New levels of performance for the cement industry

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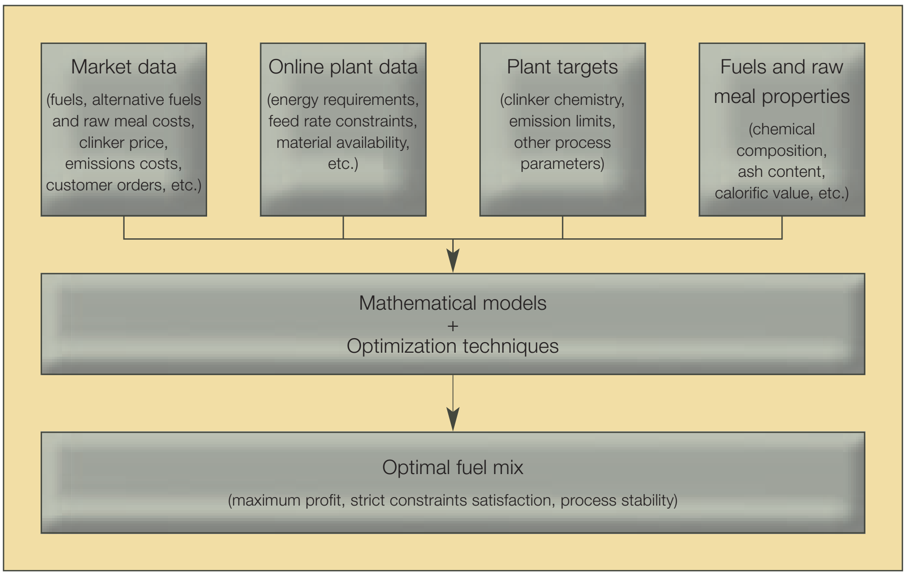
The cement industry, like most other industries, is under pressure to increase profit and margins while ensuring sustainable and environmentally friendly use of natural resources. This puts the onus on plant owners to develop new strategies that will support a quick, optimized response to changing conditions, often involving complex scenarios with conflicting goals.

As good as they are, standard plant information management systems alone cannot manipulate the received data; nor do they have the required optimization capability. ABB has developed new modules and algorithms aimed at solving this problem.

To implement effective optimization strategies, tools are needed that enable cement plants to perform at their optimum economic level within the given technological, environmental and contractual constraints. They must work in real time, and the information they process must be consistent and always correct. It goes almost without saying that an efficient information management system is a precondition for this.

Two areas for which ABB has already developed such tools are thermal energy management and electrical energy management. The first module, which is based on dedicated mathematical models and state-of-the art optimization techniques, computes the lowest-cost fuel mix that satisfies the current process and market constraints. It uses real-time information from sources that include laboratory analyses, market prices, forecasts of alternative fuel availability, environmental constraints and process conditions. The second module is a *scheduling tool* that enables cement mills and silos to be operated in such a way that the production goals are reached at the lowest possible energy cost.

1 Data flow envisioned for economic process optimization



The software modules can be used in decision support mode or in closed-loop control mode. Customers benefit not only from an immediate reduction in their energy bills but also from more stable operation, leading to higher quality and lower maintenance costs.

> Optimization strategies depend on tools that enable plants to perform at their optimum economic level within the given constraints.

The vision…

Intelligent, flexible process control systems, constantly performing at the highest level and able to coordinate their actions, are the key to successful strategies for meeting profitability and sustainability goals. A number of technological advances have made such systems possible today:

- The superior performance offered by relatively low-cost hardware (PCs, digital buses, etc).
- New software that permits seamless interconnection and operation of diverse systems.
- Advanced control technology. Combined with the computational power now available, this has opened up completely new possibilities in plant process control, scheduling and planning, leading to true economic process optimization.

ABB's Industrial^{IT} initiative is instrumental in the realization of this vision. Industrial IT enabled solutions not only control and optimize the different parts of the process but also make it possible for these parts to communicate and cooperate with each other for overall performance optimization.

…and its realization

Industrial IT (IIT) is not only a new technology; it is a new way of doing business. IIT seamlessly integrates a company's distributed industrial and business assets to make them more versatile, more efficient and more profitable. Two outstanding characteristics contribute to this:

- Real-time integration of information systems and automation systems across the enterprise.
- Economic process optimization, made possible by integration of the enterprise systems.

Having process-wide, real-time information available lets companies:

- Monitor all parts and their specific characteristics.
- Know how parts interact with each other.
- Diagnose problems instantly.
- Prevent serious downtime.
- Track productivity.
- Trouble-shoot.
- Optimize processes.
- Continuously coordinate every part of the process according to key performance indicators (KPIs).

While this might seem like a 'wish list', it is absolutely realistic. A closer look at how IIT is being instantiated in the cement industry shows why.

From raw data to useful information

To provide the most complete picture of a cement plant's performance, data from many different sources have to be collected and evaluated. However, here there is a problem: The raw data from these sources are often inconsistent because of the limited accuracy of the instruments used. And some key data may not be available at all if it has not been possible in the past to justify the cost of installing the necessary sensors.

The problem can be overcome by taking an integrated approach to data management. The data flow between departments and data sources, etc, is then automated, data inconsistencies are corrected (mathematical methods play a central role here), and all information is made available, in real time, to authorized users.

> Industrial^{IT} seamlessly integrates a company's distributed assets to make them more versatile, more efficient and more profitable.

An integrated data management system relies on data from different sources being available. The system can usually collect these data directly from the subsystems already installed in many plants for recording process data. An ideal data management system would therefore be able to take data straight off sensors, process control systems and other data collectors, like historians. Obviously, the key here is to have built-in flexibility, so that the systems already installed can be used.

ABB has had a data management system with these characteristics on the market for some time [1]. It combines all the necessary technical features and architecture with ease of use, thin client implementation and Microsoft Windows™ 'look and feel.'

From information to decisions

Economic process optimization will be one of the key factors driving the cement industry in the future, largely because of how production efficiency can be increased through the timely, optimal use of resources.

Model-based strategies could not be used extensively in the past for on-line computation of process targets. This was due to the inherent complexity of industrial processes, which resulted in mathematical problems that could not be solved in a reasonable amount of time. Poor model accuracy was another problem, and meant that the value of the setpoints was also open to question. Obviously, these problems have to be solved first.

The way forward

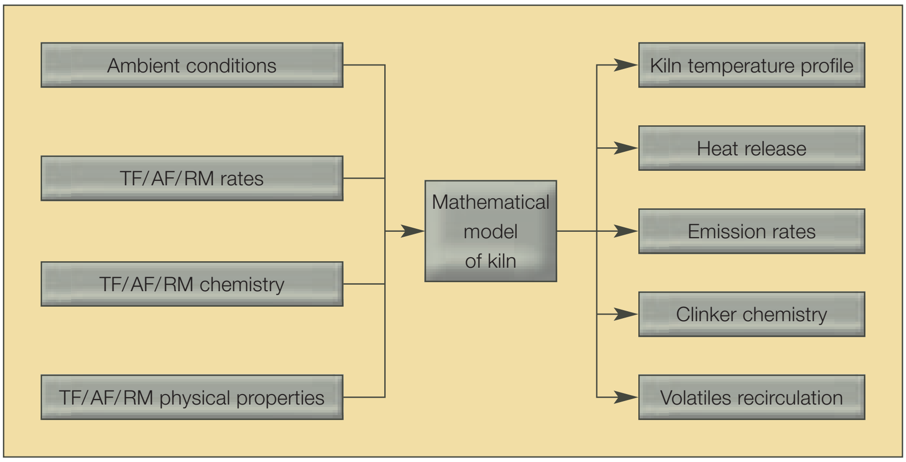
Three recent technological developments have made it possible to overcome these restrictions:

- Modern mathematical modeling techniques provide a uniform framework for efficient modeling of complex industrial systems.
- Advanced control and optimization techniques have become mature enough to be used to drive process and business decisions.
- Mixed-integer and non-linear programming technology offers an efficient and robust means of solving the described problems.

1 shows a data flow diagram for the kind of solution envisioned here.

There are several ways in which optimal solutions of the described problems can be approximated. One interesting, and widely adopted, approach to solving control problems involving systems which are subject to input and output

2 Kiln model inputs and outputs



AF	Alternative fuels
RM	Raw meal
TF	Traditional fuels

constraints is *model predictive control* (MPC) [2].

MPC is based on the so-called *receding horizon philosophy*, ie, a sequence of future optimal control actions is chosen according to a prediction of the short- to medium-term evolution of the system during a given time. When measurements or new information become available, a new sequence is computed which then replaces the previous one. The objectives of each new sequence run are the optimization of performance and protection of the system from constraint violations. The latter objective introduces an important issue – the efficient handling and satisfaction of the problem constraints. To this end, it is convenient to model the plant using the Mixed Logical Dynamic (MLD) framework [3]. This does, however, involve relatively complex mathematical techniques.

The issue of model tuning and adaptation also has to be solved. Indeed, model-based control relies on the ability of the models to represent the real plant to a certain degree of accuracy. ABB ensures the correctness of this assumption through the use of parameter identification techniques. Subspace identification, Kalman filtering, and neural networks are used extensively to identify model characteristics (parameters, etc), estimate non-measurable physical values (volatility coefficients, etc), and forecast boundary conditions such as power prices, fuel availability and market constraints **2**.

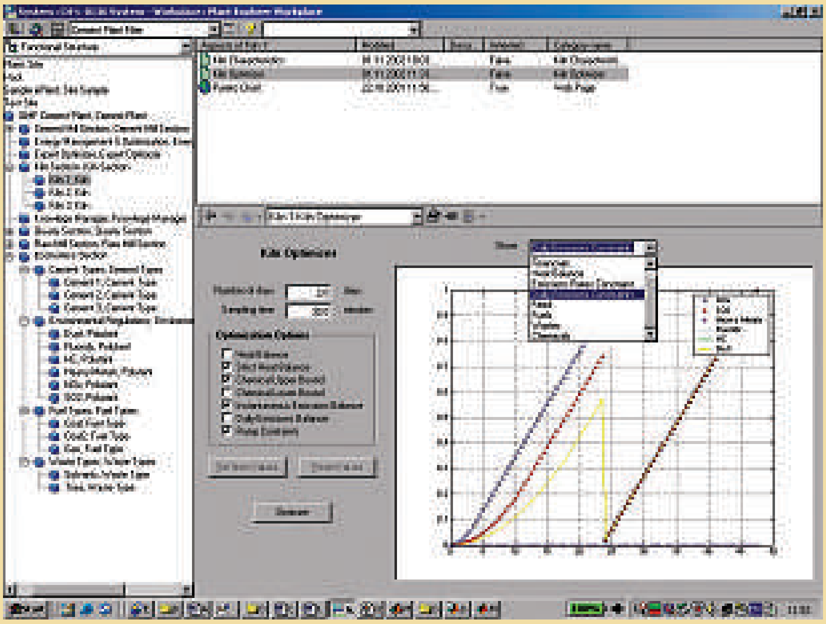
Together, these mathematical techniques provide a comprehensive and flexible toolbox for tackling the overall economic optimization of industrial plants.

ABB's Industrial^{IT} vision for the cement industry

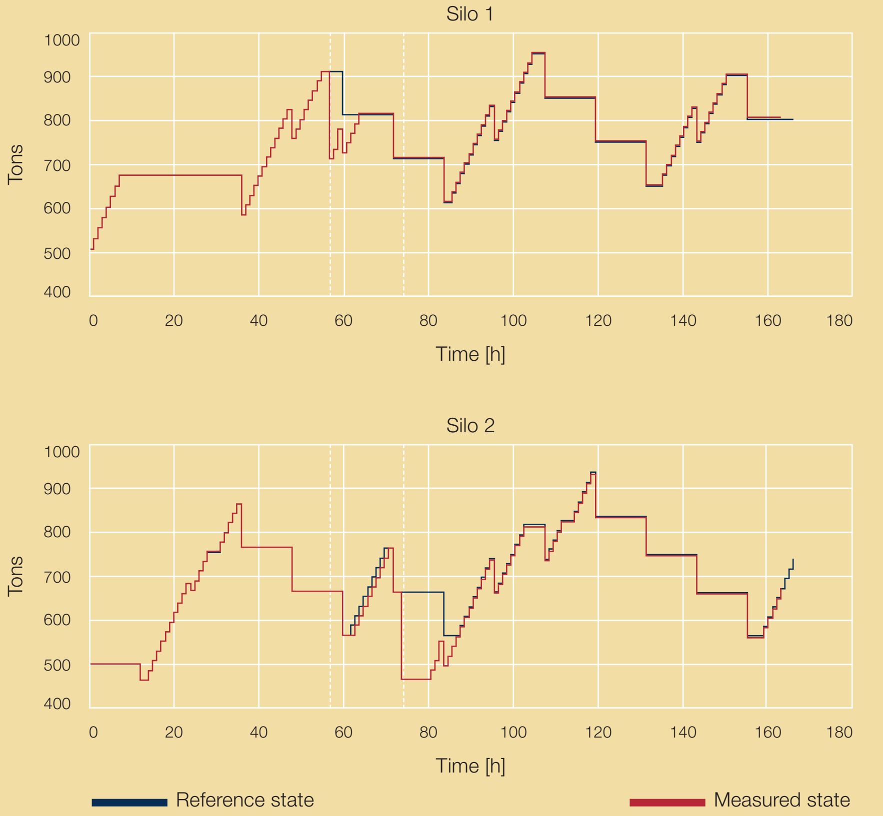
Thermal energy management: kiln fuel mix optimization

ABB already offers the cement industry a state-of-the art product for stabilizing and optimizing kiln operation. Called Expert Optimizer, it builds on the excellence of its predecessor, Linkman Graphics. The Expert Optimizer system

3 Implementation of the new algorithms for kiln fuel mix optimization



4 Cement grinding plant scheduling: silo levels



combines rules-based control with modern tools like neural networks and fuzzy control.

In addition to Expert Optimizer, ABB's cement portfolio is now being enhanced with an Alternative Fuels Optimization module. Developed to meet the industry's need for a tool that will allow optimal management of alternative as well as traditional kiln fuels, this module can significantly enhance the economic performance of kilns.

The module uses data gathered by the various information management systems to calculate *online* the lowest-cost fuel mix able to satisfy the process and business constraints. These can be numerous, and may include the heat balance, excess oxygen level, clinker chemistry, volatiles concentration, emission limits, actuator speed change, operative constraints on fuel consumption, and contractual conditions.

A dedicated mathematical model, developed in Matlab/Simulink™, is used to implement the (model predictive) controller. This model can estimate cooler, flame, burning zone, back-end and preheater temperatures, kiln energy requirements, emission and volatiles levels, etc. The model parameters are tuned using a combination of neural networks and Kalman filtering techniques. The optimization algorithms are able to cope with both hard and soft constraints, which considerably enhances the reliability of the optimization process.

The input data are updated at sampling times of 15 to 30 minutes, and new process setpoints are computed and passed to the Expert Optimizer strategy for implementation. Between samplings, the 'standard' Expert Optimizer strategy guarantees process stability and highest performance. In particular, this strategy enforces an economically optimal response to changing conditions in fuel, waste and raw meal quality, as well as ensuring strict satisfaction of the environmental, contractual and technical constraints.

A prototype implementation of this algorithm is currently being tested at a Swiss cement plant, where it is improving operating profits 3.

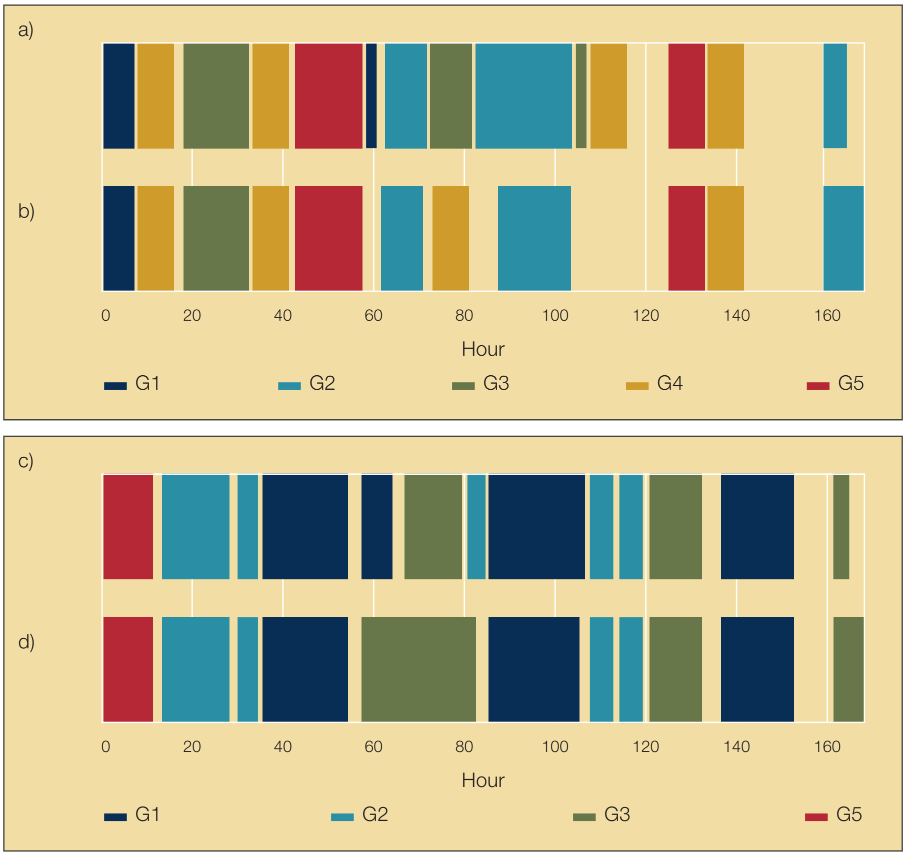
Electrical energy management: cement grinding plant scheduling

In the final stage of cement manufacturing, clinker is ground with additives. The different cement types, or grades, are defined by their chemical composition and particle size. Grinding takes place in huge mills, where rotating steel balls crush the material until the required grain size distribution is reached. The produced cement is then conveyed to different silos according to grade before being packaged and shipped to customers.

This solution provides a powerful tool for monitoring and adapting organizations to changing micro and macro needs.

Cement mill scheduling, ie deciding when to produce a certain cement grade and in which mill, is currently performed manually, using heuristic rules and relying on operator experience. However, the numerous mills, grades and silos, plus the various operating constraints, make the problem a complex one. Too often, the operator's choices are far from optimal.

5 Inner-loop MPC response: on/off control sequence



Mill 1
a) MPC weekly scheduling
b) Reference scheduling

Mill 2
c) MPC weekly scheduling
d) Reference scheduling

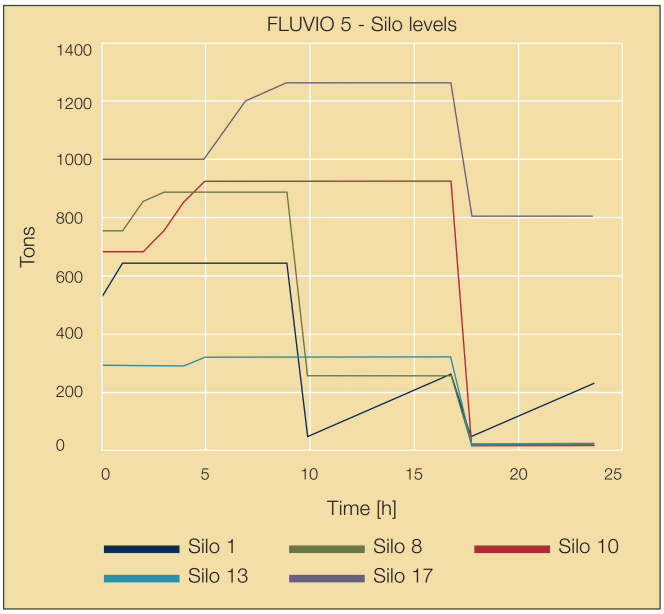
Based on customer orders and energy price forecasts, an outer-loop MPC is executed at least once a week and its output used as a reference schedule for mill operation. Here, the cost functional represents costs associated with electricity consumption and the amount of low-grade cement produced (cement produced during the switch from one grade to another). Electricity cost reduction is achieved by committing the production to time periods when the tariffs are lower, and by managing the mills in such a way that contracted thresholds of maximum electrical power are not exceeded. Reductions in low-grade cement are obtained by penalizing the number of production switches. The cost functional also includes components related to soft constraints.

Unplanned events, such as component failures or unexpected sales are, however, frequent, and an inner-loop MPC is used to react to these disturbances. In this phase, the state variables are the silo levels, and the control variables are the switching commands to the mills. The cost functional is a weighted sum of deviations from the values given by the outer-loop MPC reference schedule. The typical sampling time is one hour.

Apart from the physical constraints imposed by the silo capacity and mill availability, there are several other constraints to consider:

- *Transition time:* Grade changes can cause delays, during which the mill's output is conveyed to a special silo.
- *Order fulfillment:* The optimization algorithm requires sales forecasts for every grade as input. If the sales forecast cannot be completely fulfilled, the algorithm will choose the grade to be produced first according to a given ranking.
- *Conveyor belts:* Possible constraints here include the possibility that there might be three mills but just two independent conveyor belts. (Multiple mills can simultaneously discharge the same cement grade to the same conveyor belt. However, belts can serve only one silo at a time and silos can be served by only one belt at a time.)
- *Silo content:* Only one cement grade can be stored in a given silo.

6 Silo levels for the one-day scheduling scenario shown in the table opposite

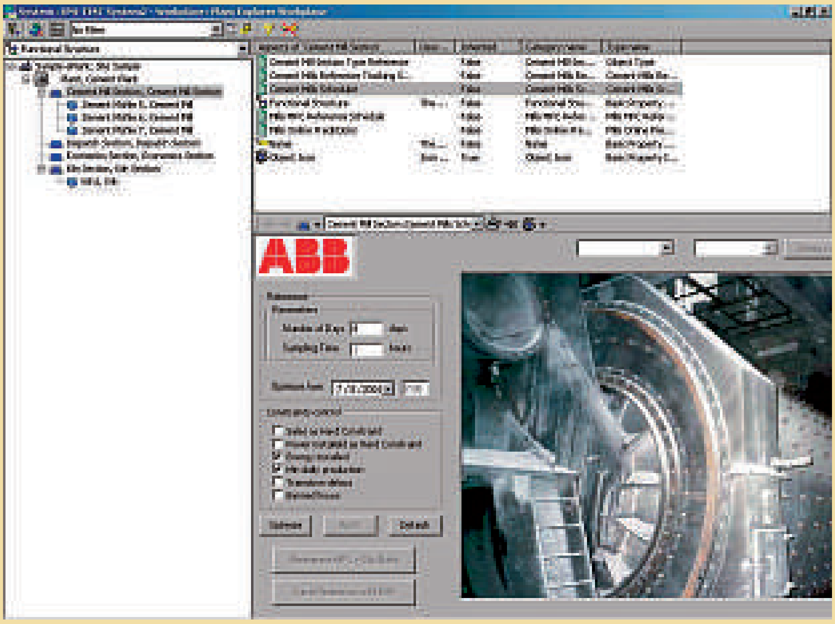


An example of rescheduling capability is shown in **4**. The blue line represents the precomputed reference levels for silo 1 and silo 2, while the red line shows the actual silo levels measured by online sensors. The deviation from the reference in silo 1 at the 57-hour mark is caused by the sale of cement exceeding the forecast.

The inner-loop MPC response for mills 1 and 2 is shown in **5**. It can be seen how the inner-loop MPC reacts immediately to the deviation, committing both mills at time t = 58 to the production of grade-one cement.

Two more things need to be specified to complete the schedule: the actual silo to which the cement grade is to be transported and the actual belt to be used. In addition, it has to be decided from

7 Grinding plant scheduler – graphic user interface



One-day schedule (simulated results for a cement plant in Switzerland)

Time	Mill 1			Mill 2			Mill 3		
	Cement	Belt	Silo	Cement	Belt	Silo	Cement	Belt	Silo
1	FLU5	B	1	FLU5	B	1	–	–	–
2	FLU5	B	8	FLU5	B	8	–	–	–
3	FLU5	A	8	FLU5	B	10	–	–	–
4	FLU5	B	10	FLU5	B	10	–	–	–
5	FLU5	C	13	FLU5	B	10	–	–	–
6	FLU5	B	17	FLU5	B	17	FOR5	A	3
7	FLU5	B	17	FLU5	B	17	–	–	–
8	FLU5	B	17	NOR4	C	2	–	–	–
9	FLU5	B	17	NOR4	C	2	–	–	–
10	FLU5	B	17	NOR4	C	2	–	–	–
11	FLU5	B	17	NOR4	C	2	–	–	–
12	FLU5	B	17	NOR4	C	2	–	–	–
13	FLU5	B	17	NOR4	C	2	–	–	–
14	FLU5	B	1	NOR4	C	11	–	–	–
15	FLU5	B	1	NOR4	C	2	FOR5	A	3
16	FLU5	B	1	NOR4	C	2	FOR5	A	3
17	FLU5	B	1	NOR4	C	2	–	–	–
18	FLU5	B	1	NOR4	C	2	FOR5	A	3
19	FLU5	b	1	NOR4	C	2	FOR5	A	3
20	FLU5	B	1	NOR4	C	2	FOR5	A	3
21	FLU5	B	1	NOR4	C	5	FOR5	A	3
22	FLU5	B	1	NOR4	C	5	FOR5	A	3
23	FLU5	B	1	NOR4	C	5	FOR5	A	3
24	FLU5	B	1	NOR4	C	5	–	–	–

which silo the cement will be taken to fulfill a given customer order. The *table* (this page) shows, as an example, the simulated results for a cement plant in Switzerland. As can be seen, mill 3 is largely idle. The silos are ranked in the order in which they are to be filled and emptied. In the case of grade FLU5, for example, silo 1 has the highest ranking, followed by silos 8, 10, 13 and 17. From the table and the silo levels shown in 6, it can be seen that FLU5 is first conveyed to silo 1. This silo is filled to its limit (640 tons) at time t = 1, after which the product is diverted to other silos with a lower priority. Sales, which begin at t = 10, result in silo 1 being emptied first, followed by silo 8. Immediately afterwards, the conveyors begin transporting the cement again to the highest-ranked silo – silo 1.

7 shows the main graphic user interface for controlling the scheduling modules.

Where customers benefit

The direct benefits of the described solution are estimated to be a saving of up to 5% in thermal and electrical energy, a reduction in low-grade cement, more stable operation, consistent clinker quality, strict emissions control, and lower maintenance costs.

Other less tangible, although not less important, benefits are the total integration of vital process data for both closed-loop and open-loop optimization, active KPI monitoring, the single process control interface, and the foundation laid down for developing value-added applications that address customers' needs.

This solution provides cement plant managers with a powerful tool, capable of monitoring their organizations and adapting to changing micro and macro needs. By implementing it, customers can expect lower costs, a consistently higher quality, environmentally sound processes, fast payback and a larger return on investments.

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