Optimal trade-offs

Achieving energy efficiency and environmental compliance is not a problem thanks to advanced process control

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Modern industry works hard to achieve efficient production. However, this can often be quite difficult because many companies are bound by complex contractual and environmental conditions. This in turn increases the complexity of operations for both the operators driving the process and the plant managers setting the production goals, requiring them to make trade-offs between the amount and type of production, the availability of energy and the volatility of its costs.

Process industries can now virtually "be all things to all market conditions." With ABB's product cpmPlus Expert Optimizer, customers have all the automatic control tools needed to stabilize and control a process to effectively manage the complexity arising from new market conditions. Moreover, state-of-the-art mathematical algorithms have been packaged to easily tackle the optimization and control problems that were intractable just a few years ago.

Sustainable processes

With ever-changing market conditions, companies cannot afford to sit back and survive from the rewards of past successes. Indeed, according to Akira Mori, one of Japan's most successful businessmen, "Past success stories are generally not applicable to new situations. We must continually reinvent ourselves, responding to changing times with innovative new business models." As well as business models, innovative products, processes and services are necessary if companies and their customers are to survive what can only be called truly testing times. Rather than waiting for change to come, companies should be looking for changes in the market that may be a developing trend. Determining early enough if this trend is likely to impact the long-term success of a business enables the best solution to be found.

For some time, successful engineering teams at ABB have been using optimization techniques on a daily basis to serve its customers. In anticipation of changing market conditions and of customers' future need to meet these changes, ABB created a comprehensive engineering tool known as cpmPlus Expert Optimizer. Featuring all modern control techniques, Expert Optimizer facilitates the speedy deployment of controllers to satisfy demanding project criteria.

cpmPlus Expert Optimizer uses available measurements to initiate automatic adjustments to plant actuators to increase efficiency at a given quality. As well as increasing process efficiency, cost effectiveness and reliability are also improved. Similar to an autopilot in an airplane, Expert Optimizer achieves results by ensuring that the best possible actions are applied accurately, tirelessly and consistently at all times. In addition, its implementation follows stringent standardization procedures to ensure a high level of success and long-term maintainability. cpmPlus Expert Optimizer has a successful track record in the marketplace with more than 300 reference sites worldwide.

This software tool has the following characteristics:
- It combines optimal production scheduling techniques with those of classical advanced process control and artificial intelligence.
- It is flexible enough to handle applications in different industries with different requirements.
- It is user friendly in that the complexity is placed out of sight, thereby allowing its usage by non-specialists.
- It reduces deployment time via modularity, reusability and scalability.

Expertly using process knowledge

One of the strengths of ABB's cpmPlus Expert Optimizer is that it can use fuzzy logic and neuro-fuzzy tools to develop applications. Fuzzy logic inference systems incorporate human knowledge to make and implement effective decisions during a process, while neuro-fuzzy networks are used to learn relationships between key process variables. The integration of these complementary control techniques, coupled with ABB's and the customer's extensive process experience and expertise, allows the engineering of powerful robust solutions, which provide substantial financial benefits to the factory for extended periods of time.

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A Model Predictive Control expert

In addition to the classical tools of artificial intelligence, cpmPlus Expert Optimizer boasts a mature model predictive control (MPC) toolbox.

How does MPC work? Based on the predictive capabilities of a mathematical model, a sequence of future optimal control actions is derived[1)]. The first term of the sequence is applied to the plant. When measurements (or new information) become available, a new sequence is determined. Each sequence is computed by means of an optimization procedure, which follows two goals:
- Optimize the performance
- Protect the system from constraint violations

Expert Optimizer allows for linear, nonlinear and hybrid models with continuous and Boolean variables. This is a remarkable feature. Indeed, while linear mathematical models are well established to control industrial processes, nonlinear and hybrid models (ie, models with mixed continuous and binary states) are only now being applied to processes in which ABB customers are interested.

MPC not only requires the development of a mathematical model to describe the process, but it also requires the selection – or design – of a suitable cost-revenue index (otherwise known as a cost function), which takes into account the goals that must be achieved. Depending on its design, the function could penalize deviations from given operating points or it can simply represent operating costs. The optimal inputs to the system are calculated through minimization of this function within the constraints defined by the process model. To be successful the minimization algorithms must exploit the structure of the problem as described by the model type (linear, nonlinear, hybrid, etc) and the optimization function characteristics.

In Expert Optimizer the same MPC framework is used to perform three complementary tasks important for advanced process control:

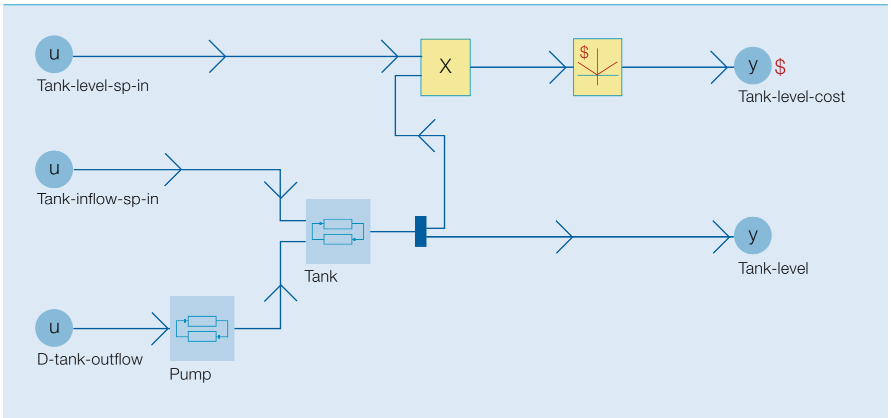
State estimation This task implements the so-called moving horizon estimation (MHE). The MHE considers the most recent past (the horizon over which the measurements are considered) to estimate the current states of the model as the initial conditions that minimize a trade-off (cost function) between sensor and process noise. This method can be exploited for parameter estimation using the augmented state approach.

Process simulation Using a given initial condition for the model states, this task simulates the model to give a future view while the manipulated variables are kept at their current values. The end result is a representation of the systems open-loop behavior at current conditions.

Process optimization With a given initial condition for the model states and a cost function, this mode calculates the optimal values for the manipulated variables that minimize the cost function over a receding horizon. The associated trajectories for manipulated variables, model states and model outputs (controlled variables) then become available for display and further post-processing.

1 The Expert Optimizer library for generic mixed logical dynamical (MLD) blocks

2 A simple tank-pump system is modeled in Expert Optimizer



Scheduling by means of MLD systems

The model-based environment of the new Expert Optimizer has adopted the mixed logical dynamical (MLD) modeling class [1]. MLD systems, developed at the Automatic Control Laboratory at the Swiss Federal Institute of Technology[2] (ETH) in Zürich, generalize a wide set of models, in particular those that exhibit both continuous and discrete behavior, ie, models that describe a hybrid system. The ability to model hybrid systems significantly increases the range of applicability of ABB's Expert Optimizer. This is because unlike linear models, MLD systems are able to model constraints such as logic relationships of the type "if unit 1 ON then unit 2 OFF"; or production constraints "either NO production, or production between MIN and MAX."

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With MLD systems, the optimization task is transformed into a mixed-integer linear or quadratic problem for which computationally efficient solvers exist. Depending on the needs, the same framework can be applied either as an open-loop, decision-making (scheduling) tool or as a closed-loop, disturbance-rejection (rescheduling) tool [2].

In short, the key advantages of using the combined MLD/MPC approach include modeling flexibility and acceptable computational requirements.

Build the model graphically

One of the goals of Expert Optimizer is to make the MPC methodology accessible to non-specialists. There is a drawback with the MPC approach and that is the need to create a process

Footnotes

1) A typical scope is the short- to medium-term evolution of the system.

2) ABB launched a strategic collaboration with ETH about nine years ago.

model with sufficient accuracy. To overcome this, ABB proposes breaking the process into smaller but sound components. For example, a hydroelectric power plant could be split into the reservoir, dam, turbine, generator and grid. The idea is to model each part independently of the others and to represent it graphically with a block. Each graphical block stores its own constraints and dynamics, and its input and output (I/O) ports match the inputs and outputs of the mathematical model. The complete process model is then obtained by graphically connecting the I/O ports of the various blocks. The cost function that defines the optimal control problem is also represented as a graphical block. If, for example, the goal in the hydroelectric plant is to maximize profits made from the sale of electricity, the output of the generator block – representing the power produced – should be linked to the cost function block where the time-varying electricity tariffs would be stored.

The modularity of the approach simplifies the modeling phase and makes it easier to engineer, modify and maintain the models. Furthermore, it allows the creation of libraries containing standard blocks that can be reused in different processes simply by dragging and dropping them.

An example of the Expert Optimizer library for generic MLD blocks is shown in 1. Included in this library are basic elements, such as I/O variables, process delays, gains, state-space models, summations of MLD variables, and soft and hard constraints. Similar libraries exist for modeling the logic part of a hybrid system. In general, any process can be modeled by simply connecting these MLD blocks together, as illustrated by the simple tank-pump system in 2. The cost functions are created using the same building blocks of piecewise linear operations. The user may, of course, import his own MLD models (for example, those originating from black box identification algorithms) into Expert Optimizer. In fact, Expert Optimizer 6.1 offers a full-blown model identification tool.

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Expert Optimizer at work

Several projects implementing Expert Optimizer's new model-based optimization capabilities have been installed and are running successfully in different domains. The most significant examples are in:

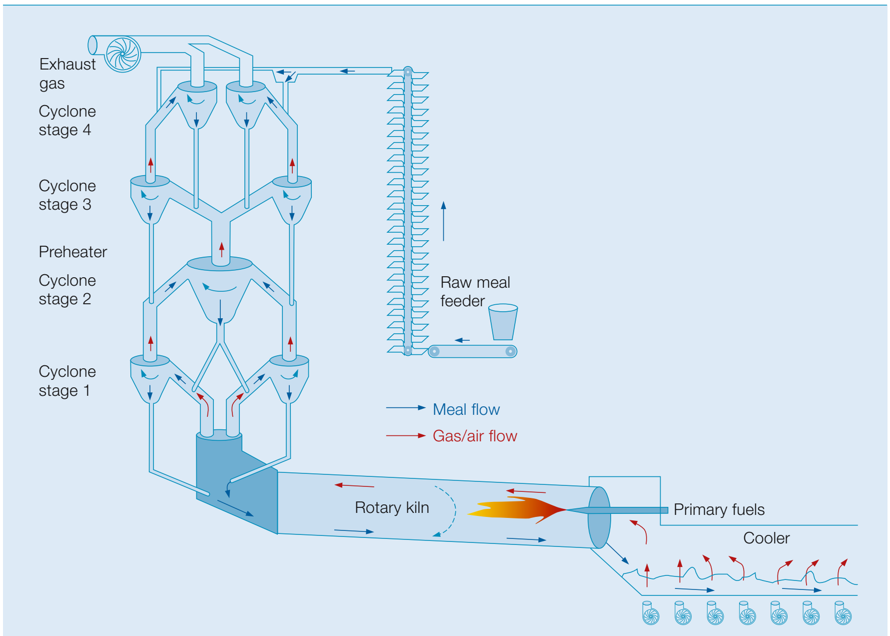
- Closed-loop process control, ie, cement mill control, blending optimization and precalciner control [3]
- Production planning and scheduling, ie, cement mills scheduling [4], titanium dioxide production scheduling and water distribution
- Economic process optimization, ie, alternative fuels management
- Thermal power plant optimization [5]

Kiln control

A standard application for Expert Optimizer is kiln control in the cement clinker production process. A cement clinker production unit is shown in 3. The clinker minerals are formed at about 1,400 °C within the rotary kiln. This process requires a lot of thermal energy, which is provided by fossil fuels and to a substantial degree by alternative fuels (tires, plastic, etc). To make the process more energy efficient the hot exhaust gas travels further up the kiln and into the preheater tower. The raw meal travels in the opposite direction and picks up energy from the gas on its way down through the preheater tower and into the rotary kiln. As it heats up, the meal undergoes chemical reactions, such as calcining, which pre-treat it before it enters the mineral-forming phase in the last third of the rotary kiln. A cooler forces ambient air through the clinker bed, thereby guaranteeing efficient heat exchange and rapid cooling of the clinker. This in turn ensures that the formed minerals remain in their required form.

The clinker production process is highly interconnected in that changing one of the main actuators (raw meal feed rate, exhaust gas flow rate, fuel input, rotary kiln speed) affects all the main process indicators (burning zone temperature, cyclone stage-two temperature, oxygen level in the kiln). Moreover, stabilization of the process depends strongly on the composition of raw meal as the energy requirements at various phases of the process are influenced by the different meal components. To reduce the amount spent on fossil fuels, up to 70 percent of the fuels used (depending on the process configuration) are alternative, such as waste. This in turn introduces

3 Cement clinker production unit: Gas flow is indicated with the red arrows and meal flow with the blue arrows



highly variable heat input from the fuel combustion. It is therefore important to know how the reaction conditions in each phase of the process are affected. The quality of the clinker depends on it. In other words, if the system cannot compensate on time as the cold meal travels along it the chemical reactions needed to form clinker cannot take place.

Expert Optimizer makes the MPC methodology accessible to non-specialists by breaking the process into smaller but sound components, which are modeled independently of each other.

The process is therefore divided into compartments or zones, with each zone influencing the one beside it. This allows predictions to be made regarding the evolution of the energy within a zone and therefore on the temperature profile along the whole production process. Until recently a fuzzy-logic-based controller was used, but this has now been replaced by the model-based MPC approach.

Predicting the feed (blue) and gas (red) temperature profiles, as shown in 4, provides valuable information when it comes to stabilizing the process to ensure the desired clinker quality and production rate. The problem is the temperature profiles have to be derived from a restricted number of measurements taken at a few points along the process (dark blue dots in 4). To overcome this limitation, MHE is used. By reformulating the optimization problem to look backwards in time rather than forwards – as in MPC – an accurate temperature profile can be estimated. This estimation enables for the MPC algorithm to derive the best sequence to change the manipulated variables such that the process targets are optimally reached.

The controller performance is shown in 5 where the temperature of the sintering zone (BZT) is kept close to its target while at the same time maintaining the temperature in the preheater tower (BET) to within a close range. The trade-off between maximizing the production (FEED) and keeping the critical process variables within acceptable ranges can easily be seen. Typically, the controller adjusts the fuel input (ENERGY). However, whenever the process temperatures indicate that the system will rapidly cool down, the controller reduces the feed rate (FEED) to support a faster recovery.

Pulp and paper plant scheduling

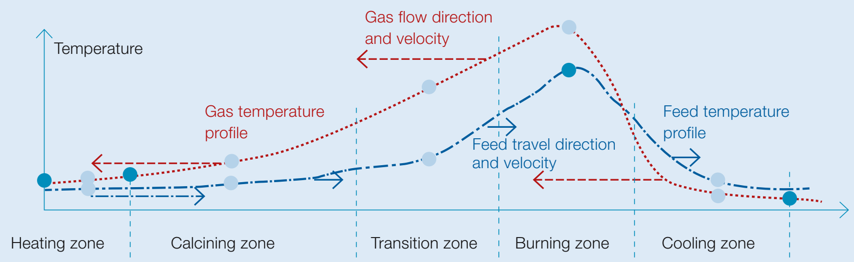
Pulp and paper plants are ideal environments in which to demonstrate the power of nonlinear MPC and Expert Optimizer. The process used in these plants is challenging in that the right mix of chemical additives must be applied at the right moment and under the right conditions in order to meet stringent quality requirements.

ABB's nonlinear MPC schema allows a mill to be better utilized by continuously monitoring its current state and giving decision support in real time, aiming for maximum profit at minimal cost. The tool optimizes mill operations by balancing supply and demand between subsystems. Every subsystem or buffer has to be fed material and sufficient supply must be available for the subsystem to produce as required.

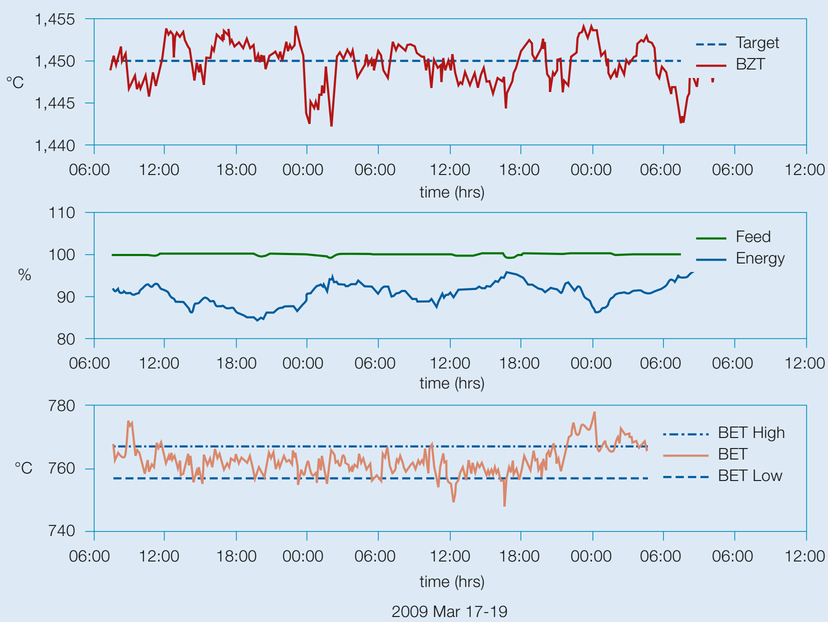
The relationships become nonlinear because they must cover a large oper-

4 Temperature profile for feed (meal) and gas (air) with the main characteristic zones of the clinker production process

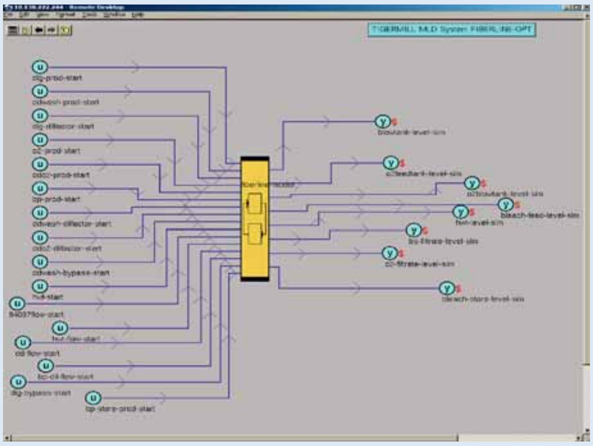
The corresponding arrows provide qualitative information about the gas and feed flow direction, and velocity. The dark and light blue dots respectively indicate where the temperature can be measured or where it needs to be estimated.



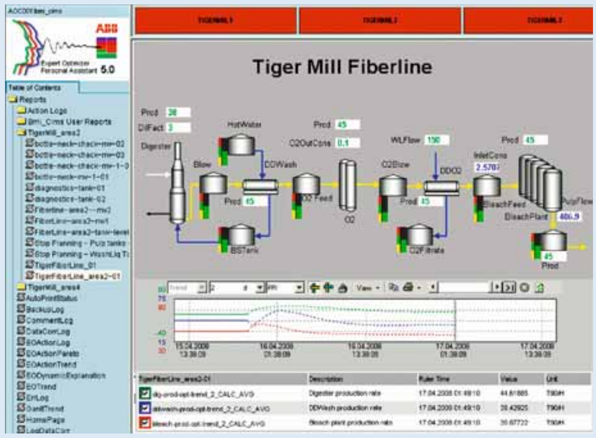
5 Performance of an MPC kiln controller



6 A Modelica model inside the Expert Optimizer run-time tool



7 A typical Expert Optimizer operator interface



ating range of plant set-points. In many cases proper scheduling necessitates a variety of models to describe, for example, the sodium and sulfur chemistry as well as the fiber balance. Very often more detailed models for fiber lines are developed to describe, for instance, kappa number and brightness **6**.

The development of cpmPlus Expert Optimizer is the result of a fruitful and long-term collaboration between ABB's business units and corporate research.

With ABB's nonlinear MPC schema, customers can typically expect the following functionality:

- Online production planning
- A stop planning tool (stops and limits capacity at certain process sections)
- Soft sensor functionality
- Diagnostics for measurement points
- Bottleneck analysis

Using the nonlinear models and real-time data from the plant floor, as well as taking into consideration events such as the maintenance of key equipment, Expert Optimizer produces predictions of all key variables, which are valid for several days. Typically, these models are large, consisting of dozens, if not hundreds, of dynamic states, and manipulated and controlled variables. In addition, they are tailored to predict the process variables that cannot be measured directly.

These "control applications" are related more to economic process optimization rather than to regulator control. In other words, they try to exploit degrees of freedom in order to increase the plant financial performance.

A model partnership

Twenty years of experience in the process industry and knowledge of established control techniques like fuzzy logic, rule-based control and neuro-fuzzy tools have been combined to create sophisticated state-of-the-art model-based optimization techniques.

Complex real-world applications in the areas of closed-loop process control, open-loop decision support, as well as advanced production planning and scheduling, and economic optimization can now be tackled by a single product. Modeling, optimization and simulation capabilities are easily accessible through the Expert Optimizer graphical interface **7**. Flexibility is ensured by a modular structure and by providing libraries of reusable components.

The development of cpmPlus Expert Optimizer 6.1 is the result of a fruitful and long-term collaboration between ABB's business units and corporate research. In fact this collaboration serves to illustrate the benefits that come about when industrial needs are met with the achievements of long-term research.

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