Model predictive control of industrial processes

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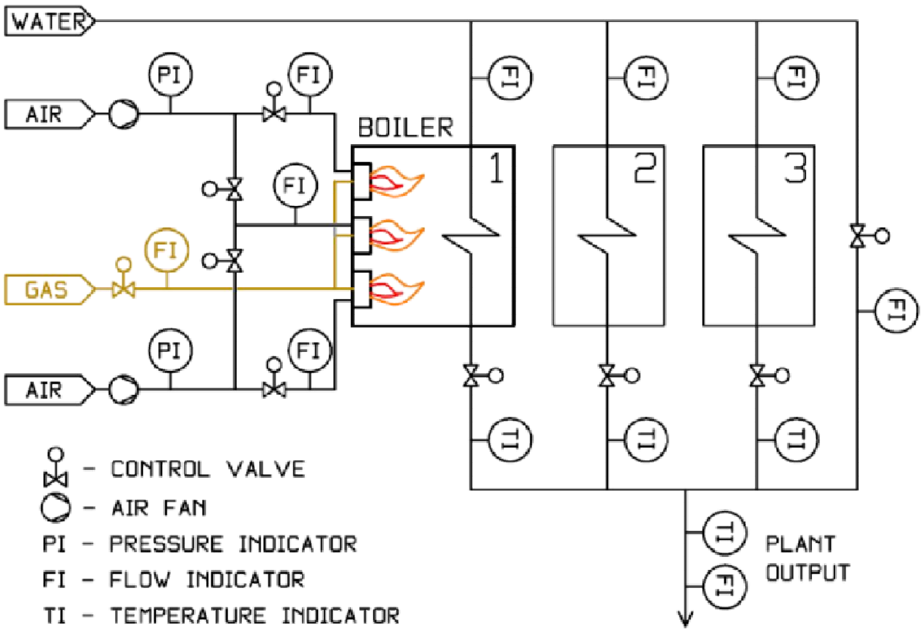
Contents

Industrial process (Iru Power Plant)

- Three similar boilers in parallel
- Each boiler can work in:
  - basic mode (constant load)
  - control mode (variable load)
- Control mode is used to control plant output temperature

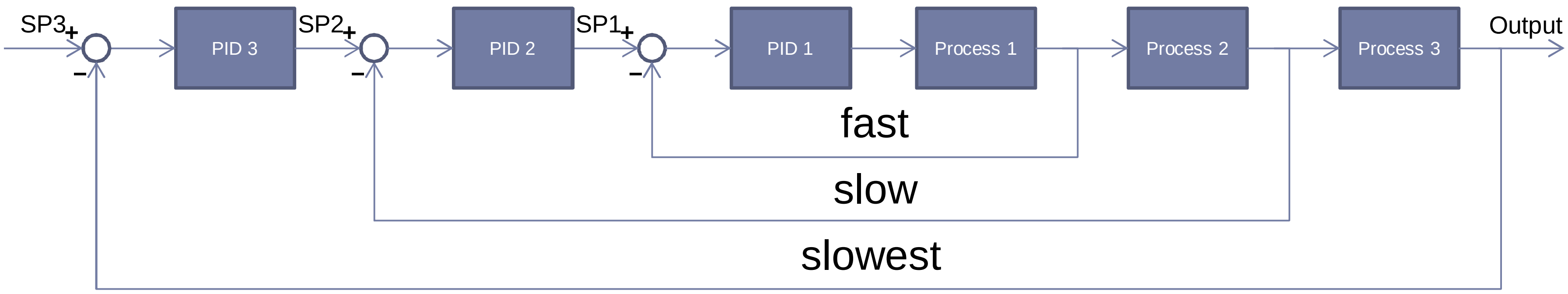


Industrial process control

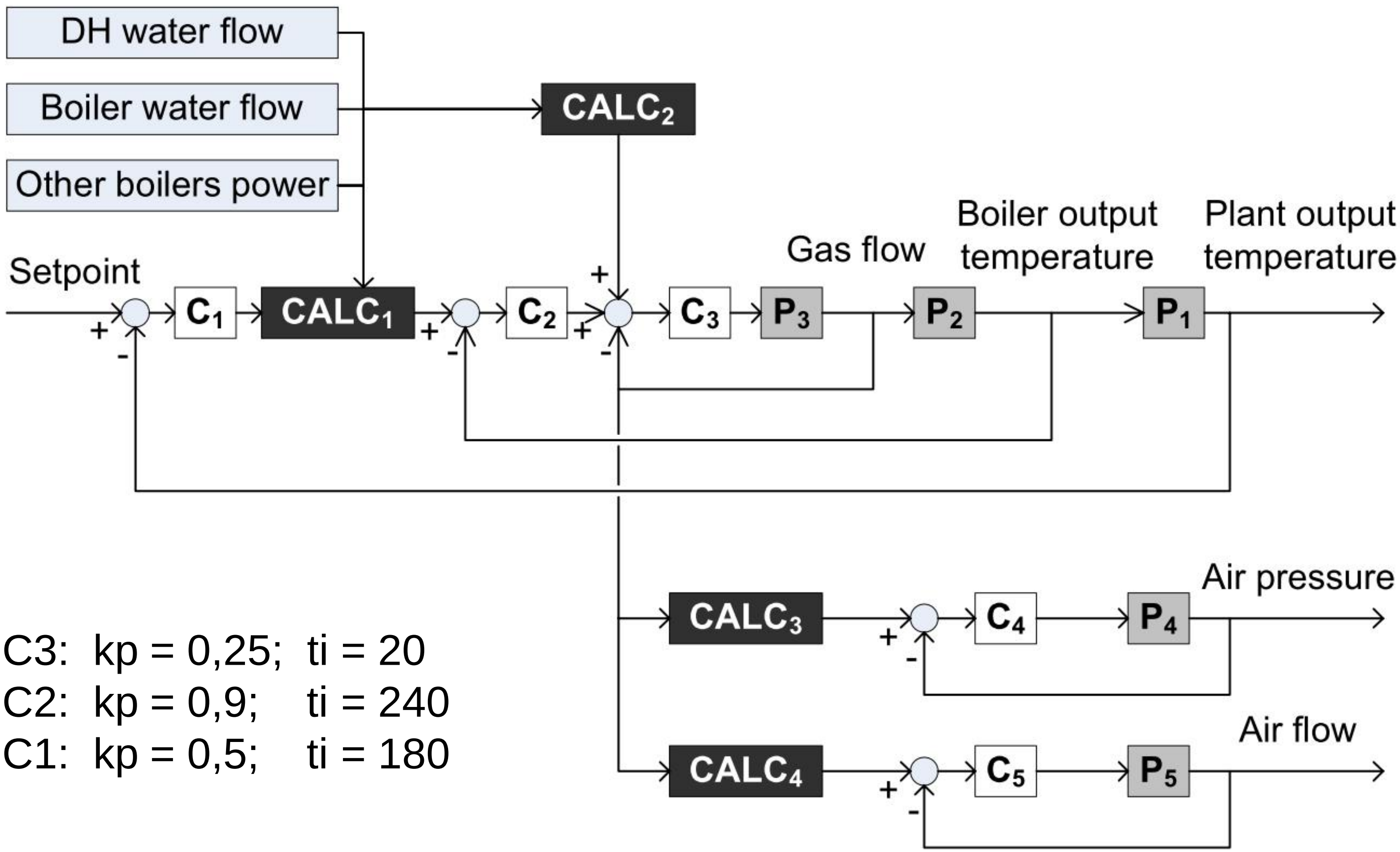
Two cascade control loop

Cascade control loop

Control loop

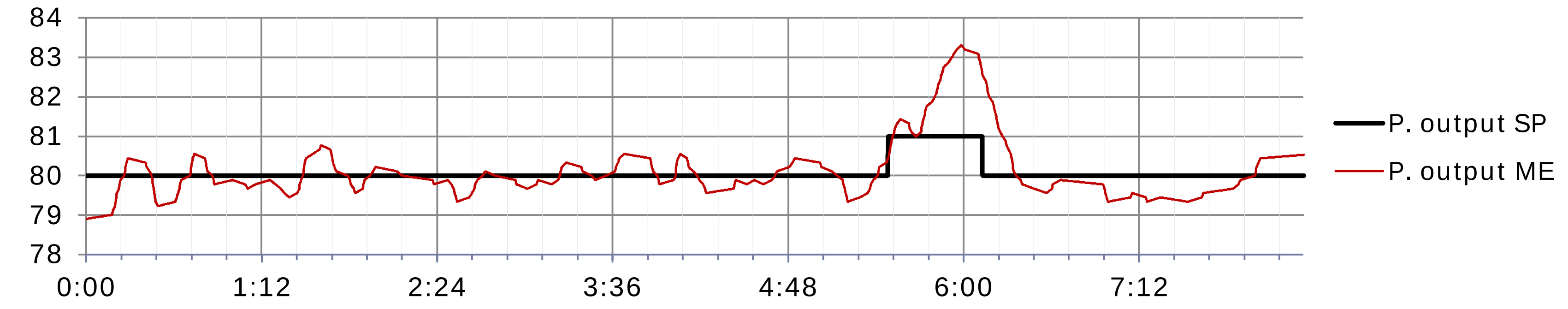


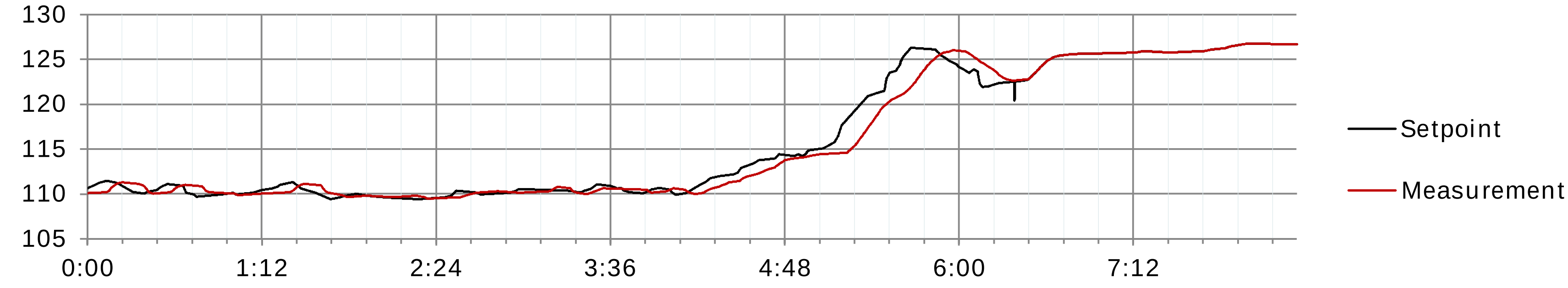
Industrial process control (Iru Power Plant)

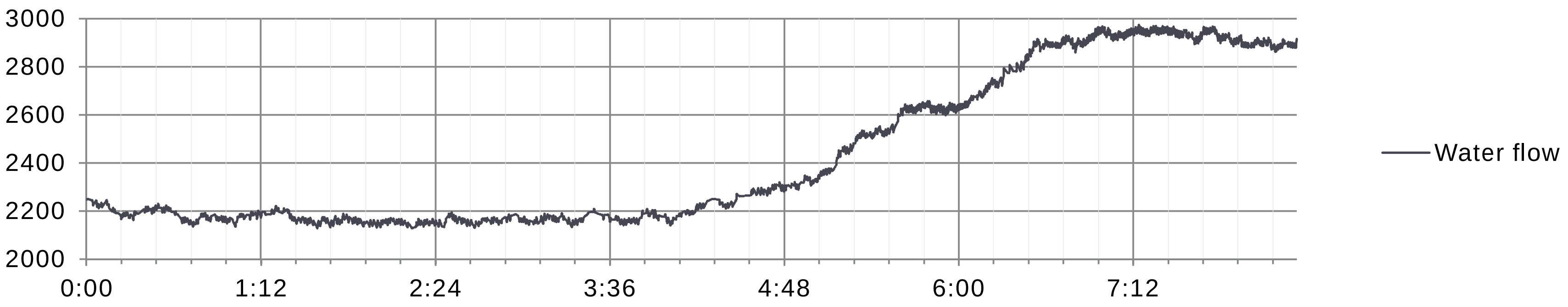


C3: kp = 0,25; ti = 20
C2: kp = 0,9; ti = 240
C1: kp = 0,5; ti = 180

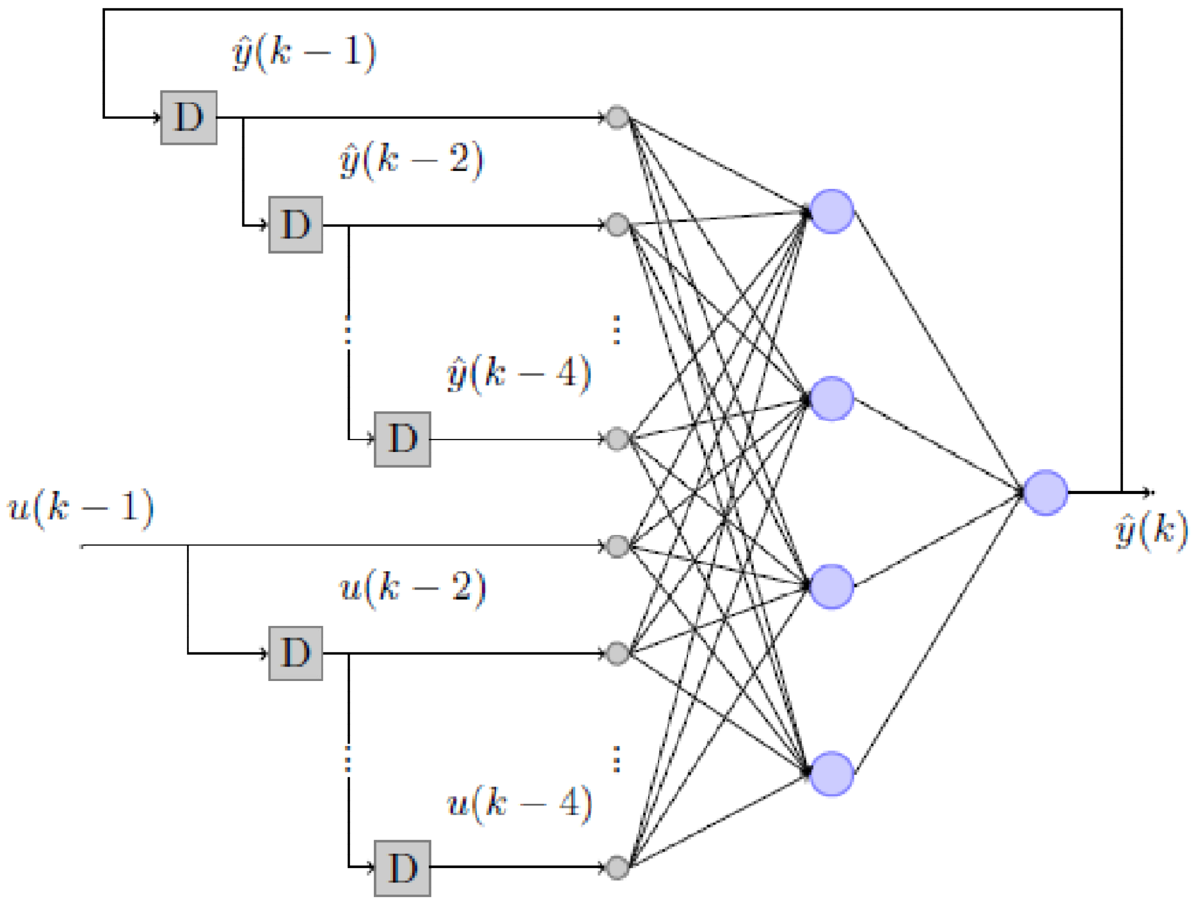
Industrial process (Iru Power Plant)





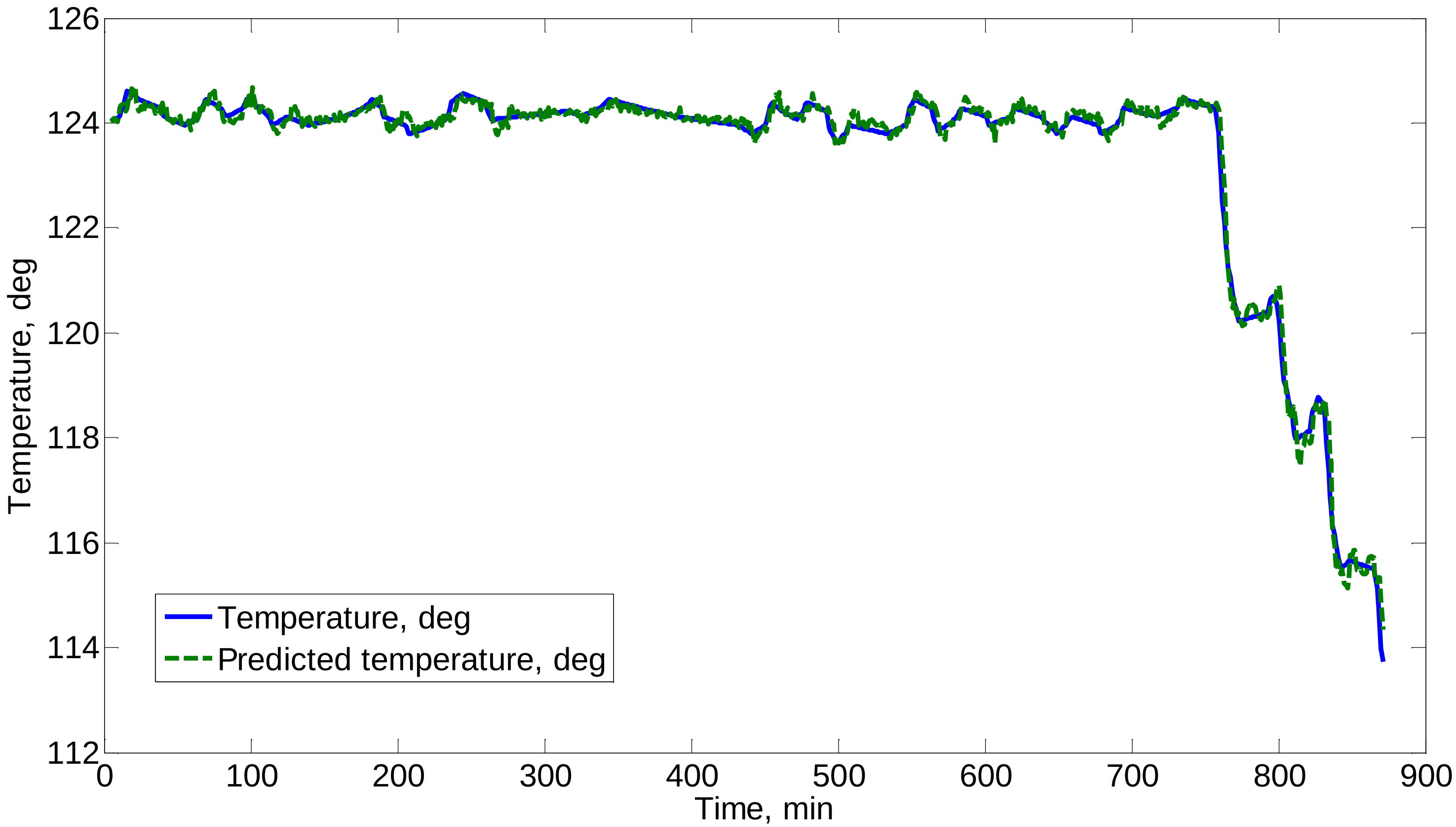


Neural network model
Recursive prediction



y – output temperature prediction
u – vector of water, air and gas flows

Neural network 5 min prediction



Neural network first results

- 5 minutes predictions were good
- Simulation was not possible
  - After 10 cycles model output was not close enough to real process output
  - After 100 cycles model output was already somewhere in outer space
- So, it was decided to start from simple things – linear model identification with conventional methods.

Process identification

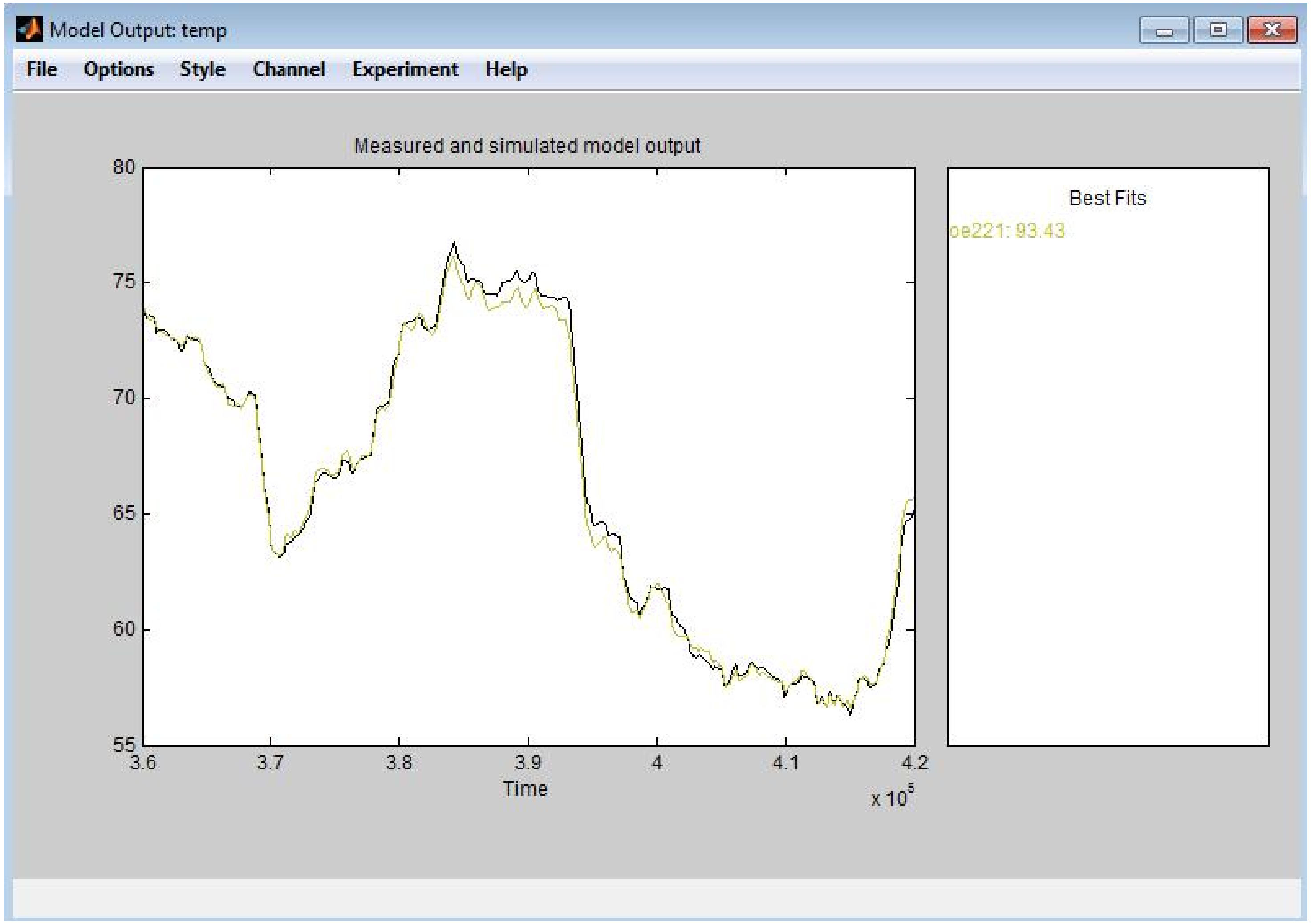
- Process is simple, but nonlinear:

$$Q \approx r \cdot \Delta m_{fuel}$$
$$Q \approx c \cdot \Delta m_{water} \Delta T$$

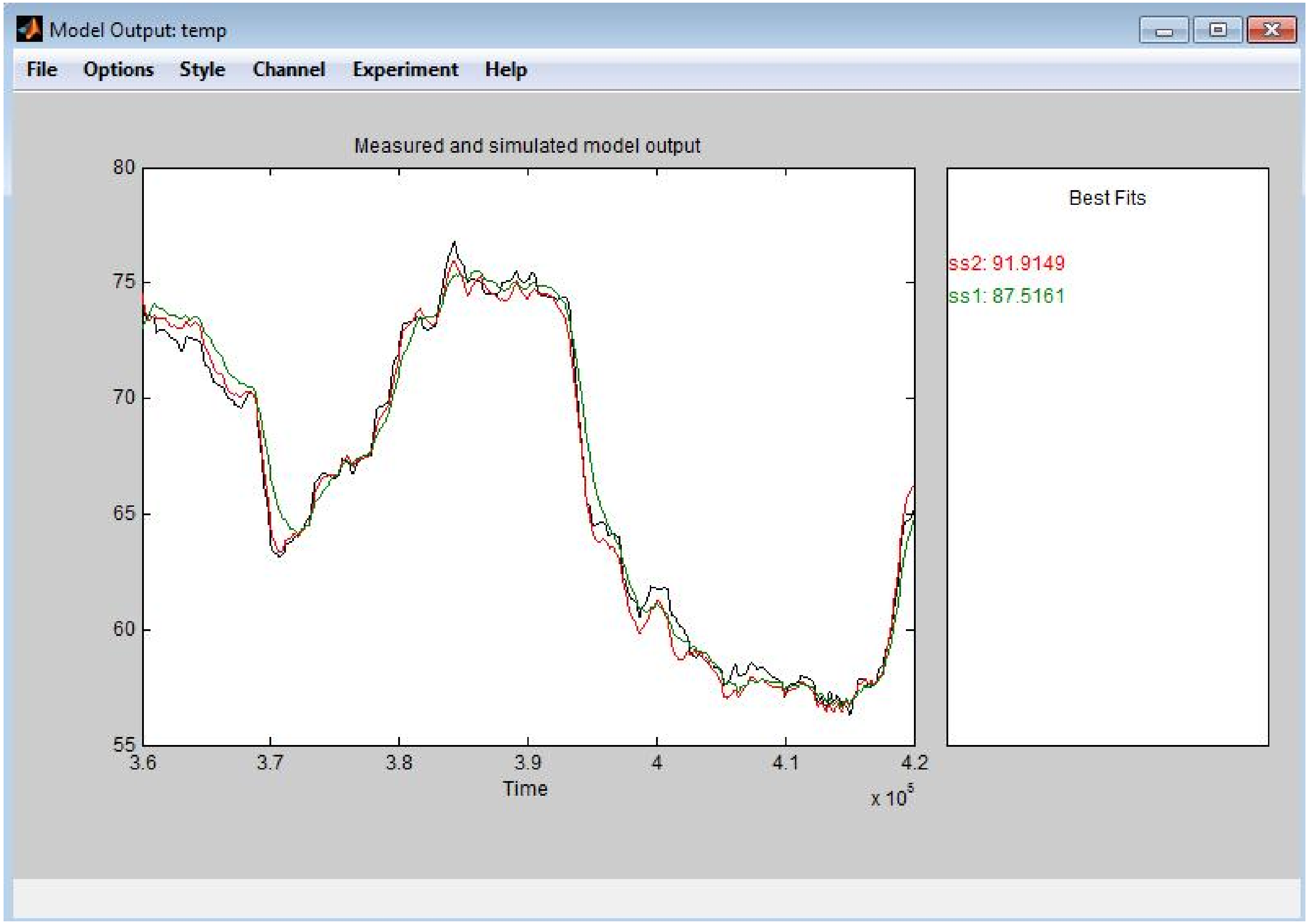
$$\Delta T = \frac{r \cdot \Delta m_{fuel}}{c \cdot \Delta m_{water}}$$

- As water flow is more or less constant during normal operation, so mainly it can be seen as linear.
- Matlab Identification Toolbox was used for identification.
- Most suitable results were acquired from polynomial and state space models.

Polynomial model identification



State-space model



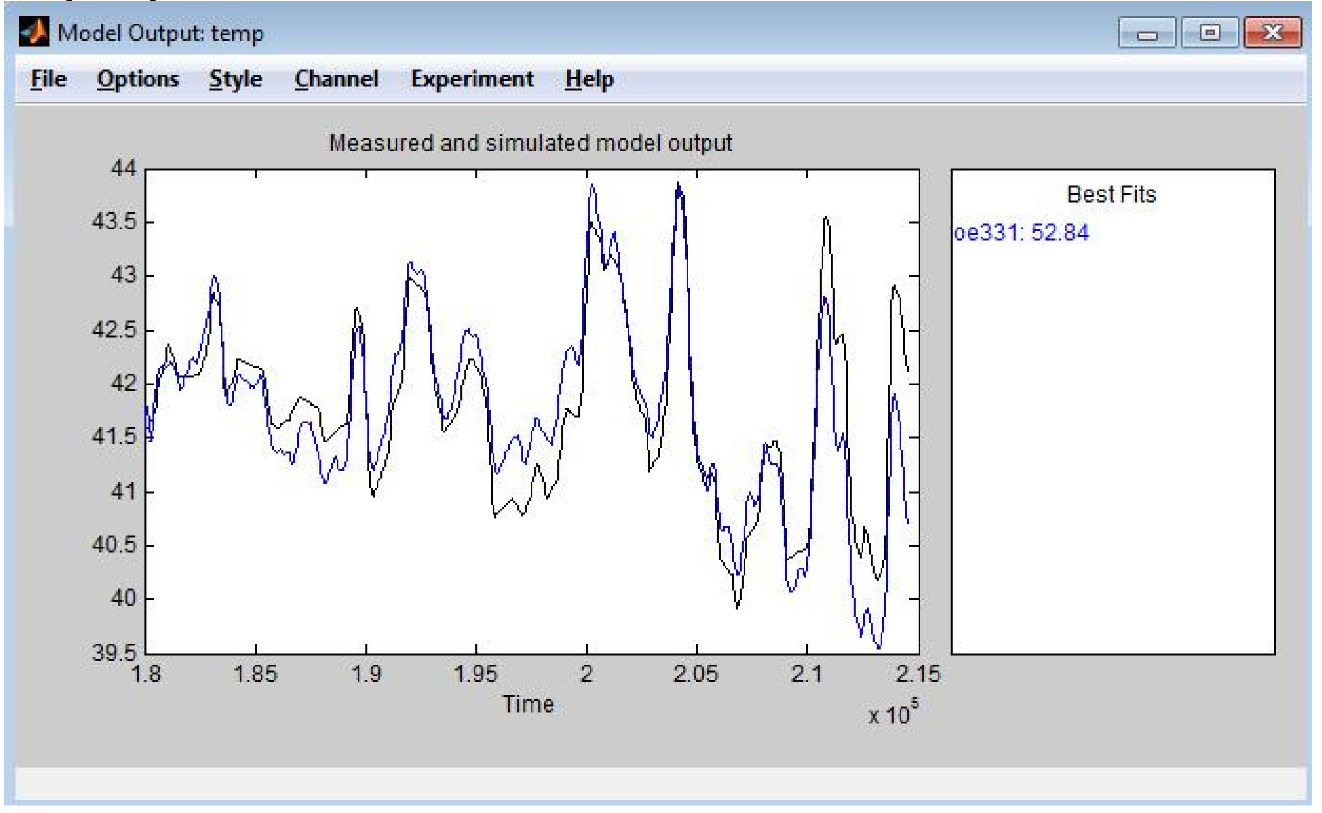
Process model

- State space model with 4 states (ss2) was selected as:
  - it is simpler than oe221 (6 states in state space representation)
  - shows better results then ss1 (1 state)

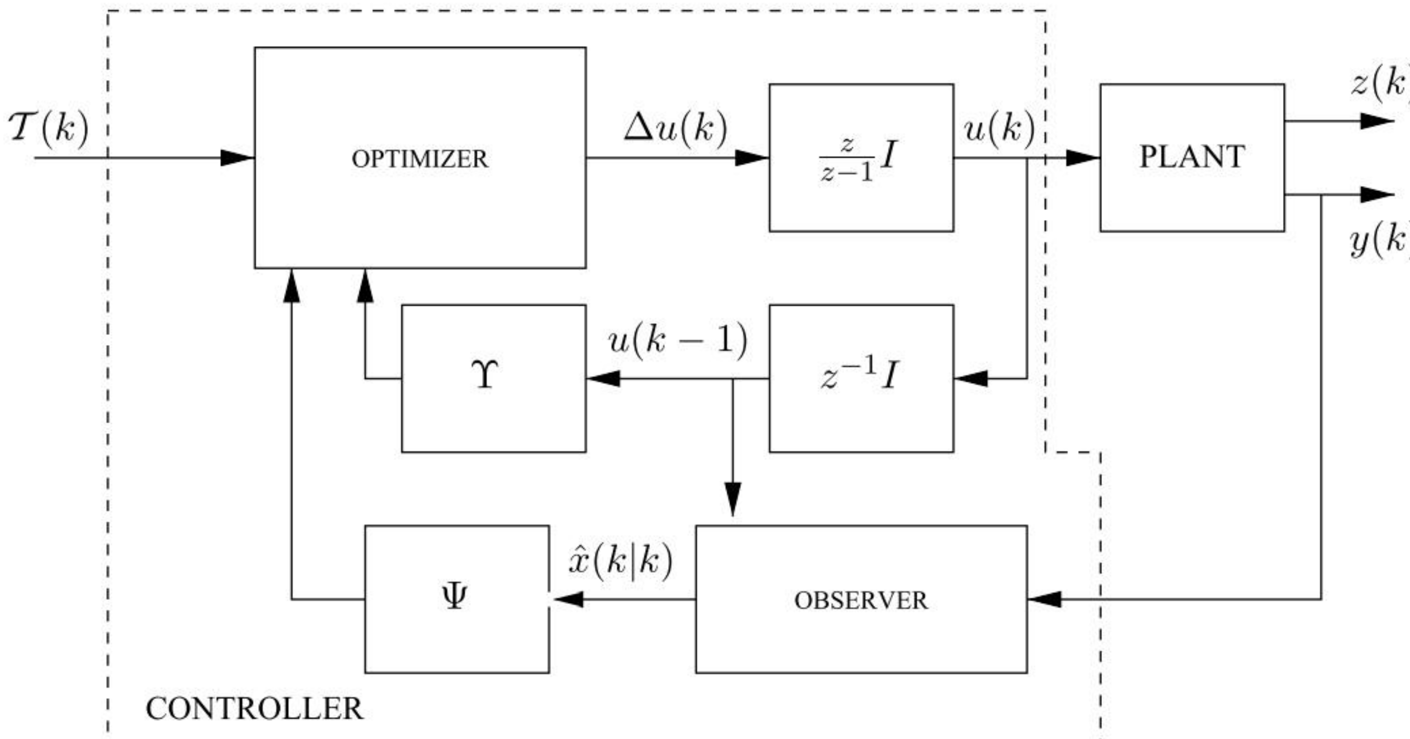
- 4 state model showed better fit among all state space models (2, 3, 5 etc. states)

MPC (Model predictive controller) Model identification

- To avoid perfect "theoretical results" model for MPC was identified from the data acquired one year later at the time when boiler load was different (~1/8 of previous example) and nonconstant.



MPC structure



MPC observer

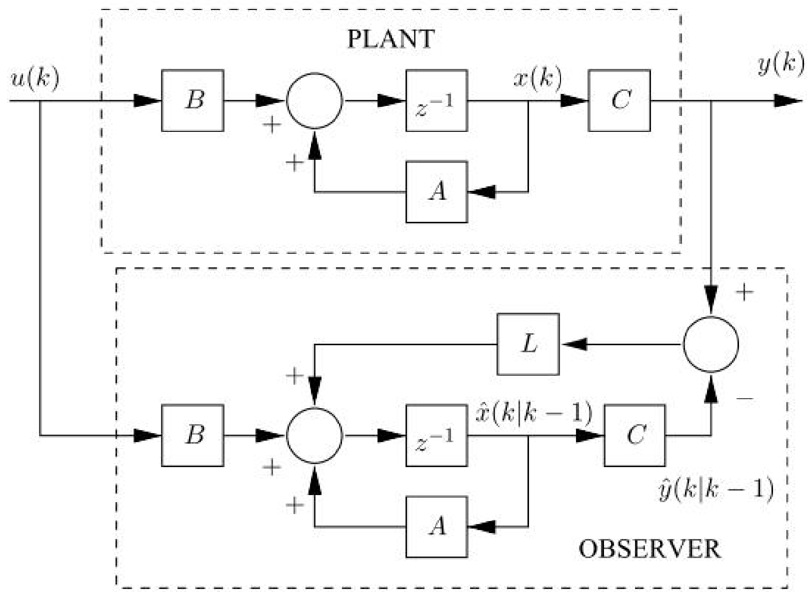
$$\hat{x}(k|k) = \hat{x}(k|k-1) + L'[y(k) - \hat{y}(k|k-1)]$$
$$\hat{x}(k+1|k) = A\hat{x}(k|k) + Bu(k)$$
$$\hat{y}(k|k-1) = C\hat{x}(k|k-1)$$

$$\Rightarrow$$

$$\hat{x}(k+1|k) = A(I - L'C)\hat{x}(k|k-1) + Bu(k) + AL'y(k)$$

$$e(k) = x(k) - \hat{x}(k|k-1) \Rightarrow e(k+1) = (A - LC)e(k)$$

Observer is stable $\Rightarrow$ estimation error converges to zero



MPC design (1)

- There is a cost function: $V(k) = \|Z(k) - T(k)\|_Q^2 + \|\Delta U(k)\|_R^2$
- where
  - Z(k) – predicted process output
  - T(k) – reference trajectory
  - ΔU(k) – process input changes
  - Q, R – weight matrices
  - $\|a\|_A^2 = a^T A a$

$$Z(k) = \Psi x(k) + \Upsilon u(k-1) + \Theta \Delta U(k)$$

$$\mathrm{E}(k) = \mathrm{T}(k) - \Psi x(k) - \Upsilon u(k-1)$$

Tracking error

Free response with ΔU = 0

MPC design (2)

- From this function optimal input changes for unconstrained case are found:

$$\Delta U(k) = \frac{1}{2} H^{-1} G$$

- where

$$G = 2\Theta^T Q E(k)$$

$$H = \Theta^T Q \Theta + R$$

MPC constraints

- Constraints are in the form:

$$E\begin{bmatrix}\Delta U(k)\\ 1\end{bmatrix}\leq 0,\qquad F\begin{bmatrix}U(k)\\ 1\end{bmatrix}\leq 0,\qquad G\begin{bmatrix}Z(k)\\ 1\end{bmatrix}\leq 0$$

- Which can be transformed to: $W\Delta U(k)\leq w$
- So, we solve constrained optimization problem:

  minimize $\Delta U(k)^T H\Delta U(k)-G^T\Delta U(k)$

  subject to inequality constraint.
- Quadratic programming problem

MPC for water boiler

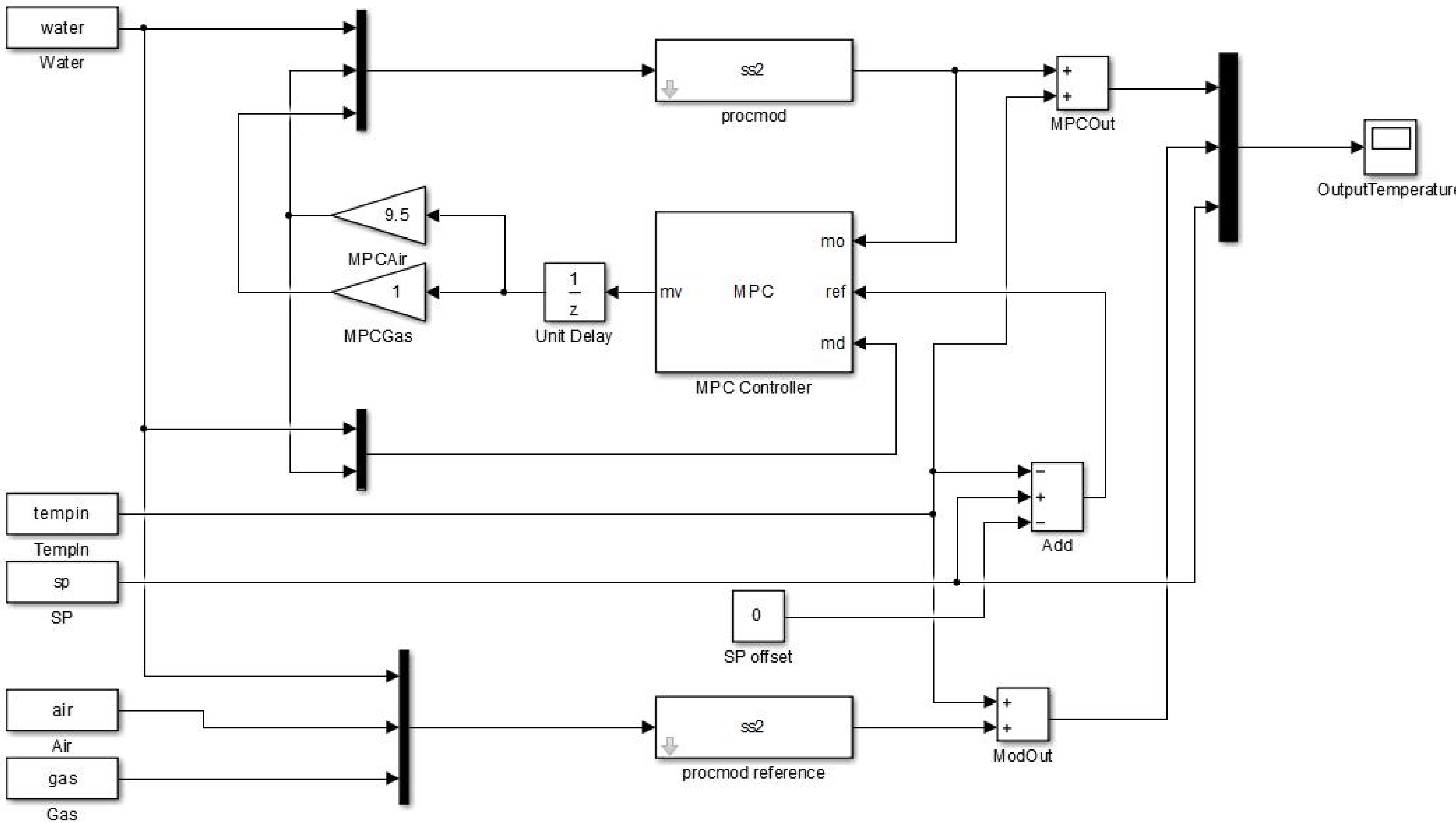
- 1 manipulated process input (gas flow)
- 2 measured process disturbances (water & air flows)
- 1 measured process output

- Prediction horizon 10 steps
- Control horizon 2 steps

- Gas flow constraints (m^3/h):
  min = 0 max = 16000
  max down rate = 2000 max up rate = 2000

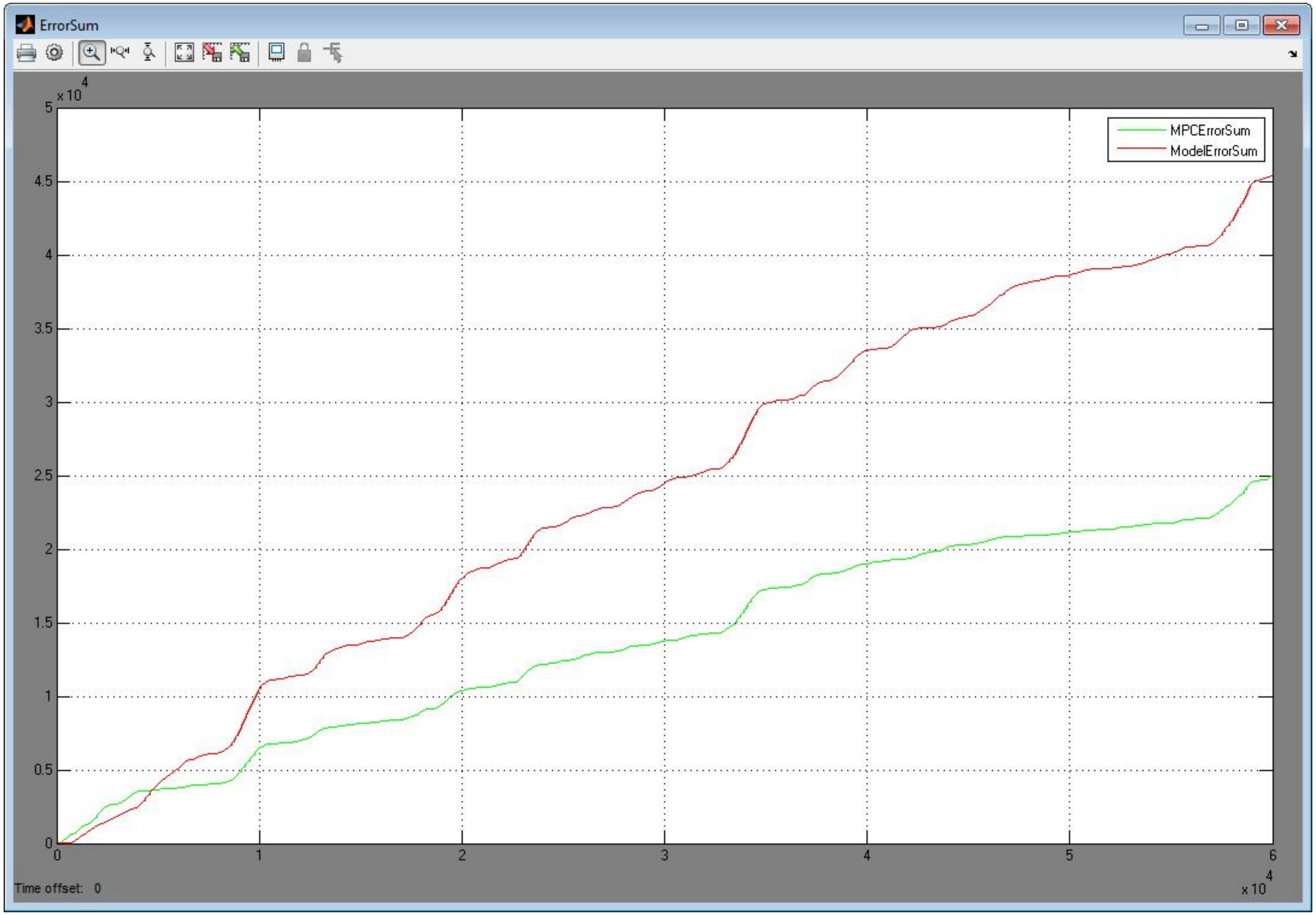
- Gas flow rate weight = 0,01
- Process output weight = 10

MPC for water boiler (Simulink)

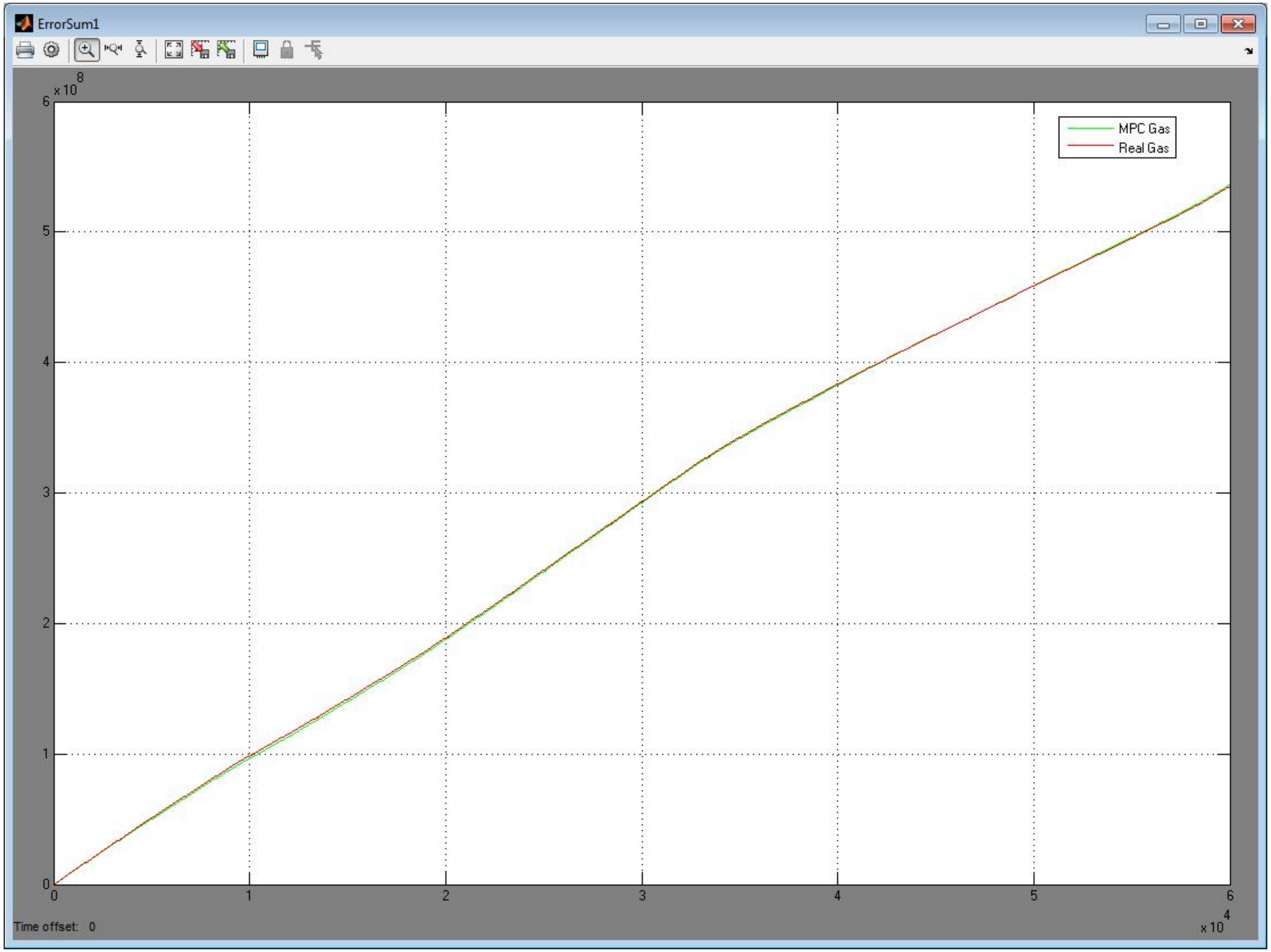


Outputs comparison

Control quality

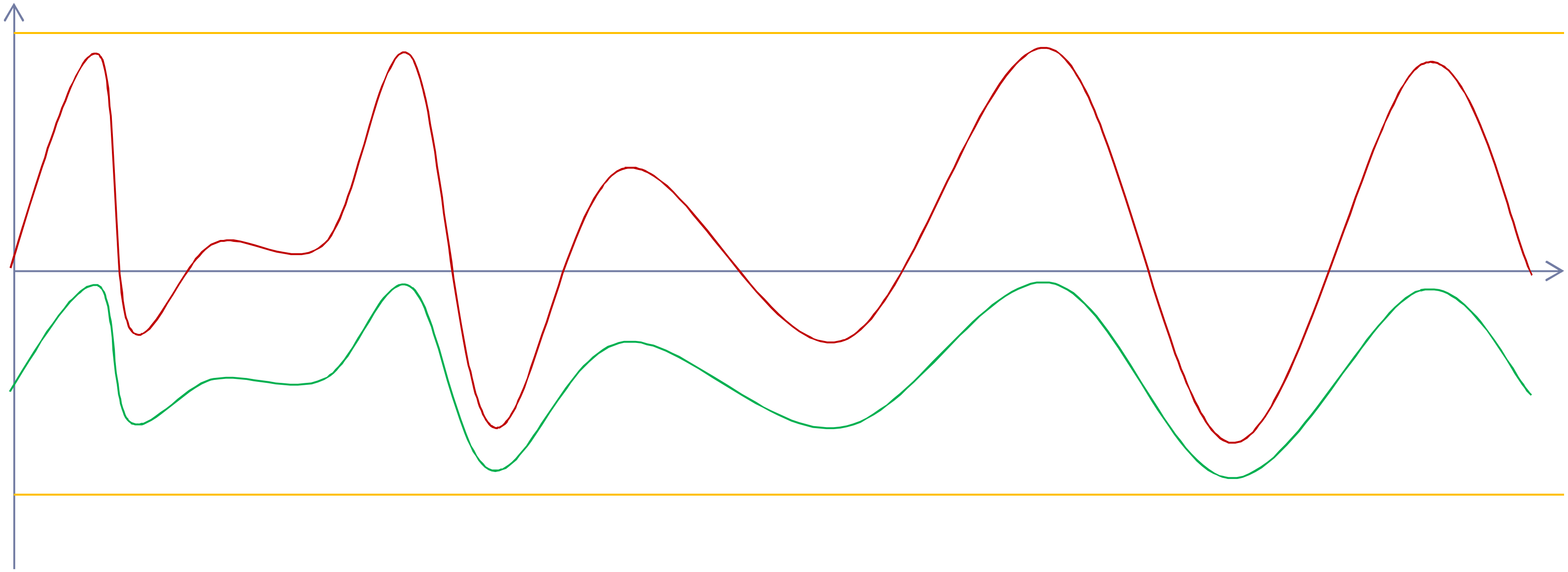


Gas consumption



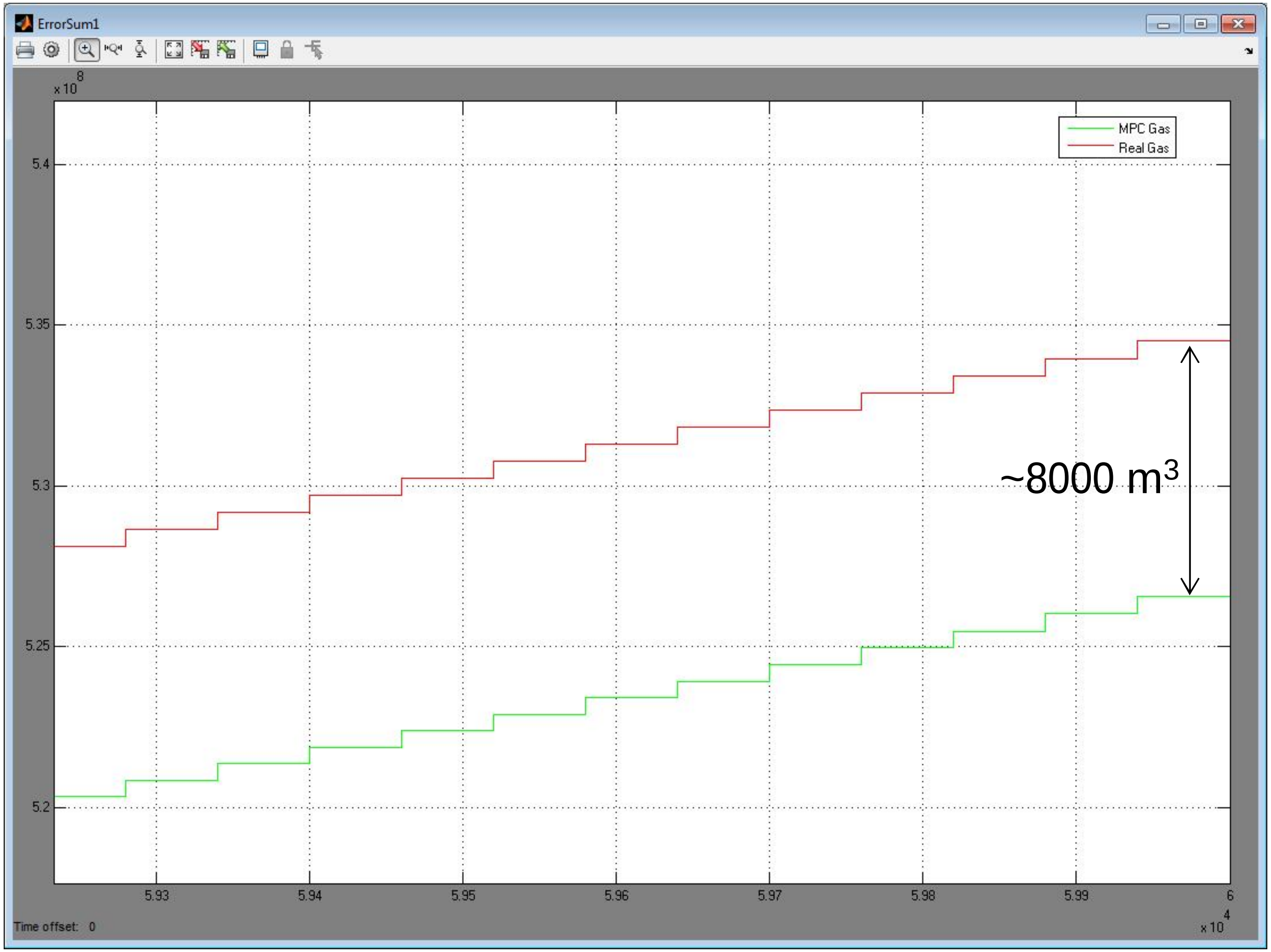
Earn some money

- Same control quality, but less raw materials

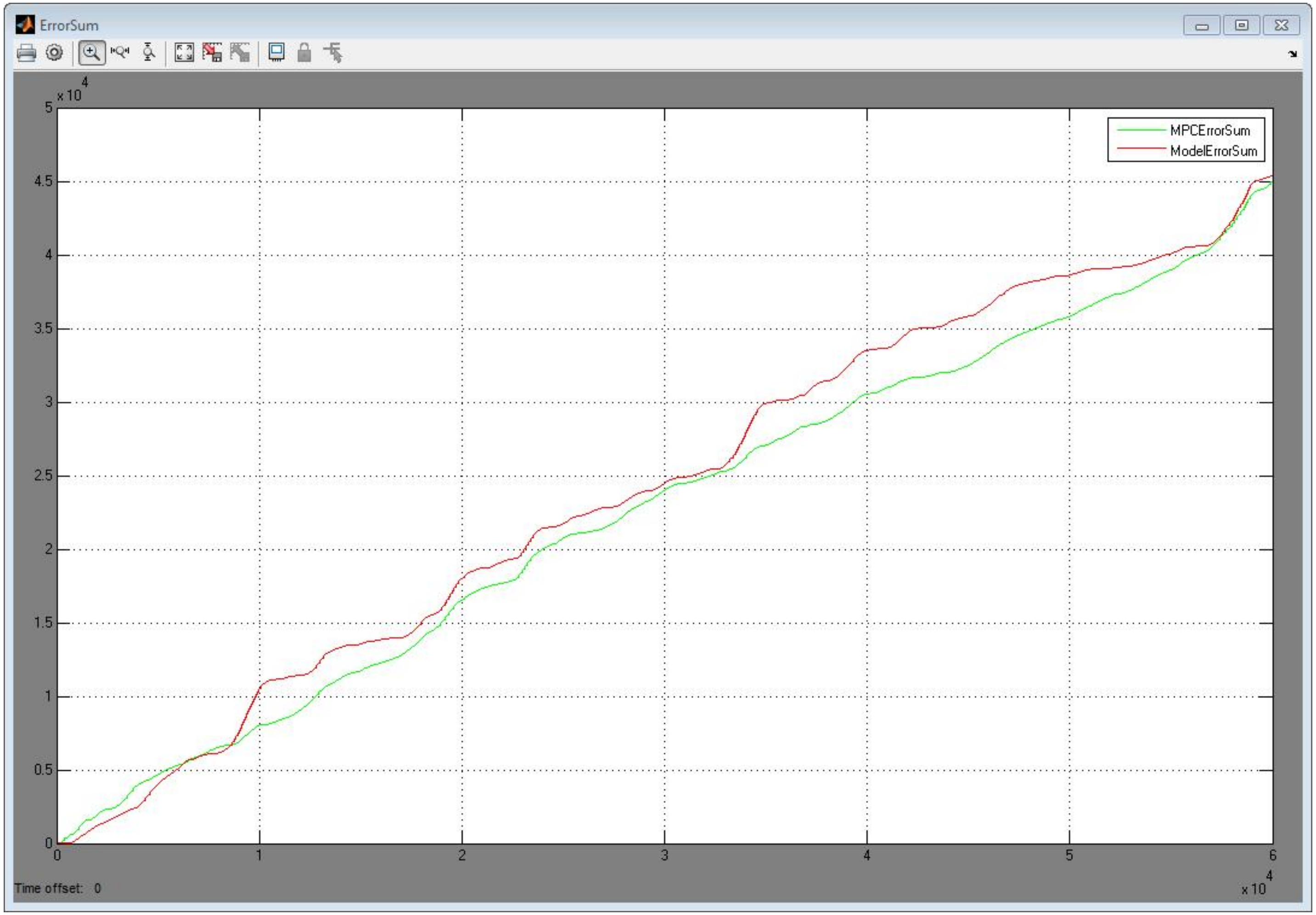


Setpoint decreased 0,6 °C (1)
Output comparison

Setpoint decreased 0,6 °C (2)
Gas consumption difference



Setpoint decreased 0,6 °C (3)
Sum of errors



Very rough estimation

- Gas price 400 € / 1000 m^3
- Difference 8000 m^3
- Period 16 hours
- Season length 50 days

- Economy
- = 50 * (24/16) * 8000 * 400 / 1000
- = 240000 € / season

Some results

- With MPC control became better:
  - Sum of errors of output are twice lower
- MPC with bad model is better than PI cascade
- Raw material consumption is on the same level
- If we change setpoint then we can decrease raw material consumption with the same control quality as PI loops have.

Future plans

- Compare MPC with simulated PI loop
- Minimize raw material consumption with MPC (not setpoint change)
- Find better way of identification
- Identify all parts of the process (including actuators)
- Make model based control closer to reality
- Try controller on real plant some day
- Etc.

References

- Oliver Nelles, *Nonlinear System Identification*, Springer, Berlin, 2001
- J.M.Maciejowski, *Predictive Control with Constraints*, pdf book, 2000
- Real life

Thank you!

Questions???