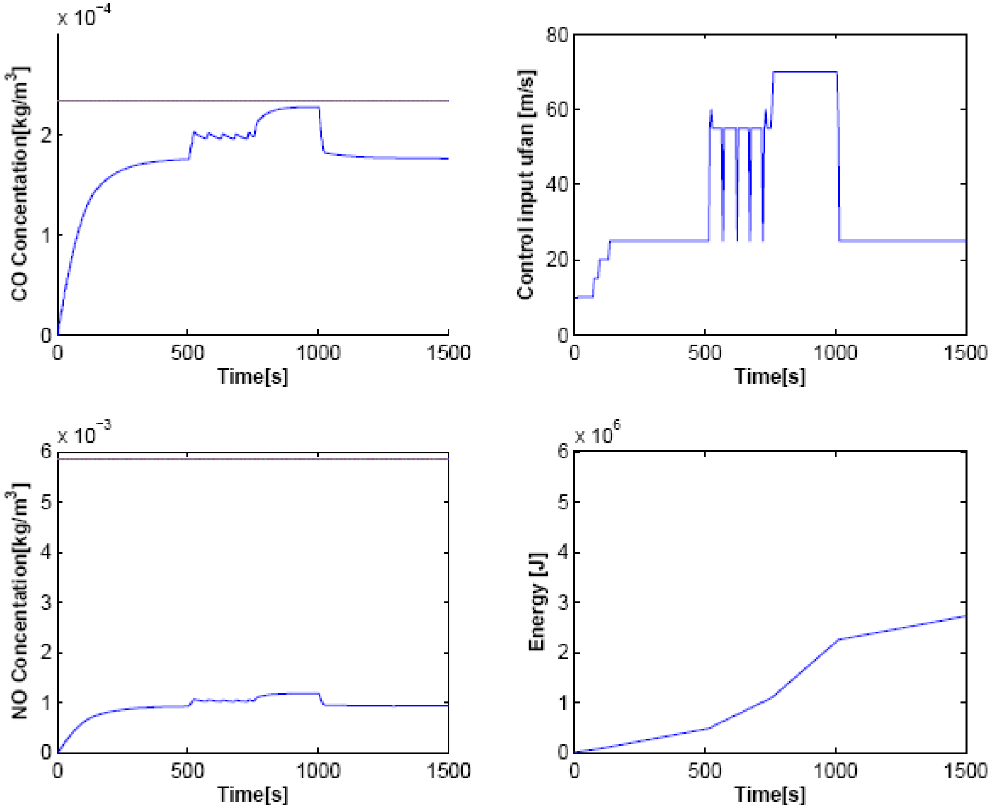
Regulation efficiency



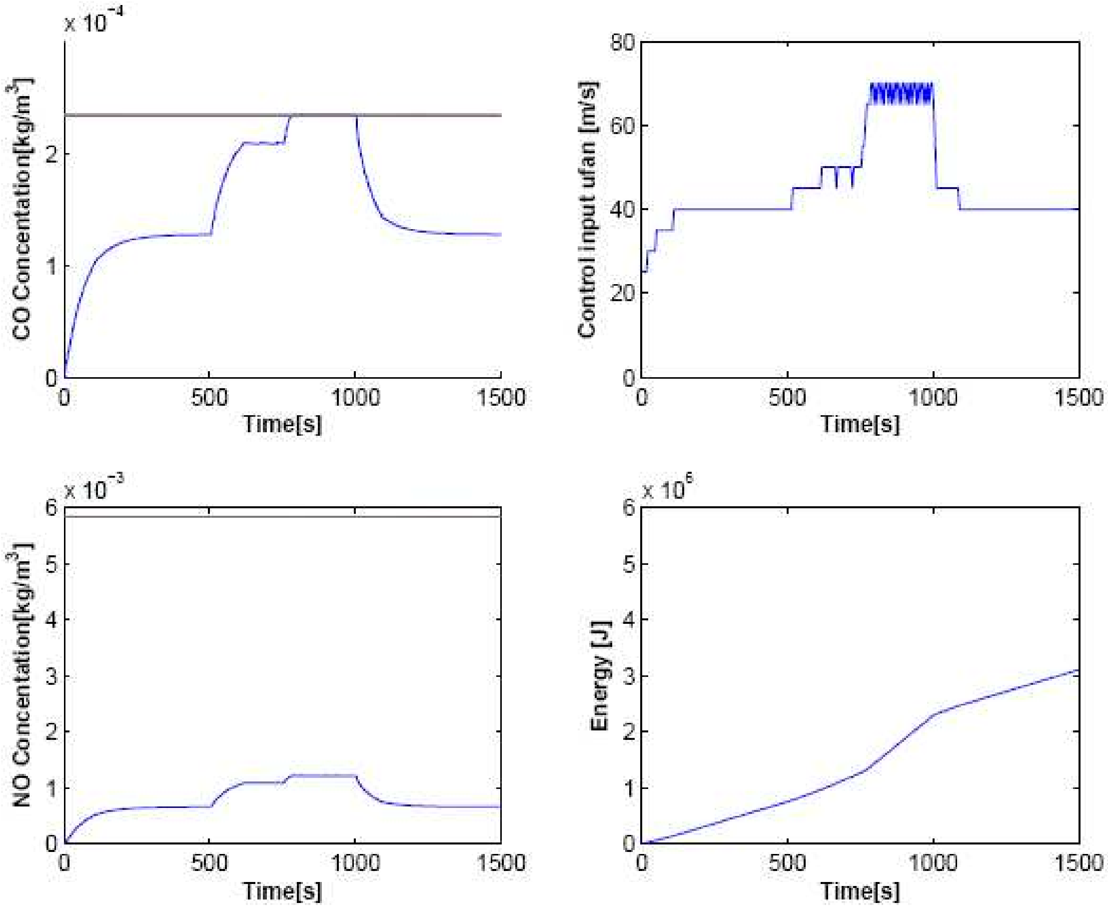
- MPC:
  - direct trade-off regulation efficiency vs. Energy min.
  - better ratio
- Threshold:
  - easy tuning
  - find the tighter band for the guards

Robustness

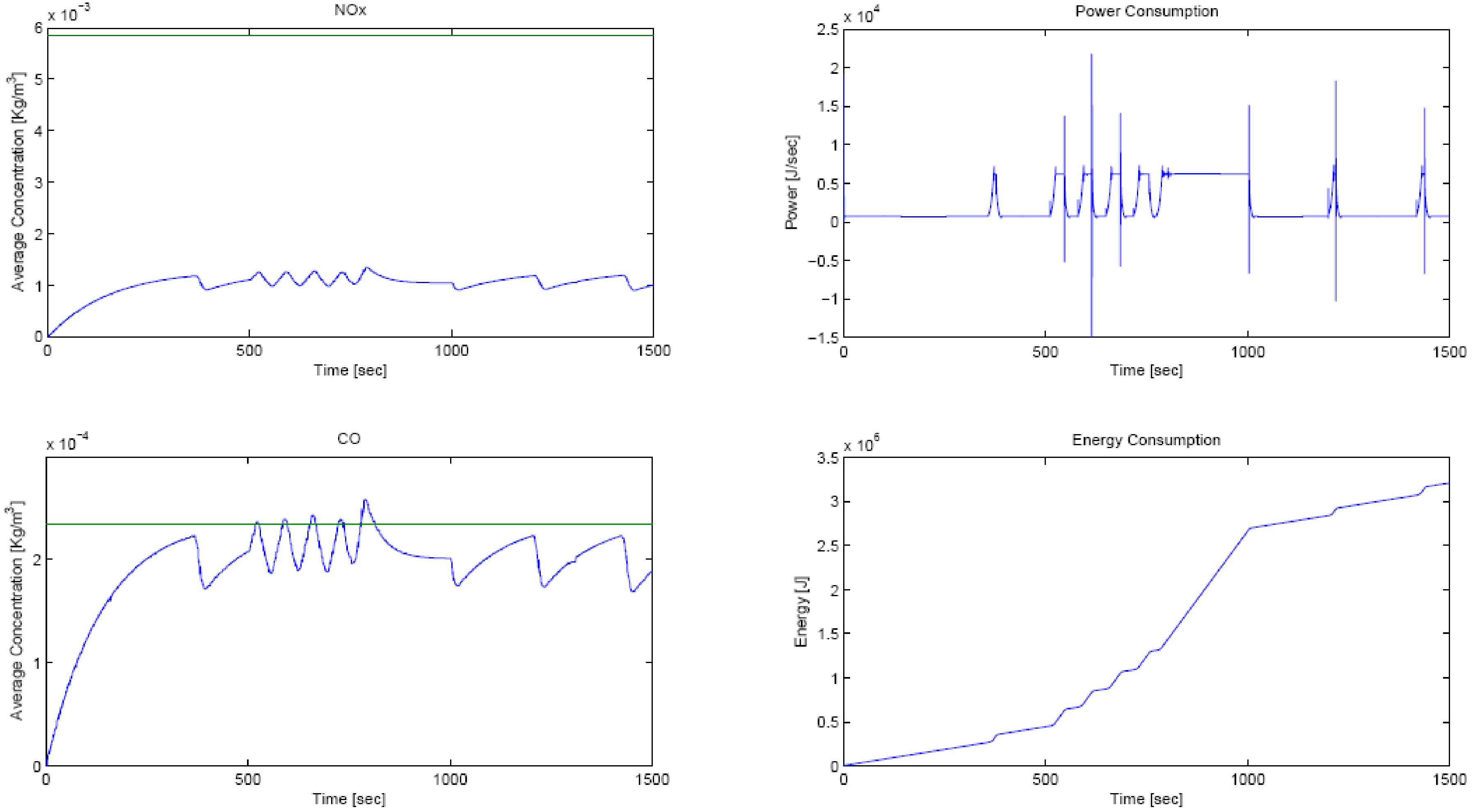
- MPC: wrt. Model error
  - underestimated values for the prediction of the pollutant sources (1 truck)



– 20% underestimated gain



• Thresholds: 80/90 % → 85/95 %



Computational complexity

- Thresholds:
  - O(1) complexity,
  - comparisons betw. meas. and safety thresholds
  - can be embedded on WSN
- MPC:
  - time consuming (1500s in 10 minutes with Matlab 2007a on a Pentium IV, 2.80GHz)
  - hard optimization problems

Conclusions

- Complex test case with multiple dynamics:
  - Transport / PDE for primary
  - Nonlinear / hybrid for secondary
  - Communication associated with WSN/PLC
  - ➢ Challenge for RT models and interconnection
- Numerous associated control issues, with significant possible improvements
- Results applicable to environmental applications
  - Ventilation control: intelligent buildings, flow transport
  - Transport in heterogenous media: plasma, firns, bread
  - Distributed sensing and actuation

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