

# Model-based Boiler Control and Optimization using Soft Sensors in a modern Utility Boiler

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# Introduction

### Why do you focus on combustion and boiler operation?

Because this is where the overall process is least perfect.

There are a number of uncontrolled and unidentified variables that greatly influence combustion performance. These influencing variables include

- mill operating conditions (primary air temperatures, air/fuel ratios, flows, grind, and moisture),
- secondary air non-uniformity (air register settings, forced draft fan bias, and windbox pressure differential),
- coal variability, etc.

*If you can't measure it, you can't control it. If you can't control it, you can't optimize it. We want to close this evident gap.*

### Why is the run for intelligent diagnostics and optimisation?

*It is not just a case of intelligent diagnostics being 'nice to have' for companies, but, nowadays, more a strategic necessity to help stay ahead of the competition.*

### Why is a real time approach to optimisation so important?

*Continuous optimisation permantely finds the best economic and technical trade-offs without ever stopping. It is as effortless as breathing.*

*Make it an arduous exercise and it will be forgotten more than once. Human nature is just too forgiving to aspects of comfort.*

### Is there a noticeable impact and will my investment pay off?

*The solutions we propose pay for themselves in less than a year.*

*Compared to conventional upgrading the capital costs appear negligible.*

*Moreover, the entire process will now seamlessly integrate into any best practices or TQM approach.*

# Achieved benefits

# Benefits quantified

|             |              |
|-------------|--------------|
| Plant       |              |
| Unit size   | 630 MW       |
| Lignite LHV | 10,300 kJ/kg |
| PLF         | 88.5 %       |

|                              |         |
|------------------------------|---------|
| Reference                    |         |
| Coal flow                    | 660 t/h |
| O <sub>2</sub> excess        | 4.0 %   |
| LoI <sub>ref</sub>           | 2.9 %   |
| T <sub>BoilerExit, ref</sub> | 199 °C  |
| η <sub>Boiler, ref</sub>     | 86.66 % |

|                              |               |
|------------------------------|---------------|
| Optimisation                 |               |
| Coal flow                    | 655 - 657 t/h |
| O <sub>2</sub> excess        | 3.2 %         |
| LoI <sub>opt</sub>           | 1.8 %         |
| T <sub>BoilerExit, opt</sub> | 191 °C        |
| η <sub>Boiler, opt</sub>     | 87.10 %       |

| Boiler Efficiency Calculation via ASME PTC 4.1 Method   |  |  |  | Table 13A<br>Combustion Calculations - Btu Method |                               |       |  |
|---|--|--|--|---|-------------------------------|-------|--|
| Data Input Sheet  |  |  |  | FUEL DATA - Coal                                  |                               |       |  |
| Test Description:   |  |  |  | Ultimate Analysis                                 | Theor. Air, Btu/1000 Btu Fuel |       | 17 H <sub>2</sub> O, Btu/1000 Btu Fuel |
| Fuel Data:  |  |  |  | carbon, % by weight                               | 80                            | 11.51 | 824                                    |
| Ash Data:   |  |  |  | ash, % by weight                                  | 8.00                          | 11.51 | 824                                    |
| Moisture in Air   |  |  |  | moisture, % by weight                             | 16.26                         |       |  |
| Additional Moisture   |  |  |  | moisture, % by weight                             | 0.0000                        |       |  |
| NOTES:  |  |  |  | CALCULATIONS, Quantity / 10,000 Btu Fuel Input    |                               |       |  |
| 1. Calculation per ASME PTC 4.1 1964  |  |  |  | [28] = [21] x [15] / [19]                         |                               |       |  |
| 2. Yellow fields indicate user input data.  |  |  |  | [29] = [21] x [15] / [19]                         |                               |       |  |
| 3. Data in white fields is auto-calculated.   |  |  |  | [30] = [21] x [15] / [19]                         |                               |       |  |
| 4. Enter economizer exit O <sub>2</sub> or excess air, whichever is known. Program will assume values less than 10.0% are excess air. |  |  |  | [31] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [32] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [33] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [34] = [21] x [15] / [19]                         |                               |       |  |
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|   |  |  |  | [36] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [37] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [38] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [39] = [21] x [15] / [19]                         |                               |       |  |
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|   |  |  |  | [79] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [80] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [81] = [21] x [15] / [19]                         |                               |       |  |
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|   |  |  |  | [86] = [21] x [15] / [19]                         |                               |       |  |
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|   |  |  |  | [88] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [89] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [90] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [91] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [92] = [21] x [15] / [19]                         |                               |       |  |
|   |  |  |  | [93] = [21] x [15] / [19]                         |                               |       |  |
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|   |  |  |  | [100] = [21] x [15] / [19]                        |                               |       |  |

|                             |               |
|-----------------------------|---------------|
| Savings                     |               |
| Δ Coal p.a.                 | > 23,000 t    |
| Cost per tonne*             | 26 EUR        |
| Annual savings              | ~ 600,000 EUR |
| Δ CO <sub>2</sub> p.a.      | > 27,300 t    |
| CO <sub>2</sub> Certificate | 20 EUR/t      |
| 'Carbon benefit'            | ~ 550,000 EUR |
| Total benefit p.a.          | 1,150,000 EUR |

## Benefits and deliverables

### Benefits ...

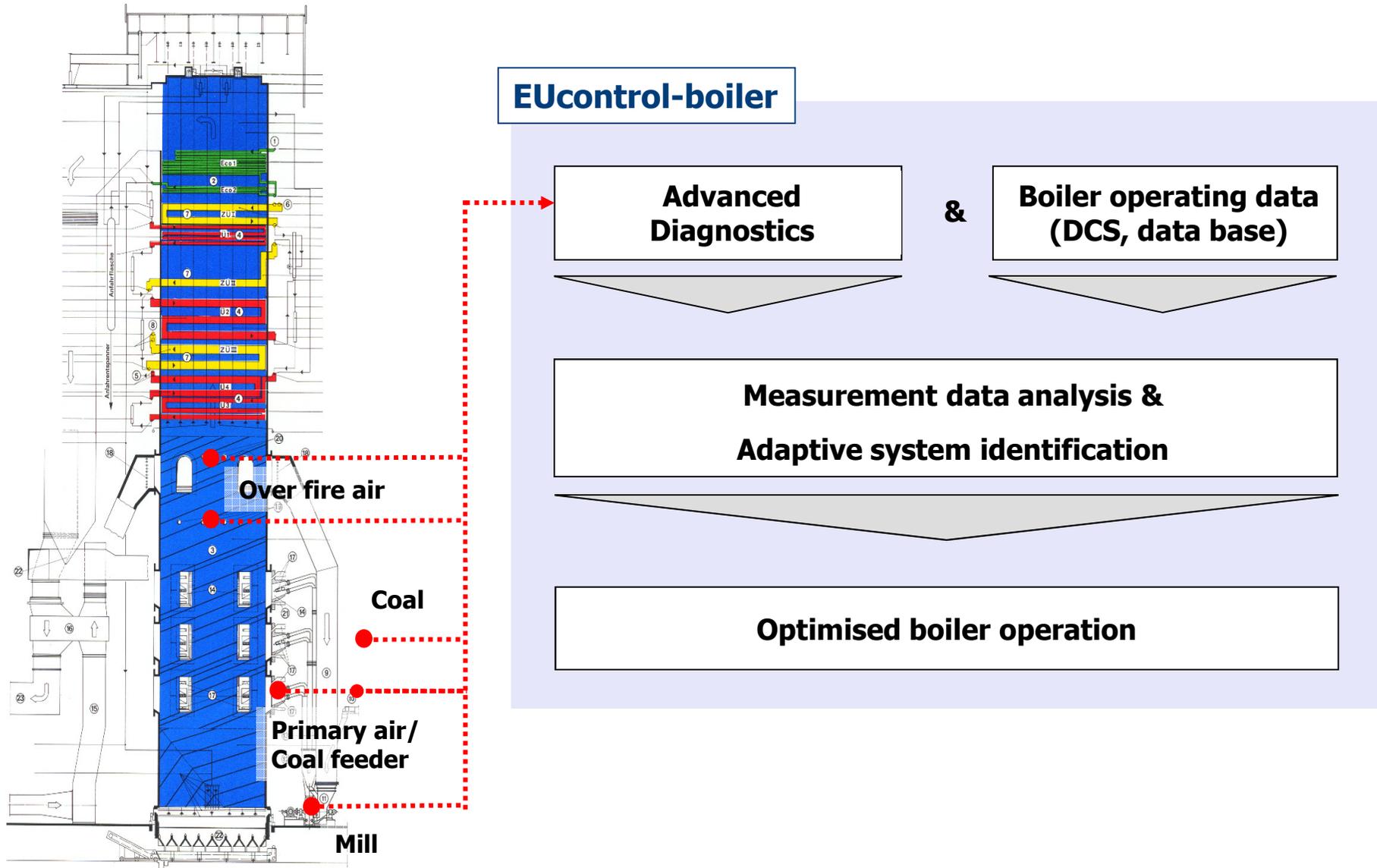
- EUcontrol-boiler is an optimal cost-value ratio option for producing sustained boiler operation under desired conditions (low NO<sub>x</sub>, reduced slagging, high efficiency)
- No modification of plant DCS system required
- Highly adaptive, automatically adjusting to changing situations
- Multivariate target optimisation (low NO<sub>x</sub> AND low fouling AND high efficiency)
- Customisable to individual plant requirements

### ... leading to a new value proposition

- Consideration of different operational objectives (technical, commercial, environmental)
- Offering an attractive means to upgrade older boilers at low cost
- Straightforward implementation at lowest risk (model based)

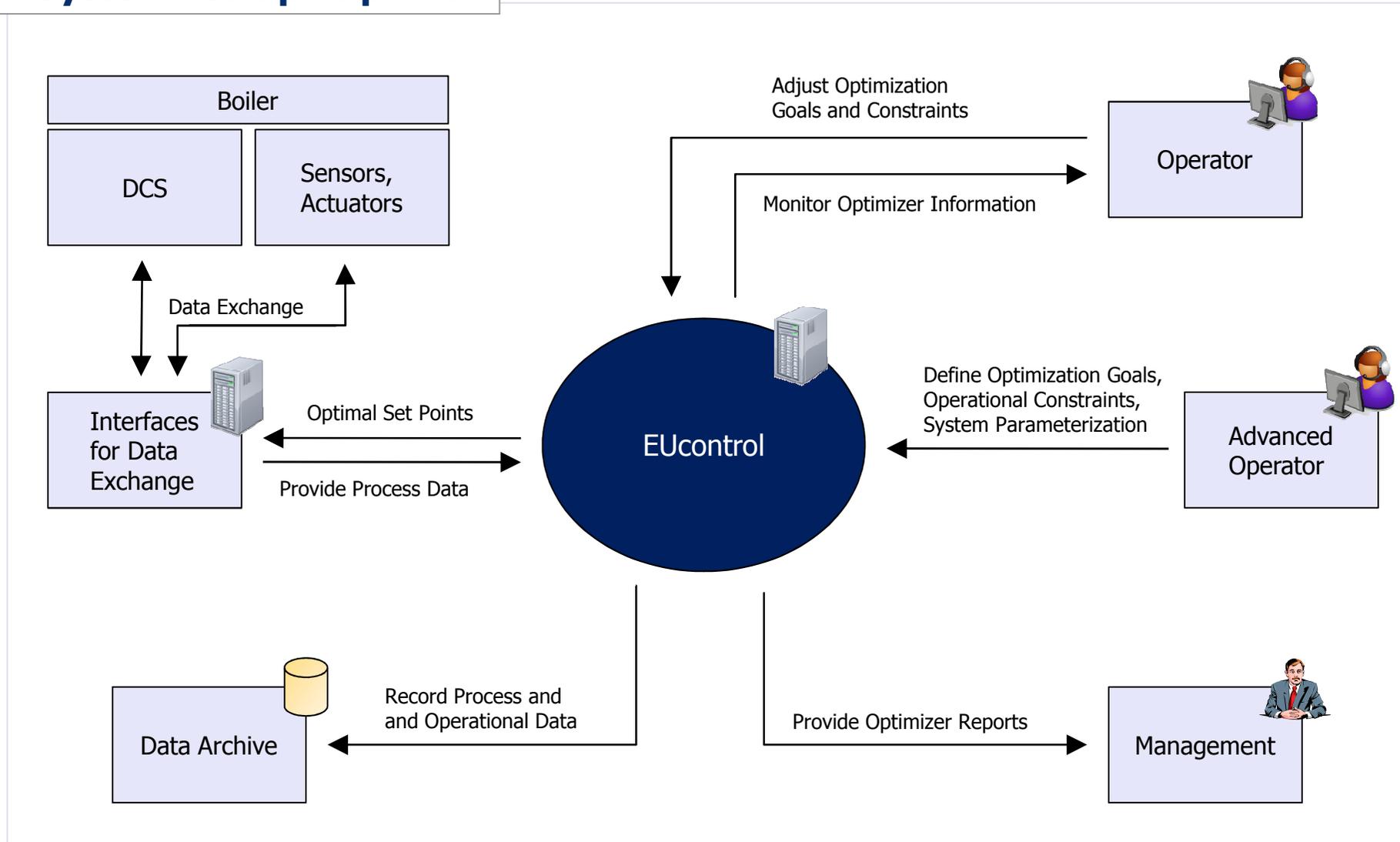
# Model-based control and optimization

# Integrated boiler management

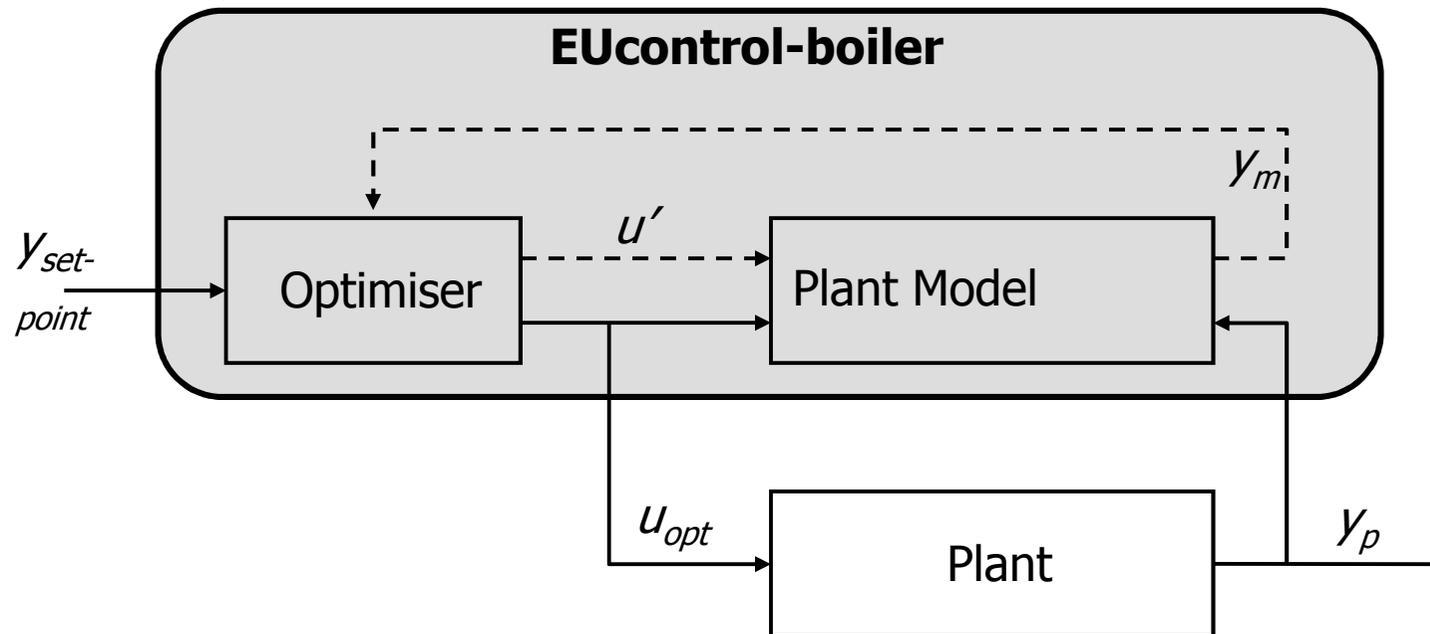


# Optimization suite EUcontrol

## System set-up at plant



## Structure of EUcontrol-boiler



The plant behaviour is predicted with an (identified) process model. An optimiser calculates the best possible combination of inputs.

Hard and soft constraints can be equally considered. Preferential adjustment of set-points is possible if the degree of freedom is sufficient.

## Data structure

### Plant model

#### INPUT (u)

##### 1. Manipulated variables

- Primary air (1...8)
- Coal hopper (1...8)
- $\Sigma$  Secondary air
- OFA 1
- OFA 2
- O<sub>2</sub> Excess

##### 2. Measured (dist.)

- Output power
- Soot blowers

##### 3. Unmeasured (dist.)

- Coal quality

#### Plant model (Boiler)

##### 4. Constraints

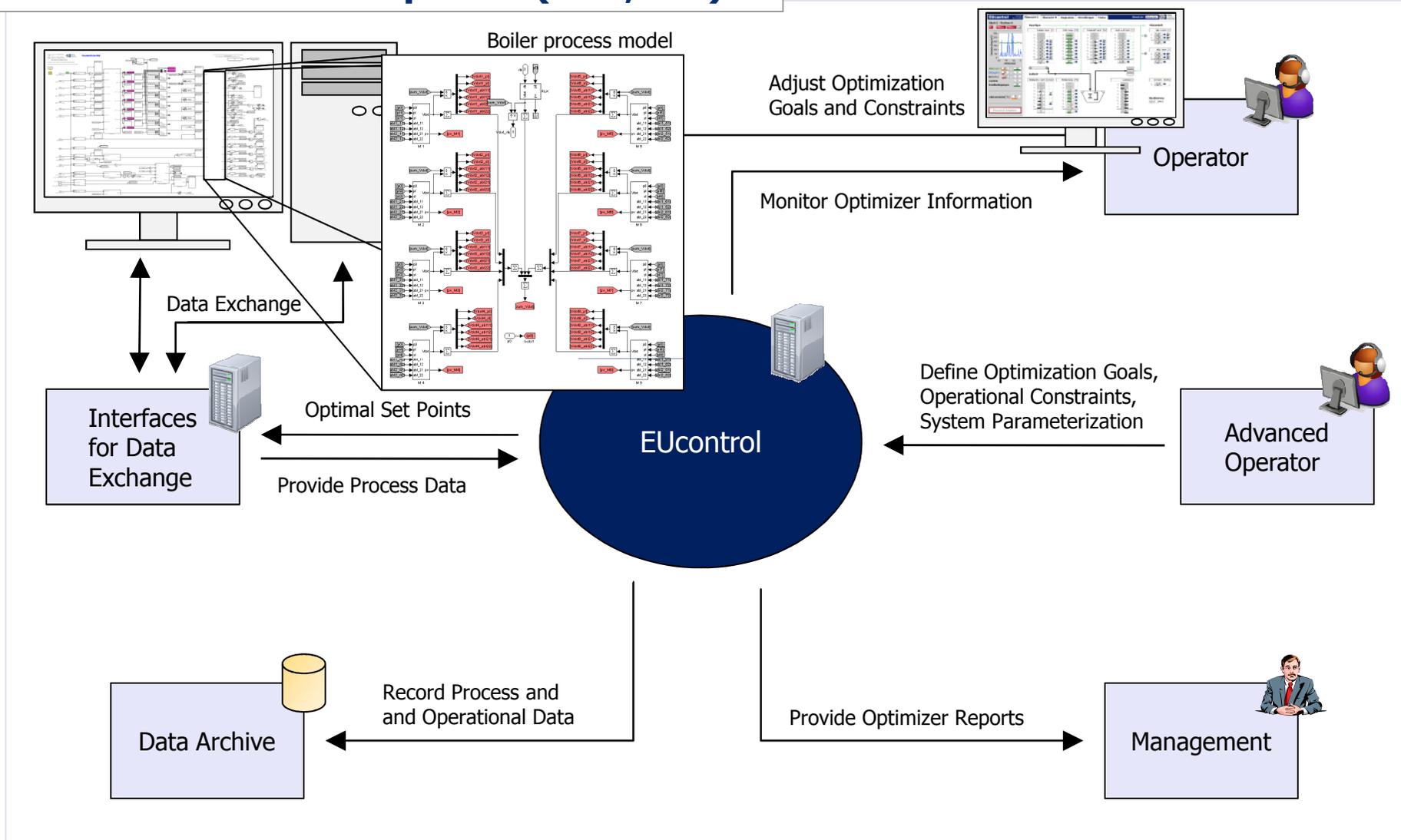
- FD fan pressure drop
- Mill temperature
- Mill arrangement

#### OUTPUT (y)

- NO<sub>x</sub>
- T<sub>FEGT</sub>
- CO
- $\eta$
- $\perp\sigma_T$
- T<sub>Mill</sub> (1...8)

# Optimization suite EUcontrol

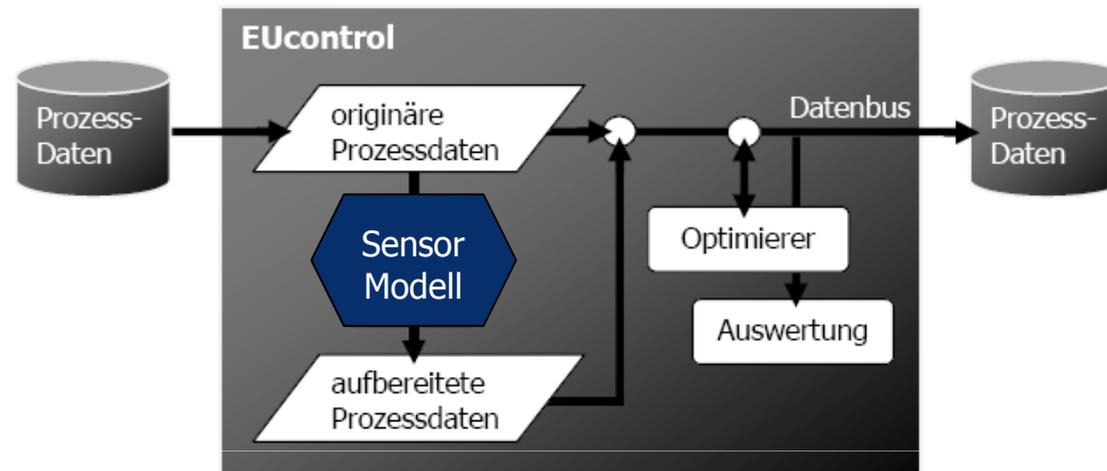
## Model-based development (RCP, HiL)



# Soft sensors

## Soft Sensors in EUcontrol

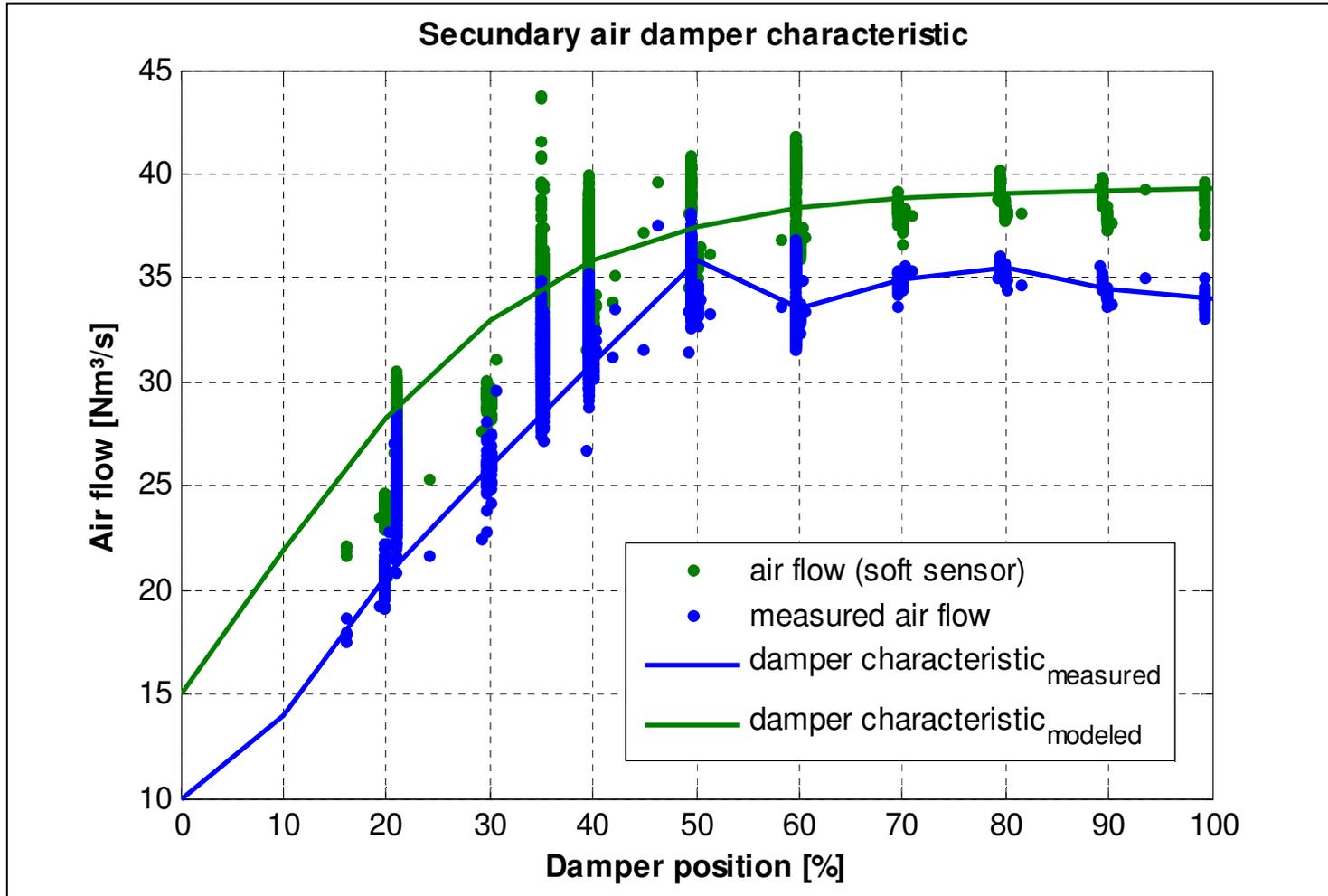
### Flow diagram EUcontrol



### Advantages

- Reduced measuring hardware requirement
- Inherent sensor validation, fault detection and diagnostics
- Provision of real-time data for advanced control requirements
- Allowing straightforward what-if analysis

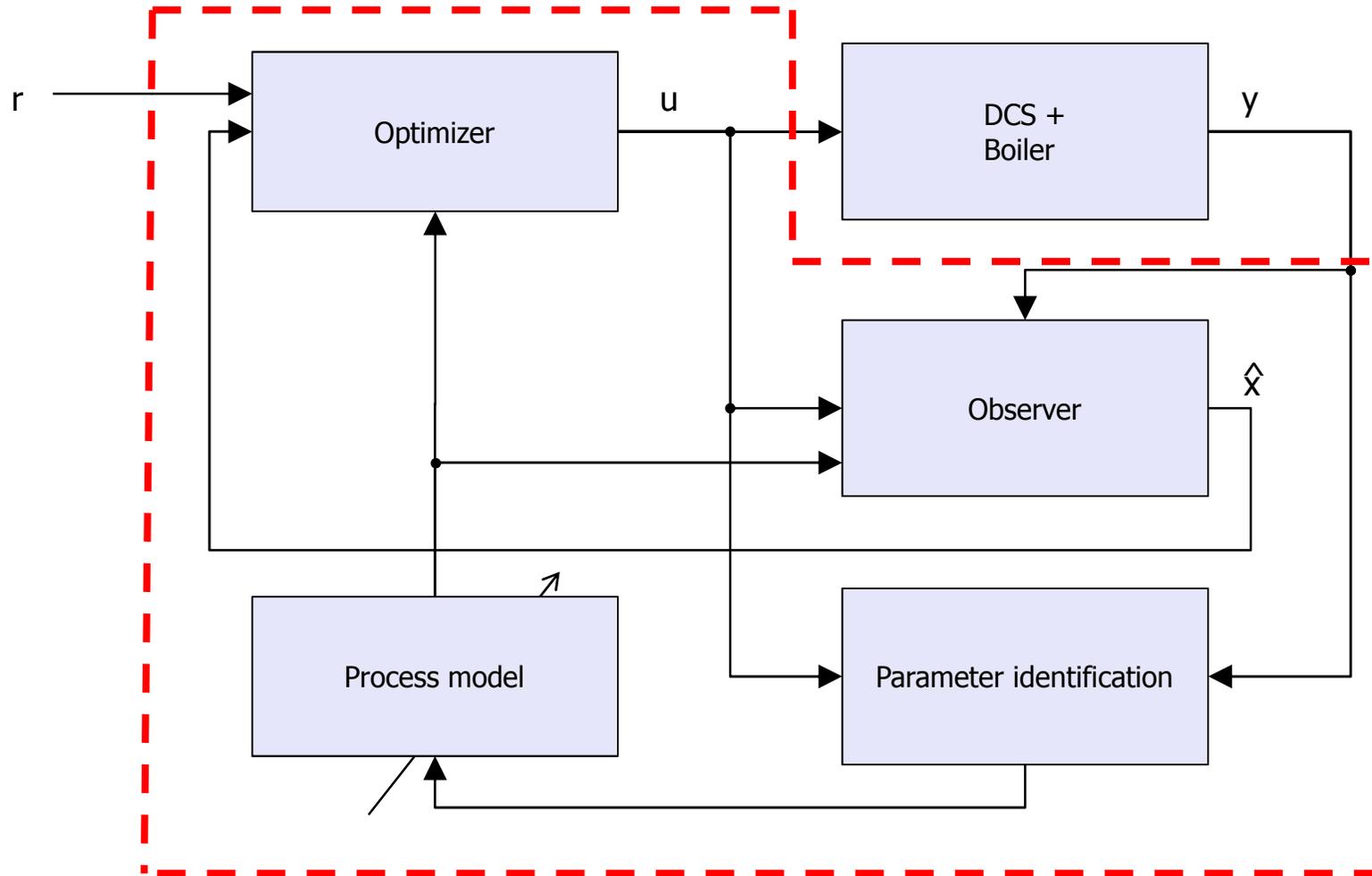
## Secondary air flow „measurement“ using soft sensor



# Model predictive control

# Model predictive control

## MPC with adaptiv process model

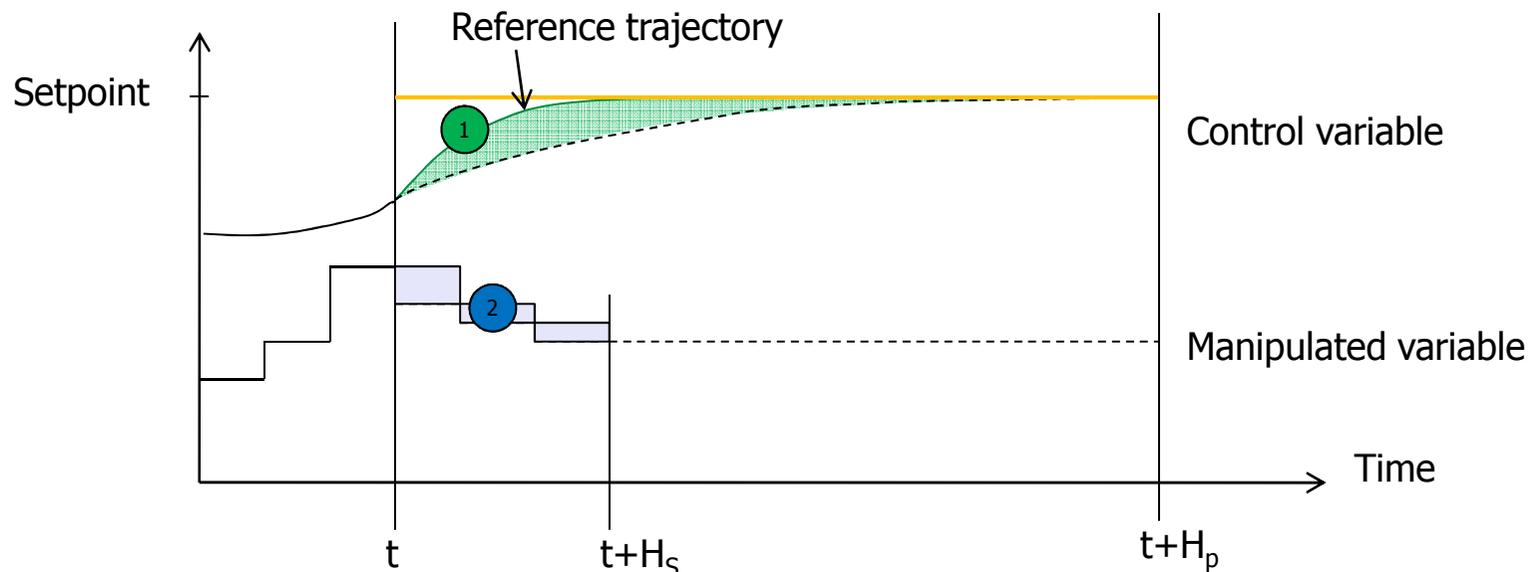


## Model predictive control

### Strategy

- Prediction horizon  $H_p$
- Control horizon  $H_s$
- Optimization of control action within control horizon under consideration of system development within prediction horizon resp. cost function:

$$I = \sum_{H_p} \sum_{Ziele} w_{1,i} (y_i - r_i)^2 + \sum_{MV} w_{2,i} (\Delta u_i)^2 + \sum_{MV} w_{3,i} (u_i - r_u)^2 + \sum_{RB} w_{4,i} (\max(y_i - M_i, 0))^2$$



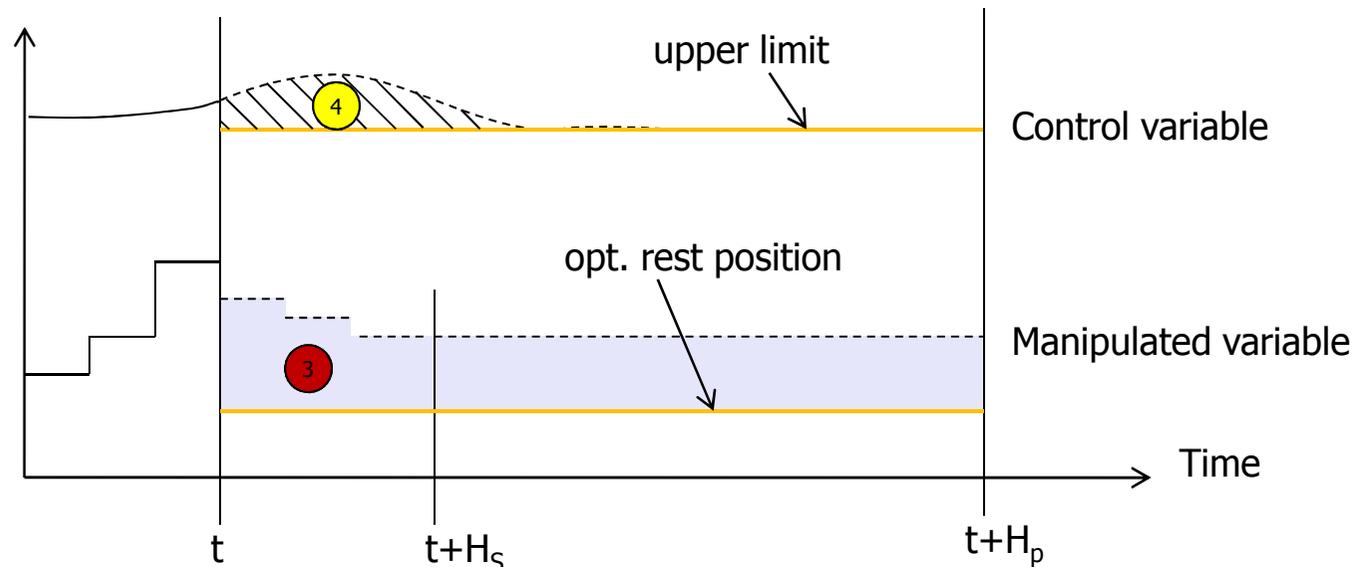
## Model predictive control

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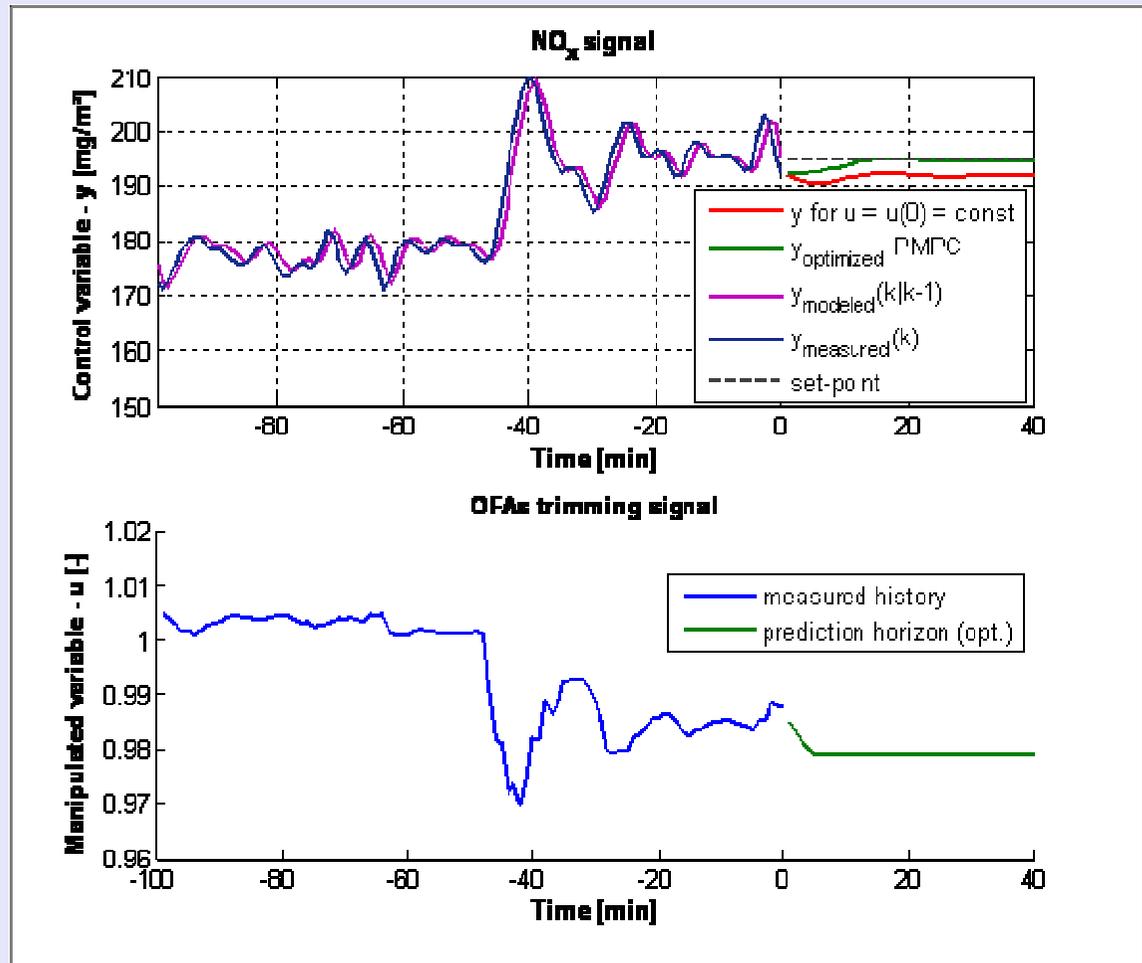
1      2      3      4



## Model predictive control

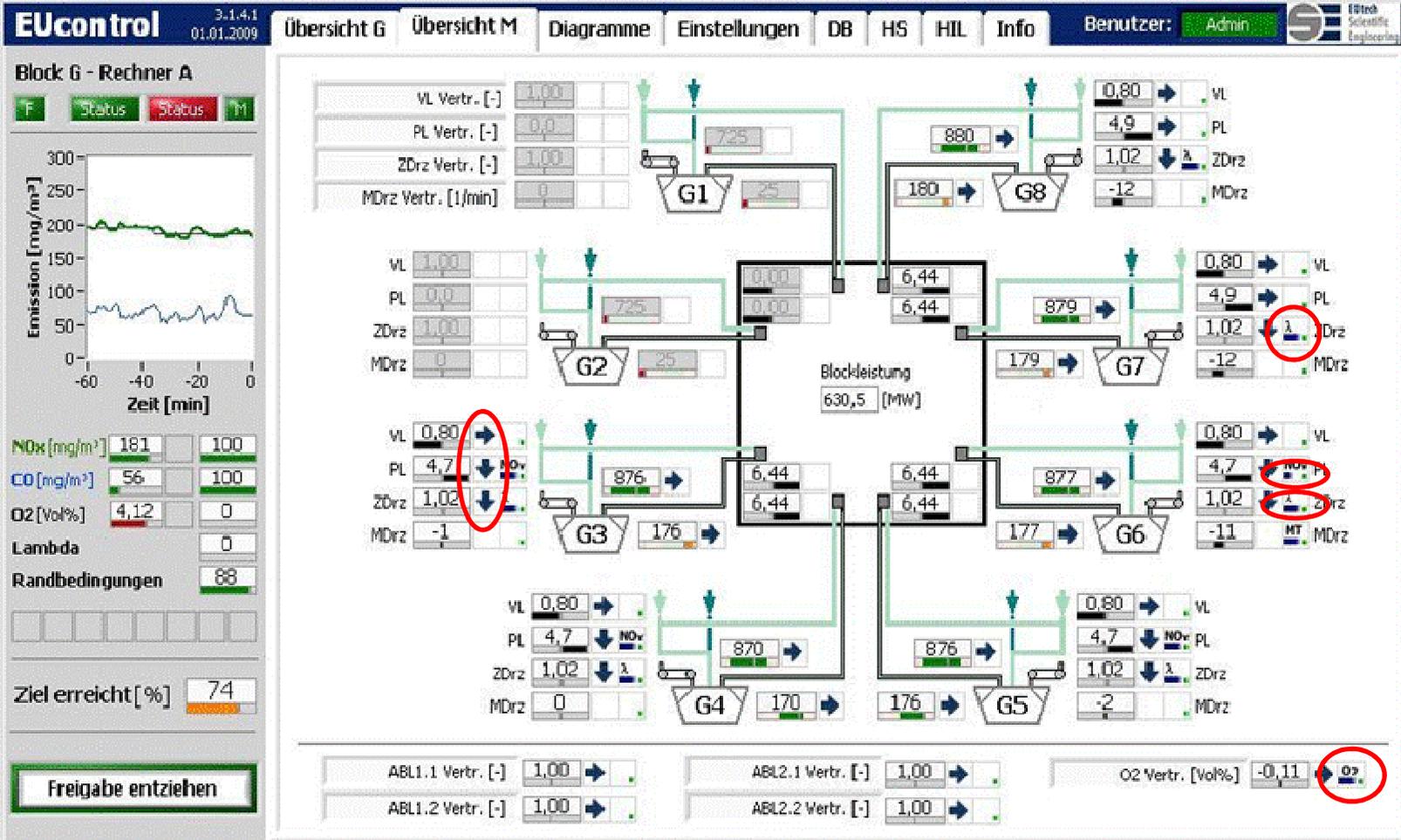
### Real time visualization

- Visualization of
  - Historical data
  - Prediction horizon
  - Target values



**Predicted effect on the control variable (green line) as opposed to unmanipulated operation (red line)**

## Controls at fingertips



**EUcontrol** 3-1.4.1 01.01.2009

Übersicht G Übersicht M Diagramme Einstellungen DB HS HIL Info Benutzer: Admin

**Block G - Rechner A**

F Status Status M

Emission [mg/m<sup>3</sup>]

Zeit [min]

NOx [mg/m<sup>3</sup>] 181 100

CO [mg/m<sup>3</sup>] 56 100

O2 [Vol%] 4,12 0

Lambda

Randbedingungen 88

Ziel erreicht [%] 74

Freigabe entziehen

VL Vertr. [-] 1,00

PL Vertr. [-] 0,0

ZDrz Vertr. [-] 1,00

MDrz Vertr. [1/min] 0

VL 0,80

PL 4,7

ZDrz 1,02

MDrz -1

Blockleistung 630,5 [MW]

VL 0,80

PL 4,9

ZDrz 1,02

MDrz -12

VL 0,80

PL 4,7

ZDrz 1,02

MDrz -11

VL 0,80

PL 4,7

ZDrz 1,02

MDrz -2

ABL1.1 Vertr. [-] 1,00

ABL1.2 Vertr. [-] 1,00

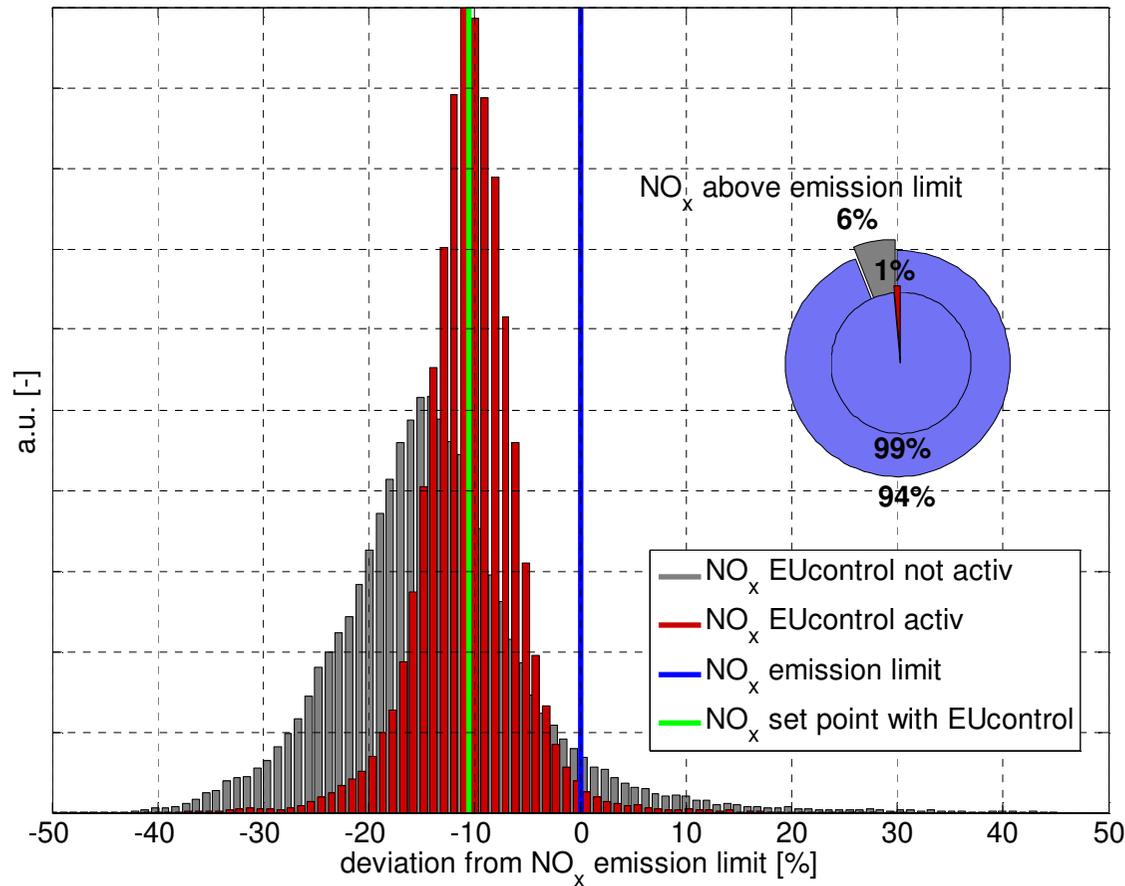
ABL2.1 Vertr. [-] 1,00

ABL2.2 Vertr. [-] 1,00

O2 Vertr. [Vol%] -0,11

# Results

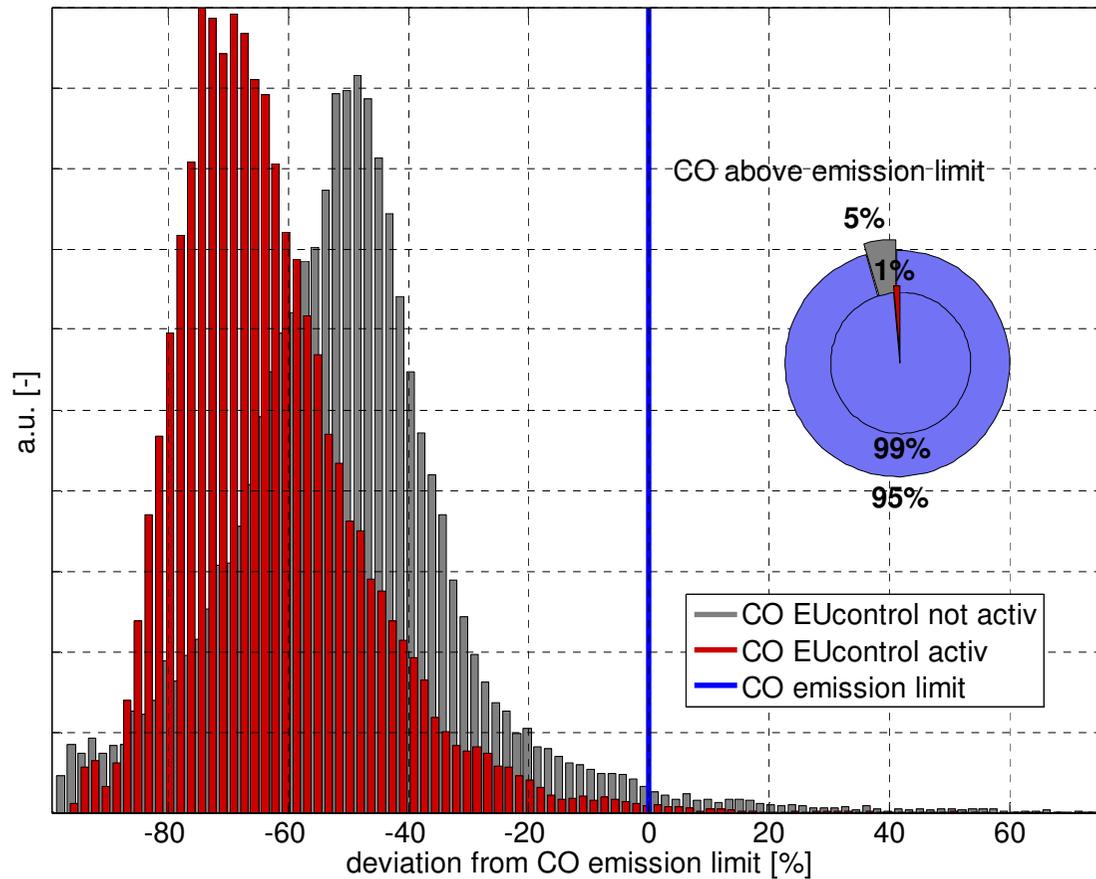
## Result of optimised settings (optimisation goal)



- NO<sub>x</sub> control
- Significant improvement of operation conditions while reducing slagging and fouling

## Optimisation - results

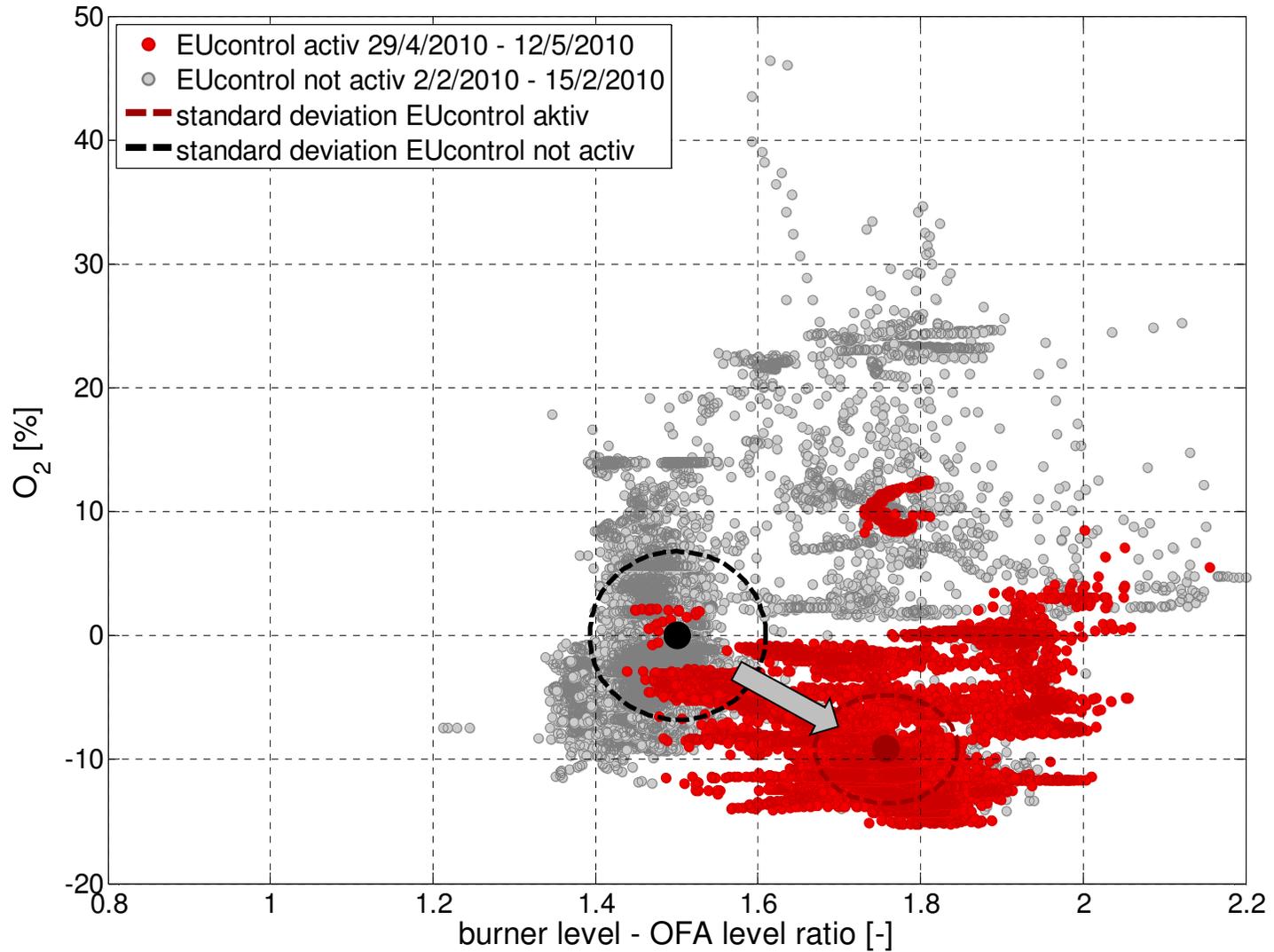
### Result of optimised settings (optimisation goal)



- CO control
- Significant improvement of combustion quality

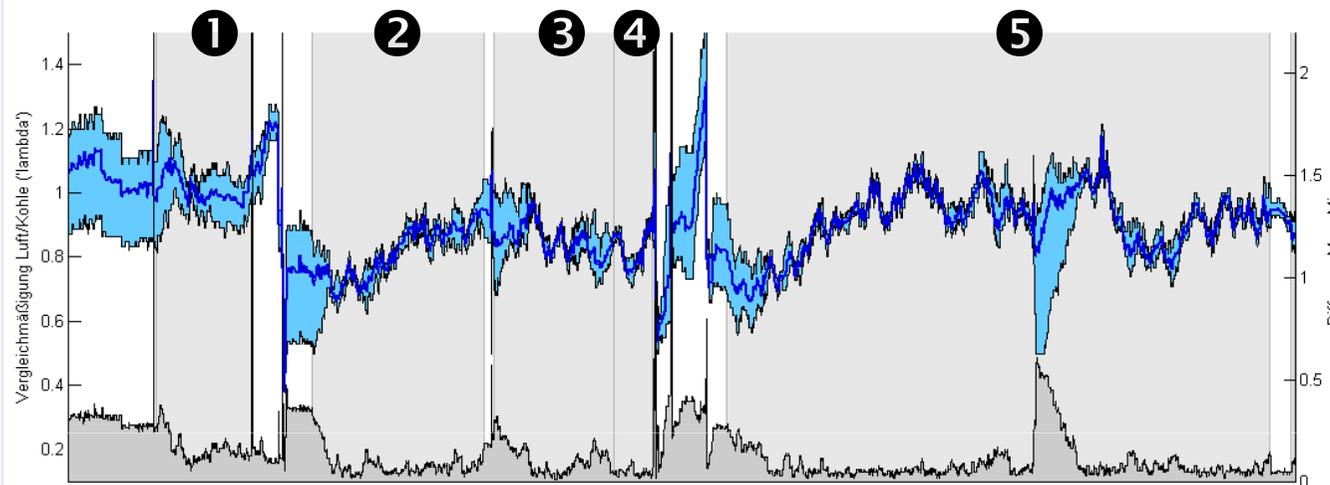
# Optimisation: $\lambda$ operating mode

## Enhance boiler operation - O<sub>2</sub> and air-fuel ratio



# Optimisation: Fuel-air staging mode

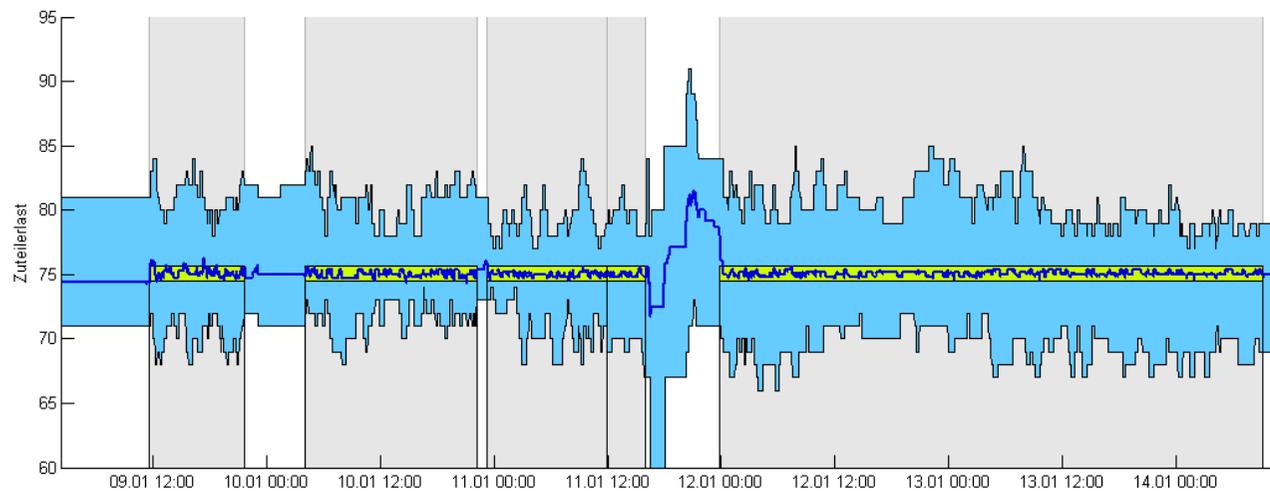
## Process stabilization



Active optimizer  
Limit values

### Air/fuel ratio 'lambda'

- Range of all active mills
- Average
- Diff. Max, Min

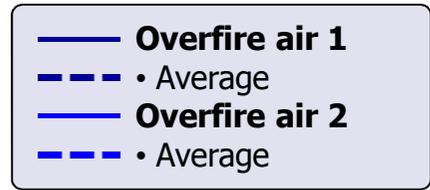
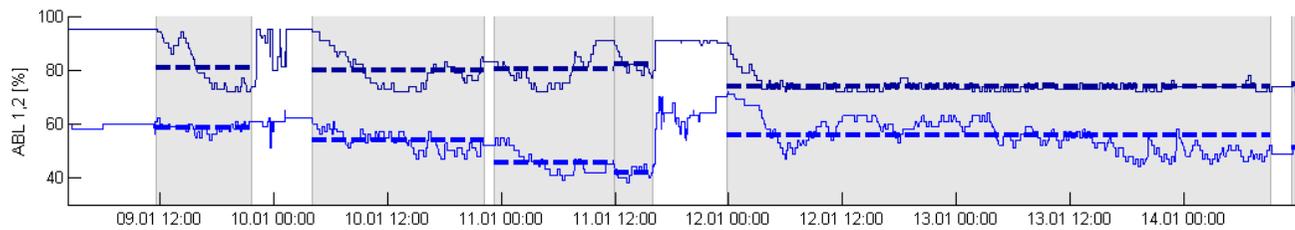
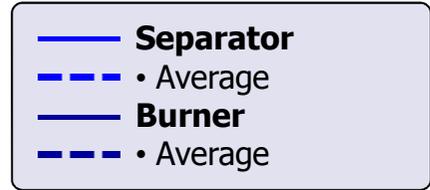
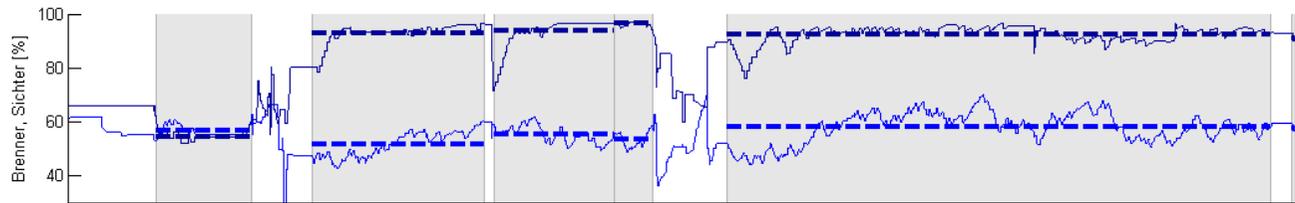
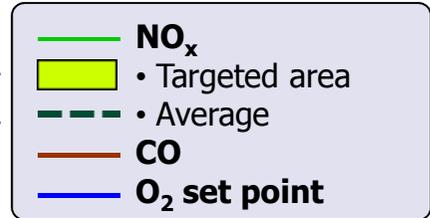
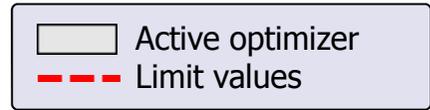
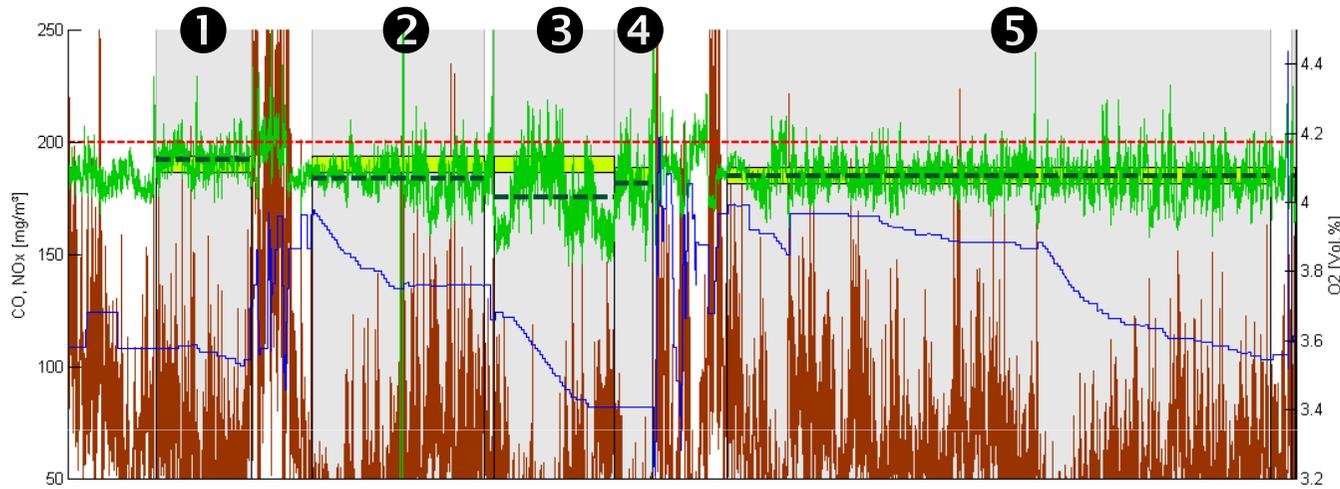


### Hopper speed

- Range of all active mills
- Targeted area
- Average

# Optimisation: $\lambda$ operating mode

**Improve NO<sub>x</sub>, CO, O<sub>2</sub> and damper positions**



### Steps to success...

- Site familiarisation and review of existing plant equipment
- Identify performance objectives
- Identify additional equipment requirements
- Review of available data and data quality
- System identification using available data
- Combustion parametric testing using Design of Experiments
- Build prediction models for control/optimisation
- Build process/plant model for model-in-the loop testing (hardware-in-the loop)
- Operate in advisory mode
- Extend to closed loop

**Typical project time is 4 – 5 months**

# Summary

## Summary

### Benefits

- Improved efficiency (0.3 to 1%)
- Reduced O<sub>2</sub> (- 5 to - 10%)
- Reduced NO<sub>x</sub> and CO emissions (- 5 to - 15%)
- Reduce slagging and fouling, limit soot blower operation
- Reduced LoI
- Less material stress in furnace due to more even temperature distribution

# Thank you for your attention

For more information, please visit us at booth G100