26. Model-Predictive Control Fundamentals

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Model-predictive control (MPC) improves the capability of process units by stabilizing operation, increasing throughput, improving fractionator performance, decreasing product quality giveaway, and reducing utility consumption. MPC provides real-time information to higher-level applications, such as planning models and process optimizers. MPC input comes from the distributed control system (DCS), advanced regulatory controllers (ARCs), and laboratory data. A well-implemented MPC controller responds once per minute – or in some cases more frequently – to changes in feedstock, ambient temperature, and so on, by moving several variables simultaneously. For major process units, returns on investment for MPC can exceed \$0.50 per barrel, not including collateral benefits, such as improving the efficiency of operators and engineers, and improving process safety.

At relatively low cost, model-predictive control (MPC) improves the capability of process units by stabilizing operation, increasing throughput, improving fractionator performance, decreasing product quality giveaway, and reducing utility consumption.

It is said that a well-implemented MPC application is like having your best operator on the control board 24/7. Operators are indispensable, certainly at critical times such as startup, shutdown and emergencies, but during normal operation, MPC can be more capable than any human.

Major process units are complex. A single change affects dozens of other variables, to one extent or another. For each variable, the response time is different. Constraints must be honored. Violating constraints can ruin products, damage equipment, and lead to loss of containment. In all hydrocarbon industries – gas processing, chemicals manufacturing, and every phase of petroleum production, transportation and processing – loss of containment can cause fires, damage the environment, and cause injuries and fatalities. Therefore, it's no surprise that during manual operation, human operators keep process variables in a comfort zone, well away from limits, leaving plenty of time to react if something changes.

In response to a change in the unit or process objectives, an operator makes small adjustments to one setting (or one group of settings) then waits until the process is steady before making subsequent changes. In contrast, MPC makes appropriate adjustments every minute – even more frequently in some cases – in response to multiple changes, all without violating operational, equipment, or product quality constraints.

A colleague cites a typical example to illustrate the benefits of MPC versus manual operation. On the US Gulf Coast, many units are limited on hot, humid days by air-cooler capacity. A sudden thunder storm can cool the ambient temperature by 10 °C within a few minutes. Under manual control, an operator might not respond at all, but MPC applications respond immediately, increasing feed rate and manipulating other variables to maintain conversion and product quality. As the storm passes and the heat and humidity return, the MPC adjusts to maximize production rates. For a 100 000 FCC unit, the incremental production could be 500 barrels – say, 125 barrels per hour for four hours – which could be worth \$10 000.

An MPC application gets input from the distributed control system (DCS), advanced regulatory control

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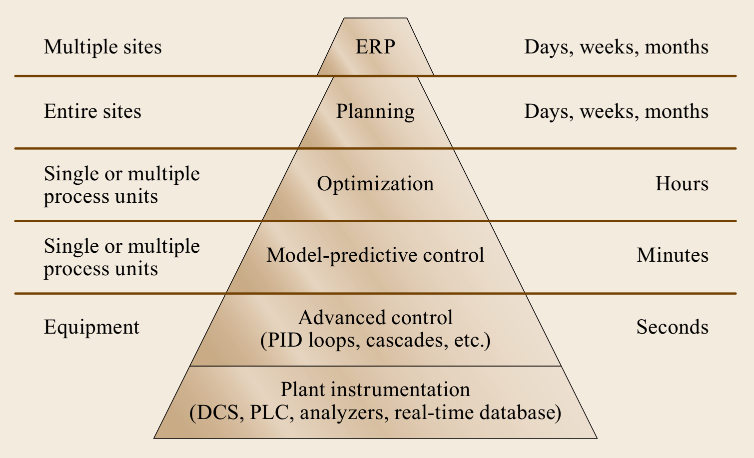


Fig. 26.1 Overview of computer control applications. ERP stands for enterprise resource planning, a software solution that integrates planning, manufacturing, sales, and marketing

(ARC), and laboratory data. It provides information to higher-level applications, such as planning models and process optimizers. For major process units, returns on investment for MPC can exceed $0.50 per barrel, not including collateral benefits, such as improving the efficiency of operators and engineers, and improving process safety.

Figure 26.1 presents an overview of refinery software applications and the frequency at which they typically run.

26.1 Useful Definitions

A *proportional-integral-derivative (PID)* controller is a feedback device. A *process value* (PV is measured by a field transmitter. A controller compares the PV to its *setpoint* (SP) and calculates the required change – for example, a new *valve opening position* (OP), expressed as a percentage – to bring the PV closer to the SP. The required change is calculated with a PID algorithm. In practice, proportional, integral, and derivative constants are parameters used for tuning.

Advanced process control (APC) and *advanced regulatory control* (ARC) applications employ control algorithms to improve process control compared to regulatory PID controllers. APC and ARC include loops or cascades, such as cascading a temperature controller to the fuel gas valve of a fired heater. They incorporate advanced control algorithms combined with regulatory control functions (i. e., lead/lag, ratio, high/low selectors, etc.) to implement a control strategy.

A *programmable logic controller (PLC)* is a small computer used to automate real-world processes. A PLC receives input from various sensors and responds to changes by manipulating actuator valves according to preprogrammed logic stored in the memory of the PLC.

A *distributed control system (DCS)* serves as the foundation of modern computer control. In a DCS, process measurements and control functions, such as PID loops, and APC and ARC applications, are connected to processors, which are networked throughout the plant. A *graphical user interface* (GUI) makes it easier for operators to view data, create plots, change setpoints, and respond to alarms. In addition to process control, modern DCS software includes sophisticated trending and data storage.

A *real-time database* adds considerable capability to a DCS system. As the name implies, it stores historical data, but it does much more than that. It includes sophisticate graphics and real-time data trending, and it can be linked to external software, such as Microsoft Excel, planning software, or process optimizers.

Model predictive control (MPC) applications use multiple independent variables to control multiple dependent variables. If a variable is truly independent, its value is not affected by other process variables. There are two types of independent variables. *Manipulated variables* (MVs) can be changed by an operator to control the process. These include setpoints for regulatory PID controllers and valve positions. *Feed-forward* (FF) and *disturbance variables* (DV) affect the process but can't be manipulated. These include ambient temperature, the quality of an external feed, or the composition of fuel gas used by fired heaters.

The value of a dependent variable can be calculated using the values of independent variables and an appropriate dynamic model. *Controlled variables (CVs)* are maintained at a desired steady-state target. *Constraint variables* are maintained between high and low limits. Many variables are dependent, but not all dependent variables are important enough to be included in the MPC application.

MPC derives dynamic process models from past process behavior to predict future process behavior [26.1]. The dynamic models can be obtained during a series of manual step tests. Modern step tests are automated and/or rely on natural process variation. The predictions are used to control process units dynamically at optimum steady-state targets. MPC applications may also include the use of predicted product properties (*inferential analyzers*) and certain process calculations. Model-predictive controllers almost always include several independent variables, often several dozen.

In this chapter, when we say *APC (advanced process control)* we mean nonpredicting collections of cascades and control loops. In practice, *APC* and *MPC* are used interchangeably.

26.2 Overview of Economics

Table 26.1 presents typical benefits for applying model-predictive control to refinery units [26.2]. It is important to say that the benefits are not additive. For a combined MPC/optimization project, the costs are always lower and the benefits might be higher than if the projects are implemented separately. Conversely, the advertised benefits of DCS and real-time database technology depend entirely on the applications for which they serve as platforms. Stabilizing a crude distillation unit with MPC will stabilize the feed to all downstream units, which decreases the impact of MPC on the other units.

Table 26.1 Typical benefits of multivariable model-predictive control

Process unit	Typical benefits ($US/bbl)	Source(s)
Crude distillation	0.015–0.03	Higher feed rate Reduced product quality giveaway[a] Increased energy efficiency
Fluid catalytic cracking	0.15–0.30	Higher feed rate Reduced ΔP across slide valves Reduced product quality giveaway[a] Increased energy efficiency
Catalytic reformer	0.10–0.20	Higher feed rate Optimum coke on catalyst (CCR units) Reduced product quality giveaway[a] Increased energy efficiency
Hydrocracker	0.10–0.20	Improved safety Higher feed rate Increased stability Better conversion control Improved control of temperature profiles Better control of recycle gas purity Reduced product quality giveaway[a] Increased energy efficiency
Gas oil hydrotreater	0.02–0.10	Higher feed rate Increased stability Reduced product quality giveaway[a] Better control of recycle gas purity
Gas plant	0.05–0.10	Higher feed rate Reduced product quality giveaway[a] Increased energy efficiency
Product blending	0.10–0.20	Reduced product quality giveaway[a]

[a] Equivalent to increased production of desired products

After installation of the requisite infrastructure – DCS, analyzers, real-time database software, operator terminals, process computer(s) – MPC projects on major petroleum refinery or chemical manufacturing units can be completed within 2–4 months. The return on investment is quite high; typical payback times usually are 4–12 months. For relatively simple gas processing plants, the costs are lower and the payback time can be shorter.

The applications that benefit most from model-predictive control have one or more of the following characteristics:

- High production capacity
- Competing control objectives
- Highly interactive processes
- Unusual dynamic behavior
- Day/night or seasonal variation
- A need to operate close to constraints
- A need to closely track optimization system targets
- A need to transition smoothly from one set of targets to another.

In refineries, the largest benefits of model-predictive control come from crude distillation units and gasoline blenders, for which the throughput is high, and from fluid catalytic cracking (FCC) and other conversion units, for which the difference in value between feeds and products usually is high. In all cases, benefits accrue from reduced product quality giveaway. In hydrocracking, MPC in conjunction with ARC can improve safety [26.3].

26.3 Sources of Benefits

The benefits of APC and model-predictive control come from one or more of the following:

- Reduced process variability
- Maximizing throughput against multiple process constraints
- Increased yield of high-value products
- Reduced product quality giveaway
- Reduced production losses [26.4].

Variability is a characteristic of all continuous processes. As shown in Fig. 26.2, simply reducing variability provides little (if any) benefit. Benefits start to accumulate when operators run the plant closer to true process constraints.

For example, if a hydrotreater must produce ultralow-sulfur diesel (ULSD) with $\leq$ 10 wppm sulfur to meet product specifications, and if there is a severe economic penalty for exceeding the specification, the refiner may set a process target of 5 wppm to ensure that the plant never exceeds the limit. In this case, the difference between the target and the limit – i. e., the cushion – is 5 wppm. A cushion of this size is not atypical for coastal refineries where feed quality and/or hydrogen composition can change significantly from one day to the next, and where there is limited ability to correct a specification violation with blending. But a 50% cushion is expensive, resulting in higher operating cost and accelerated catalyst deactivation. If increased stability allows the process target to be raised from 5 to 8 wppm, hydrogen consumption will decrease, heater firing will decrease and catalyst cycle life will increase significantly. To achieve maximum bene-

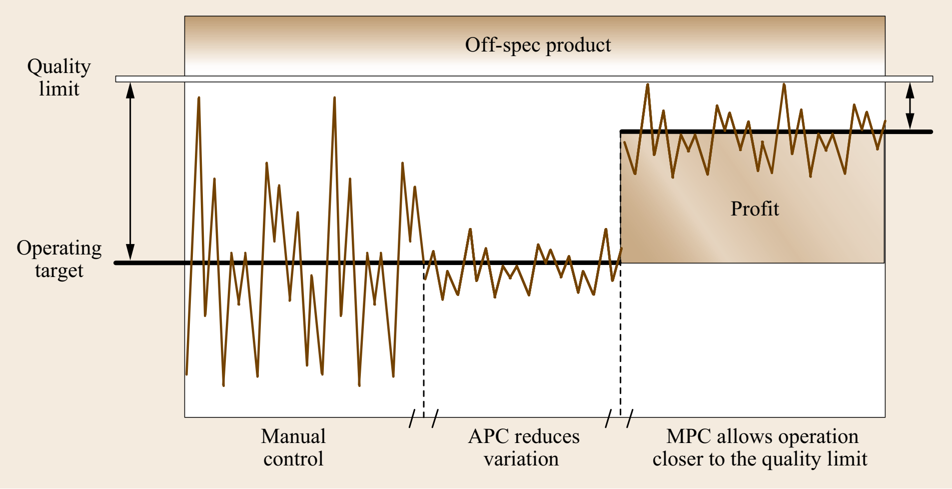


Fig. 26.2 Reducing variability with APC allows MPC to operate the process closer to a product quality limit

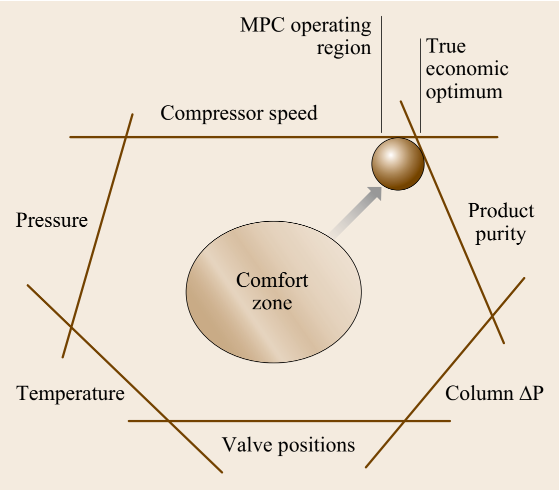


Fig. 26.3 Operating near the right constraints: a major source of MPC benefits

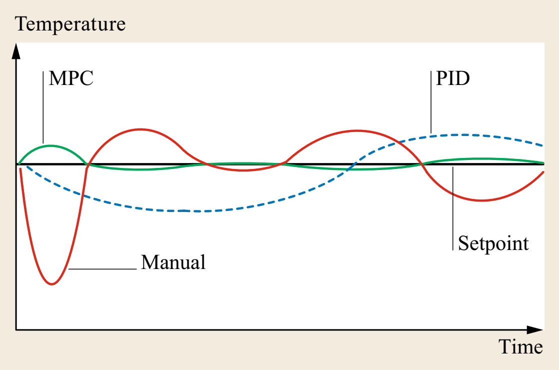


Fig. 26.4 Response to a disturbance: comparison between manual (*red*), PID (*blue*) and MPC (*green*) control

fits, automation requires good and timely information. Hydrotreaters equipped with online analyzers on both feed and product streams are in a much better position than those which rely on thrice daily laboratory measurements.

Speaking of measurements: Operating companies are always looking for ways to cut costs. In the recent past and even today, companies are reducing safety training budgets and analytical costs – with justification. Technology is improving the quality of training while allowing personnel to train when it's most convenient. Automated training includes testing, which provides some assurance that an employee actually learned something. Automation of laboratories is improving the reliability of test results. Unfortunately, cutting tends to go too far. Deprived of laboratory information, inferential analyzers tend to degrade, sometimes so much that they become useless.

Figure 26.3 illustrates how model-predictive control can achieve additional benefits by pushing against process constraints, such as safe compressor speed, product purity specifications, temperature, pressure, and pressure drop across a column. A well-tuned model-predictive control application can move a unit out of the comfort zone of manual operation into more profitable operation, by pushing simultaneously against multiple process constraints. Special techniques, such as move suppression, are used to prevent the plant from moving too far too fast.

Model-predictive control diminishes the impact of disturbances and quickly returns the process to the desired setpoint. Figure 26.4 compares how response to a disturbance might differ between manual control versus feedback (PID) control versus model-predictive control (MPC). The red line shows open-loop (manual) response. The dotted line shows better response with a PID controller. The green line shows that MPC (1) detected the disturbance in advance and took immediate remedial action, and (2) was the first to return to stable operation at the setpoint.

26.4 Implementation

The implementation of MPC requires four main steps – plant response testing, model analysis, commissioning, and training.

During plant response testing, independent variables are moved and dependent-variable responses are captured electronically. Obtaining good plant test data from which accurate models can be regressed is the key to a successful MPC project. For this reason, special care must be taken to ensure that the underlying instrumentation – meters, analyzers, and PID controllers – are properly tuned and calibrated. Traditionally, independent variables were moved manually and one at a time during the plant response test, but with recently developed software, an engineer can obtain equivalent plant test data using closed loop testing methods. Proprietary identification software converts the data into dynamic models for the plant. Response-test models can be used to predict future plant behavior with the following control equation

$$\delta \mathbf{CV} = \mathbf{A} \times \Delta \mathbf{I} , \tag{26.1}$$

where $\delta \mathbf{CV}$ is the predicted change in a given $\mathrm{CV}(i,j)$, $\mathbf{A}$ is the gain matrix obtained during the model analysis phase, and $\Delta \mathbf{I}$ is a matrix of independent variable.

Fig. 26.5 Example of the control equation in matrix form, where the predicted result is the product of the dynamic response gain matrix **A** and a matrix of independent variable changes $\Delta \mathbf{I}$ ▶

$$\delta \mathbf{CV} = \mathbf{A} \times \Delta \mathbf{I}$$

$$\begin{bmatrix} \delta CV_1 \\ \delta CV_2 \\ \delta CV_3 \\ \delta CV_4 \\ \delta CV_5 \\ \delta CV_6 \\ \delta CV_7 \end{bmatrix} = \begin{bmatrix} 1 & & \\ 4 & 1 & \\ 6 & 4 & 1 \\ 7 & 6 & 4 \\ 7 & 7 & 6 \\ 7 & 7 & 7 \\ 7 & 7 & 7 \end{bmatrix} \times \begin{bmatrix} \Delta I_1 \\ \Delta I_2 \\ \Delta I_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 4 \\ 4 \\ -1 \\ -5 \\ -7 \\ -7 \end{bmatrix}$$

Figure 26.5 shows an example of the control equation in matrix form.

Model predictions are used to control the plant against constraints, as shown in Fig. 26.3. This is not a trivial matter, because the application must cope successfully with the following:

- Plant/model mismatch
- Instrument failure
- Unmeasured disturbances
- Input data error
- Diverse process dynamics
- Changing process objectives.

Despite these challenges, when implemented by qualified personnel, MPC applications provide considerable value for manufacturing plants throughout the world.

26.5 Costs versus Benefits

Figure 26.6 illustrates the infrastructure required for computer control. APC and model-predictive control software usually run on a separate process computer, which uses a *data highway* to communicate with the

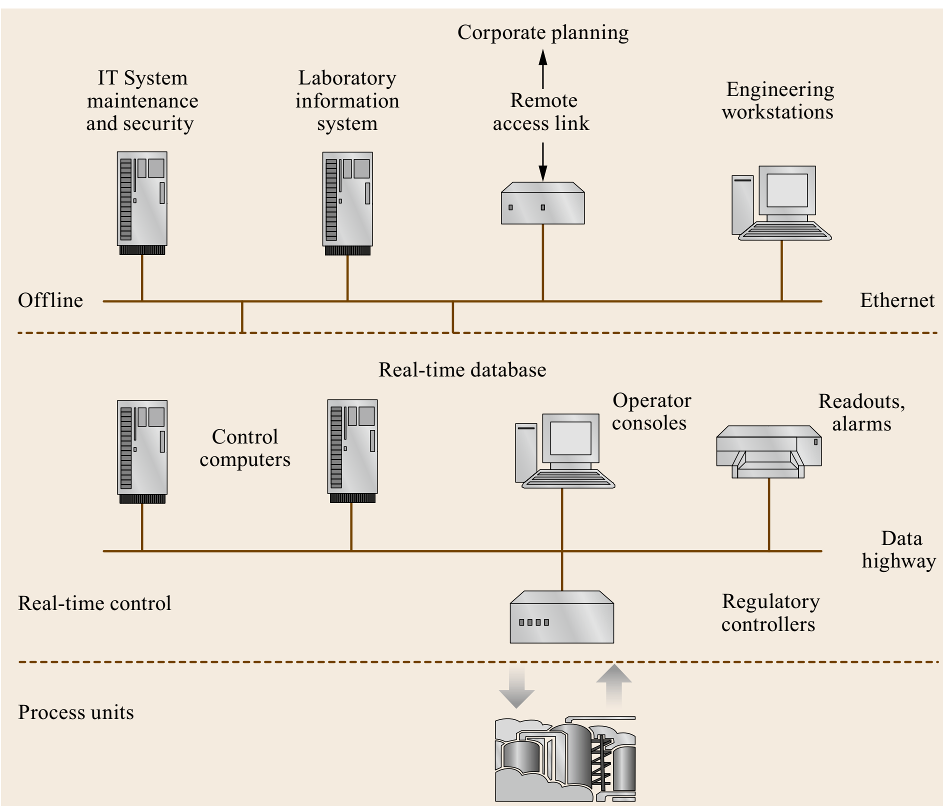
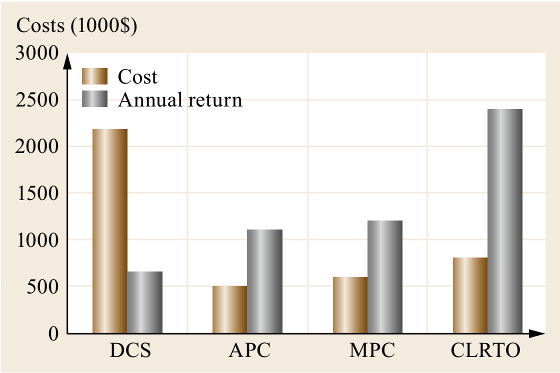


Fig. 26.6 Automation infrastructure

Fig. 26.7 Relative costs and benefits of process computer applications. DCS = distributive control system, APC = advanced process control, MPC = model-predictive control, CLRTO = closed-loop real-time optimization ►



DCS, the laboratory information management system (LIMS), and a real-time database. Advanced applications receive process values from the DCS, calculate the sizes of MV moves, and send setpoints back to the DCS.

Figure 26.7 compares the relative costs and benefits of computer applications. As is the case for a personal computer, hardware accounts for most of the cost, but software provides the benefits.

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