Optimizing Combustion using State-of-the-Art Model Predictive Control Strategies

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Introduction

The overall performance and availability of a fossil-fired thermal power plant is predominantly affected by the steam generating unit and the combustion process. Even though conventional plant control systems ensure a safe and reliable operation, they do not rigorously optimize boiler operations or take care of special combustion problems. Not to mention that much of the information gathered by modern IT systems and advanced monitoring equipment remains untapped. Thus, many plant operators decide to unearth these "hidden reserves" by way of software driven intelligent add-on technologies supported by advanced measurement diagnostics.

This article not only illustrates the achievable benefits of an advanced real-time boiler optimization solution but also touches on the decision making and implementation process.

Model predictive control

Boiler operation is determined by dynamic behavior and transient incidents (load ramps, coal quality, component deterioration etc.) so that a true optimization requires dynamic management and control of the manipulated variables. EUcontrol is a dedicated model-based boiler optimization system based on adaptive, multi-variable model predictive control strategies and centered on a physical boiler model (Physical Model Predictive Control). It provides real-time optimization of the complex boiler operation and combustion (Figure 1). Using this physical understanding of the process, it differs from the numerous purely numerically driven black-box system identification approaches.

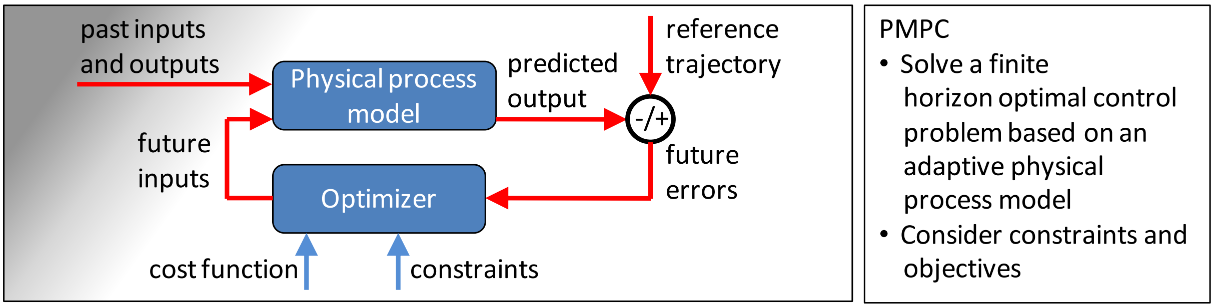

Figure 1: Principle structure of a Physical Model Predictive Controller (PMPC)

Dynamic process models represent the relationship between independent variables (model inputs) and dependent variables (model outputs). The inputs include the manipulated variables (MV), e.g. damper settings, feeder speeds as well as measured, e.g. the current load, and unmeasured, e.g. coal quality, disturbances. The models predict future outputs based on the past and calculated future values of the input variables, while the physically motivated structure of the models enforces signal causality and always leads to reasonable physical solutions. The approach thus uses explicit *and* implicit knowledge of the process dynamic behavior and considers all the interactions between the involved process variables. Thereby many hard and soft constraints with complex interactions must be taken care of. The optimizer rigorously reduces operational variance and shifts the operating point close to the optimum.

Optimization is based on a multi-criteria objective formulation. A cost function incorporates and consolidates the different and often conflicting requirements/objectives by weight functions. Thereby the modular structure of the software allows for flexible and easy integration of additional objectives and constraints that may become important in the future and need to be incorporated. EUcontrol works as a set-point optimizer – an ensemble of process models incorporates and combines customer specific objectives with their individual weight functions with the various applicable constraints. The actual optimizer then adjusts the model inputs (the set-points) such that an overall optimum in terms of a weighted cost function is attained.

Periodic predictions and set-point/bias changes are calculated faster than the response time of the plant hardware including the combustion process and enable real time optimization. The optimized set-point differentials are fed into the plant DCS system – either manually in advisory mode or automatically in closed-loop mode. A direct interference with the existing plant DCS is avoided and potentially conflicting actuator settings can definitely be ruled out.

One significant advantage of the chosen approach is its ability to dynamically handle process noise, process variability, and process drift over time, including significant process control changes, such as fuel type, or boiler draft configuration. The optimizer automatically adapts to changing plant conditions by continuous online re-tuning, as required by operating conditions and discerned by the model confidence intervals. This on-line adaptivity ensures that the control system not only does the right thing, but also that the models accurately reflect the generating unit's actual operating conditions, deal with instrumentation drift and recalibration, disturbance rejection, model mismatch, equipment performance degradation and maintenance (Figure 2). This approach provides continual, automated improvements to boiler control.

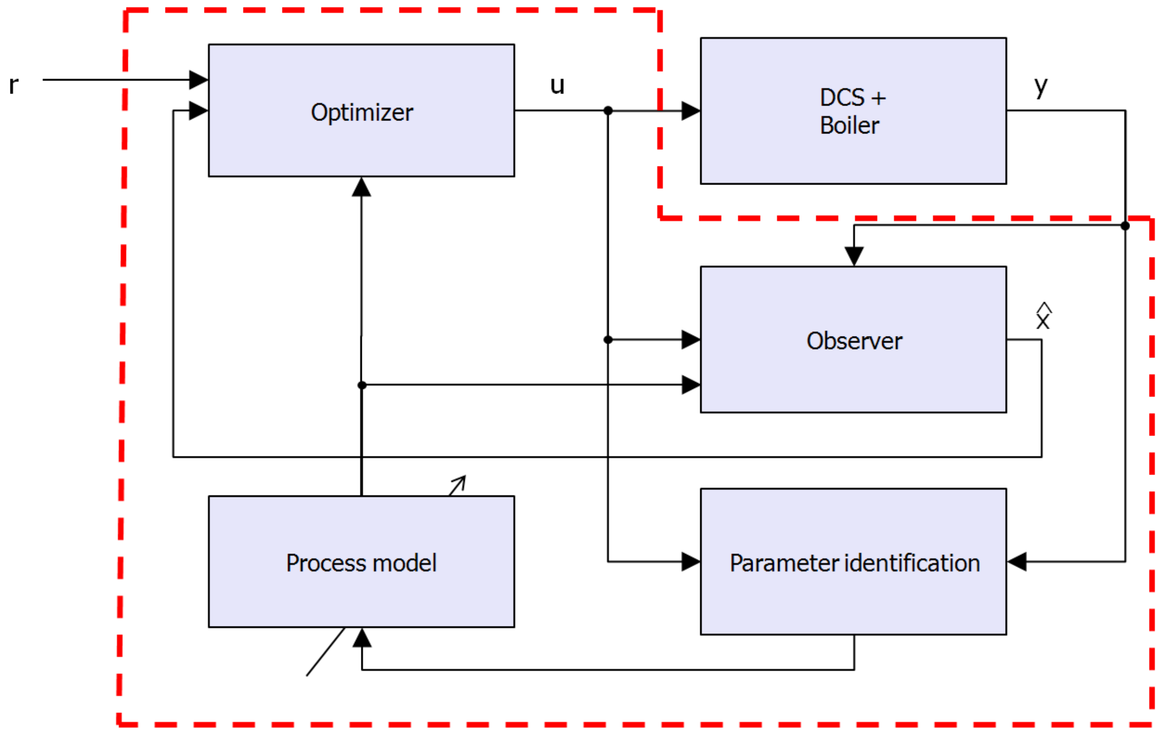

Figure 2: MPC with adaptive process model

First steps to prepare the project

Often, a project is touched off by the need to redress some known and particular operational short-coming, rather than by a vague and indistinctive desire for improvement. In many such cases the solution will have to be custom tailored to the problem, and a "one-fits-all" approach is failure prone. Compared to hardware-based alternatives or physical retrofits, software based solutions preserve existing assets, require significantly lower capital expenditure and have a much lower installation lead time while offering high flexibility. Although offering a very attractive cost-value ratio, the willingness to engage in an optimization project will depend on the level of confidence that can be established in advance. To this end a rigorous model-based pre-evaluation is carried through, in which *available* plant data is used to design and calibrate a physical model of the plant. The plant model is then used to analyze and assess the expected outcome of the proposed installation within acceptable confidence levels. With the help of a plant model, we see that the reduction is very substantial. Further findings are also very important in that:

- modeling and predicting NOx and CO is possible, accurate and reproducible,
- key variables for controlling NOx are excess-O2 and the air-distribution,
- the sensitivity of the parameters appears to be in line with theory,
- the optimization approach can be verified,

- the controller is robust and
- there is substantial room for optimization.

Project start

After the preliminary investigation corroborates the financial and technical feasibility – which it usually does – the next step is to formulate detailed requirement specifications. Thereby not only functional aspects are considered but also system handling, operator requirements and training, trouble-shooting, upgrading flexibility and maintenance. Also, it is helpful to discuss possible limitations of the proposed solution. With the help of established guidelines these otherwise tedious steps can be easily taken. Thereafter, the technical situation and boiler operation will be appraised, covering

- available and required plant equipment (sensors, actors)
- boiler set up and combustion,
- control loop structure,
- data availability and accessibility,
- communication (DCS) interfaces and DCS structure,

to name a few. The appraisal is done on-site by a dedicated team of qualified engineers. Available data is analyzed, P&I schemes are studied, and control loops are analyzed.

Good models require high quality data. Also, the relevant data must be gathered online with a reasonable time resolution. From experience, a 10 – 60 sec. sample time will work depending on the particular objectives and system dynamics. Statistical procedures are then applied to ensure consistent data quality (filtering, outlier detection, interpolation of missing data, correlation analysis, causality chain, data aggregation etc.).

Input data

In some cases, the performance of the optimizer may be significantly enhanced by extending or improving the available measurement data base in the plant by advanced diagnostics. A good example is the accurate measurement of the two-dimensional temperature distribution at the furnace exit by an array of optical pyrometers. This straightforward information can be used to centre the flame ball. Moreover it helps to identify the optimal trade-off between the flame ball position and the amount of spray water injected for balancing the main-steam temperature at the exit of the superheater and reheater. Spray water injection has a negative impact on the heat rate and as such it should be minimized. But to what extent? Certainly not to the extent of completely displacing the flame position to compensate for the temperature differences, as this may cause other adverse effects.

In other cases the installed measurement technology may prove unreliable. With sufficient data redundancy in place, a soft or virtual sensor may be constructed which uses reliable data as an input to a model and has as its output the desired sensor information to supplement or replace the unreliable original sensor readings. Figure 3 shows the example of a flue gas temperature sensor that is replaced by a smart sensor model with sufficient accuracy and much higher reliability. This approach is again motivated by the desire to maintain physical causality and plausibility.

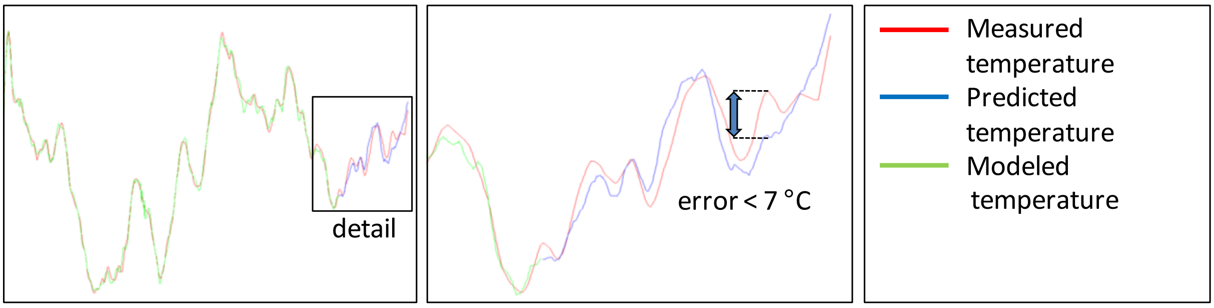

Figure 3: Temperature prediction over 4h using a soft sensor based on redundant process data

Physical plant modeling

The design process can be substantially facilitated by using Model-based Design methods, especially if these offer Rapid Control Prototyping and Hardware-in-the-Loop (HiL) capabilities. For most engineers, working with a model of a physical system provides a convenient way to experiment with various design and control ideas.

The engineer first develops the plant model with the available data and then designs the optimizer/control system in an offline environment. The philosophy is simple and straightforward:

1. First build/adapt a dynamic plant or boiler model, then simulate, analyze and calibrate the model.
2. Design the system control and optimization strategy and test it against the plant model.
3. Transfer the code from the host PC to the control target.
4. Validate the system by using rapid prototyping or hardware-in-the-loop simulation.

The communication device drivers are part of the model. HiL simulation enables embedded software testing at an early stage against a real-time dynamic boiler model, where corrective action is simple and easy, without the expense, risk or impracticality associated with a test at the real plant. By using suitable enabling technologies that offer a fully integrated end-to-end design environment, the development effort is substantially reduced.

Integration of MPC

The optimizer connects to any underlying automation system via a standard OPC protocol. If required proprietary DCS communication protocols can also be addressed. In a typical configuration as it is depicted in Figure 4, the communication is fed through a data base server, which in turn reads data and sends control commands to the underlying automation system or DCS. Hardware and software redundancy is established.

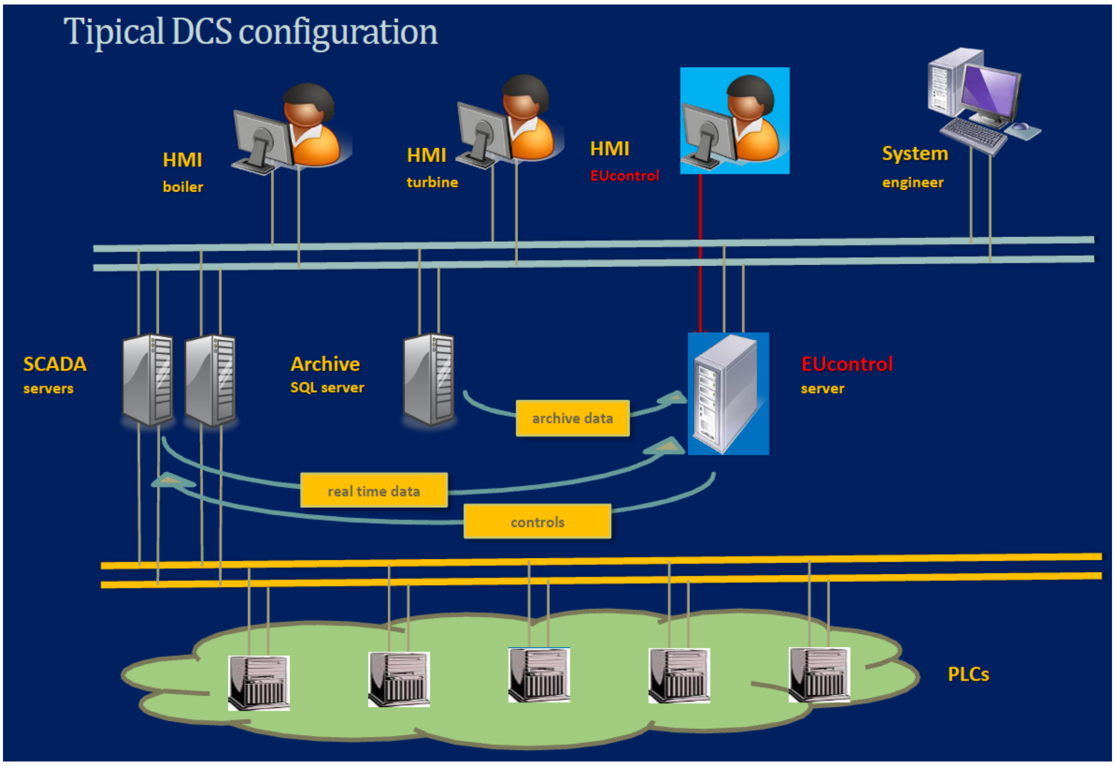

Figure 4: Integration of the add-on optimizer into the plant automation and communication structure

A web based client-server structure allows for remote (observatory) desktop access through plant engineers from within the plant´s LAN and service and maintenance tasks can be done from external remote access.

The configuration is easy and straightforward and is done via an intuitive graphical user interface, Figure 5. Optimization is multi-criterial and based on a cost function that incorporates and consolidates the different and often conflicting objectives by weight functions. Parameter settings are adjusted, hard and soft constraints are defined and alarm thresholds are set. Various configurations can be predefined and stored for later use. During operation engineering and reporting tools assist the user in data visualization, performance monitoring, and engineering analysis.

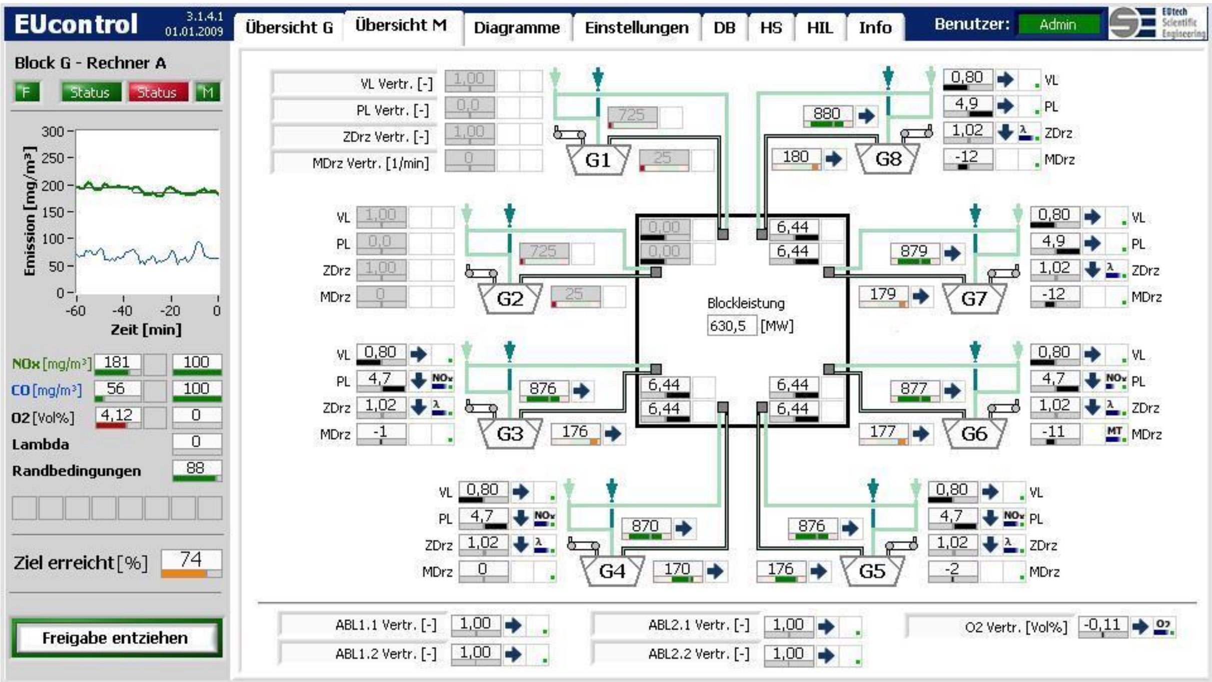

Figure 5: Intuitive user interface – controls at fingertips

Commissioning

After successful verification of the functionality and signal testing the system is connected to the base automation of the plant and taken into operation according to a well defined procedure.

Before this takes place, however, much care is taken to instruct and train the plant personnel and get everyone involved accustomed to the new system. It is the people who are key to success; therefore an elaborate and hands-on simulator training provides an authentic feeling of what the system does – covering all aspects of handling, configuration, reporting including a brief on trouble-shooting, Figure 6. The simulator has the look and feel of the real thing – only that it is a model of the plant/boiler that is being “optimized”.

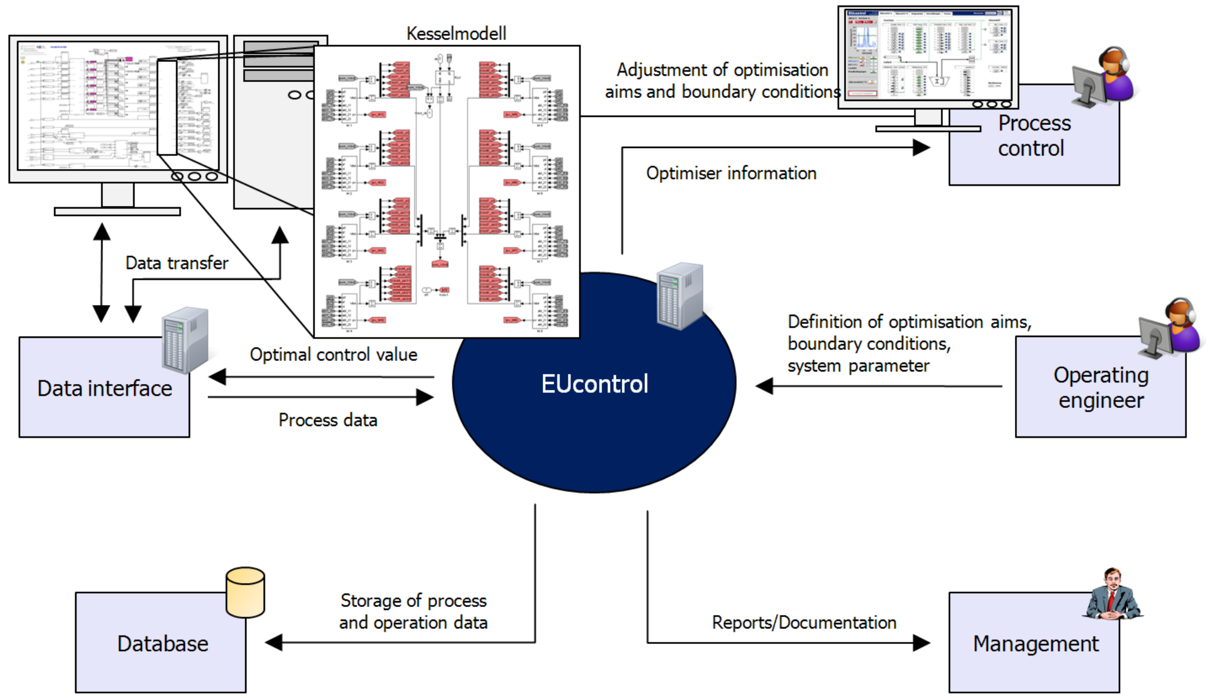

Figure 6: Example of the optimizer in real-time (RT) HiL simulation mode

In the start-up phase the optimizer will run in advisory mode or, if in closed-loop, the control and optimization settings are tuned such that they only lead to “soft” interference with the boiler operation. Test scenarios are examined and the responses are analyzed. Step by step the complete functionality is validated and where necessary fine-tuning takes place.

Achievements

Combustion optimization adjusts the fuel and air biases within the furnace to improve the combustion process, thereby *controlling emissions*. The NOx-CO trade-off is looked after by adjusting the air dampers, mainly along the “vertical” boiler axis, adjusting primary, secondary and, if available, over-fire air (OFA) in conjunction with the excess oxygen control. This trade-off is a very essential aspect not only in terms of heat rate but also in terms of boiler slagging. Fuel-air imbalances at the burner level lead to incomplete combustion in the lower furnace and coal particles will hit the convective boiler sections at too high temperatures, which sometimes may even exceed the ash fusion temperature. This is a situation that must be avoided. Low-NOx strategies, if not carefully implemented and controlled tend to mask unfavorable combustion.

The level of *excess oxygen level* plays an important role for achieving minimum heat rates. Biasing O2 levels downward by only 0.2% on a long term basis under otherwise constant conditions leads to significant heat rate improvements above one percent.

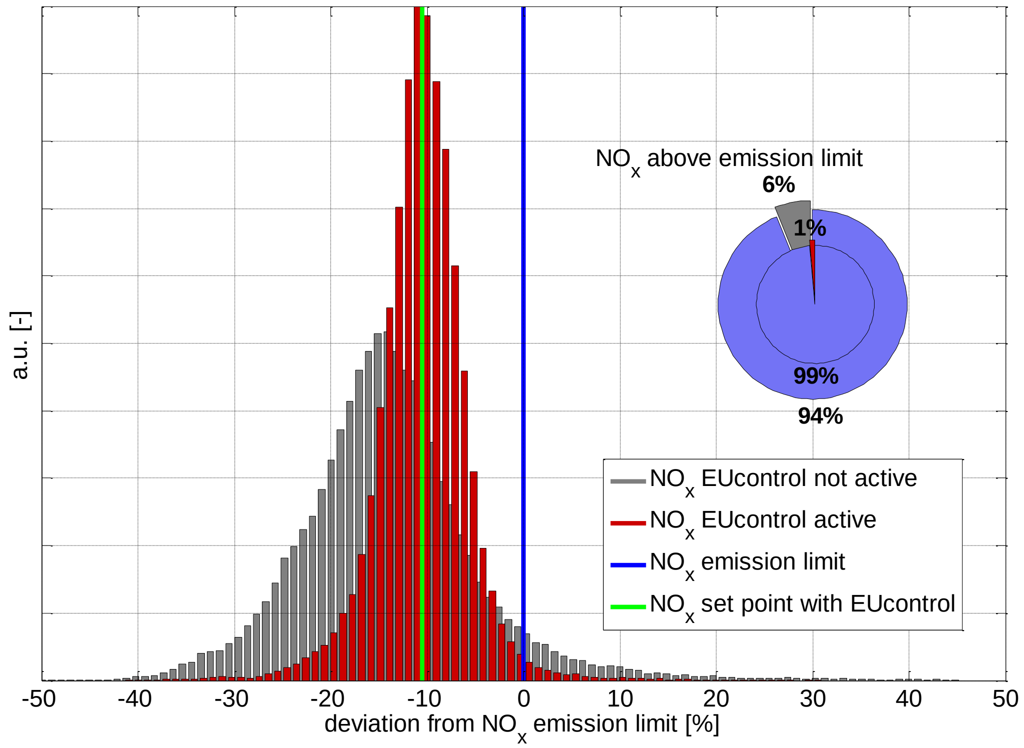

Figure 7: NOx-Emission control

The NOx- and CO-emissions are controlled (Figure 7) and held just below their limit, while the overall excess oxygen is simultaneously being reduced. Further investigations show that the reason is the improved fuel air mixing which leads to more vigorous and complete combustion in the reaction zone at burner level. Figure 8 shows how the optimizer changes the combustion regime by shifting more air to the burner level and reducing OFA – entering areas otherwise untouched.

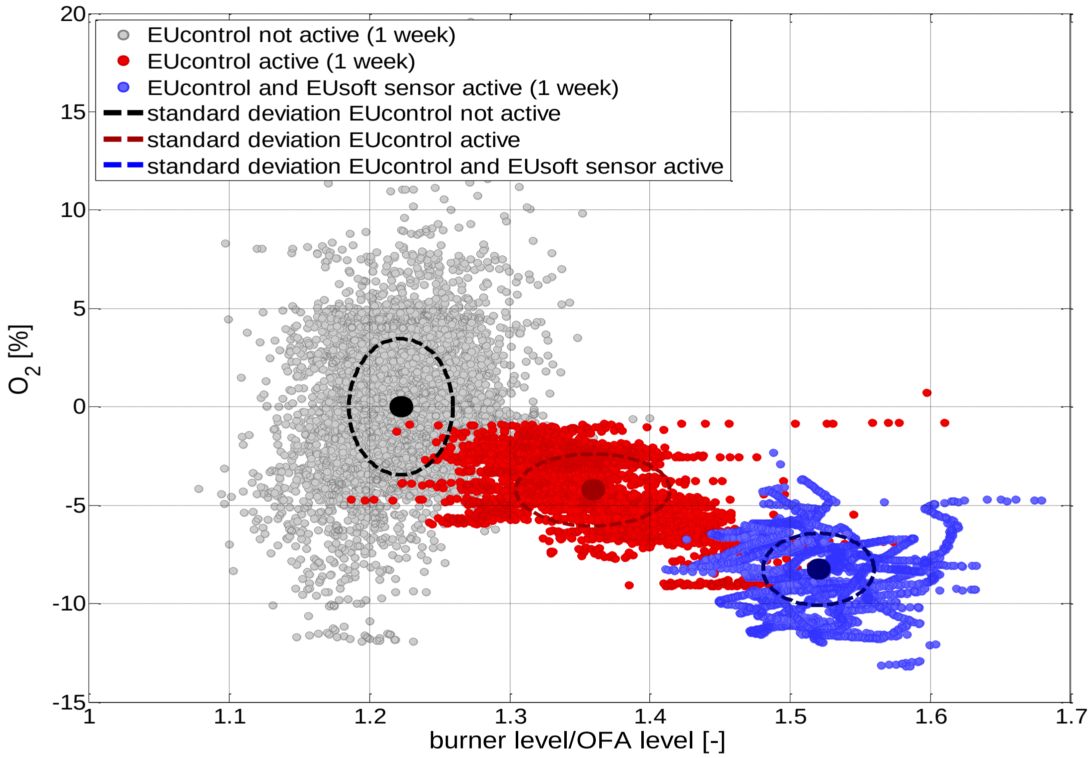

Figure 8: Changing the regime of combustion with optimization

In the case of lignite fired boilers the horizontal balancing of the air-fuel ratio at the burner level further contributes to this improvement as shown in Figure 9 (top). The optimizer narrows the band air-fuel band at which the different burners operate.

This is not quite as simple a task since the *mill temperatures* must be kept under control. The mill temperature is governed by the primary air, the coal load (feeder speed), the mill speed and the classifier settings. Commonly, the primary air adjustment is used to control the mill temperature, since the coal feeders have to maintain a through-put according to the unit load demand while the classifier settings have to ensure a coal size spectrum that is optimal for combustion. The optimizer uses an ensemble of models for each mill that are continuously adapted taking account of degradation, wear & tear and coal quality changes. The lower part of Figure 9 shows that the optimizer can handle this constraint with ease.

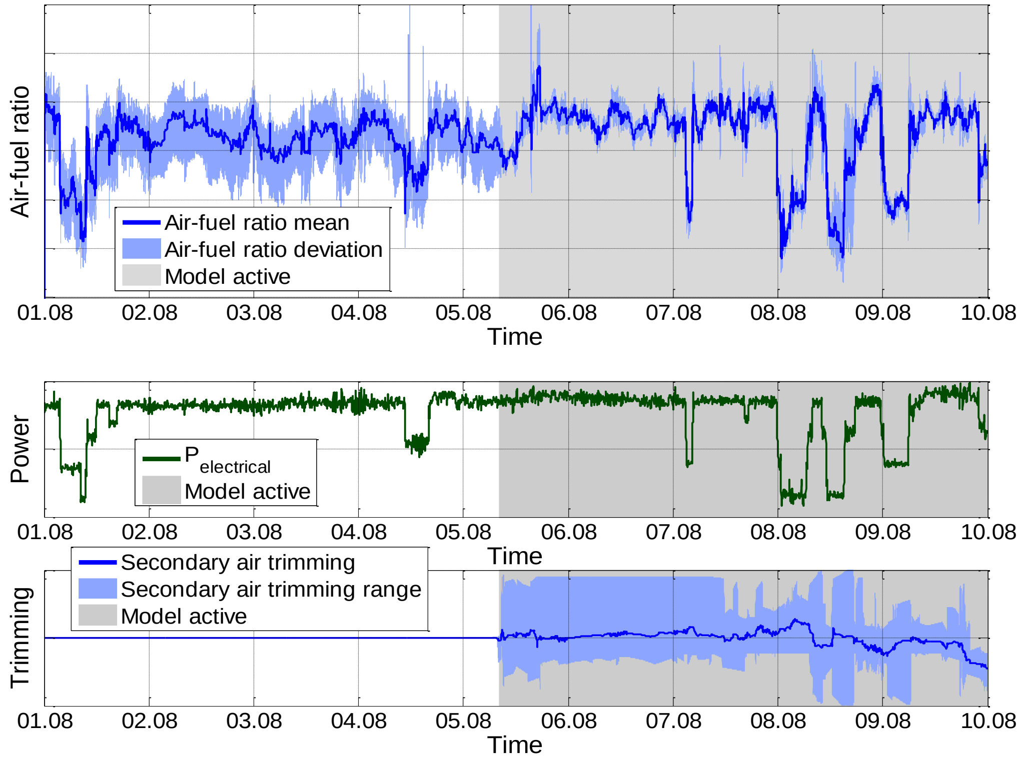

Figure 9: Air fuel ratio (top), electrical power (middle) and secondary air trimming (below) with and without optimization

The main steam temperature balance at the exit of the superheater and reheater is maintained by *spray water*. The larger the furnace exit gas temperature (FEGT) imbalance, the more spray water is usually required - which has a negative impact on the heat rate. In order to reduce spray water injection the reheat spray valve demands are included as constraint variables, with a suitable target of preventing control output saturation. The key to spray water reduction is homogenizing FEGT distribution, and as mentioned, a two-dimensional, direct flame temperature measurement system can prove very helpful in redressing these imbalances straightforwardly. Reducing the reheat spray flow rates contributes to heat rate improvement, typically in the range of 0.3% - 0.6%.

The opportunity cost (lost profit) associated with reduced availability are enormous and need not be elaborated upon. Fortunately, plant *availability* is affected very positively in that the optimizer streamlines the fuel air distribution and balances the fuel lines, takes care of intricately interdependent constraints, and avoids local temperature excursions, excessive slagging, material stresses or other operational irregularities. Additionally incorporated fault diagnostics help to detect and identify anomalies corresponding to measurement problems, signal quality or changing process behavior. Often, problems can be identified early on and damages or even forced outages can be reduced.