White Paper

Honeywell

Honeywell Process Solutions

Optimization Solution White Paper

Layered Optimization: A low-risk, scaleable approach to driving sustainable plant wide benefits

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Introduction

Advanced Control and Real-Time Optimization

Advanced control and real-time optimization (RTO) tools have become necessary technologies for today's process operating companies to compete and maintain profitable operations. It is widely accepted that the benefits of advanced process control (APC) technology include improved profitability through enhanced process stability, increased throughput and yield, decreased operating costs, improved product quality, and increased operating flexibility. Another benefit of advanced process control is that APC forms the foundation for on-line optimization, which typically adds an additional 20 percent of the advanced control benefits with project paybacks often in less than six months. The following table shows typical APC and optimization benefits that several industrial plants and mills have experienced.

Petrochemicals	**Benefits (/yr)**
Ethylene	2-4% increase in production
VCM	3-5% increased capacity / 1-4% yield improvement
Aromatics (50KBPD)	3.4M - 5.3M US$
Chemicals	**Benefits (/yr)**
Ammonia	2-4% increased capacity / 2-5% less energy/ton
Polyolefins	2-5% increase in production/Up to 30% faster grade transition
Oil & Gas	**Benefits (/yr)**
Upstream production	1-5% increase in production
Industrial Utilities	**Benefits (/yr)**
Cogeneration/Power Systems	2-5% decrease in operating costs
Pulping	**Benefits (/yr)**
Bleaching	10-20% reduction in chemical usage
TMP (Thermo Mechanical Pulping)	$1M-$2M
Refining	**Benefits ($0.01/bbl)**
Crude Distillation (150 KBPD)	5-13
Coking (40 KBPD)	15-33
Hydrocracking (70 KBPD)	13-30
Catalytic Cracking (50 KBPD)	13-30
Reforming (50 KBPD)	10-26
Alkylation (30 KBPD)	10-26
Isomerization (30 KBPD)	3-17

In the past, many companies underestimated the cost and complexity of implementing and maintaining real-time optimization systems. Traditionally, companies involved in optimization projects adopted a “top down” approach using detailed non-linear steady-state process models. These traditional, steady-state optimizers sent targets to multivariable controllers which drove the plant toward optimum operation. However, unless plant personnel were committed to understanding and maintaining such systems, most of these real-time optimization systems went out of service within the first year. Although there is a need for optimization based on detailed modeling in some cases, a large portion of the optimization problems in the process industries today can be addressed more directly with more leverage of plant data and less extensive, targeted modeling that focuses on key units that exhibit significant non-linearity.

Even so, detailed process modeling has proven invaluable to operating companies as a tool for process design, operator training, and operations planning, monitoring and optimization. Detailed modeling is essential for performing tests which are not feasible on the real plant. For example, a model may be used to evaluate different reactor catalysts or to evaluate a process retrofit. For use in on-line optimization, however, the trade-off between process benefit versus added cost and ongoing maintenance effort is very real and must be considered carefully. In many cases, a less extensive modeling approach may be used for on-line optimization because process measurements are available to correct for model inaccuracies on an ongoing basis.

The challenge for the process industries is to provide a level of optimization which realizes the best return on investment (ROI) for the customer. This ROI includes not only the cost of implementing a project and the expected optimization benefits, but also the cost of maintaining the system with the customer’s available resources.

To meet this challenge, a layered approach to optimization is necessary and includes:

- Controller-based optimization
- Distributed dynamic optimization
- Non-linear gain updating
- Traditional steady-state non-linear optimization
- Dynamic non-linear optimization

A company positioned to provide the level of optimization needed for a particular application, from robust multivariable control and dynamic optimization to detailed first-principles modeling and non-linear optimization, is necessary. In addition, process and optimization consultants that can analyze the process to determine which technology is most appropriate is beneficial.

This paper describes the components of layered optimization, the advantages and benefits of this approach, as well as methods for determining optimization benefits of a particular application.

Layered Optimization Solution

As shown in the figure below, advanced control and optimization are dependent on other enabling technologies such as advanced regulatory control and inferential modeling tools. In addition, optimization occurs at a number of layers in the control and optimization hierarchy, from unit control and optimization to multi-unit optimization to plant-wide optimization. These layers represent increasing optimization scope.

The layered optimization approach also consists of different optimization technology layers, from linear dynamic optimization, to non-linear steady-state optimization, to non-linear dynamic optimization.

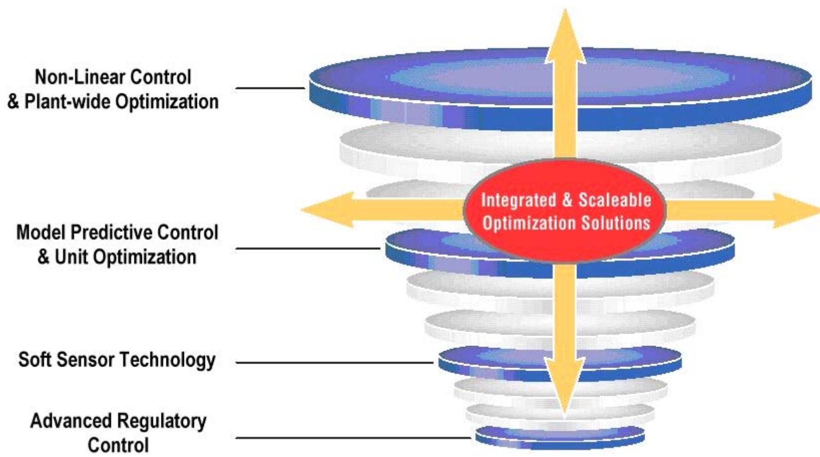

Figure 1: Advanced Control and Optimization Layers

Optimization technology can be divided into four categories:

- Linear model-based predictive control
- Non-linear model-based predictive control
- Dynamic optimization
- Steady-state optimization

We will discuss the differences and the relationship (and relative benefits) of these in this paper.

Overview of Optimization Technologies

Optimization technologies are often used in combination with APC technologies. These advanced control technologies also contain embedded optimization to enable optimization and control to be performed simultaneously. The advantage of a layered optimization strategy is that the appropriate combination of technologies can be selected to solve specific customers' problems, rather than using the same technology for each problem. Figure 2 shows six optimization configurations that have been successfully implemented for customers.

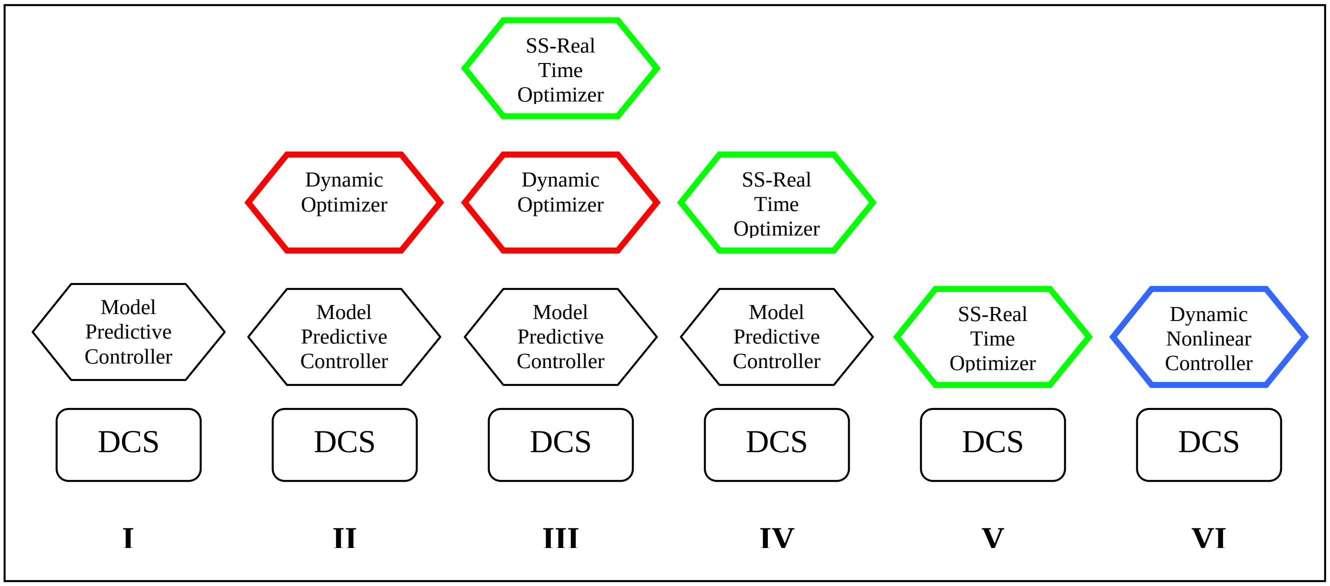

Figure 2: Optimization Configurations

The appropriate optimization solution for a specific customer's application is based on the following criteria:

- Expected ROI:
    - Initial investment
    - Maintenance costs (e.g. rigorous models versus data models)
    - Potential benefits (e.g. tangible and intangible)
    - Complexity of solution (affects application uptime)
- Process changes (magnitude, frequency, type)
- Process flexibility (degrees of freedom to adapt to changes)
- Level of customer technical expertise (less expertise may require a less complex solution)
- Implementation requirements
- Maintenance requirements

The goal in selecting the appropriate optimization technology is to maximize the ROI and achieve an optimization solution that has sustained benefits over the long term with minimized lifecycle costs. Accounting for both the magnitude of potential benefits, as well as a customer's ability to maintain the solution, ensure that the benefits are sustainable.

Optimization Solution Components

Briefly, a layered optimization solution includes the following technology components:

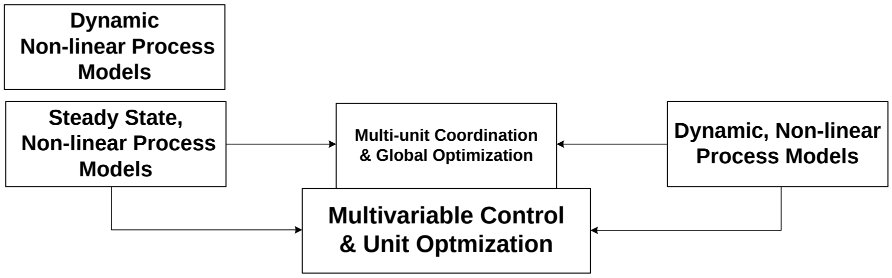

Figure 3: Layered optimization solution components

Unit Optimization

The first level of optimization used with APC is the Product Value Optimization (PVO) component built directly into the multivariable control application. The PVO option provides economic optimization for a process unit (or sub-unit) based on a quadratic (QP) objective function. The user specifies product values and associated production costs, which are then used to maximize the most valuable products, subject to unit constraints. The optimizer uses the controller's dynamic process models and is fully integrated with the controller to provide dynamic optimization. Therefore, both the optimum steady-state solution and the best path to that optimum are calculated at each iteration as part of the optimization process. PVO is illustrated in Figure 4.

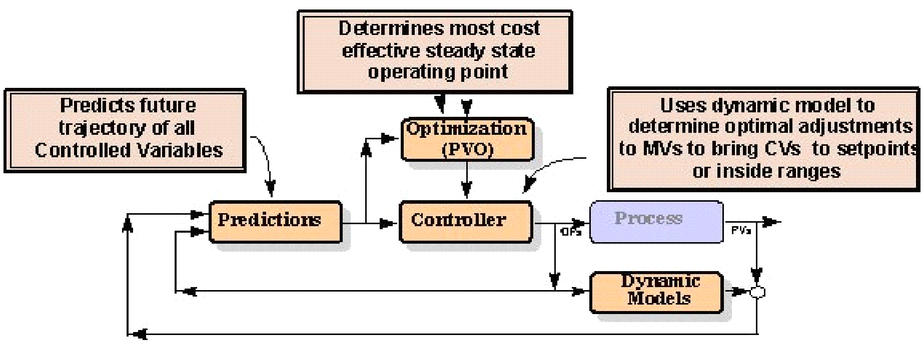

Figure 4: Product Value Optimization within the controller

PVO is ideally suited for small-scale optimization problems that involve pushing unit constraints. In most process plants, distillation columns are ideal candidates for PVO. For large-scale optimization involving multiple units or highly non-linear or unconstrained optimum operations, PVO is elegantly integrated with the optimization system using external global optimum targets (ideal resting values), a feature inherent in the QP objective function.

Multi-Unit Dynamic Optimization

The second level of optimization in the control and optimization structure consists of multi-unit dynamic optimization based on distributed quadratic programming. When process units interact with other units, it is important to consider the dynamics of their interactions and shared constraints when formulating the optimization problem. For example, one may want to maximize feed rate to an upstream unit but be limited by the production capacity of a downstream unit. Multiple unit optimization considers multiple process units, their multivariable controllers and any dynamic interactions between these units. Traditional attempts to solve this problem were to either:

1. Include the multiple units into one large multivariable controller (MVC) and use the MVC optimizer on the combined units *or*

2. Use a detailed model to simulate the combined units, calculate global optimum targets, and pass these targets to multiple MVCs

The first solution, combined control, is relatively easy to implement but has several limitations:

- **Time delays degrade performance.** Processes with significant time delay between units are not well suited for combined control, thus degrading control performance. In addition, process models are extremely difficult to identify between units with long delays.
- **Cross-unit control is often undesirable.** Control may not be acceptable if the controller attempts to manipulate variables in one process unit to dynamically control variables in a different unit.
- **Distributed hardware may be a problem.** Control across multiple DCS data highways and/or computers is not always feasible.
- **Optimization often is all or nothing.** The combined controller cannot break the optimization problem into smaller sub-optimization problems if part of the process is off-line.
- **Bigger is not better.** As the size of the controller increases, tuning becomes more complex, operator acceptance and percent on-line time declines, maintenance is costly and difficult, and overall benefit goes down.

The second solution, detailed modeling for optimization, allows for multiple independent multivariable controllers but has its own disadvantages:

- **Detailed modeling is expensive.** Detailed process modeling is a complicated and costly process which can be difficult to maintain by in-plant personnel.
- **Matching plant operations and model predictions is difficult.** The process must be in steady-state before the models can be updated to match actual plant results. As optimization often occurs under non-steady-state conditions, the parameter estimation for model updating is disabled or simplified dynamic predictions are used to augment more detailed steady-state models. The end result in either case, however, is more system complexity as well as reduced benefits during non-steady-state operations.
- **Extensive data input increases solution risk.** Detailed modeling of the process requires many inputs and increases the probability of problems resulting from erroneous instrument or manually entered data.
- **Plant dynamics are a problem.** Steady-state models do not account for process dynamics. This can be problematic if optimum targets determined from steady-state models are downloaded simultaneously to many units with long delays between units. Although much of this can be avoided through careful implementation, an over-simplified transition to the dynamics of the real plant can result in downstream processes going off-spec or violating constraints until the upstream moves take effect.
- **Optimizers and controls can “fight.”** Careful coordination between the optimization system and MVC is necessary to prevent conflicting objectives. Otherwise, the tendency of the two systems is to “fight” each other. Multiple process models, LP or QP objective functions, and different execution frequencies must be effectively managed.

- **Extensive modeling is often not a requirement for success.** Optimization via detailed modeling is often an overkill solution for many optimization problems which can often be solved much more simply and cost-effectively through the practical application of linear process models and appropriate real-time plant feedback. Many times, however, extensive process modeling efforts are unnecessarily placed ahead of simpler but more effective approaches that leverage plant data, without the overkill effort that can be associated with detailed modeling.

To address these problems and to provide the best return on investment for customers, companies should offer multiple unit optimization with the distributed quadratic programming optimization component. The advantages of this include:

- **Reliability -** provides a multiple unit optimization solution which is highly reliable and easy to maintain and operate.
- **Dynamic optimization -** provides a robust solution which handles non-steady-state operation and process dynamics between process units, and coordinates implementation of the optimization solution across multiple units, resulting in higher benefits compared to traditional steady-state optimization as shown in Figure 5.
- **Works with controllers -** integrates multiple unit optimization with unit-level controller optimization (uses same models and economics as local optimization through the PVO option).
- **Leverages control investments -** capitalizes on the investments of predictive control models. Much time and expense is put into the development of dynamic MVC models. Using the same models significantly reduce implementation and maintenance costs.
- **High return on investment -** Dynamic optimization costs significantly less to implement and maintain than a detailed modeling optimization approach and can often return the same optimization benefit, especially when non-linear control software is added (see next section).

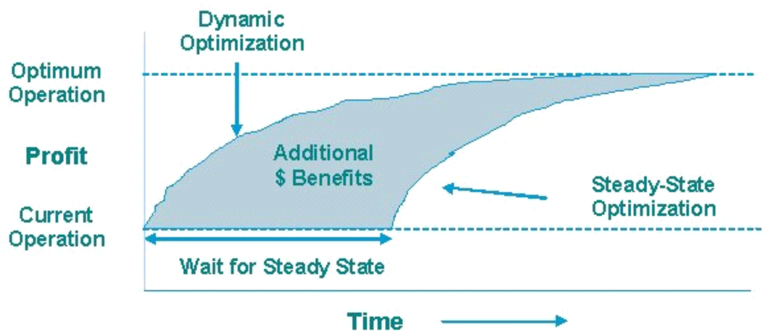

Figure 5: Comparison of dynamic and steady-state optimization

Dynamic optimization is an extension of the lower-level optimization technology found in most commercial model-based, predictive controllers (MPC + PVO); however, multi-unit dynamic optimization combines the QP objective functions from two or more PVO applications. This type of technology can be quickly configured and implemented on top of existing controller-based applications. By using existing MVC models and a set of sensible graphical user interface (GUI) tools, large-scale optimization is feasible in a much shorter time and at a significantly lower cost than compared to traditional steady-state RTO solutions. Figure 6 illustrates a typical Profit Optimizer installation.

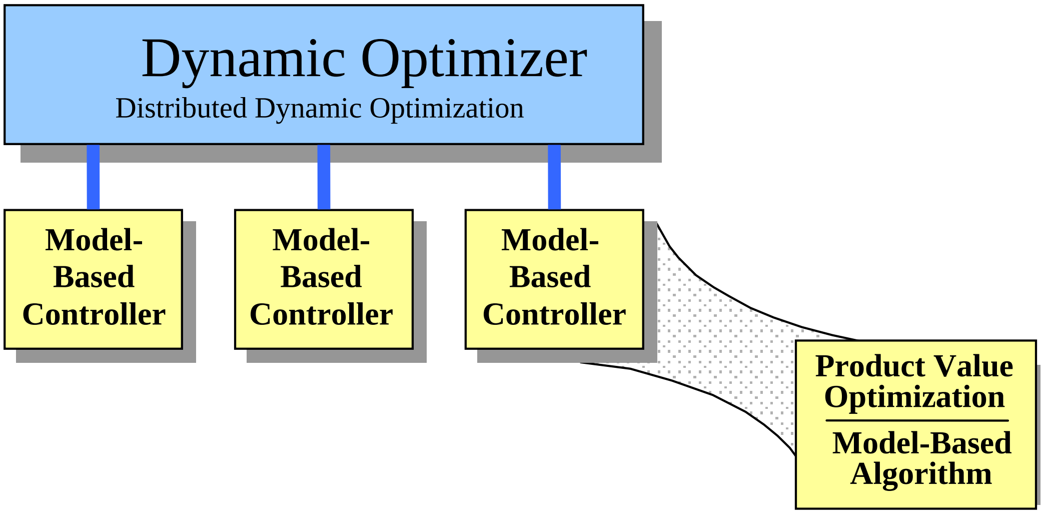

Figure 6: Multiple unit optimization with dynamic optimizer

Dynamic optimization technology is ideally suited for mid- to large-scale optimization problems on most processes. It applies to both linear and non-linear processes, uniquely leveraging the continuous process feedback design to combine step-wise linear modeling with quadratic optimization at each execution cycle (typically once per minute). For non-linear systems with local optima in the optimization search space, non-linear gain updating or traditional steady-state non-linear optimization is recommended.

Non-Linear Dynamic Optimization

The next layer of the complete optimization adds the non-linear control and optimization aspect in the heirarchy via a set of dynamic gain extraction and gain mapping (DGEM) software. By updating the linear models embedded in the base control and optimization applications with information from user-supplied non-linear process models, DGEM technology represents a high performance alternative to large-scale, rigorous optimization systems.

Generally speaking, DGEM software is capable of automatically detecting the onset of process nonlinearities, extracting gain information from non-linear models and regularly updating the control and optimization models to reflect this information. The result is improved control and optimization benefits, since varying conditions that affect the optimum, such as changing feeds, economics and environmental factors, can be accounted for automatically.

DGEM software (as shown in Figure 7) integrates non-linear process models with controller-based and/or multi-unit dynamic optimization applications to deliver enhanced control and optimization benefits. The software automatically extracts gain information from these models and updates the linear models with the information. This gain-updating feature provides superior control and optimization capability since the control and optimization models are constantly updated to reflect the current operating conditions.

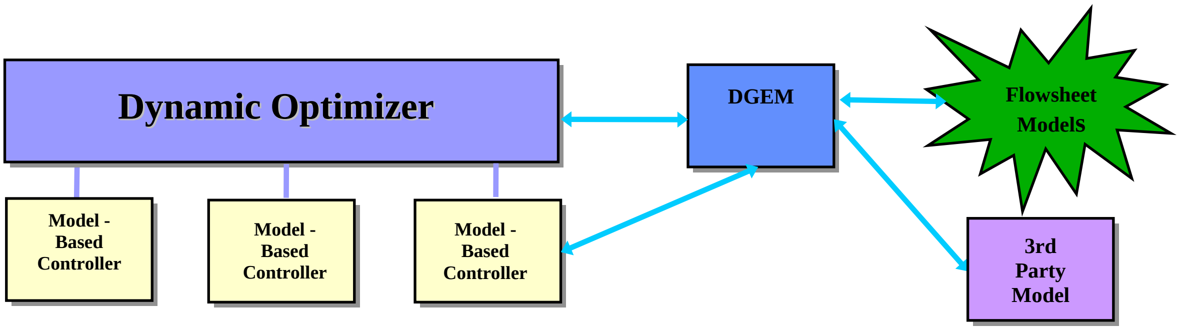

Figure 7: DGEM architecture

DGEM software employs existing process models developed for off-line use in process design and analysis, thus leveraging the investment made to create these models, and ensuring consistent models for both off-line and on-line use. The software is not limited to a specific type of process model; it can be easily configured to use models provided by most modeling systems or it can use custom user-written models within dynamic flowsheet simulation packages.

Another advantage of DGEM software is that it allows smaller scale models to be used. Rather than modeling the entire process, the software allows selective use of non-linear models when and where they are needed. Smaller scale models translate into lower installation and maintenance costs, higher execution speeds, and higher service factors, all of which add to the benefits achieved from improved process performance.

DGEM software should be used where non-linear process behaviour could result in an unconstrained optimum (i.e. FCC unit overcracking region), or a change in the optimal constraint set (i.e. ethylene plant optimization with varying feeds).

Converging on an Unconstrained Optimum

Typically, most units operate in a constrained mode where there are few available degrees of freedom. However, in some cases there is the potential for an unconstrained optimum, such as in FCC operation, where the optimal Riser Outlet Temperature (ROT) is chosen to maximize production of a specific component, such as naphtha.

The use of DGEM software for gain updating of multivariable control applications is ideally suited for such an application and enables convergence of the solution to an unconstrained optimum. An LP solution with static gains will always reside at the intersection of constraint limits. When an unconstrained optimum is encountered using gain updating, the solutions of subsequent optimization runs will switch from one constraint intersection (i.e. corner) to another, and the multivariable control application will move the process to the solution subject to the configured optimization speed. By using the concept of MV soft limits (essentially a more restrictive set of limits honored only by the optimizer) to define MV step sizes, the distance between subsequent optimization solutions can be reduced by limiting the search space that the control application has for its optimization calculations at each optimization interval. Some multi-variable control applications have the unique ability to separate the control horizon (time over which constraints are met) from the optimization horizon (time over which the optimization targets are reached) and ensures that the controller does not oscillate when an unconstrained optimum is reached. Though minor oscillations occur as the solution switches between soft limits, these fluctuations are normally not observable and are close to the magnitude of the noise of the measurements. Figure 8 illustrates how this technique will converge on an unconstrained optimum with respect to, for example the ROT in an FCC unit. Location 1 represents the initial operating conditions and 2-5 represent subsequent operating points with 4 being the optimum. The bounds around location 4 are the soft limits (say 0.5 ºF). A sufficiently small step size is used to avoid having the solution drift from the optimum.

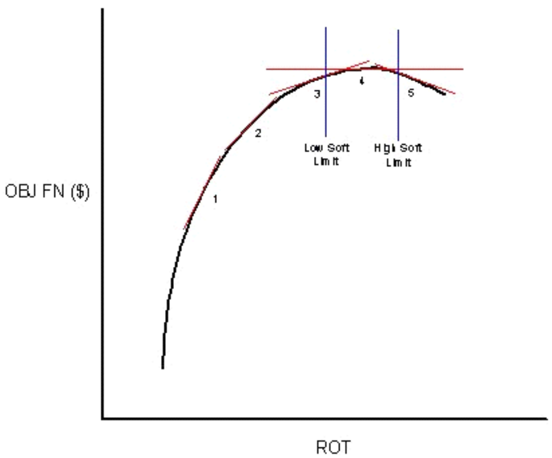

Figure 8: Converging on an unconstrained optimum with gain updating

The main benefits of using DGEM software in conjunction with multi-variable control applications and distributed dynamic optimization compared to traditional steady-state RTO are:

1. Low cost
   - Typical project cost ($200-400K) of a non-linear control software project is significantly less than the typical $1M for full-scale, rigorous, model-based solutions
2. Quick delivery of benefits
   - Implementation time of 3-6 months compared with about 12 months for full-scale, rigorous, model-based solutions
3. Sustainable benefits
   - Much easier to maintain
   - Typically requires 5-10 percent of an engineer’s time to maintain
   - On-line availability typically > 95 percent
   - Low training time
4. High ROI
   - Similar benefits result in typical payback < six months

Non-Linear Steady-State Optimization

The next level of optimization includes a non-linear steady-state optimization (often mistakenly referred to as “Real Time Optimization [RTO]) solution. This technology is typically used where multiple local optima or significant non-linear behaviour is observed. In addition to on-line optimization, this technology can be used for predictive simulation, process monitoring and troubleshooting, engineering studies, development of regressed models for control, planning and scheduling, and operator training. Certain non-linear steady state technologies can be run in on-line or off-line modes with varying levels of practical difficulty.

Additionally, non-linear steady-state optimization should integrate with simulation software to determine optimum steady-state targets that can be downloaded to the APC application. This allows the application the flexibility to carry out the steps required for traditional RTO such as data validation, steady-state detection, data reconciliation and parameter estimation, optimization, etc.

Dynamic Non-Linear Control and Optimization

Dynamic non-linear control and optimization (DNLCO) technologies allow the plant to carry out both control and optimization simultaneously, primarily for polymer applications. Delivering robust control and optimization, such technology is designed to control nonlinear processes in both process gains and process dynamics. The use of a rigorous process model that describes process equipment geometry and chemical kinetics removes the need for step testing the plant. This model also combines the advantages of reliable multivariable control and optimization of on-line process and dynamic off-line simulation for new product grades in polymer applications.

Each of these optimization technologies have merit depending on the application, and as a result, each of these technologies form part of the layered optimization solution.

Recommended Optimization Approach and Benefits

In general, the recommended RTO solution is to use controller-based optimization for single unit optimization, distributed dynamic optimization in conjunction with controller-based optimization for multi-unit optimization, and then add DGEM software as necessary to account for significant non-linearities that could result in an unconstrained optimization solution. This solution approach is the most practical optimization solution available and results in significant, sustainable benefits with low maintenance costs. Extensive experience with this technology reveals significant benefits comparable to traditional RTO, but with less maintenance requirements and higher on-line time (>95 percent). Project implementation times of 3-6 months for this recommended approach is significantly less than traditional RTO (typically 6-12 months), and training time is low for engineers and operators because the solution leverages existing advanced control technology and user interface(s) without the need for another level of end-user complexity.

In some cases, traditional RTO is still necessary and therefore traditional steady-state non-linear solutions are appropriate. For example, mixed integer non-linear programming (MINLP) problems that might occur with utility systems when determining the optimal driver selection (steam vs. electric) is an example where this type of solution is required. Also, traditional RTO has some additional features such as the ability to do process monitoring, however the drawback is that the large models are often difficult to maintain for control engineers.

Dynamic non-linear control and optimization (DNLCO) is recommended for those cases where step testing is difficult (or prohibited), significant non-linearities exist in the process and there are frequent changes due to product specification changes. An example where this solution has been successful is in control and optimization of polyethylene production where frequent product transitions may occur.

Optimization Benefit Estimation

Generally speaking, there are no easy ways to estimate optimization benefits since optimization benefits are affected by equipment constraints, product constraints, process constraints (i.e. degrees of freedom) and changing economic conditions. However, the following three approaches can be used to assist in estimating optimization benefits during project justification.

1. Use typical industry standard estimates as indicated in the benefit table presented earlier. Take 20 percent of the benefits in the table and assume that optimization can provide that amount. This method is subject to a significant amount of error, but can provide some rule-of-thumb benefits.

2. If advanced control benefits have been estimated or are known for the particular application, then estimate the optimization benefits as 20 percent of the known or estimated APC benefits. Again, this is a rule-of-thumb estimate, but is more accurate than method 1 since it accounts for the specific application.

3. Undertake a benefit study to estimate benefits – contact consultant to determine if necessary. Typically such a study requires a site visit and 3-6 weeks of effort, and involves running a model of the process (supplied by the customer) to determine the non-linear behaviour of the plant over the expected operating region and observation of the active constraint sets under varying process and economic conditions. The study can more accurately identify the anticipated benefits and also whether the non-linearity of the process justifies using DGEM software to supply gain updating or potentially non-linear steady-state optimization software. In many cases a good commercial dynamic flowsheet simulation software package can expedite this approach.

Summary

In summary, a layered optimization solution can solve all types of optimization problems. The result of a layered approach is a solution that achieves significant benefits with low risk, requires low lifecycle maintenance costs and sustains benefits in the long term.

For More Information

To learn more about Honeywell's Optimization Solutions, visit our website www.honeywell.com/ps or contact your Honeywell account manager.

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