THE IMPACT OF EXPERT SYSTEMS IN THE OPERATION OF A LIME KILN

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INTRODUCTION

Kiln automation is accomplished by the skillful combination of three basic elements:

1. reliable process measurements and actuators;
2. repeatable and accurate process controllers;
3. successful implementation of a strategy for maximizing kiln performance.

These three elements are required for success. The order of implementation must be 1, 2 and 3; any other order leads to failure. This paper discusses the third and final element, which is usually implemented using “Expert Systems”. Expert systems optimize the kiln operation, train the operator, and help to identify plant deficiencies. They are configured to meet the requirements and peculiarities of each individual kiln.

The expert system relieves the operators from trying to remember long sequences of operation and all the various remedies to recover from upsets. The expert system suggests or implements the best response to “off spec” operating conditions. The diagnosis and explanation of these actions are a powerful tool for the operator to better understand how the kiln works and how its performance can be improved.

THE THREE W’S

What is an Expert System?

First, we want to define what an expert system is. An expert system is basically a program that runs and executes a set of rules in the form: IF conditions, THEN actions.

The program is designed in such a way that it can resolve the different rules to lead to the expected results.

Edward Feigenbaum [1] defined an expert system as:

> “An expert system is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. Knowledge necessary to perform at such level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners in the field.”

Why Do We Need an Expert System?

As stated in the definition above, the goal of the expert system is to replicate the expertise of the best practitioners in the field. Once the logic is encapsulated in the rules, it will:

- produce consistent results (the expert system is not submitted to outside pressure; it does not get bored or tired);
- preserve knowledge (knowledge stays within the company; an experienced operator changes jobs or moves);
- knowledge is permanent (human expertise is perishable);
- establish new procedures (during the exercise of the knowledge base building, the process is analyzed to detail, limitations are determined, operational ranges defined, etc.);
- explain the results (it displays the reasons behind a particular action).

When Do We Need an Expert System?

After plant upgrades up to the standard automation level are completed. Typically, this includes the following upgrades:

1. Electrical and mechanical equipment upgrade (motors, dampers, etc.);
2. Instrumentation upgrade: reliable process measurements and actuators (thermocouples, flow transmitters, level transmitters, etc.);
3. Control system upgrade: Programmable Logic Controller (PLC) or Distributed Control Systems (DCS);

Once the plant has been upgraded, the expert system can be successfully implemented.

CONTROL STRATEGY

The typical problems encountered in lime kilns are:

- inefficient use of fuel;
- short refractory life;
- product quality variations.

To address these problems, goals must first be defined. We want to control the calcination process within the kiln based on the following premises:

- maximize production;
- minimize fuel consumption;
- maintain the produced lime within acceptable ranges in Loss-On-Ignition (LOI) and reactivity.

In order to do this, the following parameters need to be controlled and kept under pre-determined ranges: kiln speed, raw material and combustible feed, air flows, cooler level, temperature profile, firing hood pressure and other variables. Control of the kiln is a complex control task exhibiting long time delays and subject to unmeasured disturbances and variations in stone and fuel. If we add variability in measurements (oxygen analyzers, material feeders, etc.) and noisy signals (air flows, kiln draft), we have all the ingredients to make the control of such a system a challenging and demanding task even for experienced operators.

Kilns run 24 hours a day, 7 days a week, therefore operator shifts need to be implemented. This is another characteristic of kiln operation, the human interaction. It is very common to find that operators will have different ways to burn, various responses to disturbances and are guided by somewhat diverse temperature profiles. In addition, kilns are processes having large capacities and long time delays, which represent a problem to an operator who is usually busy dealing with current situations and does not pay enough attention to the long-term effect.

It is part of human nature to discard from memory past observations; when current stimuli are considered relevant, humans move back or eventually discard previous information that was being processed. This is a shortcoming of human operators that can be detrimental for the appropriate control of large capacity processes. This is why the same operator often reacts in a different way when subjected to the same or similar conditions. In many cases, operator actions are the primary source of disturbances upsetting the kiln.

In order to bring more consistency and better control in the lime kiln operation, advance control strategies are required to counteract the process characteristics and the human limitations. Our approach is a hierarchical control system. An expert system is used to encompass the operational knowledge in the rule-base and a predictive-adaptive controller is used to maintain the key variables close to the desired set points.

In the past, several systems have been implemented to deal with the kiln optimization. Mathematical modeling, statistical processing, fuzzy logic, expert systems, adaptive control and others [2]. In some cases a solution will use a combination of techniques; in our case we developed an adaptive controller and then the expert system. The expert system approach using IF-THEN rules has proven to be effective and "user friendly".

CONTROL SYSTEM HIERARCHY

The expert system application is usually the last step or at least a step further in the optimization of the process. As mentioned earlier, there are several technical prerequisites for proper implementation of an expert system. In general, the plant should be able to run steadily and safely under manual kiln control.

Fig. 1 shows the hierarchical system developed for a typical automation project. The different levels are shown.

Moving up in the pyramid will give us more global processing as the modules deal with the interaction of several variables and the general state of the kiln. At the same time, the modules operate more slowly as they take into consideration averages and historical process values, not only the current values.

It must be stressed that the lower level tasks of the pyramid must be functioning properly for the higher levels to perform optimally.

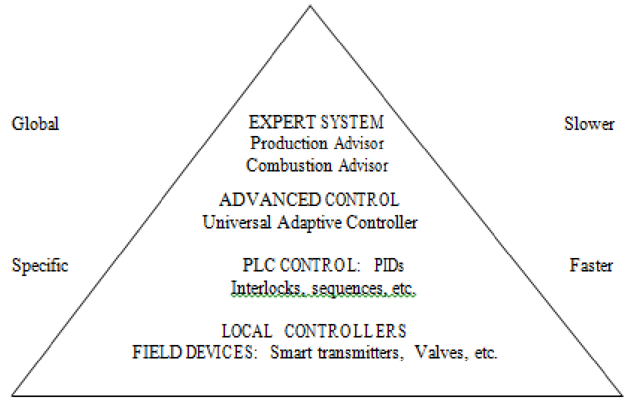

Fig. 1. Control System Hierarchy

THE EXPERT SYSTEM

We decided to use a commercial expert system shell. The tool selected needed to comply with the following criteria:

- an established and well known commercial product;
- true rule-based knowledge representation;
- no need for any programming language (C, Prolog, LISP, etc.);
- expert system engine with back and forward chaining, object oriented;
- tool kit to interface to real-time databases;
- report and troubleshooting utilities;
- fuzziness, certainty factor;
- reasonable cost.

The software shell selected satisfied most of the above requirements.

A graphical rule browser is a very valuable tool for designing and troubleshooting. This is a feature that allows users to understand the rule tree and experiment with it. This tool is available offline.

The expert system diagnosis capability is one of the most important features. Each rule has an explanation field that can be displayed if the rule was fired and the result is true. In this way, the operator will be informed "why" the Advisors are proposing or executing, depending on the Advisor mode, this or that action. This property allows us to include "semantic statements", in plain English, which are related to the kiln state and operation. The "why statements" can be modified online, providing the option to change the relevance of a particular result based on a different situation in the kiln.

KNOWLEDGE ELICITATION

One drawback in successfully implementing a real-time expert system is the time-consuming task of knowledge elicitation. Process knowledge needs to be collected, processed, analyzed and transformed. The knowledge, facts, premises, process conditions as well as any other particular heuristic needs to be encapsulated into the rule knowledge base.

The basic framework of our knowledge bases was developed following the results of previous applications [4] and personal interviews with our in-house experts and the customer's experts. In addition, extensive field verification such as recording data and performing trend analysis, using statistical tools (data cross-correlation). The disseminated knowledge needs to be concentrated into the rules.

Experts and operators are usually interviewed in several informal sessions. The main parameters to be controlled and the global strategy are established during these sessions, having as a reference point the operator's expectations and needs as well as our experience gained during previous applications. Fig. 2 shows a diagram with the different parts involved during this task.

The knowledge elicitation process is much quicker and better results are achieved if the "Knowledge Engineer" already has first-hand lime plant operating experience.

Human Behavior

Intrinsic to any expert system development is the human behavior to be considered. It is the aim of any expert system to transfer human experience and knowledge to a set of rules, procedures, objects definitions, etc. The final product of this translation will be used by human operators; human behavior is then a very important aspect.

Subjective and biased knowledge needs to be filtered by the knowledge engineer during the elicitation process.

Modeling human reactions to process states or events requires an understanding of the human attitude towards the process and the new control system as there are subjective parameters affecting human reaction. In a typical plant, we may find a wide range of human attitude to the new system: True Believers, Open Minded, Curious, Skeptic, Fearful and Contrary.

Therefore, during informal interviews and time spent with the experts, supervisors and operators while they are controlling the kiln we have to deal with some of the previous psychological aspects.

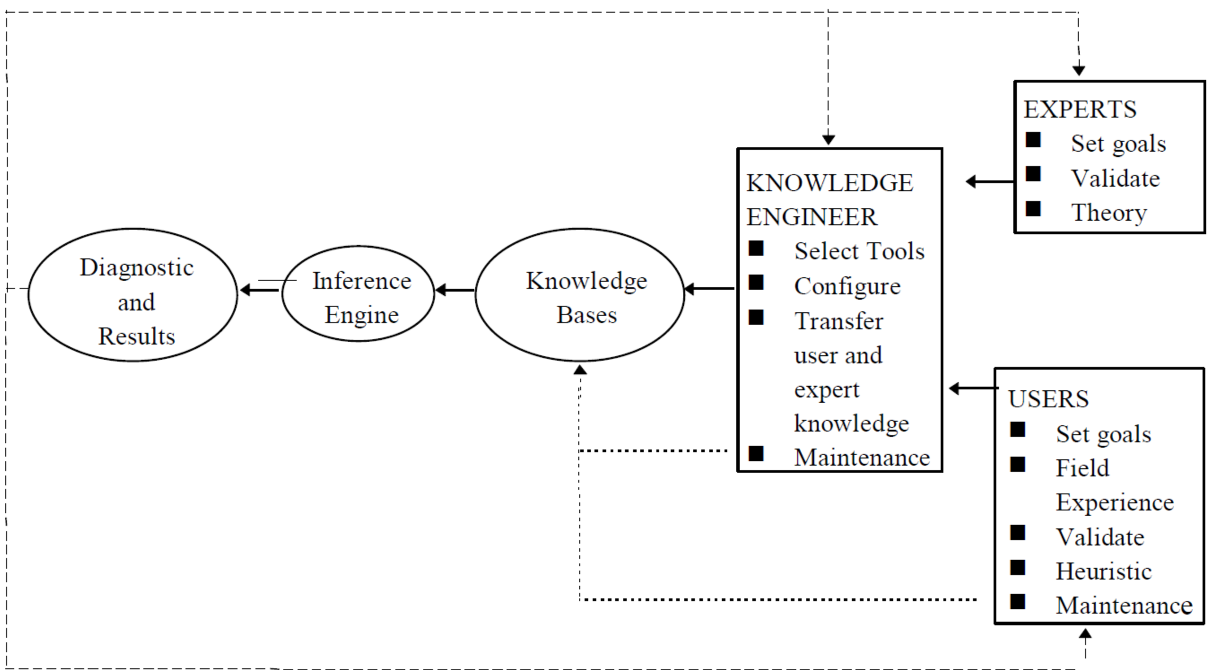

Fig. 2. Knowledge Elicitation

Plant Limitations

We say that the expert system helps you to identify the plant limitations and deficiencies because during the development process the process operation is scrutinized and studied in detail. The different burning procedure, empirical data, theoretical background, kiln particularities, etc., are all included in a large bag of knowledge that will lead to the expert system rules. The expert system Advisors work with the data coming from the sensors and the process devices. We need to know where the limits are and we need to identify the plant deficiencies to counteract them, if possible.

Fig. 3. Bag of Knowledge

We recognize that every plant is different, and even within a plant, every kiln is different. It has its own signature and this is due to different wear and tear, repairs, shared devices, etc. The expert system Advisors are aware of these differences and are configured to deal with them.

The Advisors

Several approaches using expert systems are based on the well known “27 Basic Kiln Conditions” for Cement Kilns [5]. These 27 conditions are the combination of the Burning-zone temperature, Back-end temperature and Oxygen. Depending on the status, high, normal or low on each variable, 27 basic conditions can arise. This is a simplistic approach, but is general for almost every kiln. We chose to build two knowledge bases, one mainly devoted to control the production, i.e., the stone feed and kiln speed, and the second one to monitor and control the fuel combustion in the kiln.

All 27 basic conditions are included implicitly in our knowledge bases but we did not structure our rules based on just these 27 conditions. In addition to the static state of the kiln, we also look at the direction and rate of change of process variables. When these other conditions are included, the basic number of states climbs to several hundreds. As we recognize that every kiln is different we prefer to deal with each kiln individually and build the rule tree based on real data and our extensions on “reasoning with time”.

Combustion Advisor

The Combustion Advisor automatically adjusts the:

- Fuel feed rate,
- Primary and Secondary Air Flow,
- Kiln Draft or Firing Hood Pressure, and
- Combustibles and Oxygen levels

to maximize the heat input to the kiln in the most efficient manner within the limits set by the kiln operator. The Combustion Advisor looks at the Oxygen and Combustibles readings from the flue gas analyzer, checks the limits on the fuel feed rate, primary air, secondary air flow, kiln draft (firing hood pressure) and the cooler discharge temperature and determines what changes (if any) in fuel rate, air flow or kiln draft will achieve better burning.

Production Advisor

The Production Advisor automatically adjusts the limestone feed rate to the kiln to maintain a predetermined kiln temperature profile and maximize production. The kiln temperature profile can be related to lime Loss-On-Ignition (LOI) and reactivity test. Stone size and chemistry also affect this relationship.

For a given amount of heat input to the kiln there is a particular stone feed rate at which the kiln temperatures are stable. If the heat input to the kiln increases, then lime production will automatically increase. If the heat input to the kiln is constant and the stone feed rate is increased, the kiln temperatures will decrease and stabilize at lower values and vice-versa.

It takes several hours for the stone feed to travel through a preheater and kiln and be converted to lime. For example, in a long kiln, a change in the stone feed rate will not significantly affect the kiln firing hood temperature for at least three hours. This long time lag between cause and effect makes the kiln difficult to control. If changes to the stone feed rate are made before the effect of previous changes are measurable, there is a good possibility the kiln temperatures will swing widely for a period of hours.

In addition to the main knowledge bases, our system has other modules to assist the Advisors in controlling the Bed-Depth and take fast action on the Oxygen.

Reasoning with Time

One drawback of continuous controllers (typically PIDs) is that they consider current values only or at the most past values indirectly. The expert system rules are evaluated periodically; they base their results on current values and on historical values and actions.

The expert system advisors will accumulate values from the previous iterations and it will infer based on the change, rate of change and direction in what we call a reasoning with time procedure.. This is similar to an operator browsing trend charts to discover any trend in the process value. This is a powerful mechanism to deal with time delays and cycling.

Pre-processing Values

The values coming from the transmitters are usually noisy; filtering and smoothing need to be done. In addition, some values like oxygen exhibit normal variations that cannot be filtered. Averages are used to avoid short-term control variations as a result of these process variable fluctuations.

Online Cross Correlation

Even if we do not have a precise statistical calculation, the rules have embedded logic and associations to take actions based on the status of different variables at the current time and previous iteration. Actions are rarely taken based on one variable. Usually, for the reasons already explained, actions are calculated on the interaction and relationship between different parameters in the kiln.

Results Explanation

The expert system diagnosis and the explanation of the action are very powerful features that help the operators accept the new system and demystify the fact that the expert system will take full control of the process, making changes automatically without any further input.

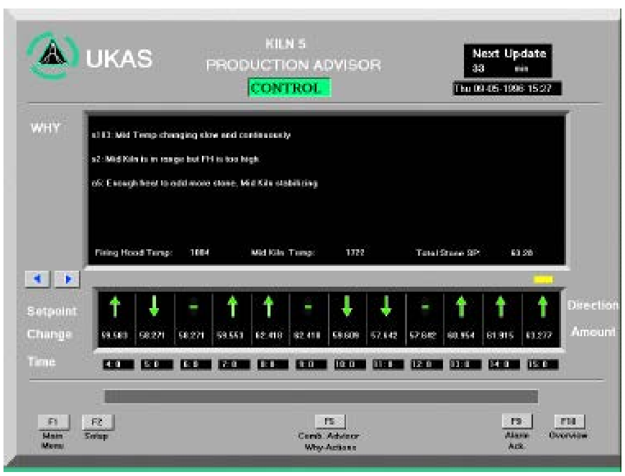

Fig. 4. Production Advisor Operator Graphic with ‘Why actions’

CONTROL LOOPS

The Advisors role is to determine new set points but it is the task of the loop controller, in our case a predictive-adaptive controller, to move the control device to achieve the new set point and keep the process variable as close as possible to the set point.

The adaptive and predictive features combined with the ability to configure feedforwards is of utmost importance in dealing with difficult control loops. A typical application is control of an I.D. fan damper subjected to frequent pressure spike disturbances coming from a Baghouse reverse air fan. Attempts were done in the past to control this loop using PIDs, with no acceptable results. Once the predictive-adaptive controller learned the model, it was put online and has been keeping a steady draft with excellent results. The Baghouse pressure was used as a feedforward to palliate the reverse air fan disturbance.

LIMITATIONS

The computer is limited to acting only on the information it receives. The kiln operator has access to a much larger amount of information about plant equipment, including unusual sights, sounds and information from plant personnel, which are normally not available to the computer. For this reason, the kiln automation system is designed to operate in steady-state conditions. The kiln operator must take over operation of the kiln during start-up, shutdown and major plant upsets. The kiln operator must be ready to step in when kiln instrumentation fails or gives erroneous signals. Similar to cruise control on a car, the driver must respond to engine trouble or a flat tire.

Fig. 5. Production Advisor Setup Display

No kiln automation system can function unless all the kiln sensors, actuators and drives are kept in good working order. It is pointless to try to optimize the operation of the kilns unless there is a strong commitment to maintain the kiln instrumentation.

POTENTIAL PROBLEMS

Operator Acceptance

This is a key factor in any control system development acceptance. Some of the operators perceived the new system as a threat and they simply could not believe that the computer could control the kiln in an acceptable way. After some training and the results of the system online, they were progressively eliminating their reservations to the point that they considered the Advisors as allies.

Unknown Kiln State

Sometimes, due to faulty instrumentation (blockage in flow measurements, O_2 analyzer, etc.) the rule base would not determine what is the kiln status as it is confronted with contradictory data. This leads to an undetermined kiln state and the Advisor will eventually hold, it will not take any further action but it will inform the operator about this situation.

Programmed Mistakes

Care should be taken when the rules are implemented as modeling human behavior may duplicate that person's tendency to make mistakes. This can be limited by having a consensus approach in which the statements of an expert are not the only source for the knowledge base determination. In addition, the knowledge base must go through a validation process when the system is going online.

RESULTS

The results during the first months of operation of a typical automation project can be found in Bittante [2]. Presently, the same system has almost two years of operation and the results confirm the goals that were established for the project. The benefits of an expert system can be divided in two categories:

Quantitative

- Increased Production
  Production is typically increased 10% or more on older kilns.
- Decreased Fuel Consumption
  The fuel consumption is typically reduced by 5% to 10%.
- Improved Product Quality
  The variability of LOI and reactivity are reduced by 20 to 30%.
- Increased Refractory Life
  The thermal stress on the burning zone is reduced by having the adaptive controller in the Firing Hood Pressure control that leads to a more stable flame.
- Decreased Ash-ring formation
  Ash-rings formation is reduced. Ash rings affect production directly as the kiln has to be stopped for shooting and dislodging the ash ring.

Qualitative

- Process Data
  The Plant has access to records of process data that can be used for offline analysis.
- Availability
  Downtime of the kilns due to cycles or unstable situations is reduced.
- Improved process knowledge
  After the exercise, plant personnel will have a better insight to their process.
- Decreased variations due to shift operation
  The new control system standardizes the control strategy and the operation procedures.

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