Getting the most from ADVANCED PROCESS CONTROL

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Advanced process control offers substantial savings, and requires less investment than you may think

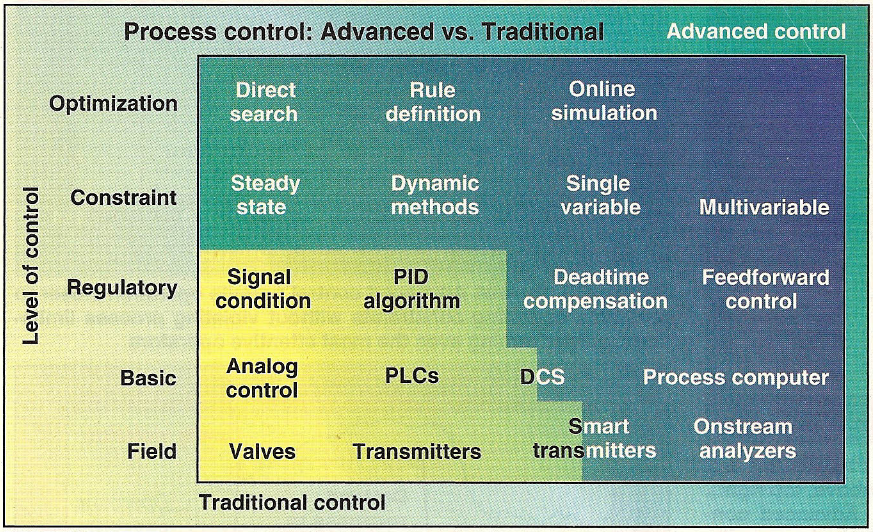
As computer hardware becomes less expensive and sensors and control equipment improve, more companies are using advanced control (*CE*, March, 1992, p. 41) to boost the efficiency and reliability of their process plants. Established since the 1970s in the oil refining and petrochemical industries, advanced process control and optimization techniques are now being used in more chemical plants.

As a result, many engineering and consulting firms now specialize in advanced control, and over 600 such systems have been installed over the last decade. Applications for the technology are growing along with demand for better product quality and more efficient, less-polluting processes.

A dynamic business is reflected in recent mergers and spinoffs, including Hartman and Braun GmbH's (Frankfurt) purchase of Applied Automation, Inc. (AA; Bartlesville, Okla.), AA's spinoff of its process control unit to Johnson-Yokogawa (Newnan, Ga.), Honeywell Icotron's (Phoenix, Ariz.) buyout of KBC Advanced Technologies' process control unit (Southampton, U.K.), and Setpoint, Inc.'s (Houston) merger with Ipcos B.V. (Best, Netherlands).

Advanced control (box, pp. 80 and 81) automates regulatory and constraint control as well as process optimization. It is particularly suited to dynamic processes and complex operations, such as cogeneration plants, in which there are many interactions between units. The technology is already being used in plants that make ethylene oxide and glycol, caprolactam, terephthalic acid, butadiene acrylonitrile, ethylbenzene, aromatics and polymers, as well as yeast reactors and carbon dioxide recovery units.

Studies [*1,2*] have shown advanced process control to save 2-6% of annual operating cost (box, p. 87), and to generate about 1% in extra revenue. Companies with the most advanced systems



The evolution of process control is mirrored by the move to smarter instrumentation. Advanced control extends the reach of PID devices to more-complex processes. Even batch processes can benefit

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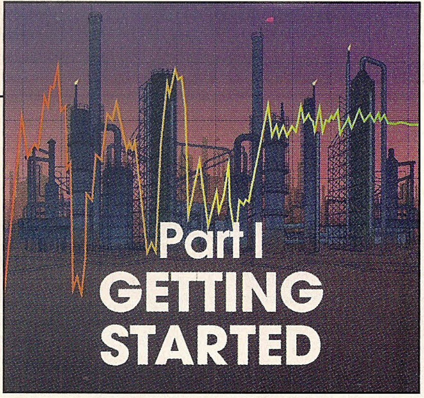
Operator acceptance is the key to success for any advanced control project, and two-way communication is crucial. As you promote any system, heed operators' opinions and address their needs, or you may be unpleasantly surprised

save an average of 15% of manufacturing costs [3]. While the systems can be expensive, payback usually takes less than two years.

More companies may be realizing the benefits that advanced process control offers, but the technology is still misunderstood. For many in the chemical process industries (CPI), it conjures up visions of wall-to-wall computing, pages of impenetrable matrix equations, and substantial cost.

As a result, many managers today still find it easier to approve major "heart surgery" projects, such as replacing the internals of a reactor, than investing in process control improvements – even though the control changes would cost far less, and lead to greater improvements in productivity. For many, the prerequisites for advanced control – digital controllers, computer hardware, and online instrumentation – are already in place, but are not being used to their full potential. As a result, many facilities are achieving 20% of the potential benefits of advanced control for 80% of its cost.

The following articles offer: an overview of advanced control engineering, with tips on evaluating existing equipment and choosing vendors; practical examples of CPI applications (p. 82); and advice on estimating the costs and benefits of advanced control, with CPI case studies (p. 86). ❐



Part I
GETTING STARTED

ARE ALL SYSTEMS 'GO?'

Since, for many plants, most of what is required for advanced control is already in place, the first step is checking your existing process control equipment. Here, it is essential to start at the first level – that of field instrumentation, including transmitters for flow, pressure, level, and temperature, as well as control valves.

Instruments that work adequately for basic control and manual operation may not be able to support advanced control. Many projects come to grief because basic controls were neglected. As higher levels of control are commissioned, such problems as poor transmitter ranging, control valve rangeability, and controller configuration and tuning show up.

The following questions are useful when evaluating field equipment:

1. Are transmitters correctly ranged and calibrated? Is their linearization correct?

2. Are control valves correctly sized and calibrated? Do they stroke correctly?

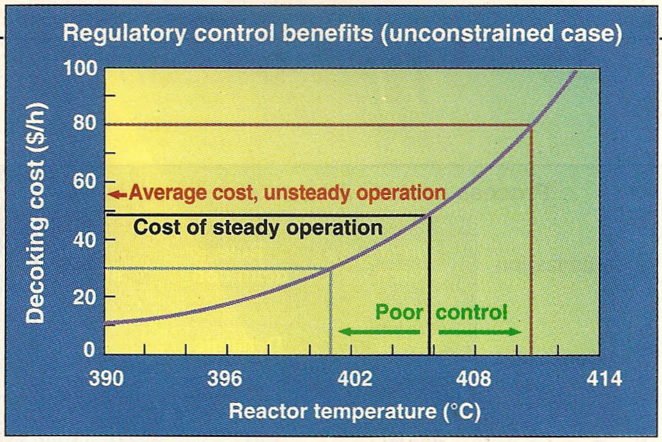
3. Has the best control algorithm been selected?

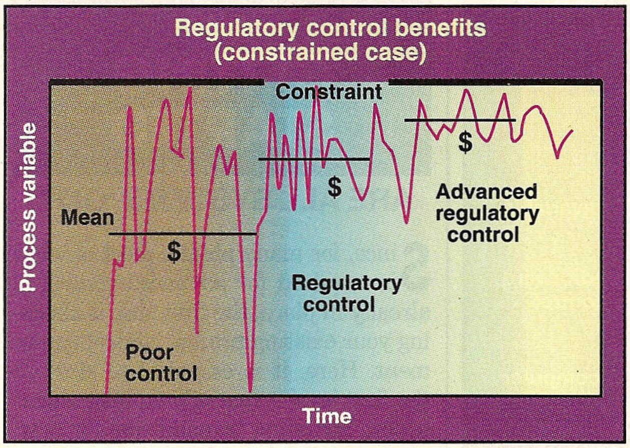
4. Is noise filtered correctly?

5. Have the controllers been tuned correctly, to account for changes in load or setpoint?

Correcting such problems is essential, but time consuming, and can significantly delay the installation of the real "moneysaving" control applications. Additional instrumentation may be required – particularly sensors (news update, p. 37). In the past, these had a reputation for being unreliable and hard to install and maintain. Lately, however, vendors have started tailoring their products to customers' needs – including the need for systems compatible with continuous process control. Near-infrared (NIR) is one technique that makes this possible [4].

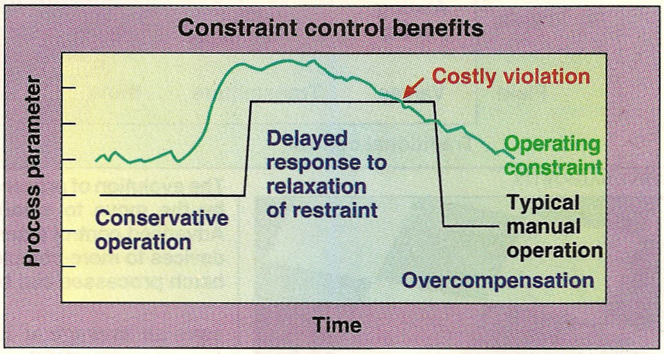
Another critical step is involving plant staff, since advanced control can only succeed if it is accepted by opera-





FIGURES 1 & 2 (above, top right). Advanced control raises quality hurdles, pushing optimum operating levels beyond what is possible with regulatory control alone

FIGURE 3. (below) Advanced control permits operation closer to profitable operating constraints without violating process limitations, outperforming even the most attentive operators



tors. Most processes run continuously for 168 hours a week. Process-support personnel, including process control engineers, are only on site for a fraction of this time, and operators who are uncomfortable with new systems can easily shut them off and go back to manual control, without having to explain why.

Generally, advanced control succeeds best in plants whose companies are committed to the technology and believe that it works. This commitment should start with senior managers, who should be proactive in ensuring that the technology is fully exploited, and hold their subordinates accountable for its success. On sites without this support, control engineers spend most of their time convincing others to use the technology and tracking down cases where applications were disabled by operators, for no apparent reason. The following may prevent such problems:

1. Listen to what plant operators see as the major problems with existing control systems, and address their needs
2. Train operators in the purpose, profitability and operation of advanced control
3. See to it that interfaces are "user friendly"
4. Get operators to recognize the benefits of advanced controls without making their work unnecessarily complex

After field instrumentation, the next level in the control hierarchy is the process controller. Here, cost is less important than how readily the system can support the technology required for advanced control. Tuning is critical, as discussed on p. 85.

By now, most companies have upgraded their older plants, replacing pneumatic or electronic analog models with digital systems. In many cases, however, few of the systems' additional capabilities are being used.

Regulatory control

For batch processes, this level in the hierarchy probably generates most of the benefits. A well automated batch process will manufacture the product in a repeatable way, resulting in consistent quality and allowing operators to experiment with varying conditions, to identify and exploit potential improvements. This can shorten batch times, allowing for production increases or more-flexible grade changing.

In continuous processes, benefits can arise from more closely approaching operating limits, as shown in figure 1. Highly nonlinear processes, such as those which produce unwanted coke (figure 2), can also benefit. In this process, cost varies with reactor temperature. This should ideally be 406°F, but, because of poor control, it varies by ±5°F. The cost of decoking at the higher

WHAT IS ADVANCED CONTROL?

The typical process control setup is hierarchical, starting with field instruments such as sensors, and moving on to digital control units. Each higher level control system passes setpoints to, and receives feedback information from, the lower level. Typical setups use single-loop controllers, each governing a primary process variable, such as flow, pressure, or temperature, based on one or more sensor signals.

The next level is regulatory control, in which the process is maintained at preset conditions, primarily through the use of proportional integral derivative (PID) devices. This is followed by constraint control, in which the operator specifies setpoints for each variable. The top level is process optimization.

Advanced control comes into play from the level of basic control through that of process optimization. Instead of having operators manually adjust control units for specific variables, advanced systems provide generalized models that automate regulatory and constraint control, as well as process optimization. In regulatory control, "feedforward" techniques can be used to supplement PID, to predict the impact of an upstream change in the process to adjust for it downstream to prevent a disturbance. Deadtime compensation techniques can also be applied to compensate for long delays in process response, permitting tighter controller tuning.

At the level of constraint control, multivariable techniques can be used. These are linear dynamic models of the process that can predict how it will respond over time to temperature is $80/h, versus $30/h at the lower, for an average decoking cost of $55/h. Improving the control to eliminate the temperature variation would reduce the cost to $49/h, saving about $50,000/yr. In other cases, advanced regulatory controls may not, in themselves, offer a fast payback, but are necessary to permit savings at higher control levels.

Constraint control

For continuous processes, more than half the gains to be realized through advanced control are made at the constraint level (figure 3). Instead of specifying setpoints, the owner defines a set of rules, derived either from experience, testing, or simulation. An example would be increasing the feed rate until one of several operating limitations is about to be violated. Such techniques can vastly outperform even the most attentive operator and significantly increase profitability. They can increase feed rate by 5% or more, when needed, or can minimize utility consumption or maximize yield.

A variety of constraint control techniques can be applied. Simple steady-state applications, which "wait and see" the effects of any changes before making further changes, are easier to implement and may be adequate. If not, then dynamic techniques may be required. These operate continuously, and take into account process deadtime and lag. The problem may be relatively simple, in that only one variable – for example, feed rate – is manipulated, although it may be necessary to check that several constraints are not being violated.

More complicated are situations in which several manipulated variables affect the same operating constraints. An example would be trying to increase both the feed rate to a fired heater and its outlet temperature. Given a limited supply of additional fuel, the control strategy must continuously select the correct combination of feed rate and temperature, so that it satisfies the supply constraint, and at least one other. If there are no other constraints, then there is no unique solution and the problem becomes one of economic optimization. Multivariable techniques are useful in dealing with problems of this type, and, generally, in processes with interacting manipulated variables and complex dynamics.

At the top of the process control hierarchy is optimization, which applies to: nonlinear problems, where the true optimum does not lie on a constraint; problems that have more manipulated variables than active operating limitations, and cases where the rules of constraint control depend on such variables as process economics or product demand.

A direct search technique can be used in some of these cases. This method makes changes to the process, determining the impact these have on profitability before selecting the direction of the next change. In most cases, some form of online process model, incorporating economics, is required. The model may be based on linear programming technology, a nonlinear equation solver, or a process-specific simulation.

Almost all optimization technologies are based on steady state analysis. The benefits of optimization should be evaluated carefully, since the techniques are expensive to implement and support. If the process optimum rarely moves, then it is better to identify its position using some offline approach, and install controls that hold the process at the required point (figure 4, p. 82). If the optimum is flat with respect to overall process profitability, there is little point in tracking it continuously.

Quantifying the benefits

One of the most difficult steps in moving toward advanced control is estimating the benefits (p. 86). Over- and underestimation are frequent, and it is easy to misinterpret process economics and their impact on goals. In many cases, advanced controls are being used to achieve the wrong operating objectives, and actually lose money [*5,6*].

Independent outside expertise should be involved in doing the benefits study. Performing the study entirely inhouse is likely to result in missed opportunities, to automate uneconomic practices, or to lead to overly optimistic claims.It can also be a mistake to contract out the benefits study to suppliers of advanced control technology. Even though they can be held to a performance guarantee, their studies tend to be biased, since suppliers are not likely to support competing technologies. Even a performance guarantee has little effect on the final product. If results are unsatisfactory, suppliers usually sacrifice only a few percent of their fees.

Identifying the costs

Costs must be accurately estimated for approval and budget control. There are still likely to be many unknowns, and the best approach is to seek outline approval for the total budget, but commitment only to the preengineering phase. Preengineering, which generally accounts for about 15% of the total project budget, includes the selection of technologies and the main suppliers, the

changes in basic operating conditions. They allow operators to prepare in advance for possible violations of operating limits, and to take advantage of constraint relaxations to maintain process conditions as close as possible to their optimum.

For continuous processes, such advanced control techniques can better coordinate the interactions that frequently occur between material and energy flows in single-loop control systems, where changing one variable requires adjusting others, to compensate for side effects. For batch processes, it can save energy and raw material costs and allow for more-uniform product quality.

In addition, it can help tame dynamic processes too unwieldy for traditional control. Examples include nonlinear processes, those that exhibit time delays, and those whose variables are measured intermittently or offline.

By reducing process variability, advanced control allows plants to run closer to their operating constraints. This, in turn, cuts energy use, as well as raw material and waste processing costs. It can also improve product yield and quality, safety and productivity while lowering pollution. In general, processes are contenders for advanced control if they involve:

• High raw material or energy costs • Tight product specifications

• Limited production • Measurement problems • Frequent upsets ❑

development of a functional design for the advanced controls, and some detailed instrument engineering. It is particularly critical for major control system upgrades, which tend to be much more complex and costly than the grassroots basis often used to develop their budgets.

Invitations to bid should be prepared well in advance, and bids should be analyzed carefully. One important question to consider is how future projects on the same site may be handled, and whether the agreement will "lock in" the owner to one particular supplier.

Personal meetings with the bidders are very important, as are site visits, which are often mistakenly seen as formalities. Much can be learned by talking with the lead engineers proposed for the project, from visiting reference sites and talking to personnel involved.

Functional design

Once a bidder has been selected for the whole project, a contract should be awarded initially, only for the "functional design." A properly prepared functional design is made up of simplified process flow diagrams with the advanced control strategies superimposed. Its purpose is to describe how the advanced controls will capture the benefits identified, so that the proposed methods can be discussed with and approved by process operations. The design should also identify any instrumentation work (i.e., new sensors or upgrades) required to support the applications, and should, ideally, provide the basis for an accurate cost estimate.

It should be sufficiently detailed, yet accessible to nonspecialists. Beware of some suppliers, who offer "black box" designs that do little more than diagram control objectives. Others may provide very detailed bubble diagrams that can impede operator acceptance.

Since the advanced control solutions offered by different suppliers are so different – e.g., some use online sensors where others offer inferential techniques (discussed on p. 83), it is important that both the functional design and implementation steps be completed by the same contractor.

Once the functional design has been completed, the advanced control supplier should be in a better position to fix implementation costs. Installation is usually completed on a fixed-price basis, and commissioning is generally reimbursable.

Technology determines how the work is divided: With the more conventional advanced control techniques, such as those based on standard distributed control system (DCS) algorithms, including biases, ratios, deadtimes, leads and lags, and simple calculations, suppliers can do most of the installation their own offices on an offline system. Multivariable control packages can usually be installed quickly, with much of the work – plant tests, for example – completed onsite. Whatever the approach, it is important to separate the phases. Thorough testing should be completed before the reimbursable work begins.

Once any new advanced control system is up and running, it will need at least some long-term support. Strategies vary with each site. Where some plants seem to need many large groups of advanced control engineers, others succeed with just one or two. Often, what makes the difference is the staff's attitude toward advanced control. ❐

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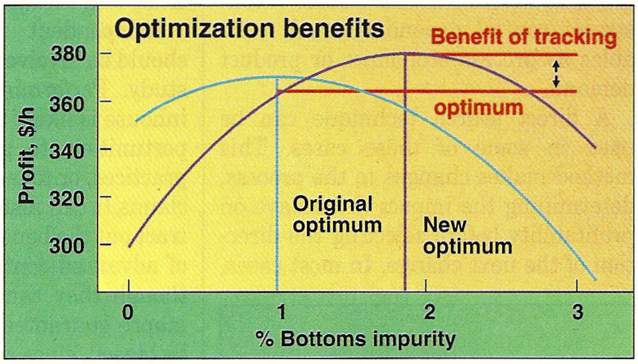
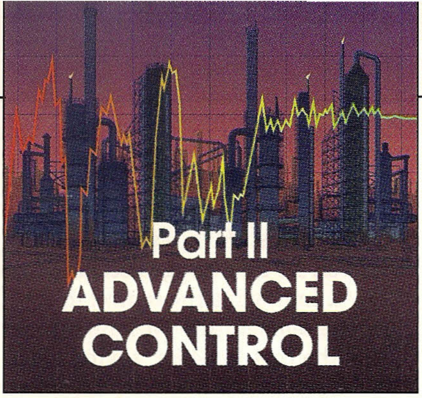
FIGURE 4. It can pay to track a moving optimum, but the technology required can be expensive and difficult to support. Care must be taken in estimating the true benefit of tracking before a decision can be made





Part II ADVANCED CONTROL

ENGINEERING IN PRACTICE

For most CPI plants, process control is carried out by a system made up of basic regulatory controls, advanced controllers, optimizers, and modules for production scheduling and planning. The ease and feasibility of integrating a plant's control system will depend on the costs and complexity of operation, on feedstock costs and product requirements.

Control becomes particularly difficult when there are interactions between manipulated and controlled variables. Typically, this arises in the case of recycle streams, or in cogeneration units and heat exchangers. A good CPI example is quality control of a binary distillation column (figure 5) for a "generic" chemical process. Pressure measured in the bottom stream is used to characterize its quality. The top stream contains both light ends and some heavy ends, and a sensor has been installed that intermittently gives the percentage of heavies.

In this case, the control system aims to maintain setpoints for top and bottom quality, and to reduce the standard deviation of both qualities, taking into account that feed rate and composition change in time.

Regulatory controls, in the form of proportional integral derivative (PID) devices, have been installed to control reflux ratio, pressure, and reboiler steam flow. The quality controller will provide the setpoints for these regulatory controllers. It is important that they be tuned correctly.

But regulatory controls are usually not enough to implement quality control when an operation has to be run under constraints, or when high performance is required. In the ideal case, top and bottom composition should be simultaneously controlled. However, this is difficult to achieve through PID control because coupling occurs between the two composition controllers. Sup-

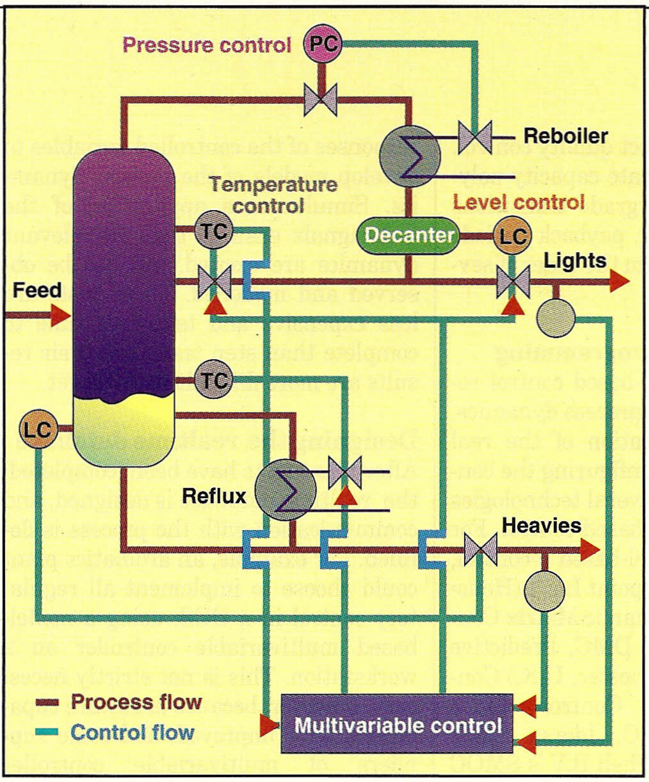


FIGURE 5. In this binary distillation column, multivariable control is used to control the composition of top and bottom streams. Reflux ratio and steamflow are used as manipulated variables, the feedrate as a disturbance variable and column pressure and composition of the bottoms as controlled variables. The control model calculates new setpoints for the control variables at each sample so that quality goals can be met

pose the concentration of lights increases in the feed. The top section temperature controller will decrease the reflux rate and the bottom section temperature controller will increase the boilup in order to respond to the temperature drop observed in the column. If the actions of the controllers are perfectly matched to each other, the column temperatures will return to their original setpoint levels without interactions.

Preventing cyclical behavior

Since, in practice, the boilup response is faster than the reflux response, pressure in the column will increase, then condensation will increase. As the level of the condenser drum rises, reflux will increase. However, the previous decrease in reflux will affect the bottom section control, resulting in a reduction of the boilup. The interactions that exist will result in a cyclic behavior.

To ensure stable operation, the individual controllers cannot be tuned to their respective optimal settings, as that may strengthen the cyclic behavior described, and result in instability. One way to overcome this problem is to implement a controller that uses a model of the column dynamic response – i.e., which describes the interactions between process variables.

This kind of control is best implemented through a model-based multivariable controller. The model describes the dynamic transfers between manipulated and controlled variables, and is used by the quality controller to calculate required actions and to predict whether violations of constraints will occur over a specified time frame.

The setpoints for this controller will be the desired pressure and the percentage of heavies. There are two manipulated variables: the reflux ratio and the steam flow. There is one disturbance variable, measured feed rate, as well as two controlled variables, pressure and the percentage of heavies. The quality controller will calculate setpoints for the manipulated variables at every sample.

Special attention should be paid to quality control of the top stream. The analyzer gives intermittent results, which may be difficult to incorporate in a controller that executes actions at a predetermined rate.

An inferential model

Also, analyzer readings are not always available. Since there is a strong correlation between the temperature in the top section of the column and the measured top quality, an inferential model may be derived that enables prediction of the change in percentage of heavies as a function of measured temperature.

This relation can be expressed as the following logarithmic equation:

$$\% \text{ Heavies} = c1 \log(T) + c2$$

where T= the temperature at a tray in the top of the column, and the constants c1 and c2 are determined by fitting the inferential model to process data. The intermittently obtained analyzer readings are used for calibration.

The top quality calculated with the interential model is adjusted on the basis of the top quality measured with the analyzer. A separate calibration control loop is used for this adjustment. This provides two advantages: Temperature reading is much faster and more reliable than the analyzer reading, and control of top quality remains possible even if the analyzer fails. Multivariable control is shown solving a similar problem in refinery operations on p. 85.

Designing and commissioning an advanced control system is a multidisciplinary project involving process engineering, plant operations, planning and scheduling, hardware and information systems, and control engineering. The time required can range from eight person-weeks for a simple application to eight person-years for an ethylene plant optimization. The typical advanced control project has six phases: benefits assessment and scoping, functional design, engineering and programming, integration, commissioning, and maintenance.

Benefits assessment and scoping

The best way to measure benefits (p. 86) is in terms of engineering units: reduction of standard deviation and operation closer to limits. There exist several methods for estimating the change in the average operating targets, such as "best operator" and "same percent limit violation." All assume a well-defined base case situation. The financial benefits can then be calculated from the associated cost figures supplied by the operation department [7].

Typically, such a project will take a year to execute, so payback will begin some two years after the project starts. During the benefits calculations and scoping, a process engineer will have to estimate the benefits from reduced variability of critical variables and related capabilities of operating closer to the plant optimum. He or she must take into account the costs of instrumentation, computer hardware and software, application engineering and project management, as well as maintenance costs.

The economic optimal point of a unit is usually found at its constraints. For a 200,000-m.t./yr ethylene plant, typical yearly benefits from advanced control have been estimated as shown in the box below.

Functional design

Once the objectives and the potential benefits have been assessed, a functional design is drawn up. As an example, one may consider applying advanced control to a polyethylene reactor that operates at low pressure in the gas phase. In this case, advanced control will improve grade transition control.

Since measuring the polymer characteristics, such as density and melt index, is a very elaborate process, and sampling typically takes one hour or more, software has been developed that can calculate the steady-state relations between polymer product characteristics and conditions within the reactor.

COST VS. BENEFITS: An Ethylene plant

Benefits	
Furnaces (yield, run length, firing control)	$1,200,000
Quench tower, demethanizer, deethanizer (recovery, energy)	$500,000
Ethylene fractionator	$400,000
Acetylene conversion, refrigeration	$200,000
TOTAL	$2,300,000
Costs	
Initial	$2,400,000
Yearly maintenance	$175,000

$$\text{Payback} = \frac{\text{Initial costs}}{\text{Benefits-maintence}} = 1.1 \text{ yrs}$$

To produce a specific polymer grade, a model that predicts polymer properties can be used to describe steady state relations. Important reactor conditions to consider are: partial pressure of the monomer, ratio of comonomer and monomer, reactor temperature, and production rate. The model determines, among other things, the required reactor operating conditions for the desired polymer grade.

Variables that can be used to manipulate the reactor conditions are: monomer flow, comonomer flow, temperature of cooling water, hydrogen flow and catalyst feed. Plant tests have to be executed to determine the dynamic models that are incorporated in the multivariable model-based controller. Such a controller can considerably reduce the transition time between various polymer grades and provide tighter product quality control. For a typical nameplate capacity polyethylene plant with grade transitions once or twice a week, payback periods have been estimated in the order of several months.

Engineering and programming

Implementing model-based control requires modelling the process dynamics, design and configuration of the real time database and configuring the controller. There exist several technologies to implement model-based control. For multivariable model-based control, packages such as Setpoint Inc.'s (Houston) SMC-Idcom, Dynamic Matrix Control Corp.'s (DMCC) DMC, Predictive Control Ltd.'s (Manchester, U.K.) Connoisseur, Treiber Control Ltd.'s (Toronto, Ont.) OPC, Idersa S.A.'s (Paris) Hiecon, and Shell B.V.'s SMOC and QDMC may be applied.

Plant tests need to be carried out to obtain a model of process dynamics. By changing the manipulated variables and observing the responses of the controlled variables, data are obtained for modelling the process dynamics. The approach is simple, and results are easy to understand. Disadvantages are that the step changes on the manipulated variables lead to steady state changes, so the procedure can be expensive and time consuming. Also, because the changes in the manipulated variables are made one after another, not all dynamic interactions can be observed and modelled. This may be a disadvantage for units in which process variables interact to a high degree, or when high performance is required.

Another solution is to make use of binary noise sequences, adding small signals to the manipulated variable values simultaneously, and observing the responses of the controlled variables to develop models of the process dynamics. Simultaneous application of the test signals ensures that all relevant dynamics are excited and can be observed and modelled. These tests are less expensive and take less time to complete than step tests, but their results are more difficult to interpret.

Designing the realtime database

After plant tests have been completed, the realtime database is designed, and communication with the process is defined. For example, an aromatics plant could choose to implement all regulatory control in a DCS, using a model-based multivariable controller on a workstation. This is not strictly necessary, however, because hardware capabilities have improved, and some suppliers of multivariable controller packages have implemented their packages in the DCS. A protocol between the workstation and the DCS has to be established, and the data link has to support the communication speed required.

The controller is configured by defining the manipulated and controlled variables and constraints, and including the process model derived from the process identification. Most of the multivariable controller packages have a configuration tool that assists the engineer in this task. During this phase, a DCS and workstation can be leased for staging and configurating the software.

The modules designed and programmed in the previous phase are linked and integrated. All programs, displays and reports are merged and tested together, to ensure that they mesh with each other and with the database, the control language and the real time operating systems. All software is tested for errors, and the functionalities are demonstrated during the Factory Acceptance Test (FAT). Considered an important milestone in any advaned control project, the FAT aims to test whether all systems functionalities have been correctly configured and implemented, and to demonstrate to the client that all software is functioning properly.

Once the advanced control system has passed the FAT, it is transferred to the plant site for integration with live

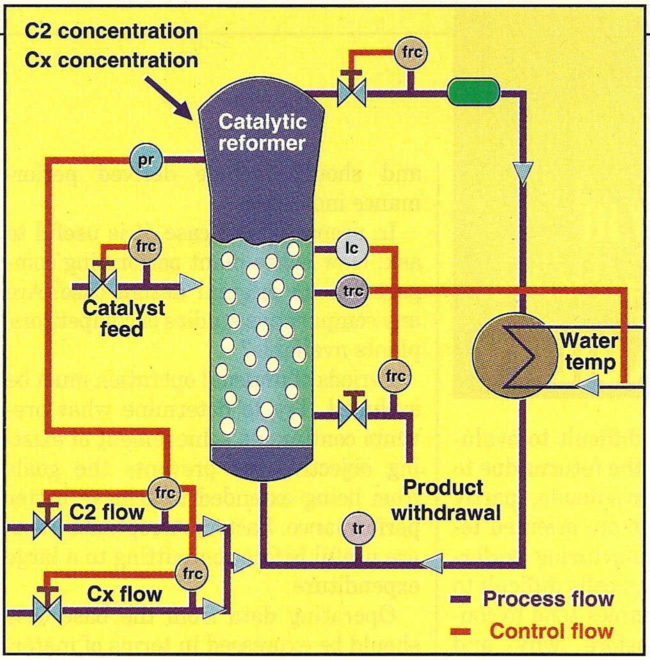


FIGURE 6. In this catalytic reformer, as in the previous distillation example, an inferential model is used to control top stream (Cx) quality. This concept can also be extended to integrate blending and reforming operations

instruments, and commissioning and tuning of all controls.

The operators and engineers are trained with the system for its operation and application maintenance. Documentation is then provided, written in concert with plant engineers involved in the project. The advanced control vendor should supply system documentation for design and implementation. The operator manual can be written by plant engineers or the system vendor.

After interfacing the advanced control system with the existing plant infrastructure, commissioning can begin. A step-by-step approach is generally most effective. First, the communication with the existing plant control system must be tested. Next, the multivariable controllers must be turned on, and each controller module tested in an open-loop model, where they are not allowed to go to the regulatory control setpoints.

After checking controller actions and tuning, each control loop is closed in an advisory mode – i.e., by the operator. Once each has been shown to work successfully, it is then closed in automatic mode. After the multivariable controllers have shown to perform as desired, the optimization package can be commissioned.

After commissioning the advanced controls, maintenance is required to ensure continuous benefits from the advanced controls. Analyzers and sensors should be checked regularly, and calibrated. Meanwhile, the advanced controller should be analyzed for such problems as overshoot on controlled variables, or more aggressive activity, which indicate that it's time for tuning.

Controllers frequently need tuning after operating a process in a working range they have not been tuned for, or after process or operational changes. As a result, process delays may change, average values of critical process variables change, and the associated standard deviations increase. The model of the process dynamics incorporated in the controller may not mirror the actual process dynamics.

Tuning will include correcting process delays, inferring static gains, or executing some plant tests to update the model of the process dynamics. Retuning is needed when product specifications and process conditions change, and when new product specifications are added.

Model-based control

Model-based control enables a user to decouple the basic dynamic behavior of a system from what would be required for optimum performance. The model-based controller allows for changing dynamics within a well-defined range, from basic open loop to dynamic behavior. The range available for modifying the system's open loop dynamics is determined by system dynamics, the operating ranges of manipulated and controlled variables, and disturbance behavior.

The open loop system dynamics determine the nominal system behavior, which can be modified by changing manipulated variables to compensate for unwanted components. Undesired dynamics must be translated into process input manipulations that result in output responses that are the inverse of the undesired components. This way, they show up only at the input side as input manipulations within the permitted operating range of manipulated variables .

Manipulated and controlled variables' available ranges clearly restrict the ability of model-based control systems to modify observed system dynamics. Speeding up a process to enable very fast changeover from one operating condition to another requires large amplitudes of the manipulated variables. The manipulated variables' available operating ranges determine the maximum achievable speed for making operating point transitions or for recovering from disturbances.

Model-based control systems offer a flexible way to manipulate the operating characteristics of unit processes [*8*]. The degrees of freedom available for manipulating these characteristics are determined by the constraints on variables and the criteria functions, which vary depending upon the control package being used.

Optimizing gasoline blending

As an example of optimization, consider gasoline blending, whose product specifications have been tightened by clean fuel requirements. In this case, an optimizer determines optimal blend header quality control and the ratios to achieve the blend. The blend quality controller maintains the instantaneous blend header quality targets, and tries to achieve this with minimal changes to the recipe provided by the optimizer .

The blending optimizer periodically calculates the optimal settings for the blend header, based on blend models. It uses information about component inventories and qualities, product inventory and quality, and predicted blend qualities and instrumentation constraints.

The blend quality controller continuously adjusts the blend heater ratios to control the blend properties. It uses anlyzer data and the blend quality predictions to meet its targets.

The optimizer will typically be implemented on a supervisory computer. The multivariable controller can be implemented either on the supervisory computer or in the DCS. Ratio controllers for the valves are implemented in the DCS with PID loops.

A number of packages available on the market can be used for process optimization, including: Aspen Tech's (Cambridge, Mass.) RT-Opt, DMCC's DMO, and Dot Product's (Houston) Nova. The packages use different algorithms to calculate the best settings for the criterion function and soft constraint parameters of the model-based systems.

Commissioning and maintenance

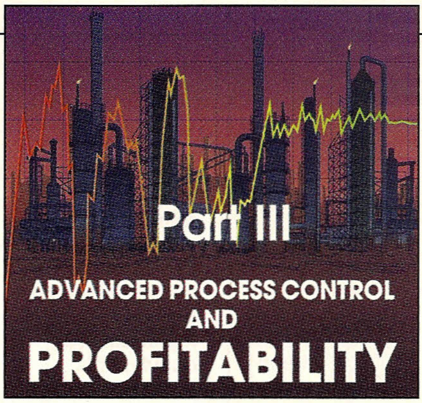
The most important aspects of any advanced control system installation are commissioning and maintenance, and improvement is needed in both areas. Most of the model-based control systems applied today require quite a bit of commissioning, and much trial and error, to get the desired behavior. System tuning is laborious and depends heavily on the experience of the specialist doing the job.

The latest multivariable process identification techniques promise to improve the accuracy of modelling for all process dynamics used for control. So far, they have been shown to result in compact models, more accurate than those obtained via such traditional approaches as step response, using step test signals to identify impulse response, or using first- or second-order Laplace models with time delays.

Models that accurately describe all relevant process dynamics can be used to determine a "condition number" for any process, which indicates how difficult its dynamic system interactions are to control. This number is expressed as the ratio of maximum and minimum gains of the multivariable process, which are observed by running the manipulated variables over their total range, maintaining the applied input signal at a constant amplitude.

By analyzing the condition number as a function of frequency, the sensitivity of the process and the related model-based control system can be shown for small changes in process behavior. This can help reduce maintenance requirements and increase the system's predictability. ❐

Ton Backx and Joost Van Loon



Part III

ADVANCED PROCESS CONTROL AND PROFITABILITY

It has always been difficult to evaluate, quantitatively, the returns due to process control improvements, partly because these projects are oriented toward improved manufacturing performance, which is intrinsically difficult to quantify. Thus, companies tend to concentrate on "how" before "why" and "what." This has led to poor project definitions, and pursuing the wrong goals. The result is often disappointment, disillusionment, and loss of credibility.

To help quantify the benefits of retrofitting advanced control to existing processes, ICI is now applying the following methods. The technique requires team work, and close communication between control engineers and operators. Success is recorded in a number of case studies [3].

Estimating benefits

Benefits analysis generally requires the five steps discussed below:

1. Setting up a project team

Small teams are best, and should involve someone with intimate knowledge of the process technology and the plant involved, as well as a process control technology specialist. A senior plant operator should also participate on a part-time basis, as should someone with a sound understanding of the economics and politics of the business. It is important for the unit to identify and provide a "champion," committed to ensuring that resources are available, as needed, to make the whole exercise successful. It is also useful to include an outspoken member, who will not be afraid to challenge the status quo.

2. Establishing a base case

The base case describes how the plant operates without the projected improvements. Plant operating data are obtained for recent representative periods. These should focus on the frequency distributions of key variables, and should include derived performance indicators.

In preparing the case, it is useful to ask: How is the plant performing compared to its original design case? Are any comparative studies of competitors' plants available?

Periods of unusual operation must be excluded. Try to determine what prevents continuous achievement of existing objectives or prevents the goals from being extended to achieve better performance. Factory Acceptance Tests are useful before committing to a large expenditure.

Operating data from the base case should be expressed in terms of material, energy and money flows, focusing, in the last case, on those areas with high potentials for improvement. Data collection is supplemented by a series of structured interviews with personnel ranging from senior management to process operators. A nonthreatening atmosphere promoting commitment must be engendered. Typical information includes:

- Operating goals for the plant, and how performance is to be assessed against them
- The sensitivity of performance to key operating variables
- Constraints on variables
- Disturbances, their source, frequency and influence on operating goals.
- Operator activities, especially those that are time consuming or difficult
- Wish lists for the "Utopian" plant

3. Preparing an opportunities list

A list of potential opportunities emerges naturally from the base case analysis, especially from:

- *Setting operating goals*. Does this suggest a need for optimization?
- *Measuring performance against operating goals*. Can it be done easily? Is there a need for better sensors, or, perhaps, inferential measurement?
- *Coping with constraints and disturbances*. Is the existing control system adequate? Is there a need to upgrade to a distributed control system and implement model-based predictive control? Would better fault detection help?
- *Improving operator effectiveness*. Would automatic sequencing assist? If scheduling is a problem, discrete event simulation might help.

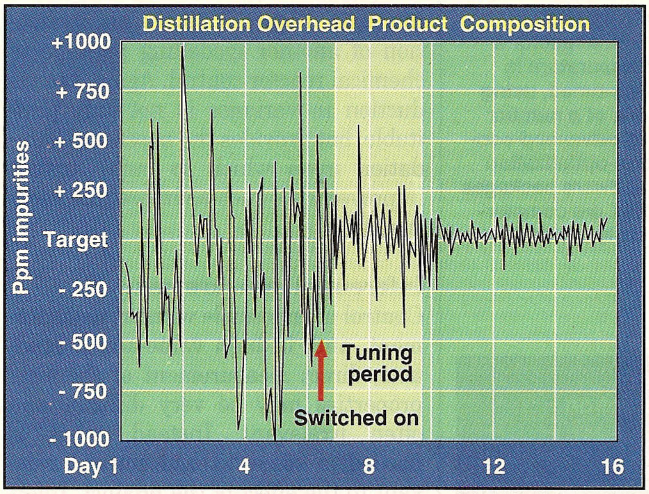
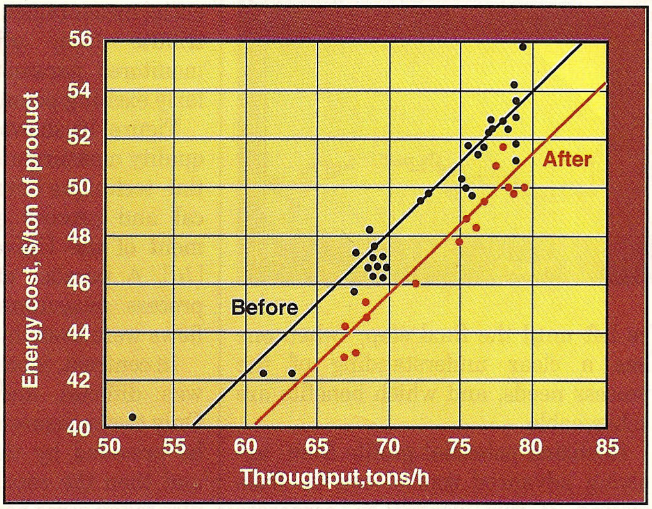


FIGURE 7. A commercial predictive control package allowed the improvement shown at left. After tuning, overhead deviates an average of 50 ppm from the desired level, compared with 1,000 ppm with conventional control

FIGURE 8. At right, the process' energy costs are compared, before and after the predictive control method was applied



- *Improving communications.* Is there a need for a Management Information System (MIS) to report on and assist with production planning?

It is important to let the list develop without being too critical or too quick to address the issue of how to implement the control. A good question to ask is "What would you, ideally, like to have?" Nothing kills the process more effectively than the voice of experience, as in "We tried that years ago. It can't be done."

4. Quantifying the benefits

Estimating benefits is the critical part of the process. Better control of a process will reduce the spread of variables about their setpoints. In most cases, the benefit follows when this is exploited, to allow the setpoint to be moved closer to the constraint, or to tighten specification on a product.

The important factors in the calculation of benefits are included in the following equation:

Benefits = Improvement x
Incremental Value x
Unit Throughput x
Time x Service Factor

The value of "perfect" control improvements can be estimated, and then converted to achievable levels. Key tools for benefits estimation include:

Examining historical operation. Seek periods when plant operation with existing systems had been very good. It is often valid to claim that a new control strategy can achieve this "very good" operation continuously, especially if the existing system relies on operators.

Running plant tests. These are sometimes necessary to test potential. It is amazing what can be squeezed out of a plant when a keen and knowledgeable plant manager is on shifts. Why can't it be achieved all of the time?

Using model-based simulation studies, both steady-state and dynamic. While time consuming and expensive, they can be useful for limited and carefully chosen studies.

Reading the literature and probing people with relevant experience. Findings can be valuable, if they are interpreted cautiously. Rules of thumb can also be useful. For example, better control should be able to reduce standard deviations about a setpoint by 50% or more.

STUDIES SHOW PROFIT POTENTIAL

Advanced process control may not be very well understood by most corporate executives, but recent studies attest to its benefits. In 1987, for example, the University of Sydney's Warren Center surveyed a number of Australian process industries, ranging from chemicals production to metal processing and waste treatment. Case studies yielded comparable results [1], and advanced process control was found to save 2-6% of annual operating costs.

More recently, Du Pont Co. commissioned a study [2] to determine what companies with the most advanced control systems were doing right. Companies exploiting the technology's full potential achieve benefits averaging 15% of manufacturing costs.

At ICI, a study was completed last year to determine what impact improved process control could have on the company's bottom line, globally. It found that advanced control could add more than a third to the Group's annual profit. The study used simple metrics to audit the state of control on the plants surveyed and to assess the potential for improvement. You might try comparing the following sample criteria with those from your own plant: (for the first and last categories, the lower the better)

Selection of Control Benchmarking Metrics	Industry Best
% of control loops in manual operation	0
% of advanced* strategies	35
# of control loops per operator	130
# of loops per control engineer	50

*Advanced means beyond PID or ratio and cascade control

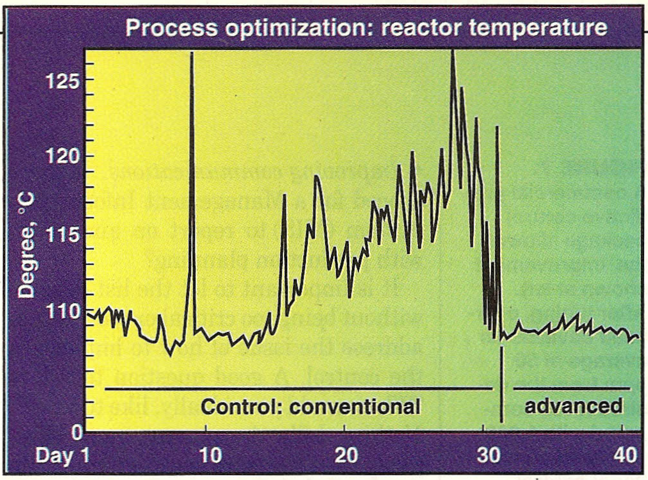
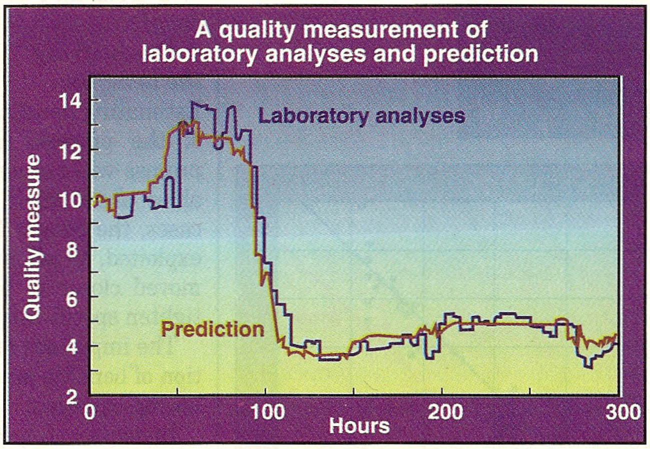


FIGURE 9. Left, a reactor's temperature is fine-tuned, using one of a number of advanced-control-optimization software packages that are commercially available

FIGURE 10. At right, an inferential model outperformed the 'true' laboratory measurements. Predictions were reliably made using frequently, easily measured process variables, while lab measurements were difficult to make and were hours late. In some cases, predictions even proved the direct measurements wrong



When the benefit from a projected improvement has been calculated, it is important to consider the appropriate "service factor" to reflect the realities of life, and to consider what training is necessary. It is not at all uncommon to see a new, very effective control system switched off for a variety of reasons.

For example, is it dependent on an online analyzer? Do the operators understand the strategy and what to do if something goes wrong? They probably know how to switch the system to manual, but do they know how to commission it afterwards? Do they care?

5. Selecting the controls and defining the projects

After benefits have been calculated, implementation strategies for improved controls should be outlined and costs estimated. Projects should be ranked by cost and benefit, with estimates of technical complexity and resources needed. Particular emphasis should be placed on assessing the degree of technical risk involved in achieving the predicted improvements. This method identifies priority projects with a high probability of financial success. Details of engineering implementation should be left until the final step, when one has a clear understanding of the process needs, and which benefits are achieveable.

Realizing potential profits from applying advanced control can be frustrating. If this weren't so, corporate management would already have jumped, unreservedly, on the advanced control bandwagon. Nevertheless, profits are easier to get from enhancing plant control than from some other investments, as the following examples show.

Case Studies in Advanced Control

Much of the work done in benefits analysis is quantifying the extent of variance in plant parameters, to see how far this might be reduced, thus allowing the mean level to be moved closer to the constraints (Figure 1). Predictive control methods such as DMC and Connoisseur are particularly effective at realizing efficient operation in the face of changing objectives and moving constraints.

Figures 7 and 8 show one model's effectiveness. In figure 8, "before and after" data are compared in a way that could convice the most skeptical plant manager. Figure 9 shows an application of another modelling package to chemical reactor control. Again, the reduction in variance is not only profitable, but provides the necessary foundation upon which to build further improvements such as inferential measurement.

Inferential measurement

Control is impossible without measurement, and, in high value-added products, direct measurement of chemical properties may be very difficult and often irrelevant. Instead, what is needed is some "measurement," relevant to the effect of the product. Inferential measurement of the desirable attribute from other, more easily monitored parameters has a particularly exciting potential.

Figure 10 shows the prediction of a quality measurement using an inferential technique developed in the chemical and process engineering department of the University of Newcastle [*10*]. A number of very easily made process measurements such as feed flows were used in the prediction.

In contrast, laboratory measurement was difficult and time consuming. Only two measurements per shift could be provided by the plant laboratory, and then the results referred to samples taken some hours before, so predictions led the "true" laboratory measurement by several hours.

Notice that a significant, intentional change in product quality occurs at about the 100-h point. The tighter control that operators can sustain, because of the insights they have gained into plant operation, has halved the production of offspec material during the product change.

In addition, it has highlighted the fallibility of some laboratory analyses. On several occasions when the "true" value from the laboratory has clearly shown a discrepancy with the prediction, it has given the operators the confidence to have the analysis checked and shown it to be wrong.

Despite the improvements made in advanced process control and optimization systems, the question now is: where will the future leadership in process control come from? Large operating companies, such as ICI, BP and

Du Pont, have slashed their R&D budgets and drastically reduced their engineering presence.

The future technology push will not likely come from the large contractors. They used to do what their powerful customers wanted, but now these customers aren't providing the lead.

New trends mean change

Recently, however, there have been some interesting and encouraging developments. One is the rise of specialist companies offering either specific technologies or general consultancy services. The other is the development of partnerships between instrumentation users and manufacturers.

Manufacturers, anxious to sell their hardware, are packaging it in new ways. First, they are offering solutions geared to enhancing profit, which is exactly what the CPI want to hear. To do this, they are often teaming up with one or more of the small specialists or consultants. These solutions can cover the whole range of services, from initial Opportunities and Benefit Analysis studies through detail design and installation to onsite maintenance.

They are also offering innovative financial deals [*11*] to attract manufacturing companies to invest in the new technology, to their mutual advantage. New, adaptable alliances are forming between control and instrumentation suppliers, and should mean interesting times ahead in process control. ■

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Edited by Agnes Shanley
with Ken Fouhy

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References

1. Marlin, T.E., Perkins, J.D., Barton, G.W. and Brisk, M.L., Benefits from Process Control: Results of a Joint Industry-University Study, *J. Process Control*, 1, pp. 57-83, 1991

2. Swallow, J.F., Best of the Best: Leaders in Advanced Process Control, "Proceedings of the Fourth International Conference on Chemical Process Control,"CACHE-AIChE, New York, N.Y.,1991

3. Anderson, J.S., and Brisk, M.L. Estimating the Economic Benefits of Advanced Process Control in "Proceedings of Advances in Process Control III", Institution of Chemical Engineers, York, U.K., September, 1992

4. Zetter, M.S. and Politzer, B.A., Online octane control with NIR analyzers, *Hydrocarbon Processing*, March, 1993

5. King, M.J., How to Lose Money with Advanced Controls, *Hydrocarbon Processing*, p.47, June 1992

6. Friedman, Y.Z., Avoid Advanced Control Project Mistakes, *Hydrocarbon Processing*, October, 1992

7. Latour, P.L., Sharpe, J.H., Delaney, M.C., Estimating Benefits from Advanced Control, in *ISA Transactions*, ISA, 25, 4, 1986

8. Froisy, B. Model Predictive Control: Past, Present and Future, presented at ISA conference, Chicago, 1993

9. Anderson, J.S., Application of Dynamic Matrix Control to a Distillation Problem in *Proceedings of CIM-Europe Workshop on Industrial Applications of Model-based Predictive Control*, Cambridge, U.K., September, 1992

10. Tham, M.T., Montague, G.A., Morris, A.J., and Lant, P.A., Soft Sensors for Process Estimation and Inferential Control, *J.Process Control*, 1, pp. 3-14, 1991

11. Haskins, D.E., How to Justify Small-Refinery Information Control System Modernization, *Hydrocarbon Processing*, pp. 69-72, May, 1993

12. Young, A.J., "An Introduction to Process Control Systems Design," Longmans Green & Co., Ltd., London, 1955