True optimisation

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In 2006 ABB installed itsExpert Optimizer™ for precalciner optimisation in the Holcim cement plant in Lägerdorf, Germany. The replacement of fossil fuels with alternative fuels in the Lägerdorf plant opened up a lot of challenges in the operation of the precalciner.

Holcim's Lägerdorf plant

The design of the precalciner kiln became ever more complex and the alternative fuels the plant wanted to use, increased the process variability even more. The process became difficult to handle and the task of optimising it became increasingly complicated.

In this article we present the challenges of using alternative fuels in modern precalciner kilns and the results obtained after a two-year operation.

The results of the implementation of Expert Optimizer applying Model Predictive Control (MPC) in a calciner are presented in detail showing in particular:

- the major process issues within the calciner and how they were addressed
- a comparison of the control of the calciner under manual and Expert Optimizer control.

The major benefits of this application include:

- coal-free operation of the precalciner kiln
- lower overall energy consumption
- less quality variation
- lower preheater cyclone blockage
- less refractory usage.

We will also show the challenges of using alternative fuels in modern precalciner kilns. Furthermore, we describe how ABB's Expert Optimizer helps reduce the variability of the process and allows it to operate under more favourable process conditions.

Based on a two-year running operation, we describe the application of model-based control in a kiln calciner, concentrating on the technology used, the real life issues that had to be solved and the solutions that were found for those problems. We also show the results that have been obtained during the period of operation.

There are a number of areas in the cement-making process where an expert system can bring benefits. Each of the individual unit operations such as raw material grinding, calcination, clinkerisation, cement grinding and blending, all lend themselves to some form of optimisation. Furthermore, with what seems to be ever increasing energy costs, the overall optimisation of thermal and electrical energy needs can lead to significant benefits.

A study of any group of kiln operators controlling the same kiln will show that certain operators perform better than others. Some are better at handling kiln disturbances and some are better at achieving the highest throughput for the kiln. What is common, however, is that most operators take actions relatively infrequently and react to, rather than predict disturbances. As a consequence, operators build in a margin of safety in the way that they run the kiln. An expert system can improve on this by firstly, applying the strategy of the 'best of the best' operator 24 hours per day without pause. Secondly it can take actions far more frequently than a kiln operator and thirdly, run the process far closer to its limits.

With the addition of Model Predictive Control (MPC) to the other techniques already mentioned, expert systems have added the ability not only to be able to react quickly to disturbances, but by modelling the key parts of the process, disturbances can be predicted and avoided altogether. What is truly unique in the application of MPC in this case is the incorporation of Mixed Logical Dynamics (MLD). For the first time, binary conditions, such as a feeder running or not running, can be included in a model that also describes the dynamic behaviour of the process (see Figure 1). So what does MPC do in practice? At Holcim's Lägerdorf plant the preheater consists of two lines, each with three cyclone stages and a separation cyclone (see Figure 2). The process at Lägerdorf operates with many different fuels. The main fuels are coal and fluff. They are transported pneumatically so have relatively short transport times and they are basically suitable as primary fuels.

In addition to these, up to five alternative fuels are transported to the calciner on long belt conveyor systems. The transport time can be up to six minutes. A NO_x reducing agent, SNCR, is also injected into the precalciner.

The aim of the Expert Optimizer using MPC was to stabilise the precalciner temperature to ensure stable precalcination of the raw meal before this enters the kiln proper. Consistent precalcination facilitates stable kiln operation and better clinker quality. A secondary aim was to ensure combustion took place under favourable conditions, paying particular attention to the levels of CO present.

Finding a mathematical model

The first step in solving the problem at Lägerdorf was to transform the complex physical situation into a mathematical model. This is where the combination of the easy-to-use programming tools in Expert Optimizer and ABB's deep knowledge of both the cement-making process and mathematical modelling was an advantage. Ease of use is further enhanced by the graphical nature of Expert Optimizer's programming language (see Figure 3). Instead of laboriously writing lines of code, objects are selected from a palette, bought to the workspace and connected together to create the control program.

Fuel transport and combustion

The first part of the calciner problem that was dealt with in the Expert Optimizer model was the transport model for the fuels. As previously mentioned there were two primary fuels, namely coal and fluff and up to five alternative fuels that were transported to the calciner by a series of hoppers. The two key elements of this part of the model was to represent the characteristics of each of the possible fuels that could be fed to the calciner and to fully take account of the time delays inherent in transporting the fuels from their point of storage to the calciner proper.

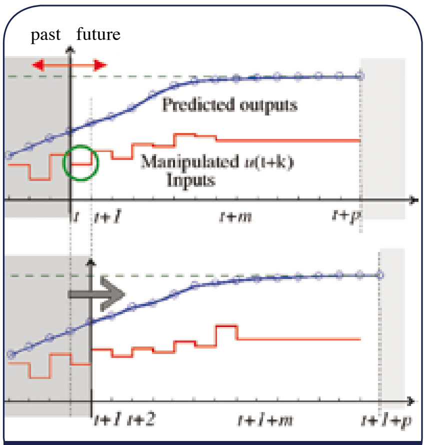

Figure 1: principle of model predictive control

Now that the transport of the fuels has been satisfactorily modelled, the next step was to model the fuel combustion in the calciner. The two main sources of oxygen for this combustion were the airflow through the tertiary air duct coming from the cooler and the airflow coming directly from the back end of the kiln. The positioning of the combustion model immediately after the transport model in Expert Optimizer reflects the influence transport delays, change of alternative fuels, etc. will have on the quality of combustion that takes place in the calciner.

To meet the primary goal of maintaining a stable temperature in the calciner a key consideration is to ensure that the heat content within the calciner remains constant (see Figure 4). Looking at each of the various heat sources in turn firstly, we have the various sources of fuels, both primary and alternative which by means of their combustion generate heat.

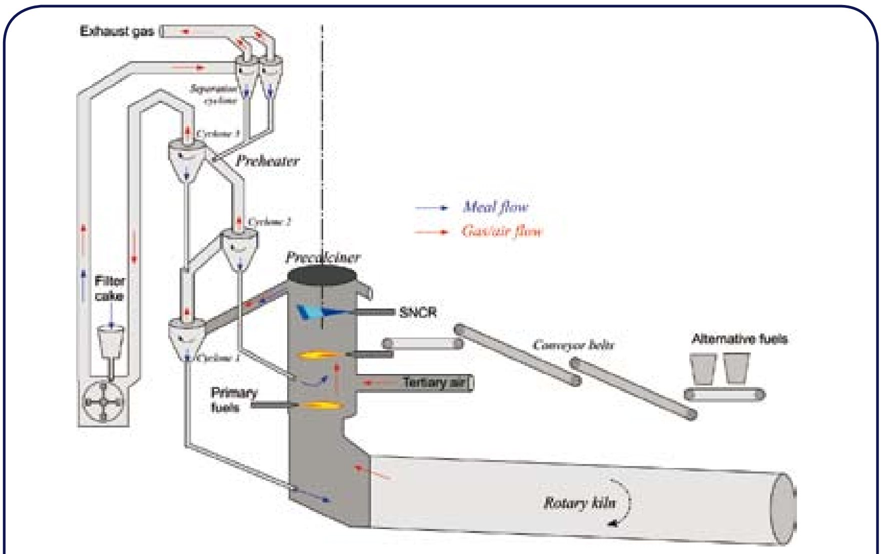

Figure 2: Holcim's Lägerdorf's precalciner kiln

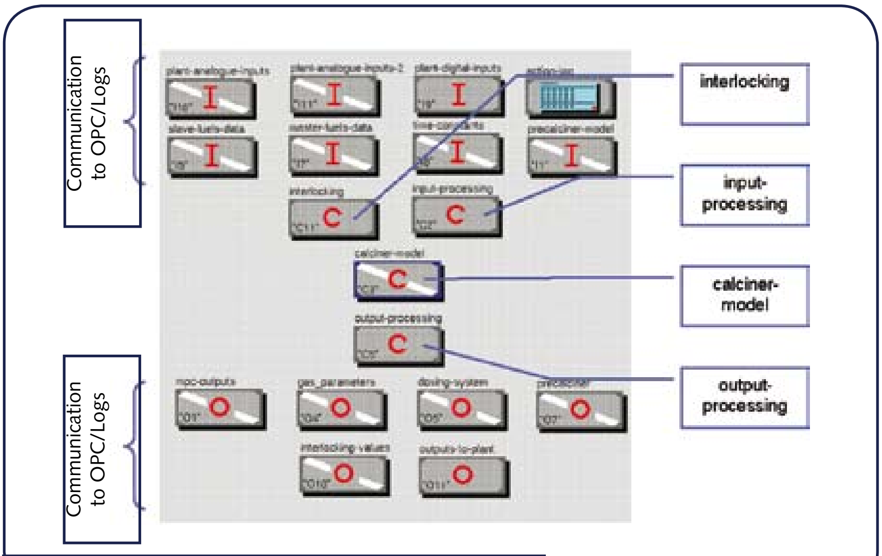

Figure 3: Expert Optimizer graphical programming language

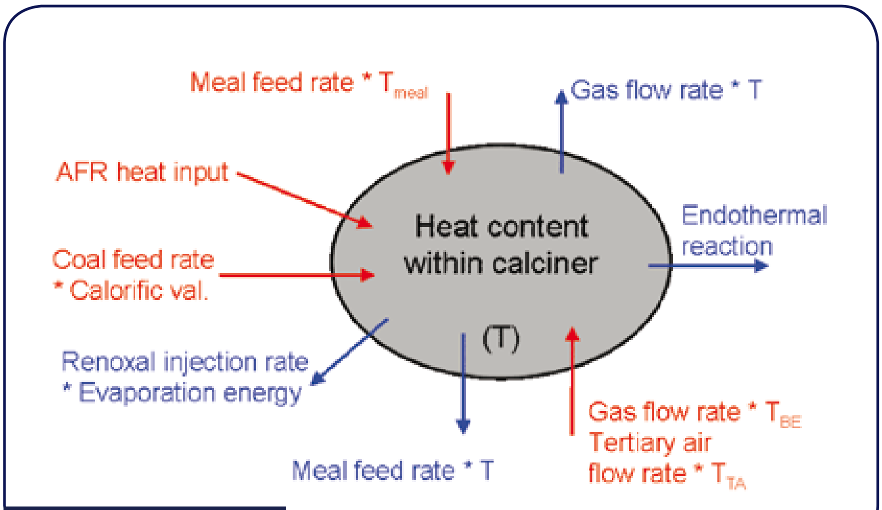

Figure 4: calciner heat balance

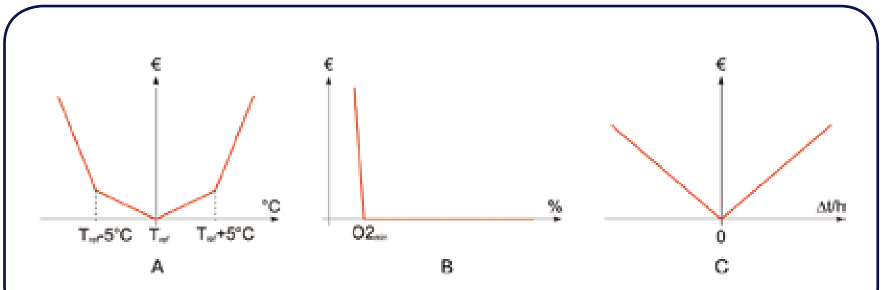

Figure 5: examples of cost functions

Secondly, we have the airflow from the kiln and the tertiary air duct which both bring heat into the calciner. Finally, the raw meal that also flows into the calciner also brings certain heat content with it. To ensure that the temperature in the calciner does not change, these heat sources must be in equilibrium with equivalent heat sinks. Taking a look at the heat sinks we have firstly, the endothermic reaction that converts calcium carbonate ($CaCO_3$) to calcium oxide (CaO). This reaction requires approximately 3.16GJ of heat per tonne of CaO. Secondly, the SNCR (Renoxal) that is injected into the calciner evaporates and so also absorbs some heat. Finally, both the raw meal, now CaO, and the air that has been used for combustion both leave the calciner at higher temperatures than when they entered and hence also absorb some further heat.

The final representation of the combustion model in Expert Optimizer shows both goals of balancing the heat and the oxygen in the precalciner.

Cost functions

Now that we have satisfactorily mathematically modelled the dynamics of the precalciner in Expert Optimizer we now need to solve the model to ensure the process remains stable and within the constraints (targets) that have been agreed with the plant management. To achieve this, a series of cost functions are used. In essence a cost function represents in a quantitative manner the penalty to be paid for breaching one or other of the process targets. In the model used for the precalciner at Lägerdorf, three types of cost functions were used.

Firstly, deviations from the calciner temperature are shown in Figure 5, example A. Deviations from set-point of ±5°C lead to relatively small increases in the cost function with greater deviations leading to rapid increase in the cost function. This allows the precalciner temperature to float quite freely in the ±5°C range, but outside of this, the model is forced to take rapid action to correct this error.

Secondly, a one-sided cost function is used to deal with deviations from the O_2 set-point. In example B there is no cost involved in having oxygen levels above the minimum level, but once the oxygen level falls below the minimum then the cost function tends towards infinity almost immediately. This represents the fact that calcination must take place in oxidizing conditions to avoid amongst others the risk of blockages in the preheater. In example C, variations in actuators from actual given set-points are represented. For example, if an alternative fuel feeder fails then the model knows that if it does not do anything the temperature will move away from target in 10 minutes taking into account the transport delays. Therefore, the cost function increases with time.

A practical example of cost functions in action is shown in the following example, for the precalciner coal feeder (see Figure 6). In this case, two separate cost functions are used. Firstly, one cost function represents the deviation of the measured value from the set-point; the more accurate the coal feeder the smaller the cost function. Secondly, a cost function represents the maximum and minimum throughputs of the coal feeder, with the constraint that the plant management at Lägerdorf always wanted to use some coal reflected in the fact that the minimum coal permitted is greater than zero.

Providing further answers

We have now described how the complex physical situation in the precalciner can be modelled using the MPC available within the Expert Optimizer and how cost functions are used to represent the

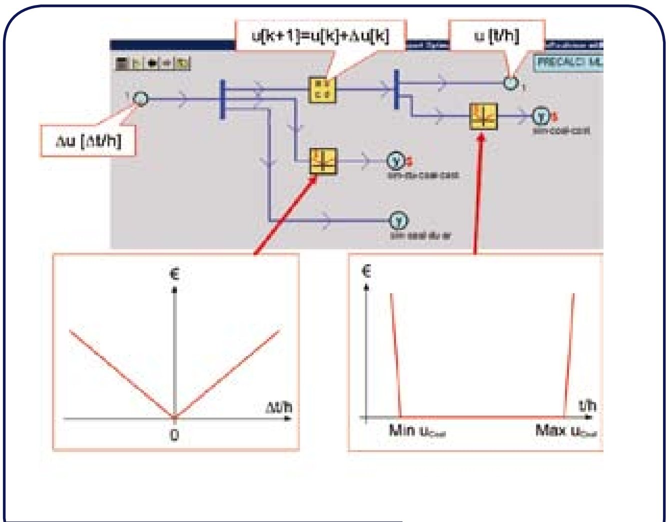

Figure 6: cost functions for pre-calciner coal

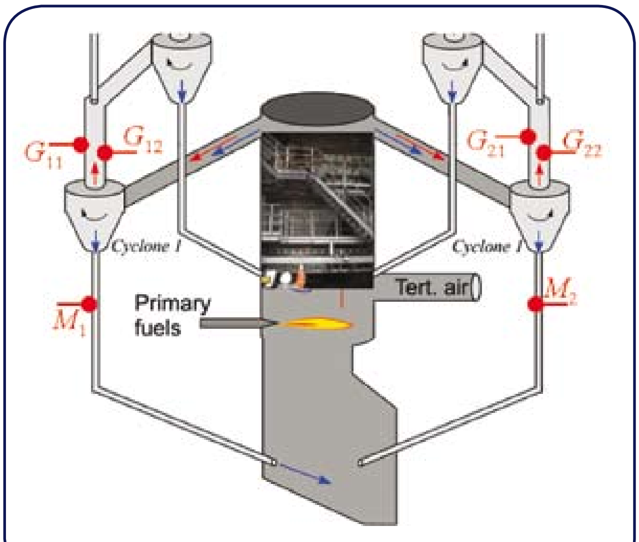

Figure 7: calciner temperature measurement

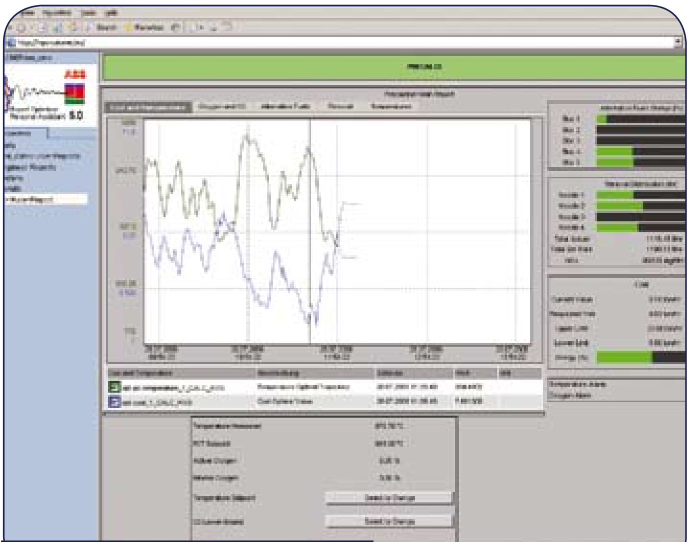

Figure 8: Expert Optimizer user interface

constraints and targets of the problem. Nevertheless some open questions still remain. For example, are all of the measurements coming from the process continually available and are they reliable?

To enhance the availability and reliability of the data coming from the plant all of the raw signals that come from the process pass through a process of input processing before they are used for the precalciner model. To illustrate this point we look at the case of the precalciner temperature and oxygen level in more detail.

At Lägerdorf the configuration of calciner and preheater streams meant that we were in the fortunate position of having redundant temperature measurements from each line. Furthermore, at the closest position to the calciner, cyclone 1 we had two gas temperature measurements and one meal temperature measurement. In estimating the calciner temperature each signal was firstly filtered with a time constant of 30 seconds to reduce short term variations. Secondly, the median of the two gas temperatures and the meal temperature of each preheater string was taken. Finally, to estimate the calciner temperature the mean of the two medians was calculated. This approach had the benefit of being very resistant to outliers caused by situations such as non-functioning or destroyed temperature probes.

In the case of oxygen, redundant O_2 measurements were also available. Here the issue was made more complex by the fact that although the system could show that there were sufficient levels of oxygen present, carbon monoxide could also shown to be present. There are various reasons why this happens, but the consequences of localised areas of the calciner or preheater with reducing conditions clearly need to be avoided. To achieve this without unnecessarily complicating the model the level of carbon monoxide measured was used to artificially lower the level of oxygen measured in the system.

To complete the model various other signals and measurements were required. This included information on the heating values of all the fuels being used in the calciner and signals to indicate whether conveyor belts are running or not. Prior to new set-points then being sent to the control system, some final processing and checks take place. Most important of these check is alarm generation in cases when

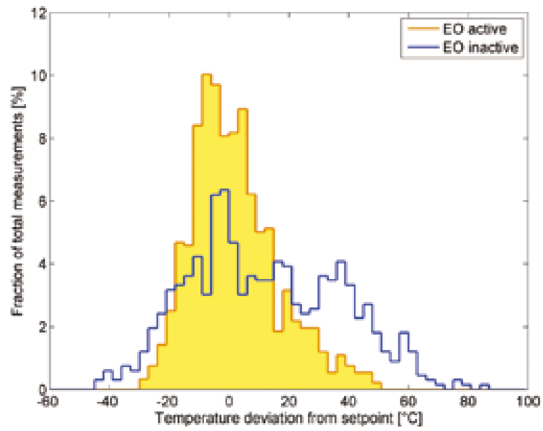

Figure 9: comparison of calciner temperature control

no solution is possible in the model due to the constraints or targets that have been set.

The human machine interface of Expert Optimizer makes it easy for the kiln operators at Lägerdorf to understand what is happening and to interact with the system. The web-based thin-client running on Microsoft Internet Explorer requires minimal installation and maintenance (see Figure 8). To allow the model to be adapted to the current needs of the plant the operator is able to modify a number of parameters such as temperature set-points, master fuels and maximum and minimum fuel rates. Expert Optimizer will inform the operator with an alarm if due to the current conditions or the parameters set by the operator, control of the precalciner is not possible within constraints set.

Operation starts

In June 2007, the coal free operation of the calciner started with the use of five different alternative fuels.

Following alternative fuels were and are still used:

- two types of EBS pellets (10tph)
- organic distillation residues (5tph)
- animal meal (3tph)
- tar-paper (3tph)

All with a constant mechanical feed to the calcinator

- two pneumatic fluff – feeds with 10tph feed each into the calcinatory where one is controlled by the Expert Optimizer

To ensure a seamless operation, even

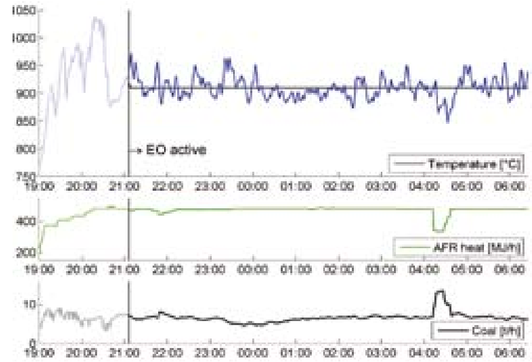

Figure 10: temperature, heat value of alternative fuels and total coal consumption (calciner and kiln)

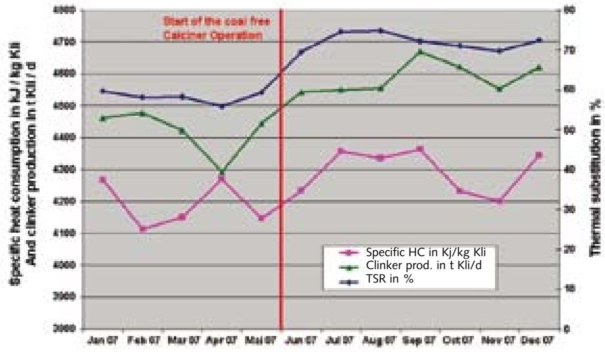

Figure 11: development of clinker production, specific heat consumption and TSR

when the alternative fuel supply is blocked or the O_2 concentration falls below the lower limit, a coal dust supply runs in stand-by and can be activated within 20 seconds.

Exceeding expectations

Now, after nearly 18 months of operation we can say that this Expert Optimizer installation is an overall success and that the expectations have been more than fulfilled. In detail we can say that a coal-free operation of the calciner has been achieved and that the temperature variation in the calciner has been reduced. Figure 9 shows that under manual control the calciner temperature varied between -45°C and +80°C of the set-point with only six per cent of the total measurements being exactly at set-point.

In the case of MPC control under Expert Optimizer the temperature variation was reduced to -30°C and +50°C with 10 per cent of measurements exactly on the set-point. This clearly demonstrates the ability of Expert Optimizer and the modelling of the calciner using MPC to improve the overall control and stability of the calciner at Lägerdorf. Figure 10 shows the temperature variation and the heat consumption of the calciner and kiln. Variations have been minimised and a failure of the alternative fuel supply was quickly compensated by the Expert Optimizer system using the coal feed system of the calciner which normally runs in stand-by.

Other benefits which were also observed during the Expert Optimizer operation included; lower overall energy consumption, less variability in product quality, a lower of risk of cyclone blockage and less trips of the system due to high levels of carbon monoxide. Furthermore, due to the fact that the calciner was more stable, the kiln was also more stable and higher overall kiln production was achieved (see Figure 11).

In summary, we have looked at a real life example of using multiple alternative fuels in a precalciner. Furthermore, we have seen how by using the advanced but at the same time simple-to-use modelling tools available in Expert Optimizer we have been able to model the real process using MPC and MLD. Finally, as the results from the calciner temperature control at Lägerdorf show, the implementation has lead to significant improvements in calciner stability and overall kiln performance.

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