ESTIMATING BENEFITS FROM ADVANCED CONTROL

P.L. Latour
J.H. Sharpe
M.C. Delaney

By Courtesy of
SETPOINT Inc.

Reprinted with permission from, *ISA Transactions*
Volume 25, Number 4, pg. 13

Estimating Benefits from Advanced Control

P. L. Latour
J. H. Sharpe
M. C. Delaney
SETPOINT Inc.

Exponential growth in the development of computer hardware and software offers the process industry many potential economic benefits. This article describes methodology to estimate actual monetary savings from applications of advanced control systems. Control system objectives are introduced. Procedures to calculate benefits generated from improved dynamic control as well as steady-state optimization are discussed. An example problem is presented to emphasize the points covered in the paper.

INTRODUCTION

Exponential growth in the development of computer hardware and software offers the process industry many potential economic benefits. Companies in growing numbers are reaping the benefits from advanced computer control. Others have delayed, not knowing where to begin to justify such an investment.

This article describes methodology to estimate actual dollar savings by particular applications of advanced control systems. Control system objectives and the benefits from dynamic control improvements and steady-state optimization are discussed.

Experience has shown that a few specific characteristics make processes good candidates for computer control, including(1):

- Difficult product specifications
- Large product price differentials or yield incentives
- Large throughputs
- Capacity limits
- High energy and operating costs

All of these factors may contribute to substantial savings generated by relatively small changes in the operating conditions.

COMPUTER CONTROL OBJECTIVES

Before benefits from a computer project can be estimated, several issues must be resolved:

- What functions will the computer be performing?
- What goals is it striving to meet?
- How are these goals going to be achieved?

The benefits from a computer control project can only be achieved if the appropriate objectives are defined for the computer applications. A computer system installed for data gathering and management reporting cannot claim credits for improved control. Even when a computer is installed for control purposes, the objectives and functions for the control strategies need to be clearly defined before the benefits can be determined.

The computer system objectives need to be in concert with the plant's operating objectives in order for the system to be of use. Typically, the operator's primary concerns are safety and meeting product quality specifications. The computer can be utilized to improve plant safety by moni-

Presented at the Chemical and Petroleum Industries Division Symposium, ISA/District 5 Conference and Exhibit, 1986.

ISSN 0019-0578/86/04/0013/09/$2.50 ©ISA 1986

toring process constraints, responding appropriately to plant upsets, and utilizing the additional alarm capability.

Given the proper inputs and outputs, the computer can also be utilized to control product quality. Product quality control as a computer objective should include not only meeting the product specifications but also minimizing product giveaway. The computer control objective could be stated as: maximize the yield of the more valuable product at the expense of lesser valued products, within specification limits.

In addition, the computer can further enhance the plant's operating objectives by incorporating plant economics into decisions that affect the direction the process will be driven. Rarely does the operator have sufficient knowledge or experience to optimize trade-offs such as energy input versus product recovery. A computer can perform this function with an economic model of the process.

DYNAMIC CONTROL BENEFITS

Tangible benefits from computer control applications result from either dynamic control improvements or steady-state optimization. For the first, the variability of the process is reduced such that the average can be moved closer to a specification or limit as shown in Figure 1. Steady-state optimization, on the other hand, generates operating targets based on an economic performance model that relates incremental processing costs and product recovery or yield value to the controlled variables. Although these two benefit areas can impact each other, they may be treated separately for the purposes of this paper.

Developing a Base Case

A good base case is important for estimating dynamic or steady-state optimizing control benefits. The base case provides the basis for comparing the process before and after advanced control is implemented. Average values and standard deviations of the key operating variables are required for the benefit calculations. These key operating variables include:

- Critical product qualities
- Important manipulated variables
- Material and energy balance parameters
- Constraint variables

Each is important in understanding where the process currently is, and how far it can be moved towards its limits.

The period of time over which the base case data is gathered is also an important consideration. It is desirable to obtain data during a period when the plant is running well at high rates. Unusual operations such as equipment outages should not be included in the base period. Operating conditions and feedstock should be typical of those that will prevail after system installation. Significant fluctuations caused by different operating modes or feedstocks should not be averaged out. Instead, additional base cases should be generated so that computer control benefits can be calculated for each of the operating modes.

It is imortant that improvements over the base case preserve the material and energy balances to prevent calculating invalid savings. It is common practice to enforce the material balance by assuming certain flowmeters are more accurate and closing on the others.

Dynamic benefit calculations focus on reducing variations of the controlled variables around their target. Enough operating data are needed to make a meaningful evaluation of the mean and standard deviation of the important parameters. Due to the cost of collecting and analyzing the data, the control engineer should gather the minimum amount of information necessary to determine these values(3). Theoretically, the sampling frequency should depend on how often disturbances are introduced into the process. If the process is frequently upset, a once-a-day sample is not enough to understand how the true process is varying. In practice, the control engineer must use the data available to him to make his best estimate of the process variability.

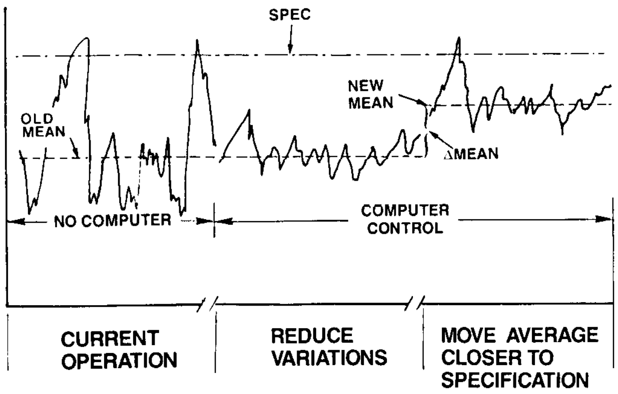

Figure 1. Dynamic control improvement benefits

Statistics — Background and Terminology

Once the base case data has been collected, the next step is a statistical analysis to determine the mean (or average) and standard deviation of the critical variables. The mean is calculated by:

$$\bar{X}_D = \frac{\sum_{i=1}^{n} X_i}{n} \tag{1}$$

Standard deviation is a measure of the variation of the data about the mean, and is defined as:

$$S_D = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X}_D)^2}{n-1}} \tag{2}$$

Another common term, variance, is equal to the standard deviation squared.

Assuming data fits a normal bell-shaped Gaussian distribution curve as shown in Figure 2, several inferences can be made concerning the probability that the data will fall a certain distance from the mean. For a Gaussian distribution, 68.3% of the data will fall within $\pm 1S$ from the mean, and 97.7% of the data will fall within $\pm 2S$ from the mean, and so on.

Any Gaussian distribution can be reduced to a standard normal distribution function where the normalized value of a data point X_i is described as t_i such that:

$$t_i = \frac{X_i - \bar{X}_D}{S_D} \qquad (3)$$

It can be shown that the mean of t is the equal to zero and the standard deviation of t equals 1.0. The probability that t will be less than any limit value Z is given by the area under the normal distribution curve, as shown in Figure 3.

Mathematically, it can be shown that the area under the normal distribution curve less than Z is given by:

$$F(Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} e^{-1/2t^2_{dt}} \qquad (4)$$

$$\text{where: } Z = \frac{X_L - \bar{X}_D}{S_D}$$

This expression is known as the normal distribution function, and its value can be found in most standard statistical tables. Some of the more useful values of $F(Z)$ are given in Table 1. Note that Z is from the mean.

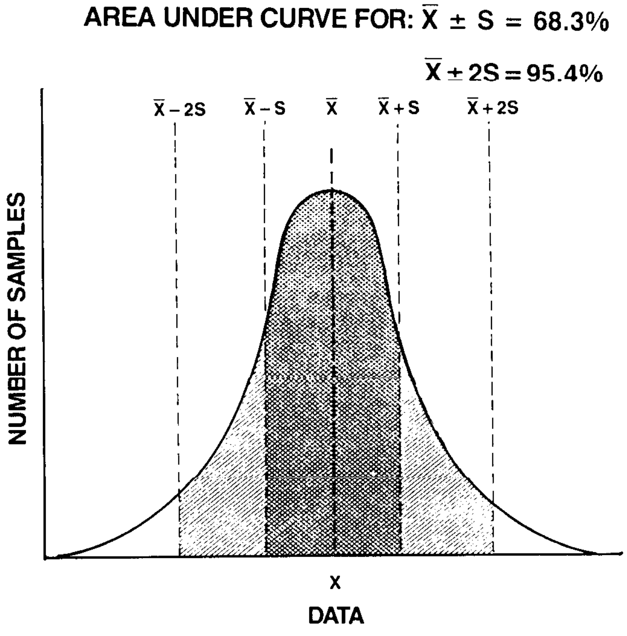

Figure 2. Gaussian distribution curve

The fraction of the data that violates a limit, X_L, is given by:

$$F(Z) = F\left(\frac{X_L - \bar{X}_D}{S_D}\right) \qquad (5)$$

If $X_L < \bar{X}_D$ then use the relationship:

$$F(-Z) = 1.0 - F(Z) \qquad (6)$$

for table values.

Many times the actual data from a plant will not fit a Gaussian distribution pattern, but is skewed away from a

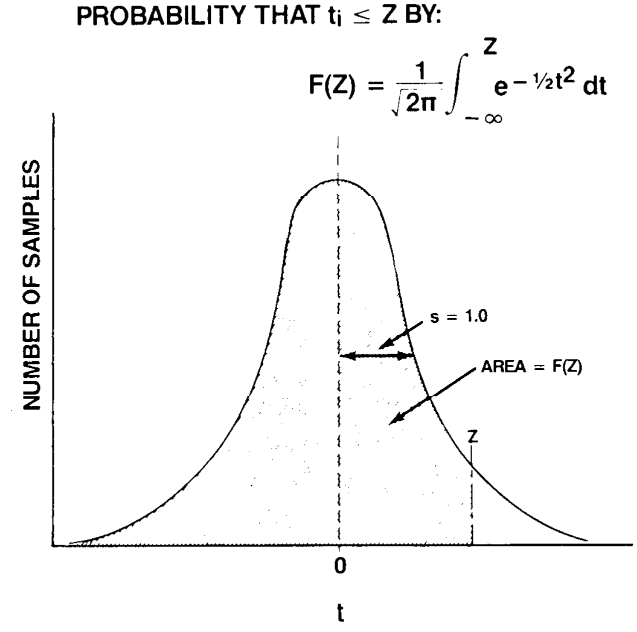

Figure 3. Standard normal distribution

Table 1
Standard Normal Distribution Function

$$F(Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} e^{-1/2t^2_{dt}}$$

Z	$F(Z)$
0.0	0.5000
1.0	0.8413
1.5	0.9332
1.65	0.9505
2.0	0.9772
2.05	0.9798
2.33	0.9901
2.5	0.9938
3.0	0.9987
3.5	0.9998

limit as shown in Figure 4. In view of the accuracy of the process models and assumptions used in the analysis, the added complications from working with skewed distributions are usually not justified for benefit estimates. It is sometimes possible to arbitrarily assume how the tail of the distribution function will be changed after computer control commissioning and thereby determine the benefits from computer control(3).

Control System Dynamic Performance

There are two possible sources of variance for measured process data:

- Process variance
- Measurement variance

Process variance is caused by disturbances to the actual process, while the measurement variance is a function of the accuracy of the measuring device. Since the computer control system can only affect process variance, the measurement variance must be subtracted from the data variance to determine the true process variance as follows:

$$S_P^2 = S_D^2 - S_M^2 \tag{7}$$

Measurement variance is often specified in terms of repeatability. Measurement repeatability is defined as the distance around the mean that would contain 95% of the points if the same sample were analyzed repeatedly. Repeatability is approximately equal to twice the measurement standard deviation:

$$R_M = 2S_M \tag{8}$$

Compared to process variance, measurement variance is sometimes very small and is, therefore, often neglected.

Computer systems continuously monitor many process variables and can detect more causes of process upsets than an operator alone. Advanced control reduces process variance by accounting for complex interactions and compensating for these more accurately and frequently.

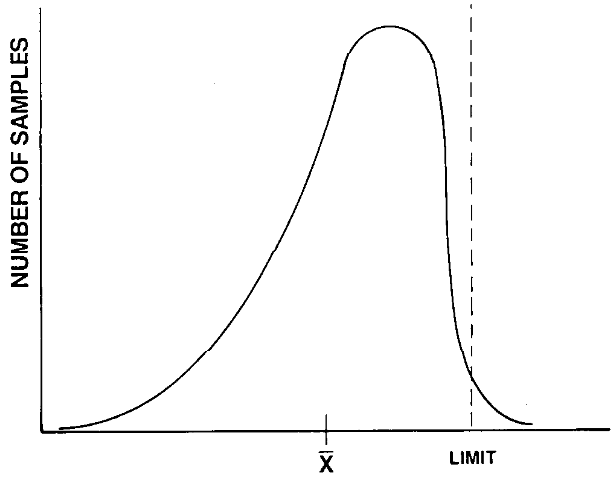

Figure 4. Skewed distribution curve

How much advanced control will reduce the standard deviation or variance of the process is up to the control engineer to estimate. This estimate depends on the particular application in question and is based on the following factors:

- Control strategy: feedforward, cascasde, multivariable
- Previous experience
- Frequency, source, and size of process upsets
- Sensitivity of the controlled variable to process upsets
- Process and analyzer dead time
- Sampling frequency

With advanced computer control, the variance can typically be reduced by at least 50%, and, in some cases, reductions greater than 90% have been achieved(1).

Once an estimate of the reduction in process variance with computer control is determined, the measurement variance must be added to calculate the variance of the data with computer control; or:

$$S_C = K(S_P^2) + S_M^2 \tag{9}$$

This variance is used to estimate how far the average value can be shifted.

Calculating the New Operating Point

Estimating the change in the average operating target depends on the particular application. There are several methods to calculate the possible change in the average value, and a decision must be made as to which method is more appropriate.

Method A — "Best Operator" Method

This method, shown in Figure 5, is based on the assumption that the computer can perform consistently as well as the "best operator" under the same conditions. The size of the credit that can be claimed is determined by the difference between the average operating point and the "best" operating point. Note that this technique is a conservative approach because it does not account for the control improvement over the operator. Even greater savings could be claimed for reducing the "safety margin" shown in Figure 5. This method has been found useful for estimating savings generated by control functions such as stripping steam ratios, reflux ratios, and solvent/feed ratios.

The new average operating point can be calculated from the current average and the "best operator" points. For example, stripping steam savings can be calculated by:

$$\Delta \overline{SS} = (\overline{SR}_{\text{Old}} - \overline{SR}_{\text{BO}})\, \overline{PR}_{\text{Old}} \tag{10}$$

where:

$\Delta \overline{SS}$ = change in average stripping steam rate after computer control

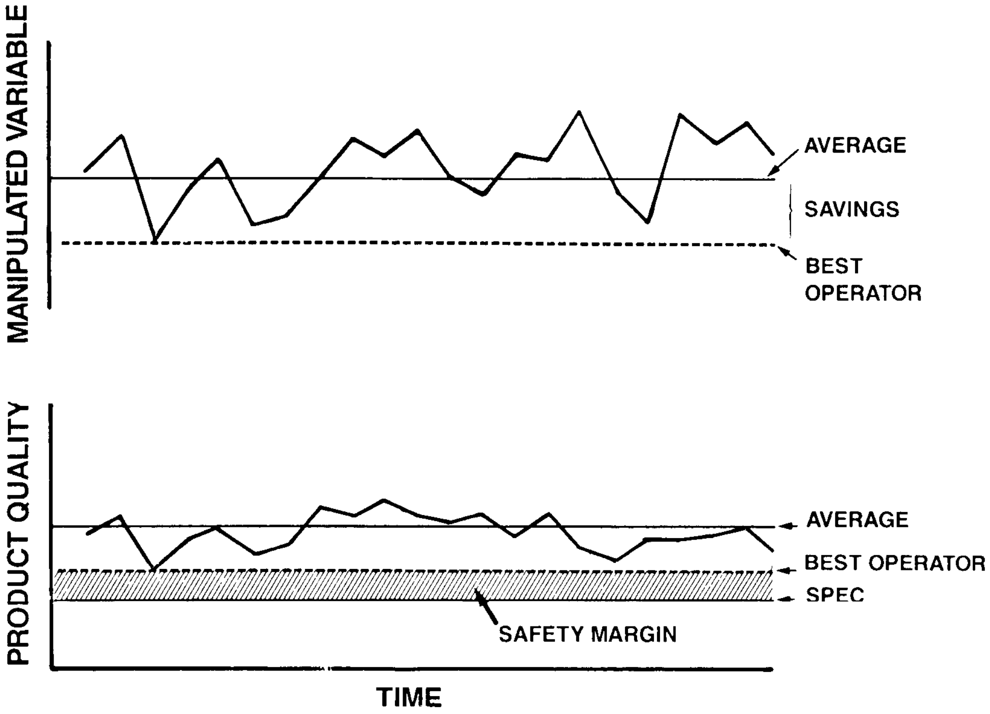

Figure 5. Moving the average (best operator method)

$\overline{SR}_{\text{Old}}$ = current average stripping steam/product ratio

$\overline{SR}_{\text{BO}}$ = "best operator" (minimum observed) stripping steam/product ratio

$\overline{PR}_{\text{Old}}$ = current average product rate

Method B — Same Percent Limit Violation

A more liberal approach is to assume that the computer can violate the limit the same percent of time as the operator does currently, as shown in Figure 6. The fraction of time the limit is violated can be calculated using the standard normal distribution function. If the assumption is made that:

$$F(Z_C) = F(Z_D)$$

then:

$$Z_C = Z_D$$

or:

$$\frac{X_L - \bar{X}_C}{S_C} = \frac{X_L - \bar{X}_D}{S_D}$$

Solving for $\Delta \bar{X} = \bar{X}_C - \bar{X}_D$ gives:

$$\Delta \bar{X} = \left(1 - \frac{S_C}{S_D}\right)(X_L - \bar{X}_D) \qquad (11)$$

WHERE:

A_{OFF} = AREA UNDER OFF CONTROL CURVE THAT IS GREATER THAN PRODUCT SPECIFICATION

A_{ON} = AREA UNDER ON CONTROL CURVE THAT IS GREATER THAN PRODUCT SPECIFICATION

NOTE: $A_{OFF} = A_{ON}$

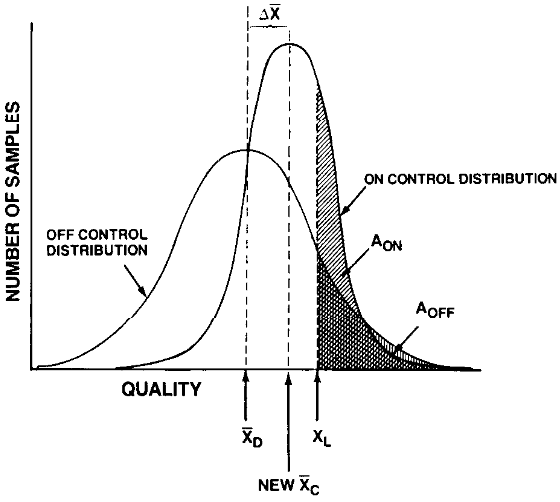

Figure 6. Moving the average (same percent limit violations)

This method is probably one of the most common ways to estimate changes to controlled variables such as product quality.

Method C — Same Percent Violations of the 5% Limit

Sometimes, a specified limit is not supported by the plant data, or the actual limit is vague or unclear. In this case, a more realistic limit could be chosen as the value beyond which only 5% of the data falls, as shown in Figure 7. The change in the average value can be obtained using the normal distribution function for a maximum limit as follows:

$$F(Z_C) = F(Z_D) = 0.95$$

From Table 1:

$$F(1.65) = 0.95$$

therefore:

$$Z_C = Z_D = 1.65$$

or:

$$\frac{X_L - \bar{X}_D}{S_D} = 1.65$$

and:

$$\frac{X_L - \bar{X}_C}{S_C} = 1.65$$

Solving for $\Delta \bar{X} = \bar{X}_C - \bar{X}_D$ yields:

$$\Delta \bar{X} = 1.65\,(S_D - S_C) \tag{12}$$

Method C has been used in cases such as maximum furnace outlet temperature that is violated more than 10% of the time.

Method D — Limit Violation *A*% of Time

A fourth method can be used to estimate the change in average value when the limit is seldom or never violated in current operation, as shown in Figure 8. This method assumes that the limit can be violated a certain percent, *A*, of the time. Again, the normal distribution function is used as follows:

$$F(Z_C) = 1 - A\%/100 \tag{13}$$

Since Z_C will be a unique function of $A\%$, the average value can be calculated by:

$$Z_C = \frac{X_L - \bar{X}_C}{S_C} \tag{14}$$

or

$$X_C = X_L - S_C Z_C \qquad (\text{for } X_L > \bar{X}_D) \tag{15}$$

and:

$$\bar{X}_C = X_L + S_C Z_C \qquad (\text{for } X_L < \bar{X}_D) \tag{16}$$

Note that this method will set the new average a certain number of standard deviations away from the limit. Method D has been used for cases such as a maximum heater outlet temperature that is never violated. The choice of the percent of violation time (*A*%) determines how conservative the estimate will be.

Calculating a Change in the Process

The effect of a change in a target or average value on the rest of the process must be evaluated in order to calculate the savings associated with that change. For example, if the statistical analysis indicates the average product purity of a distillation column can be reduced by 0.1%, how does that

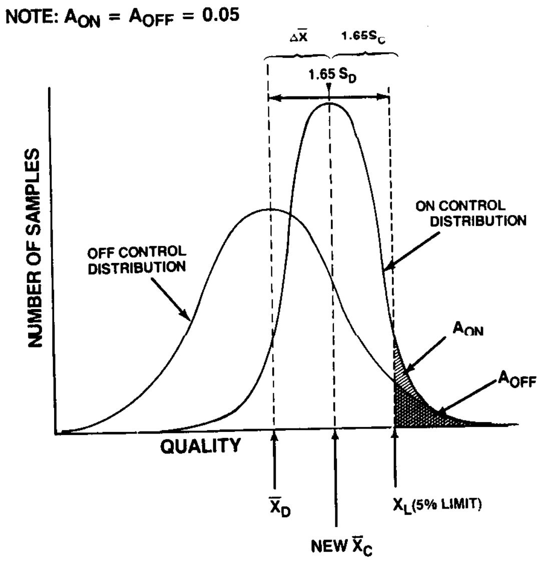

Figure 7. Moving the average (same percent violation of 5% limit)

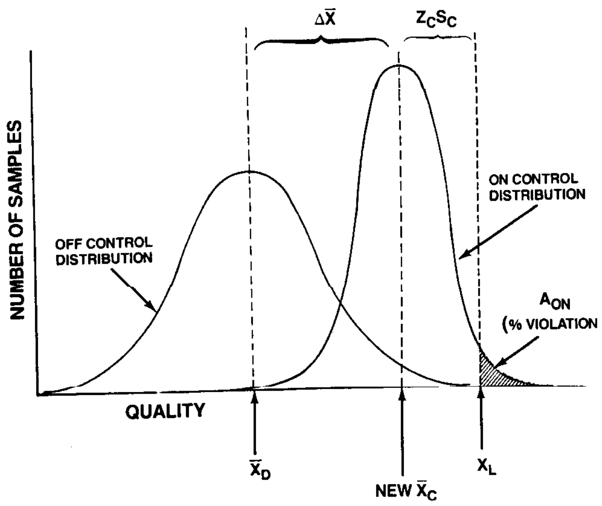

Figure 8. Moving the average (violation of limit a% of time)

shift affect the product yields and column reflux? A change in a target value must be related to product yields and energy requirements based on a process model. The model can be as simple as a series of gains or as complex as a detailed computer simulation of the process.

Product values and energy costs must be determined to evaluate the economic impact of the change in operating point. These prices should be incremental values. For example, if a portion of the bottoms from a stabilizer column feeds an aromatics unit, but the remainder is blended into the motor gasoline pool, then the value of the bottoms stream is its value as motor gasoline. This is because an incremental change in the product rate will be reflected in the amount of product going to motor gasoline.

The same concept applies to energy costs as well. For instance, the incremental cost for a furnace fired with both fuel gas and fuel oil will be the value of the fuel that is manipulated for duty control.

Many times intermediate processing costs must be considered when determining product values. The sales price may not be the appropriate value to use in the economic analysis if there are intermediate units prior to the product tankage. Intermediate operating costs should include incremental costs only, because items like manpower, cooling water, and pumping costs will not be significantly affected by a slight change in product rate. Only items affected by throughput, such as fuel costs, refrigerant cost, and compressor costs, need be considered. Energy costs may actually be negative if a stream is used for refrigeration or steam generation. Intermediate costs are usually calculated in terms of dollars per quantity of product or feed so that they may be subtracted directly from the sales price.

Since the product stream may be made up of several components that have different ultimate dispositions, the value of each component may be required in order to calculate the total stream value. In addition, if computer control for a unit such as a distillation column affects stream compositions (as well as rates), the savings generated is a function of the value of particular components rather than the total stream value. In the following stabilizer example, the benefit of improved bottoms RVP control required the value of butane and pentane to motor gasoline versus LPG (stabilizer distillate). Slight changes to the column material and energy balances will affect primarily butane and pentane distribution in the overhead and bottoms streams.

STEADY-STATE OPTIMIZATION BENEFITS

Dynamic control benefits are based on reducing variability in the process and, on average, moving the controlled variables closer to specified targets. In this case, the specified target is a given. Steady-state optimization, on the other hand, provides a basis for determining values for those targets that are consistent with the economic and business objectives of the process. The benefits of steady-state optimization, then, must be a result of improved process economic performance.

The key to estimating benefits of steady-state optimization is an economic performance model that defines, in quantitative terms, the economic objective of the process as a function of the independent control variables. It consists of both a process model and an economic model.

Base Case

The economic performance of any process will vary over a period of time in response to a variety of factors. Changes in product prices, raw material costs, and energy costs will most certainly have an impact on economic performance. For a given set of independent control variables, changes in feed composition also will have a significant effect on economic performance. The starting point for estimating benefits, then, is to determine a base case that represents the economic performance of the process over a representative period of time, as shown in Figure 9.

In practice, the base case can be defined by a series of discrete points based on average steady-state operating conditions. Daily averages can be used for periods of relatively smooth operation. The period of time over which data is gathered should be sufficient to reflect the normal variation in economic conditions and process disturbances.

Benefits Prediction

For each operating point included in the base case data, the economic performance model is used to determine the optimum performance. The series of optimum performance points defines the optimum case, as shown in Figure 9. A delta value for each point is determined based on the difference between the optimum and base case. This delta value represents the potential benefit of steady-state optimi-

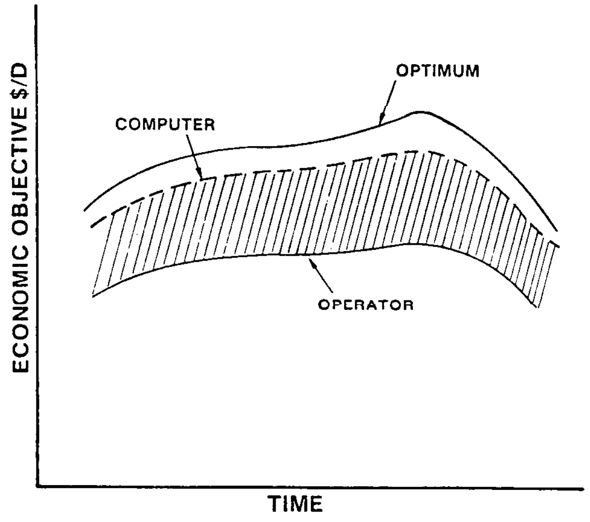

Figure 9. Optimization benefit

zation. An estimate must also be made of the portion of this delta value that can actually be achieved with advanced control. The benefits of steady-state optimization are then estimated based on the integrated average of the delta values between the computer case and the base case.

EXAMPLE PROBLEM

The stabilizer shown in Figure 10 has a maximum bottoms RVP specification of 0.7 kgf/cm^2. Currently, the average RVP is 0.422 kgf/cm^2 with a standard deviation of 0.14. The computer control strategy will utilize a calculated RVP to manipulate the tray 25 temperature controller. After installation of the computer control system, the RVP process variance is expected to be reduced by 70%. Product values and operating costs are given in Table 2. The lab RVP analysis has a specified repeatability of ±0.07 kgf/cm^2. Evaluate the savings expected from the computer due to control of the bottoms RVP.

Solution

First, the objectives for computer control need to be defined. Judging from the product prices in Table 2, it appears that the bottoms RVP should be pushed to its limit because C_4 is worth more to motor gasoline than to LPG. In addition, C_5 is also worth more in the bottoms, so that loss of C_5 to LPG should also be minimized.

However, distillation columns have only two basic parameters that can be adjusted to control both the overhead and bottoms compositions: (1) the material balance or distillate-to-feed (D/F) ratio, and (2) the energy balance or energy-to-feed ratio. In this case, the D/F ratio is manipulated by the tray 25 TRC set point to control the bottoms RVP, and the energy requirement is set by the reflux controller, which determines the amount of C_5's in the distillate.

Table 2
Example Problem Data

Product Values	VALUE
Reformate to Gasoline	
C_4	38.6¢/kg
C_5	37.0¢/kg
C_6+	38.1¢/kg
Fuel Gas (based on ethane heating value)	18.1¢/kg
C_3 Product	30.0¢/kg
C_4 Product	35.9¢/kg
Operating Costs	**VALUE**
Stabilizer	
Reboiler	4.09$/Gjoules
Condenser	0.0 $/Gjoules
Deethanizer (DC2 Op. Cost)	0.22¢/kg feed
Depropanizer (DC3 Op. Cost)	0.44¢/kg feed

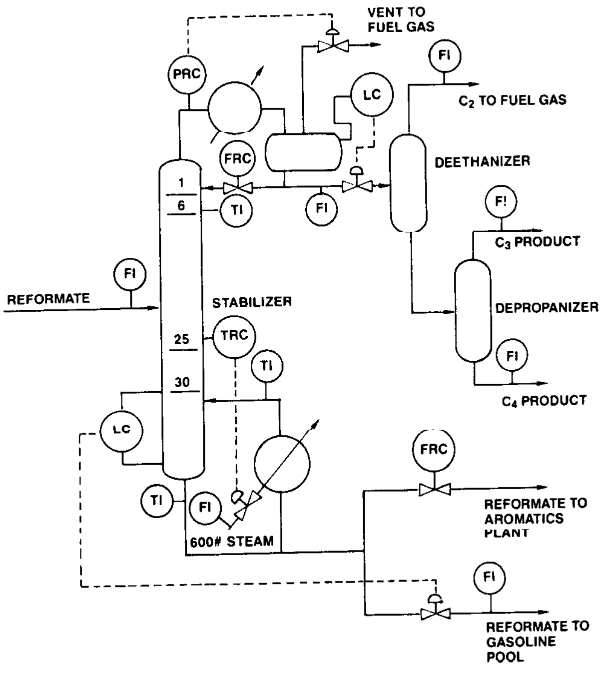

Figure 10. Stabilizer column

Therefore, the computer can adjust only one composition at constant energy input, i.e., bottoms RVP. A tradeoff exists between the energy consumption and the overhead C_5 concentration, which can be optimized. The optimum energy input occurs at the point where the cost of an increment of energy just equals the incremental product value recovered by that energy.

The computer control objectives for the stabilizer column are:

- Maximize the bottoms RVP to the product specification
- Optimize the C_5 concentration in the overhead against energy consumption within product specifications and column constraints

The benefits for control of the bottoms RVP can then be calculated as follows:

(1) Calculate Process Variance

Current –

$$S_M = \frac{R_M}{2} = \frac{0.07}{2} = 0.035$$

$$S_P^2 = S_D^2 - S_M^2$$

$$S_P^2 = (0.14)^2 - (0.035)^2 = 0.0184$$

New -

$$\left(S_P^2\right)_C = 0.30\ S_P^2 = 0.3\ (0.0184) = 0.0055$$

$$S_C^2 = \left(S_P^2\right)_C + S_M^2$$

$$S_C^2 = (0.0055) + (0.035)^2 = 0.0067$$

$$S_C = 0.082$$

(2) Calculate New Average RVP

Use Method B (Same % as Off-spec)

$$\Delta \bar{X} = (1 - S_C / S_D)\ (X_L - \bar{X}_D)$$

$$\Delta \mathrm{RVP} = (1 - 0.082/0.14\ (0.7 - 0.422)$$

$$= (0.41)\ (0.278)$$

$$\Delta \mathrm{RVP} = 0.114$$

$$\Delta \mathrm{RVP}_{\mathrm{New}} = 0.536$$

(3) Calculate New Material Balance

From plant data, the RVP was correlated to the bottoms C_4 concentration. This correlation was used to determine a bottoms C_4 concentration at the current and new RVP targets. A simple separation model was then used to determine the new material balance split at con stantd energy input. The results from the model are summarized below:

	Current	New
Feed, t/hr	145.1	145.1
Distillate, t/hr	7.4	6.3
Bottoms, t/hr	137.7	138.8
Reflux, t/hr	23.0	24.2
Bottoms RVP, kgf/cm^2	0.422	0.536
Tops Composition, wt%	99.69	99.75
C_4-	0.31	0.25
C_5		
Bottoms Composition,	3.25	4.05
wt%		
C_4		
C_5+	96.75	95.95

(4) Determine Component Values (from Table 3)

Tops C_4 & C_5 = C_4 Product Value - DC2 Op.
(C4T) Cost - DC3 Op. Cost

= 35.9¢/kg - 0.22¢/kg
 - 0.44¢/lb

= 35.2¢/kg = 352\$/t

Bottoms C_4 = 38.6¢/kg = 386\$/t
C4B)

Bottoms C_5 = 37.0¢/kg = 370\$/t

(5) Calculate Savings from Improved Control

Benefit = (ΔDistillate) (C4T) + (ΔBtm C_5)
(C5B) + (ΔBtm C_4) (C4B)

= (6.3 - 7.4t/hr) (352\$/t)

+ [(0.9595) (138.8) -
(0.9675) (137.7) klb/hr] (370\$/t)

+ [(0.0405) (138.8) -
(0.0325) (137.7) klb/hr] (386\$/t)

= -387\$/hr - 17\$/hr + 442\$/hr

Benefit = 38\$/hr = 912\$/day

If plant stream factor is 94% and control system availability is 99.5%, annual revenues would be:

$$\text{Benefit} = 912\ \frac{\$}{D} \times 365\ \frac{D}{Y} \times 0.94 \times 0.995$$

$$= 311{,}343\ \$/\mathrm{yr}$$

REFERENCES

1. Tolfo, F., "A Methodology to Access the Economic Returns of Advanced Control Projects," presented at American Control Conference, San Francisco, CA., June 24, 1983.
2. Miller, I. and Fruend, T. E., *Probability and Statistics for Engineers*, 2nd ed., Englewood Cliffs: Prentice-Hall, Inc., 1977, p. 487.
3. Pryor, C., "Autocovariance and Power Spectrum Analysis Derive New Information from Process Data," *Control Engineering*, Oct. 1982, pp. 103-106.

NOMENCLATURE

Variables

X	Value of a single data point
n	Number of data points
X	Mean of X
S	Standard Deviation
S^2	Variance
t	Normalized value of X
Z	Number of standard deviations that a limit is from the mean, given by: $Z = (X_L - X)/S$
$F(Z)$	Normal distribution function evaluated at Z
R	Repeatability of measuring device ($R = 2S_M$)
K	Reduction in process variance with computer control

Subscripts

i	Value at time interval i
L	Limit value
D	Current data
P	Process
M	Measurement
C	Computer