Energy-efficient operation of a Medium Density Fibreboard flash dryer through Nonlinear MPC

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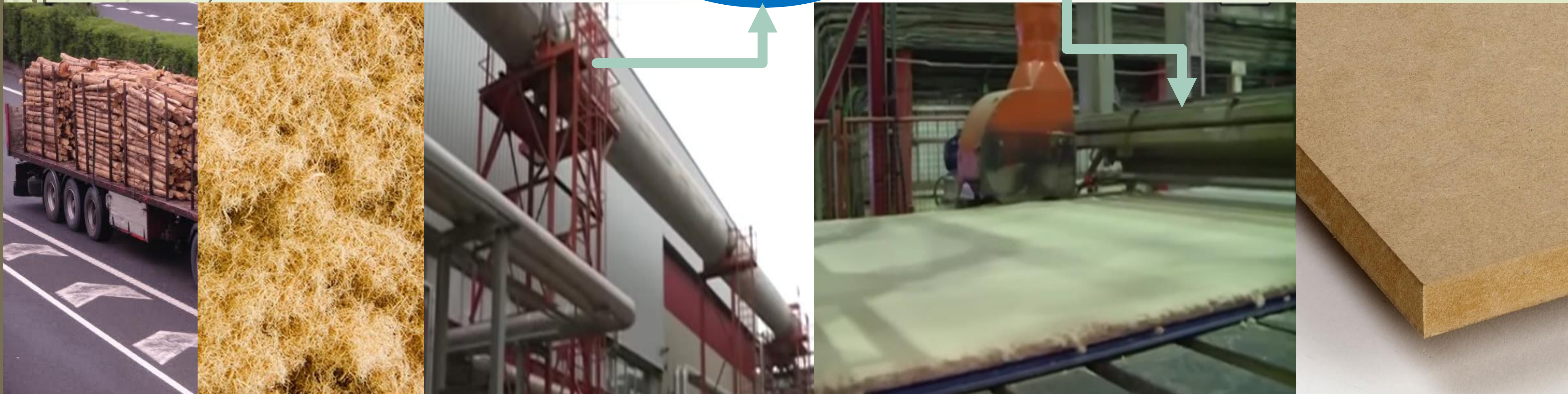
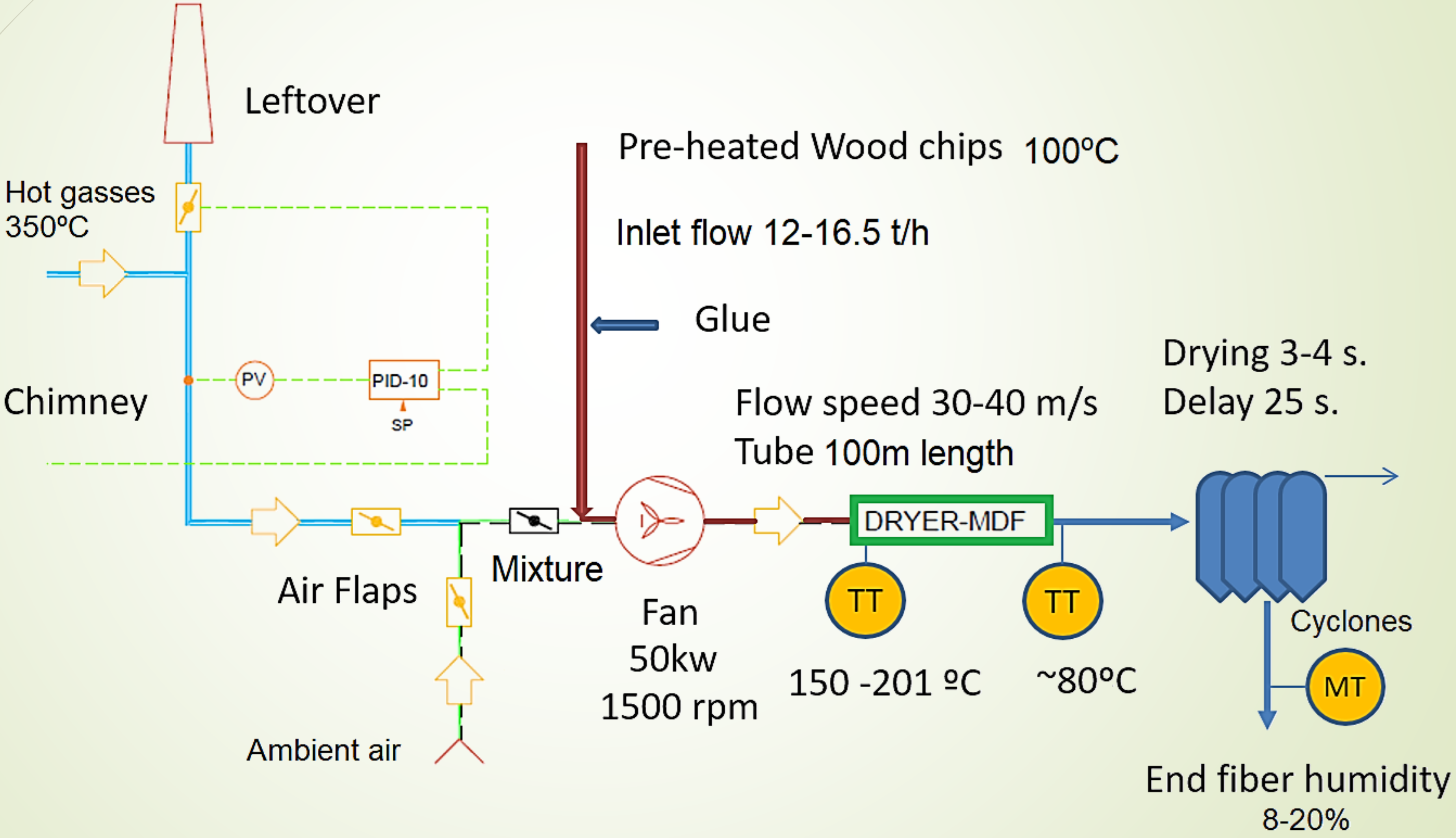
Sonae Arauco’s facilities to produce wood-based panels

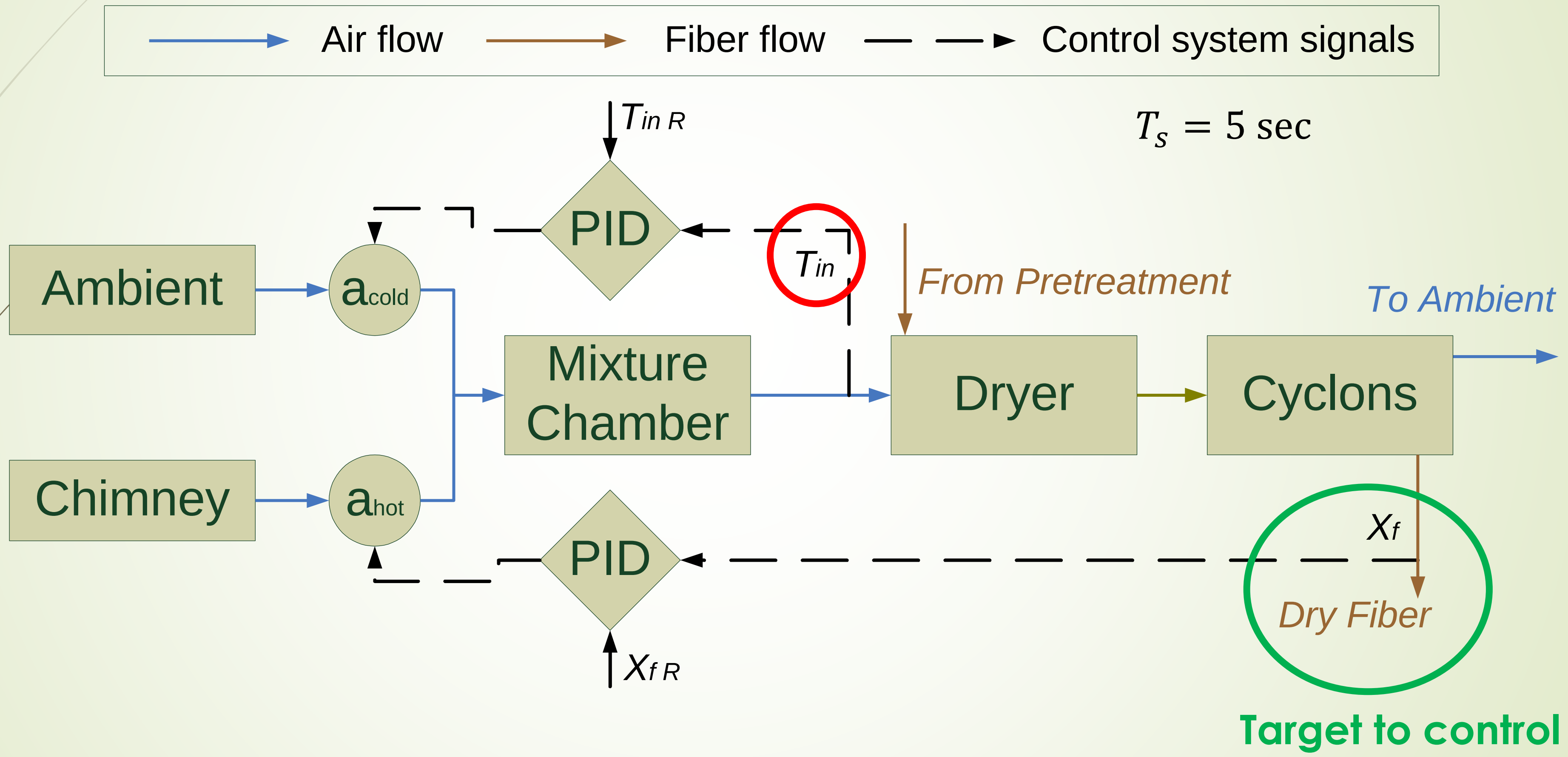
WOOD CHIPING → WET FIBRES → FLASH DRYER → MAT HOT PRESSING → FINAL PANEL



MDF tube flash dryer at Sonae



Dryer with former SISO control structure

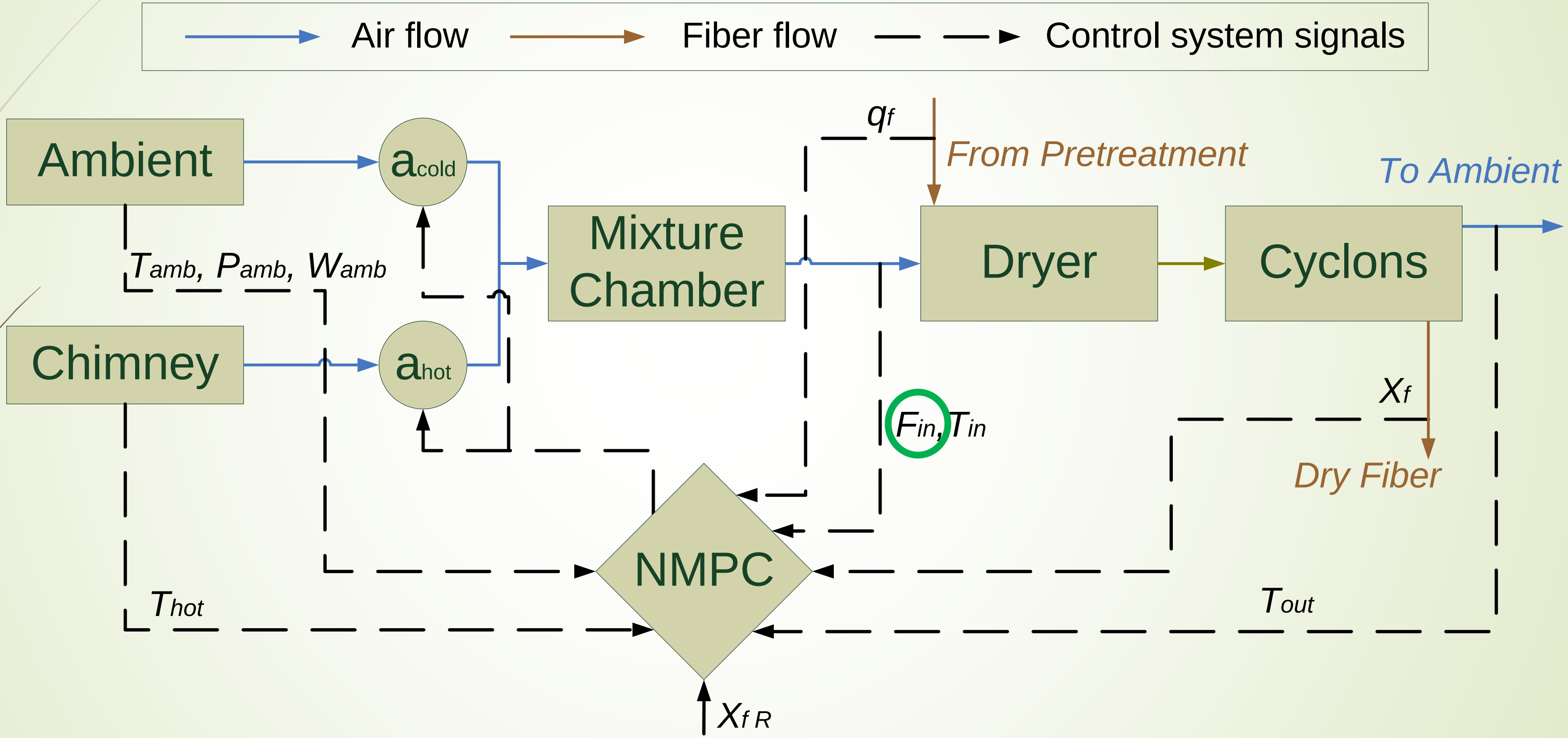


-Auxiliary control loop required with SISO PID scheme: Feasible air temperature SP set by operators.

Challenges to face

- **Important system delay:** ~25 sec. residence time of fibers in the cyclone stage
- **Scarce measured variables for modeling and control:** only air temperatures at the tube extremes and fiber humidity after the ciclones
- **Sampling time larger than the residence time of fibers in the tube dryer**: no information about the (spatial) drying dynamics
- **Different operation regimes due to product changes**: inlet fiber humidity X_0, fiber diameter/length, fiber flow q_f…
- **Nonlinear effect of the actuators** (air flaps) in the controlled variables.

Proposed centralized MPC scheme



-No fixed temperature SP is required: <u>degree of freedom for economic optimization</u>

-All reliable measurements are employed to enhance prediction performance

Grey-box lumped-parameter model

- First principles:
  - Global mass & energy balances
  - Heat loss to ambient
  - First-order dynamics plus delay at the cyclones

- Assumptions:
  - Thermal equilibrium at dryer outlet
  - Instantaneous drying: spatial dynamics (PDEs) neglected
  - Energy accumulation in the tube dryer
  - "Constant" Inlet fiber humidity

- Need of experimental equations:
  - Air flows (hot and cold) as function of the control actions (a_{hot} , a_{cold} openings)
  - Relationship between outlet air temperature T_{out} and fiber humidity X_f
  - Some model parameters p

$$\boxed{\begin{array}{c}\dot{x} = f(x, u, z, p, d),\\ h(x, u, z, p, d) = 0\end{array}}$$

$$x := [T_t, X_f]$$

$$u := [a_{\text{hot}}, a_{\text{cold}}]$$

$$d := [q_f, T_{\text{amb}}, W_{\text{amb}}, T_{\text{hot}}, X_0]$$

Grey-box modeling procedure

1. COMPUTE COHERENT ESTIMATIONS FOR ALL PROCESS VARIABLES
   - With all sensors data and the first-principles equations, solve a dynamic data reconciliation problem
   - Estimated values over time are consistent with the process physics
   - Not-trustable sensors are automatically discarded

2. FORMULATION OF ADDITIONAL EXPERIMENTAL EQUATIONS
   - With previous estimations, get each black-box submodel via constrained regression
   - Consistency of data-driven equations with process physics is ensured

Experimental customization to actual plant

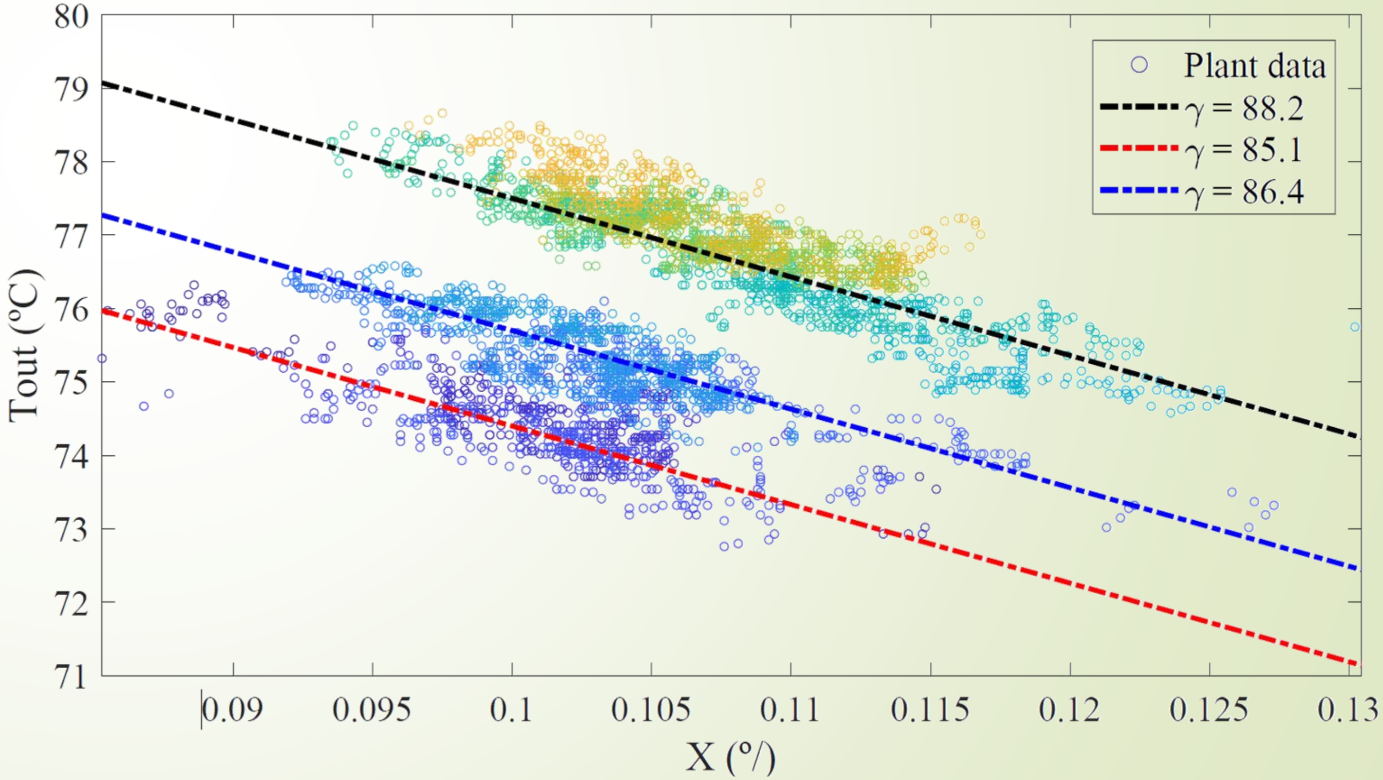
- $F_{\text{in}} = K_f \cdot \left(1 - e^{-7{,}1(a_{\text{hot}} + a_{\text{cold}})}\right)$
- $\frac{F_{\text{hot}}}{F_{\text{amb}}} = K_T \sqrt{\frac{a_{\text{hot}}}{a_{\text{cold}}}}$

K_f, K_T are “constant” regression parameters

- $T_{\text{out}} = -107 \cdot X + \gamma$

γ is a bias parameter
that fits the operation point

Linearity supported by the
the Gay-Lussac's law



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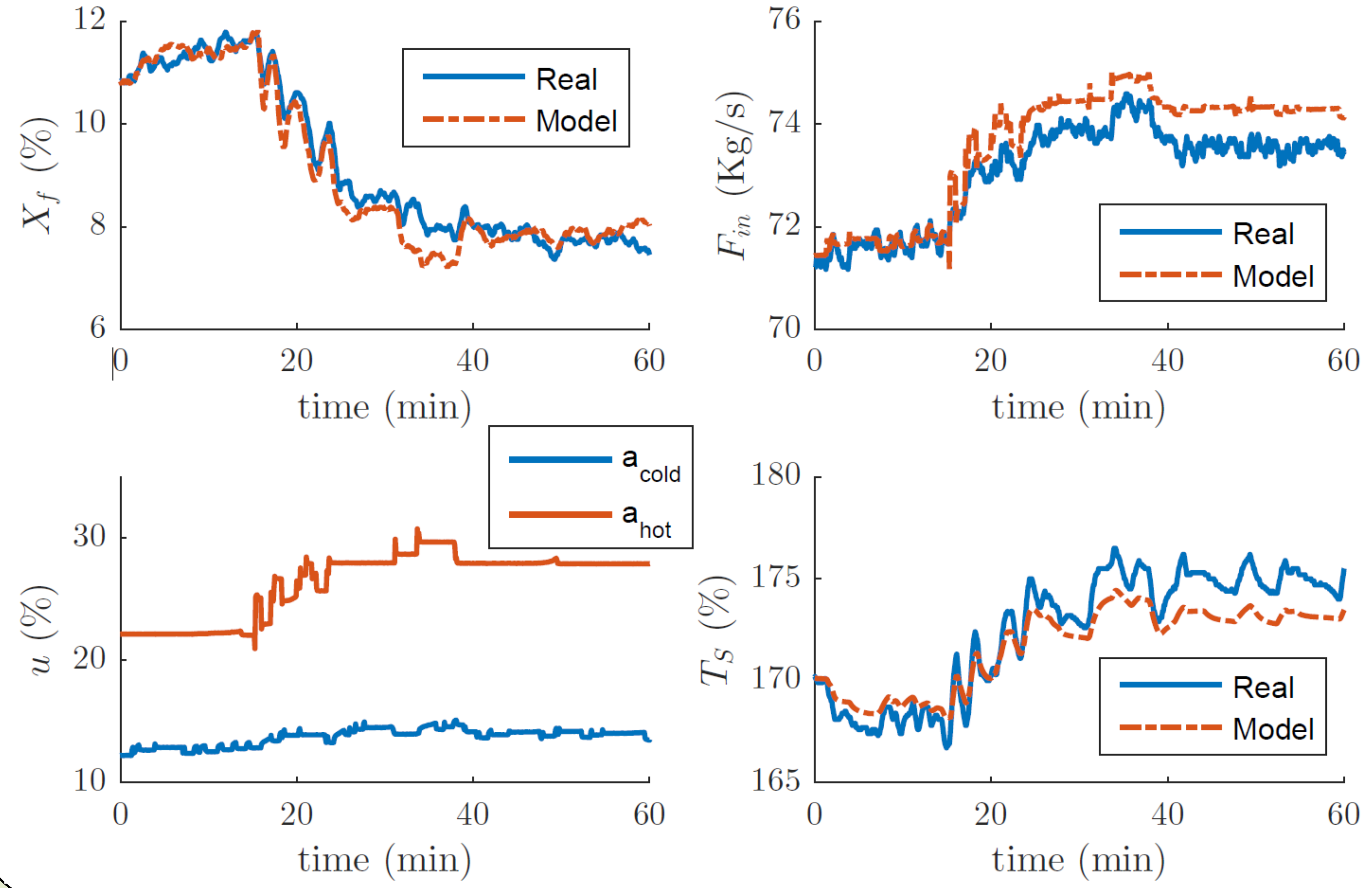


12
10
8
6
X_f (%)
0
20
40
60
time (min)
Real
Model
76
74
72
70
F_{in} (Kg/s)
0
20
40
60
time (min)
Real
Model
30
20
10
u (%)
0
20
40
60
time (min)
a_{cold}
a_{hot}
180
175
170
165
T_S (%)
0
20
40
60
time (min)
Real
Model

Unknown inputs and state estimation

- A Moving Horizon Estimator (MHE) is used to provide the values of the time-varying parameters, unmeasured states and disturbances
- MHE estimations will be coherent with MPC predictions: model equations are the same for both optimization problems.
- Correct bias-state estimation achieved in steady state.

$$\min_{\alpha,x_0} \int_{t=-H_E}^{0} \underbrace{\left\| w_f \cdot \left(y(t) - \hat{y}(t)\right) \right\|_2^2}_{\text{Output error: Plant-model mismatch}} + \underbrace{\| w_\alpha \cdot \Delta_\alpha \|_2^2 + \left\| w_{x_0} \cdot \Delta_{x_0} \right\|_2^2}_{\text{Regularization: penalty to high changes w.r.t. the previous estimation}}$$

$$\text{s.t.:} \quad \dot{x} = f(x,u,z,p,d), x(0) = x_0;\; h(x,u,z,p,d) = 0; m(x,u,z,d) = 0$$

$$\boldsymbol{\alpha} = [\boldsymbol{T_{t0}}, \boldsymbol{X_{f0}}, \boldsymbol{K_f}, \boldsymbol{K_T}, \boldsymbol{\gamma}, \boldsymbol{X_0}]$$

Mixed tracking-economic NMPC design

- ***Virtual setpoints*** $\boldsymbol{y_S} = [\boldsymbol{X_{fS}}, \boldsymbol{T_{\text{in}S}}]$ added to guarantee stability: Additional decision variables that are always reached at the end of H_P
- **Tracking target:** $\boldsymbol{X_{fR}}$. The L_1-norm guarantees X_{fS} eventually reaches X_{fR}
- **Economic target:** $\boldsymbol{T_{\text{in}R}}$. Indirectly minimizes the use of hot gases.

$$\min_{u, y_S} \overbrace{\sum_{t=1}^{H_P} w_y \cdot \|y(t) - y_S\|_2^2}^{\text{Error w.r.t. virtual SPs}} + \overbrace{\sum_{t=1}^{H_C} w_u \cdot \|\Delta u\|_2^2}^{\text{Penalty to aggressive } \Delta u} + \overbrace{w_{sp} \cdot \left\| X_{fS} - X_{fR} \right\|_1}^{\text{Actual tracking objective}} + \overbrace{w_e \cdot T_{\text{in}R}}^{\text{Economic target}}$$

$$\text{s.t.:} \quad \dot{x} = f(x, u, z, p, d), x(0) = x_0;\ h(x, u, z, p, d) = 0; m(x, u, z, d) = 0;$$

$$\underline{\mathbf{T}} \leq T_{\text{in}} \leq \overline{\mathbf{T}}; \quad \underline{\mathbf{u}} \leq u \leq \overline{\mathbf{u}}; \quad |\Delta u| \leq \boldsymbol{\delta}$$

$$\left.\dot{x_S} = f(x_S, u_S, p, \delta) = 0; \quad u(t) \equiv u_S\ \forall t \geq H_C \right\} \text{Ensure the virtual SPs are stable steady states}$$

Technical implementation

- Model dynamics discretized in time via Orthogonal Collocation
  - Finite elements of 5-seconds length, 2-degree interpolation
- Nonlinear optimization problems coded in CasADi
  - Automatic-differentiation features
  - Easy integration with the control system at SONAE through MATLAB
- Numerical resolution by the NLP solver IPOPT
  - Horizons set to: $H_E = H_C = 8;\ \ H_P = 20$ (system delay is 5 samples)
  - Total execution time (MHE+MPC) is around 1,5 sec. (<T_s =5 sec.)
- Connection with the plant data-collection system through OPC-DA

Comparison with PID control in simulation

- Model for simulation taken from specialized literature:

Pang (2000), Mathematical modelling of MDF fibre drying: Drying optimisation. Drying Technology, 18(7),1433-1448.

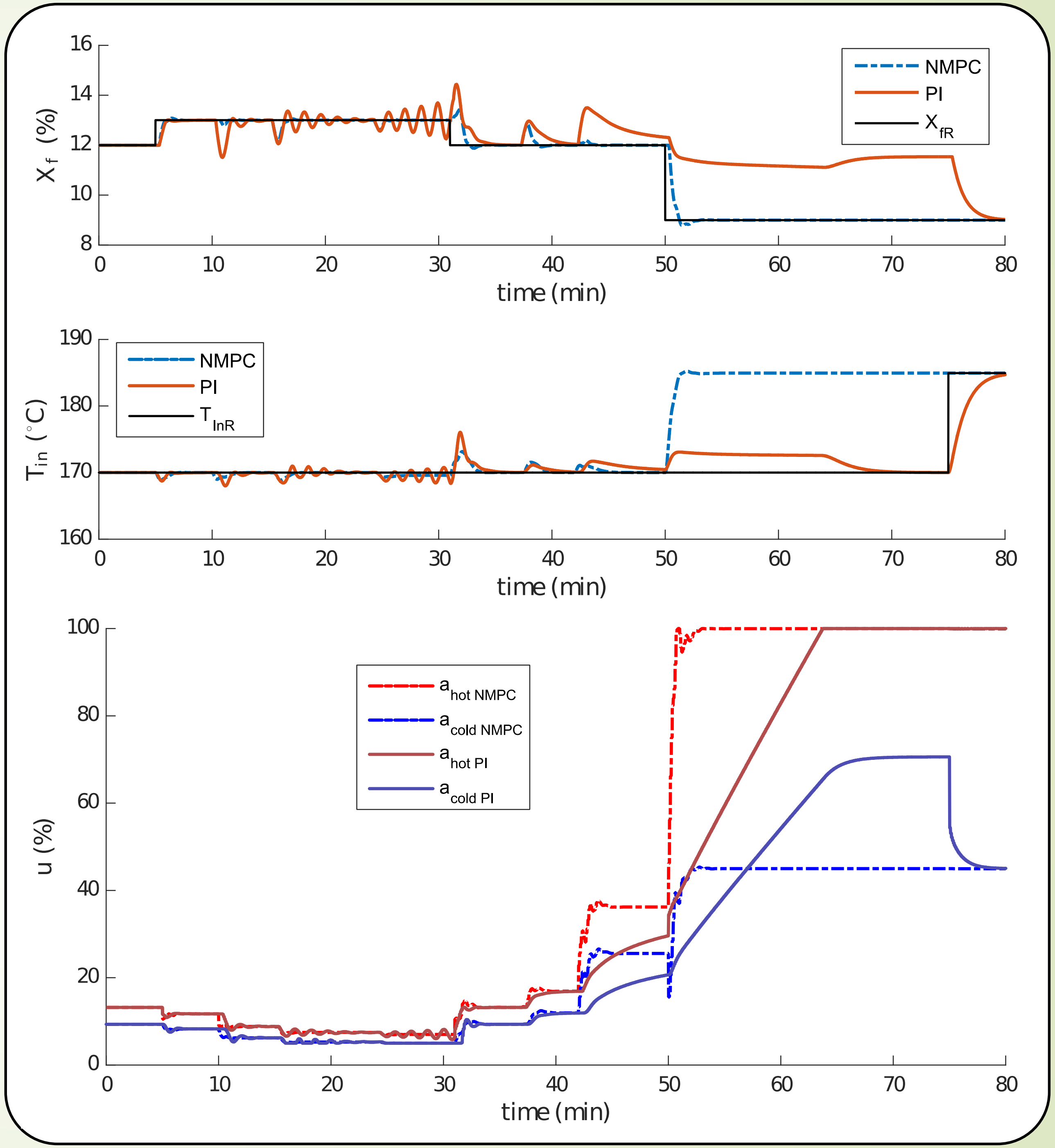
- Spatial drying PDE dynamics for flash tube dryers:

$$\frac{\partial X}{\partial l} = v \cdot \left(\frac{2}{L_f} + \frac{4}{d_f}\right) \cdot U \cdot \frac{T_{db} - T_{wb}}{\Delta H_w \cdot q_f}$$

- SISO PID loops were tuned for the simulation model following the SIMC rules

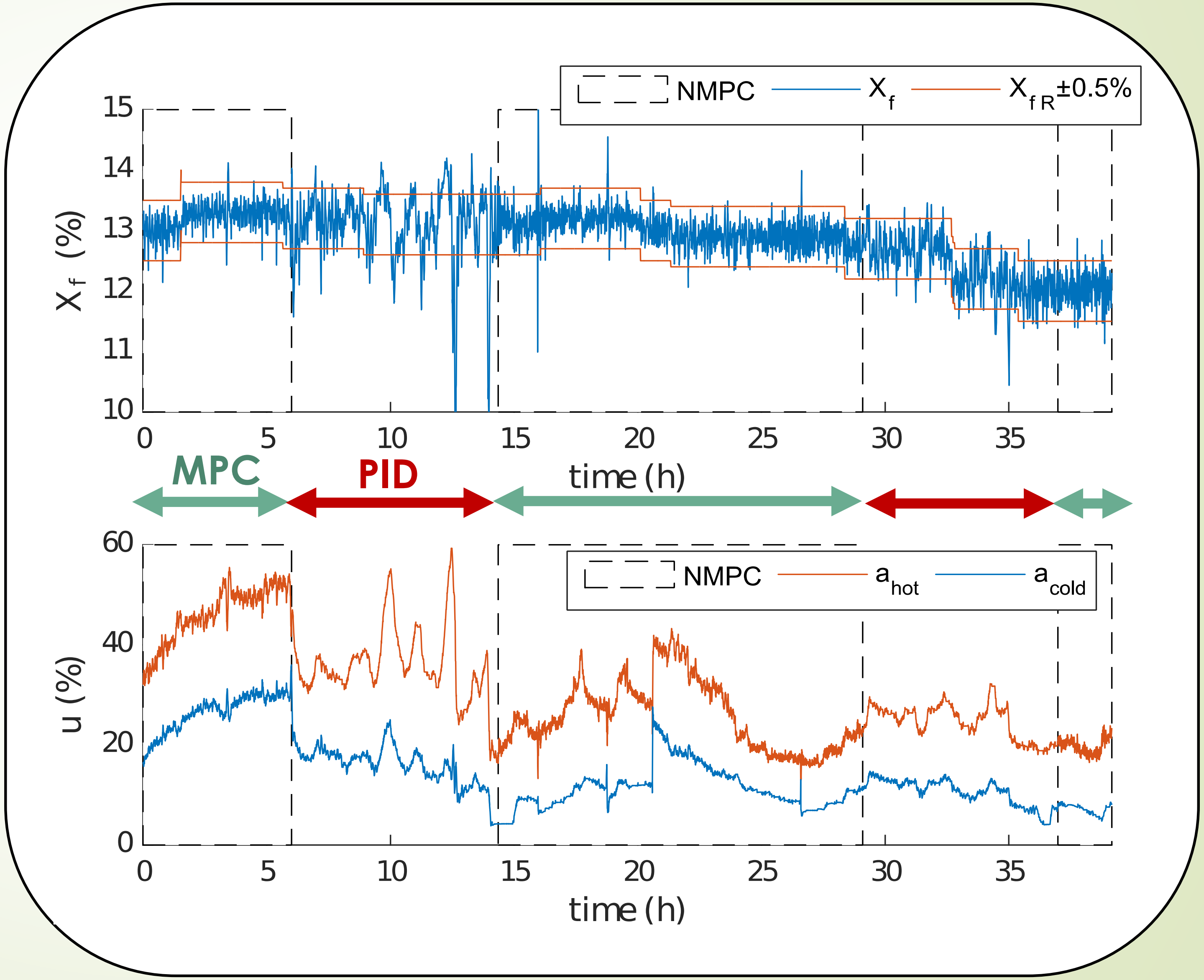
Results

- Control performance improved when facing disturbances in X_0, q_f
  - *PID control oscillates when operating with flaps a_c, a_h quite closed.*
  - *Measured disturbances are instantaneously compensated with NMPC*
- No need for operator intervention when the operation point changes
- Target humidity always achieved with NMPC, if feasible of course

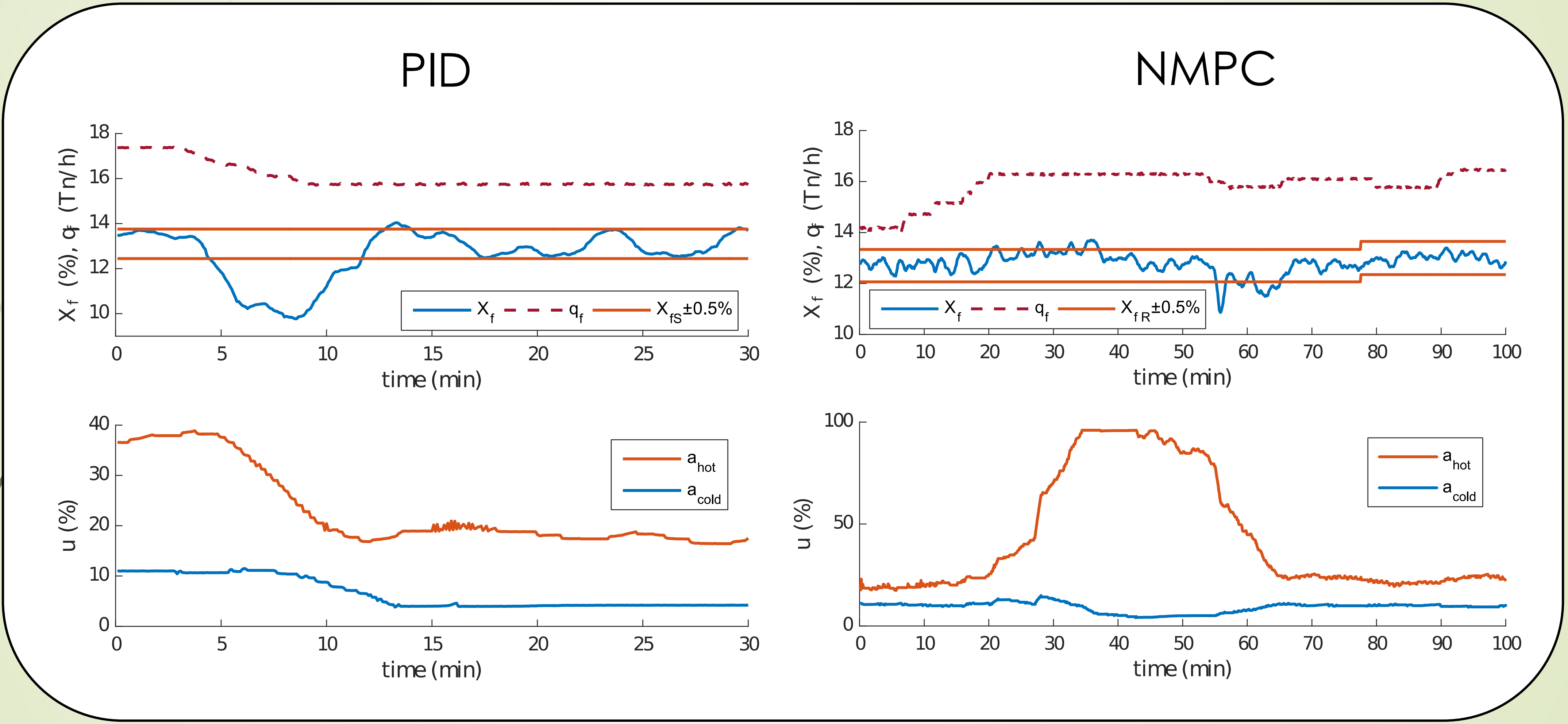


Experimental evaluation onsite

- COMPARISON WITH ACTUAL PID CONTROL:
- ISE reduced by 63%
- Time the humidity is outside a ±0,5% confidence band decreased by 76%



Disturbance rejection



* Actual data recorded from the plant

Summary & final remarks

- COMBINATION OF FIRST-PRINCIPLES AND DATA-DRIVEN EQUATIONS IN A (LIMITED COMPLEXITY) *GREY* MODEL IS KEY:
  - Keeps consistency with the process physics → reliable predictions
  - Proven suitable for real-time
- MODEL ADAPTATION IS REQUIRED TO ENSURE LONG LIFE OF DESIGNS:
  - Unmodelled (microscale) drying dynamics and unmeasured nature of some input disturbances affecting the process (i.e., X_0)
- STABILITY, FEASIBILITY & OPTIMALITY IS GUARANTEED IN THE NMPC:
  - Operators' work load is reduced

References

Contact:
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