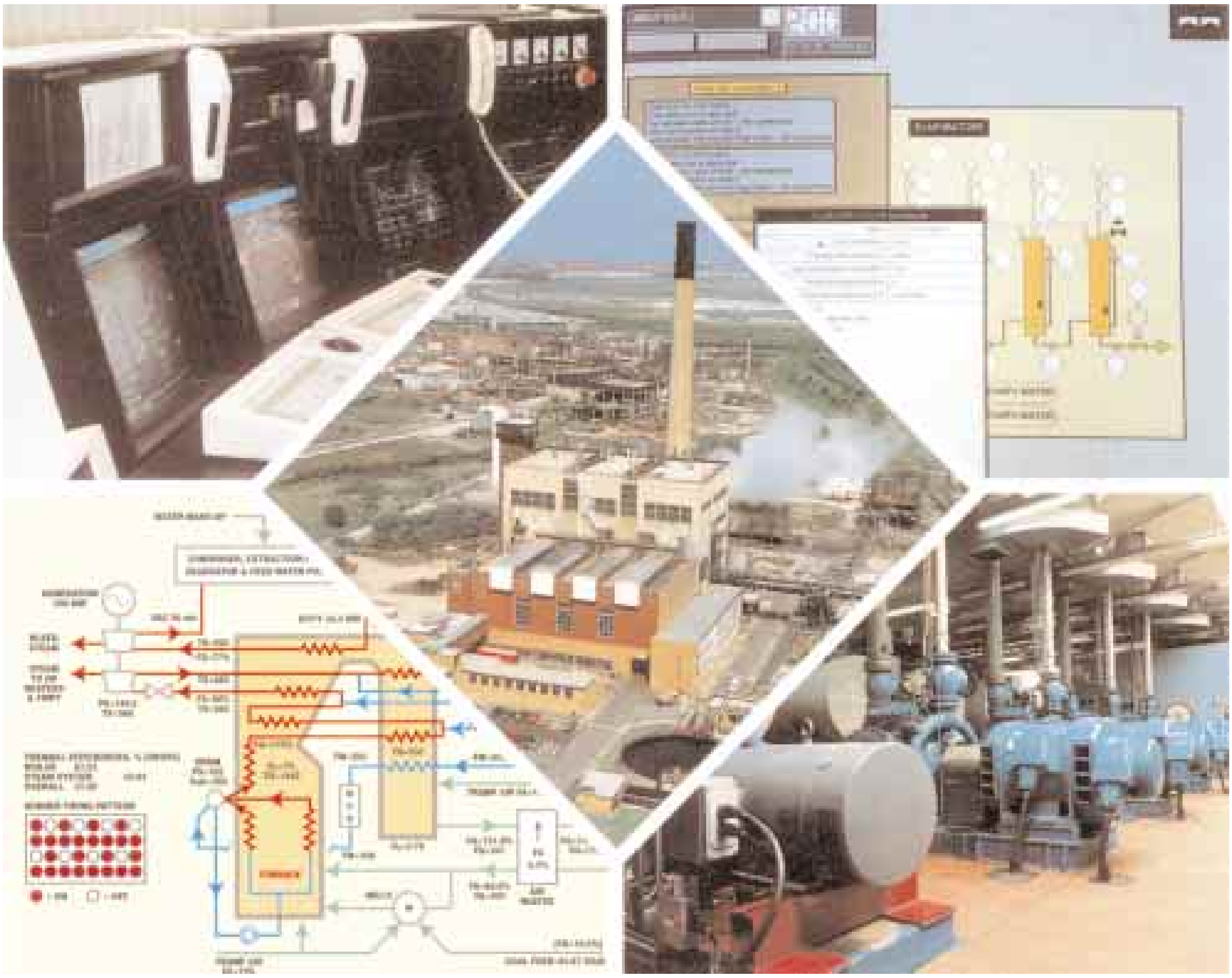
GOOD PRACTICE GUIDE 215

Reducing energy costs in industry with modern control techniques



GOOD PRACTICE GUIDE 215

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ENERGY EFFICIENCY

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The Institute of Measurement and Control
The Institution of Chemical Engineers Subject Group on Process Control

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REDUCING ENERGY COSTS IN INDUSTRY WITH MODERN CONTROL TECHNIQUES

This is No. 215 in the Good Practice Guide series and offers advice about the scope to reduce energy costs in process industries through the application of advanced computing and control techniques.

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FOREWORD

This Guide is part of a series produced by the Government under the Energy Efficiency Best Practice Programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

— *Energy Consumption Guides:* (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— *Good Practice Guides:* (red) and *Case Studies:* (mustard) independent information on proven energy-saving measures and techniques and what they are achieving;

— *New Practice projects:* (light green) independent monitoring of new energy efficiency measures which do not yet enjoy a wide market;

— *Future Practice R&D support:* (purple) help to develop tomorrow's energy efficiency good practice measures.

If you would like any further information on this document, or on the Energy Efficiency Best Practice Programme, please contact the Environment and Energy Helpline on **0800 585794**. Alternatively, you may contact your local service deliverer – see contact details below.

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PREFACE

This Guide will help you to identify cost-effective opportunities to reduce energy costs

This Guide provides an introduction to how modern control techniques can reduce energy costs in the process industries. These techniques range from simple, conventional controls to advanced optimisers, and represent some of the most cost-effective opportunities to save energy.

The Guide is intended to help engineers and managers to identify opportunities appropriate to their own organisations.

The opportunities described are relevant to companies in the oil and gas, petrochemical, chemical, utility, food and drink, paper and board, metals, minerals, mining and general process industries. While energy efficiency is the main focus, the various techniques can also be used to improve process performance more generally, helping organisations, for example, to:

- improve quality
- increase yield
- reduce emissions
- increase output
- enhance reliability
- reduce maintenance costs.

The Review Panel

This Guide is endorsed by the Institute of Measurement and Control, and the Institution of Chemical Engineers

This Guide has been prepared and reviewed by a team of specialists from leading organisations in the UK, including process companies, equipment suppliers, energy consultants and academics. It has been endorsed by the Institute of Measurement and Control, and the Institution of Chemical Engineers.

An outline of the Guide

The Guide is divided into four main sections:

- Section 1 introduces modern control techniques
- Section 2 explains the reasons why these techniques provide benefits and identifies the symptoms of poor control
- Section 3 discusses the various techniques in some detail
- Section 4 presents a step-by-step action plan for achieving benefits.

In addition, there are two Appendices to help readers unfamiliar with the topics:

- Appendix 1 provides a glossary of commonly-used terms: those words and phrases included are *highlighted in italics* when they first appear in the text
- Appendix 2 details some of the more advanced, *artificial intelligence* techniques.

1

AN INTRODUCTION TO THE GUIDE

1.1 What is modern control?

Modern control techniques can improve energy efficiency and process performance

Modern control refers to a set of techniques that can be used to improve process performance, including energy efficiency.

The techniques include:

- conventional controls
    - *Proportional-Integral-Derivative (PID) control*[1]
    - *dead-time* compensation
    - cascade control
- advanced controls
    - *model-based predictive control (MBPC)*
    - *adaptive control*
    - *fuzzy control*
- optimisation and scheduling
- performance management techniques
    - monitoring and targeting (M&T)
    - statistical process control (SPC)
    - *expert systems.*

These and other techniques can be applied to:

- ensure that process and utility system operations are more stable and respond appropriately to changing requirements
- find the most economic set-points and operating schedules
- rapidly detect business opportunities, through better management information and decision support systems.

1.2 Four categories of techniques

Many techniques to improve process operation are covered in this Guide. For ease of understanding, the techniques are divided into four categories:

- infrastructure
- process control

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[1] Words and phrases appearing in italics are explained in the glossary in Appendix 1.

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- optimisation and scheduling
- performance management.

Fig 1 illustrates the relationships between the four categories.

The opportunities are divided into four categories for ease of understanding...

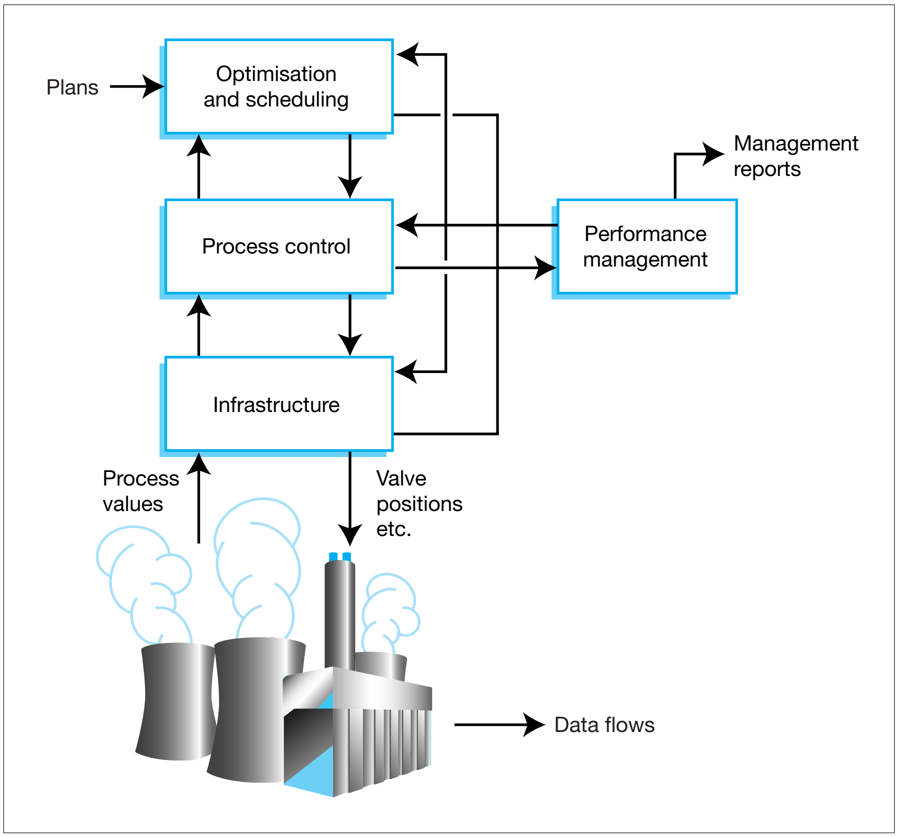

Fig 1 Four categories of modern control techniques

‘Infrastructure’ refers to the sensors and instrumentation on the plant, as well as final control elements such as valves and dampers. Infrastructure also includes *programmable logic controllers (PLC), supervisory control and data acquisition (SCADA) systems* and *distributed control systems (DCS)*. These systems can provide timely and usable data to other computing systems as well as to operators/engineers, and many modern control strategies can be implemented through them.

... infrastructure, ...

‘Process control’ includes the range of conventional and advanced techniques that can be used to achieve the desired stable conditions. ‘Optimisation and scheduling’ includes techniques to find the best set-points and operating plans.

... process control, optimisation, and ...

‘Performance management’ refers to techniques that support process efficiency and energy management, and those that reveal new profit opportunities, and diagnose poor operation. Examples include process simulation, data mining methods and statistical process control (SPC).

... performance management.

1.3 The benefits

The benefits of modern computing and control can be significant, and include:

- reduced energy costs and environmental impact
- improved safety
- increased throughput
- reduced maintenance/longer plant life
- increased yield

- higher, more consistent quality
- fewer process and plant trips
- reduced manpower requirements.

Case studies have demonstrated rapid payback, sometimes months or even weeks

Case studies have demonstrated that these benefits can be achieved cost-effectively. Payback periods of one year or less are typical, especially where a modern control and monitoring infrastructure (ie DCS or SCADA system) is already in place. In some cases, payback periods of months or even weeks have been demonstrated.

Many leading organisations have reduced energy use by applying modern computing and control techniques

- British Sugar has reduced steam costs at its Ipswich site by 17% using a *rule-based optimiser*
- Joshua Tetley reduced refrigeration costs at its Leeds brewery by 30% using expert systems for fault diagnosis
- BP Chemicals has reduced energy use at its Hull site by 8% using a site-wide energy management information system
- Corus has reduced furnace energy use by 2% to 6% using expert systems to improve scheduling.

These companies have participated in advanced projects supported by the Government's Energy Efficiency Best Practice Programme, along with others including ICI Chemicals and Polymers, Carlsberg Tetley and Blue Circle. Throughout the world there are many examples of leading organisations implementing similar projects.

The benefits appropriate to each of the four categories of modern computing and control are summarised in Table 1.

Table 1 The benefits of advanced computing and control techniques

Category	Results from improvements	Further information
1. Infrastructure	More comprehensive, accurate and reliable data - a key requirement for successful operation. Provision of timely and comprehensive data for use by other systems to improve performance. Flexibility of control.	Section 3.1
2. Process control	Improved process stability, allowing operation closer to target, constraint and optimum values.	Section 3.2
3. Optimisation and scheduling	Identification of the best set-points and schedules.	Section 3.3
4. Performance management	Improved understanding of operations. Better decisions. More rapid detection of problems and opportunities. Detection of a larger percentage of potential problems and opportunities. Increased awareness, motivation and interest. More credible reporting of performance (eg environmental performance). Section 3.4	

From April 2001 the Government proposes to introduce a Climate Change Levy. The Levy will be charged on industrial and commercial use of energy and covers primary and secondary fuel used for the purposes of lighting, heating, motive power and power of appliances. Primary fuel is defined as that obtained directly from natural sources such as coal and natural gas; secondary fuel is defined as that derived from primary sources of energy, such as electricity generated by burning coal, gas/oil and coke.

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The Levy will increase the incentive for UK industry to reduce energy costs, with the energy-intensive industries needing to reduce their energy consumption substantially to obtain a rebate of the levy. Modern computing and control techniques should be examined closely when looking at ways to reduce energy use, as they represent some of the most cost-effective opportunities available.

The modern computing and control techniques promoted in this Guide offer proven, well-established and cost-effective ways to reduce energy use

The performance monitoring techniques described in this Guide (see Section 3.4) can also be used to demonstrate improved performance, achievement of targets and compliance with environmental regulations, eg Integrated Pollution Prevention and Control (IPPC).

It is important to recognise that the techniques promoted in this Guide are proven and well-established, not research and development ideas, and have been taken up by many leading organisations, some of which are identified in the various Case Studies throughout this Guide.

1.4 Some barriers

Typically, any investment in modern computing and control produces rapid returns; however, there are often barriers to overcome before management support for capital expenditure can be obtained.

There are some barriers to investment ...

- The number of opportunities and the range of techniques that can be applied is often bewildering, such that it can prove difficult for non-specialists to reach clear conclusions. The information in this Guide is intended to overcome the problem, although specialist advice may be needed in some cases.
- It can be difficult to estimate in advance the benefits that are likely to result from improved control. This is a very significant barrier: without a clear statement of benefits, it is difficult to prepare a sound justification for capital expenditure, and any proposed project may well be rejected as a result. Estimating benefits is also addressed by this Guide, although, again, specialist help may be needed.
- Other barriers include:
    - concerns about the ‘robustness’ of modern, complex techniques
    - fears that the techniques are too difficult to understand and maintain
    - poor presentation of the opportunities to senior management
    - a shortage of experienced personnel.

Long-term success

The Blue Circle ‘LINKman’ system provides an excellent demonstration of the long-term success of an advanced control system. ‘LINKman’ is an expert system which is used to provide on-line, continuous control of cement kilns. It has been operating very successfully at a number of Blue Circle sites for over ten years, providing huge benefits. An independent audit has identified the following factors as key to its continued success:

- the business benefits it generates, that are essential to Blue Circle
- the ‘robustness’ of the system, which has been continuously improved
- the commitment from Blue Circle, at senior management, engineer and operator levels.

Although barriers do exist, they should not be regarded as insurmountable, but as a challenge to be overcome!

... but these are not insurmountable.

2

ENERGY SAVINGS WITH MODERN CONTROL - THE BENEFITS

2.1 The benefits of improved operations

The application of modern computing and control techniques can improve operations and produce significant benefits - including energy savings - by:

- enabling the operation of process and utility systems closer to constraints and optimum values
- using optimum set-points and schedules
- providing more consistent operation
- reducing the number of 'abnormal' events
- enabling faster 'grade' changes.

Each of these operational improvements is discussed further in this Section.

2.1.1 Operation closer to constraints and optimum values

Constraints should be challenged regularly

With improved controls, a process can operate closer to constraint and/or optimum values. Typical constraints include minimum or maximum temperature, composition, moisture content and pressure. It is always worth challenging the validity of a constraint, as it may no longer apply.

Fig 2 compares a 'poorly'-controlled process with a well-controlled one.

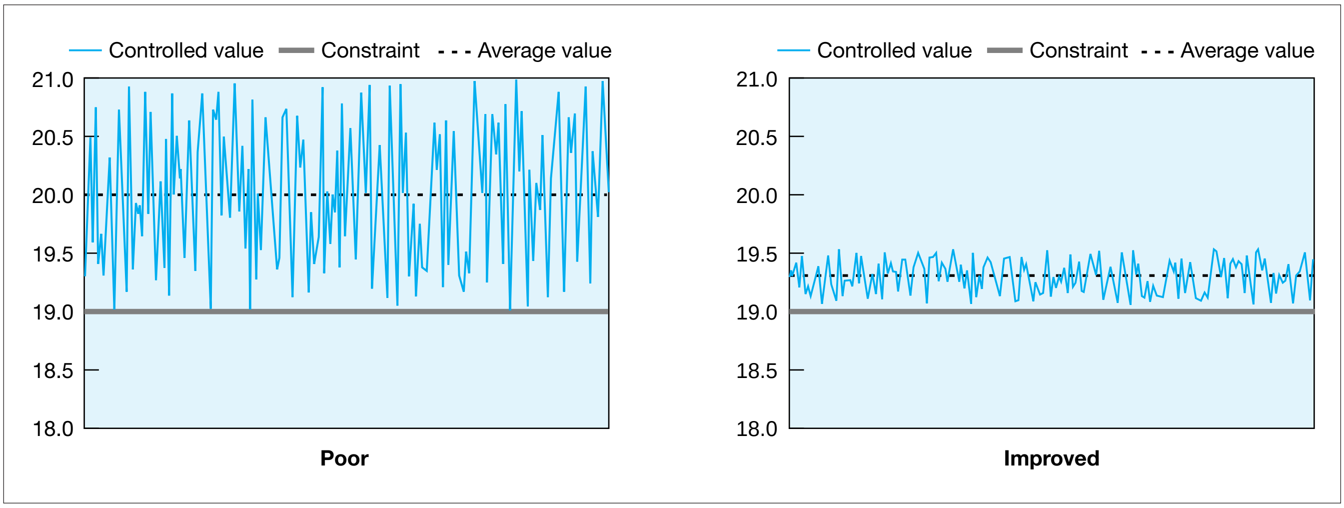


Fig 2 Improved control stabilises key parameters, allowing operation closer to constraint and/or optimum values

The well-controlled process operates with a set-point substantially closer to the constraint value than that for the poorly-controlled process, without violating the constraint any more frequently.

Fig 3 shows the frequency distributions for the controlled parameter in both cases. The set-point needs to be approximately three standard deviations from the constraint value to ensure that the constraint is not violated more than ~1% of the time (or two standard deviations for a ~5% violation). The well-controlled process can therefore be operated closer to the constraint value, typically by three-times the difference in standard deviations.

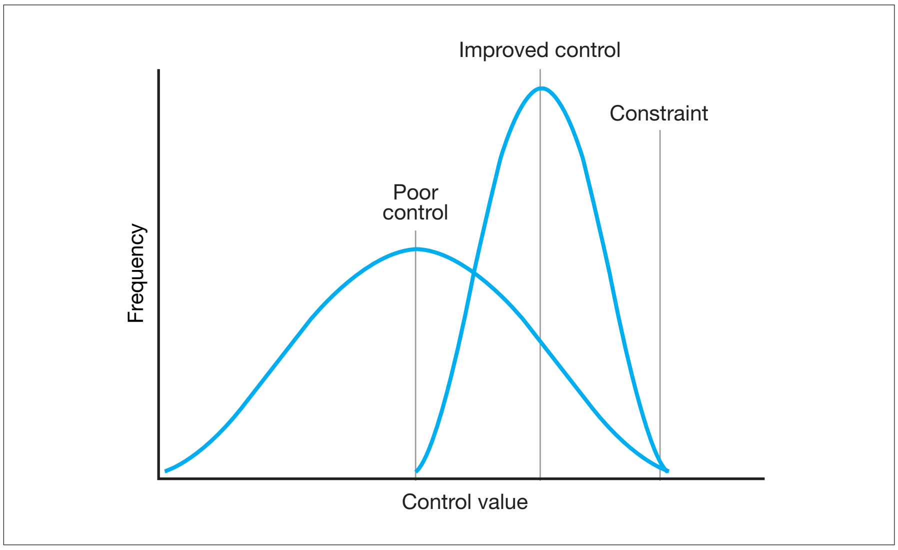


Fig 3 Frequency distributions for the controlled parameter

As a rule of thumb, improved controls typically halve the variability (standard deviation) in a process. In this case, with improved control the set-point can be closer to the constraint value by at least the standard deviation of the poorly-controlled process.

Improved control can result in operation closer to the constraint, moving the set-point typically by at least the standard deviation of the poorly-controlled process

For example, if the process parameter is a temperature controlled above a 180°C hard constraint with a 20°C standard deviation, then improved control could allow the set-point to be moved some 20°C towards the constraint.

Case Study 1 Improved control of drying operations

A mining company introduced improved controls on its drying operations, shown schematically in Fig 4. The wet feed passes from a centrifuge to the dryer, where it contacts hot gases from the combustion of oil that dry and heat the feed.

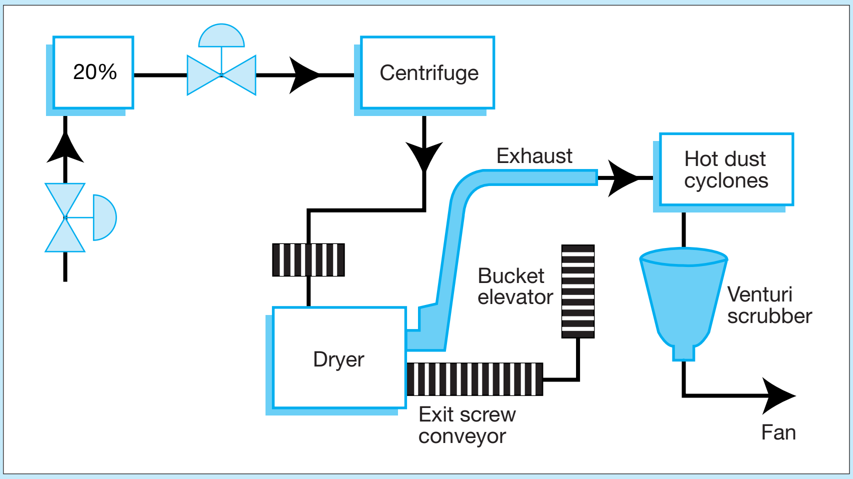


Fig 4 Schematic of the feed dryer

Case Study 1 ***continued***

Manual control of drying was difficult. The controller was aiming for product which was completely dry at 180°C. However, changes in feed rates and feed moisture levels (which are not measured directly) meant that oil rates needed to be constantly adjusted. Time delays in the dryer between a change in oil firing rate and the effects of the change on the product temperature took many minutes and complicated the control - if the controller waited for a fall in product temperature before adjusting firing rate, it would be several minutes too late!

Fig 5 shows the product temperature frequency distribution before new controls were introduced. Product temperature control was achieved by controlling the exhaust gas temperature at a set-point and allowing the product temperature to fluctuate. Operators adjusted the exhaust gas temperature controller set-point to counter significant variations in product temperature away from the ideal 180°C. However, as operators were unable to keep a constant watch on product temperature, significant variations did occur and the dryers were operated conservatively.

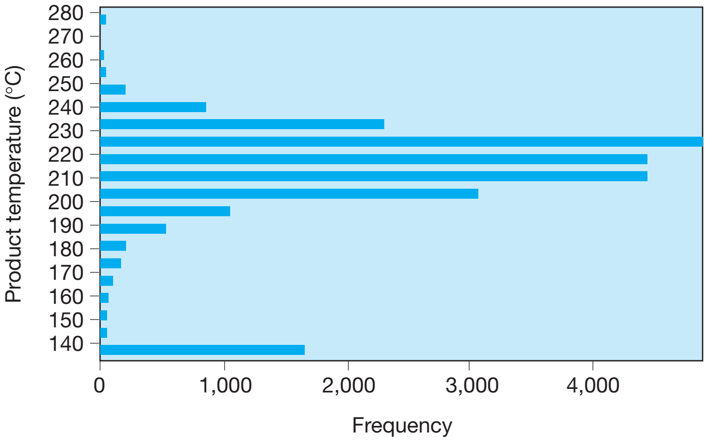


Fig 5 Product temperature frequency distribution with the old control scheme

A new control system was introduced that was able to predict future product temperature (eight minutes ahead), based on the current dryer conditions and historic values. Using the difference between this prediction and the target value, the exhaust gas temperature controller set-point was automatically adjusted.

Fig 6 shows the frequency distribution of product temperature during trials of the new system. The standard deviation in product temperature was reduced from 20°C to 5°C, allowing the dryer product temperature to be reduced by 25°C and saving £40,000/year.

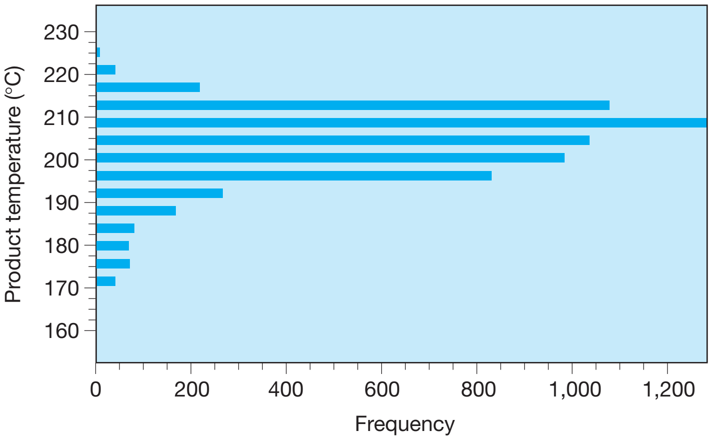


Fig 6 Product temperature frequency distribution with the new control scheme

The new control scheme was implemented at low cost, using the facilities of the SCADA/PLC system that was already in place and a predictive model for product temperature, built from historical data. The scheme cost £15,000, giving a payback period of just five months.

2.1.2 Optimum set-points

An optimum set-point is one that maximises throughput and minimises energy use, etc, while maintaining conditions within constraints.

There are a number of techniques to help identify the optimum set-points for an operation, including first principles (mathematical) models and optimisers, and techniques to analyse historical operating data. Some more advanced control systems incorporate optimisers.

2.1.3 More consistent operation

The combination of improved controls with performance monitoring and decision support systems enables more consistent operation.

The causes of inconsistent operation include:

- differences in opinion about set-points, operating strategies, etc
- failure to detect deviations from ideal operations, for example as a result of faults
- lack of understanding of process operations.

Effective performance monitoring systems can quickly report poor operation, alerting key personnel that action needs to be taken. Decision support tools, such as expert systems, can be used to ensure that the correct advice is provided in a timely and consistent manner.

Fig 7 shows a ‘control chart’ identifying a deviation from normal performance. The parameter plotted might, for example, be a key process performance parameter against time.

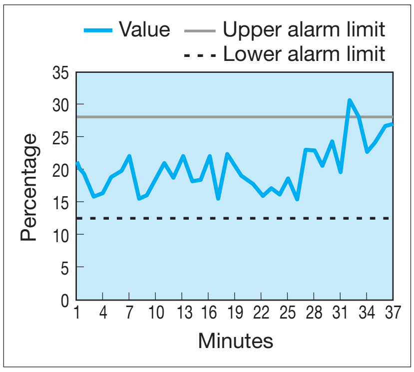


Fig 7 Example statistical process control chart

2.1.4 Reduction of abnormal events

An abnormal event, such as a process trip or operations well outside normal, can directly result in excess energy use. Furthermore, the fear of such an event and its impact may lead to processes being operated in a conservative (and inefficient) manner to minimise their occurrence and impact.

With improved control, the likelihood of abnormal events is generally reduced, since the various process parameters are held more tightly at, or near to, their desired values. Abnormal events can, however, still occur.

Techniques that ‘learn from data’ (data mining) can help to identify the causes of an abnormal situation and, once this is known, steps can be taken to provide alerts and implement corrective actions where possible.

2.1.5 Faster ‘grade’ changes

In many processes, it is necessary to change process operating conditions to:

- produce a different grade of product
- cope with altered process feeds
- simply to re-start a process.

Generally, off specification material is produced and energy wasted in the transition period. Rapid and controlled changeovers can therefore reduce losses considerably.

Improved control techniques can ensure that a process moves to a new operating point at the optimum rate, either by automatically adjusting parameters at the correct rate to the new set-points, or by providing advice to allow operators to make the necessary adjustments manually.

2.2 The symptoms of poor control

‘Poor control’ simply means a control system that could be improved and can be identified in a process in a number of ways. If it is established that it is worth further investigation into ways to improve control, the various modern techniques can then be considered in more detail, in a structured manner (see Section 3).

There are many symptoms of poor control

The main symptoms of poor control include:

- **variability in key process parameters** such as energy use (normalised to take account of throughput, etc), quality, output and similar, or other key performance indicators (boiler efficiency, refrigeration coefficient of performance (COP)).
- **frequent violation of constraints**
- **frequent processing problems**
- **evidence of conservative operations** either from operating data or operator knowledge, eg over-purification.

Poor control can be hidden by:

- **poor understanding of variability in process performance**
- **lack of modern systems**, including DCS or SCADA/PLC systems and modern controls
- **no access to process data via computer**.

3

MODERN COMPUTING AND CONTROL TECHNIQUES

Further details on each of the four categories of modern techniques introduced in Section 2 are given in this Section. Infrastructure, control, optimisation/scheduling and performance management are discussed in turn.

3.1 Infrastructure

3.1.1 DCS and SCADA systems

DCS and SCADA systems refer to computer systems that provide the link between the process (sensors and instrumentation) and the operators, engineers and managers. These systems:

incorporate many modern control, monitoring and other capabilities

provide the infrastructure for a well-controlled and managed process

can be regarded as the de facto standard for a modern efficient process.

DCS and SCADA systems are the de facto standard for a modern, efficient process

A schematic of a typical SCADA installation is shown in Fig 8.

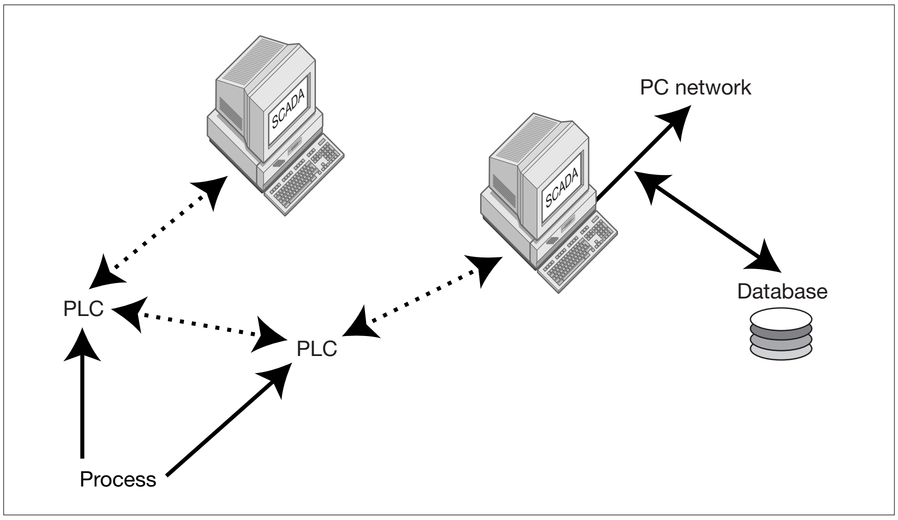


Fig 8 Typical SCADA installation

PLCs generally provide process control and communicate data to the SCADA package, that in turn acts as a human-machine interface (HMI). In addition to displaying current and historical process data, the SCADA package often incorporates advanced control routines, expert systems and similar programs. Most SCADA packages enable storage of historical process data in database format, for analysis by other computing packages. SCADA/PLC networks are usually integrated into the general IT network and can thus provide live data to engineers and managers in control rooms or at their desks.

DCS systems, while similar in concept, tend to be used for more complex processes. These systems are more centralised, and incorporate greater computing power and control capabilities.

3.1.2 Data Quality

Accurate, reliable and comprehensive data are essential for control, optimisation and information systems

The importance of accurate and reliable data for control, optimisation and information systems cannot be over-emphasised. For systems addressing energy efficiency, this includes data on energy consumption and influencing factors.

Data problems include:

- incorrect readings
- unreliable readings
- no readings.

Problems with measurements are one of the main reasons for failure of control, optimisation and information systems.

The importance of accurate and reliable data

A drying process is intended to yield product with a moisture content of 5% ± 0.5%.

If the product moisture sensor is inaccurate and reads 5% when the actual value is 2%, product is being over-dried and energy is being wasted. The out of specification product may also cause problems downstream.

If the sensor reads 5% when the actual value is 10%, product is not being dried enough and may not meet customer needs.

Finally, if the meter provides a reading only intermittently, the process operators may - in frustration - disable the control system and return to manual control.

Conventional solutions to data problems include ensuring that sensors are robust, correctly located, well-maintained, properly and regularly calibrated, and appropriate and fit for the purpose.

Advanced techniques can be used to improve data quality

More advanced techniques, such as expert systems, modelling methods and statistical methods, can be used to improve the quality of data supplied to a control, optimisation or information system. These techniques can:

- verify data
- identify when sensor problems occur
- provide reminders about servicing and calibration
- diagnose faults with sensors
- estimate values that cannot be measured directly.

Verification of sensor data might involve:

- Checking that a value is within expected limits. For example, boiler flue oxygen level might normally be between 1% and 4%: a 7% reading would thus be suspicious and worth investigation.
- Analysing the rate of change of the reading (ie is it too slow or too fast), and the ‘spread’ or standard deviation of the values.
- Using models to cross check data. For example, the energy use of a site might vary with production rates, product types and ambient temperature. A model could be built to predict energy use from these parameters, derived either from first principles (ie heat and mass balances) or from measured site data.

3.1.3 Intelligent sensors

Intelligent sensors that can improve data quality have recently become available. These sensors have in-built computers that can, for example:

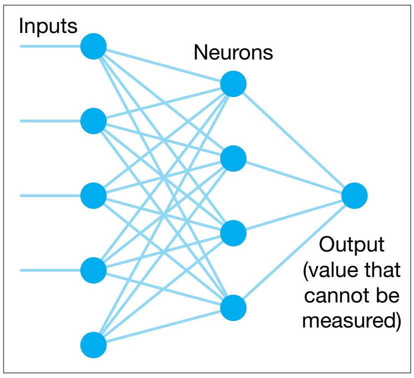
- linearise, average and smooth readings from the sensing element
- correct data as a result of changes in other variables (eg pressure, temperature)
- store information relating to service records, calibrations, etc
- carry out internal diagnostics.

3.1.4 Soft sensors

Soft sensors use modelling techniques to provide estimates for variables that cannot be measured directly, perhaps because:

- direct measurement technology is not available
- direct measurement involves excessive cost
- introducing a sensor would lead to undesirable effects
- other barriers, such as safety and inaccessible location, prevent direct measurement
- the existing sensor is not operating properly.

A classic example of a variable that cannot be measured directly is product quality.



Neural networks (see Appendix B) are one technique for modelling and can be used to infer values that cannot be measured directly

Case Study 2 Quality prediction using neural networks

The paper coating process (Fig 9) involves applying hot resin to paper using counter and co-rotating rollers.

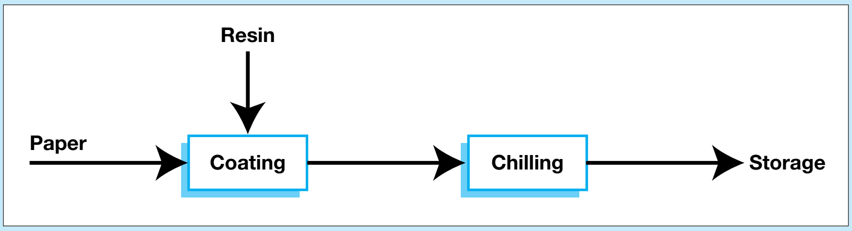


Fig 9 Schematic diagram of the paper coating process

Paper products of different grades are produced from raw paper of varying qualities. Following coating, the paper is chilled and then rolled for storage and further use.

Achieving consistent product quality is critical. Quality depends on both the starting conditions of the process and the running conditions (eg roll speed, roller temperature). Direct, on-line measurement of paper quality is not practical and, therefore, a model must be used to ‘infer’ quality from other parameters.

There are three common approaches to modelling: first principles models, *linear regression* and neural networks. For this application, neural networks were chosen, because there was insufficient knowledge to develop a first principles model, and linear regression could not handle the *non-linearities* in the process.

A model to predict paper quality was built from historical measurements, such as paper thickness, colour and resin weight per area. This was then used in a dead-time compensation controller to adjust roll speed.

Use of the model resulted in a substantial improvement to quality control. In addition, operational margins were less conservative, increasing throughput by 50% and thus reducing the utility cost per unit of paper by 50%. The payback period for the modelling system was just six months.

3.1.5 Manual data collection

Automated data collection systems are cheap reliable and practical - manual data collection should only be used as a last resort

Manual collection of data is still widely used for certain tasks, such as energy monitoring. It should, however, be regarded as a last resort for modern process sites. While manually-collected data is better than none, automated data collection is cheap, reliable and practical. Many *data acquisition* packages are available, most of which are reasonably priced, easy to customise, modern, well-supported and '*open*' (systems that can be easily networked).

3.2 Modern process control

Over the last two decades, considerable research effort has produced a vast range of modern control techniques and methods. It is often difficult to identify which technique is the most appropriate.

In some cases, a relatively simple control system will prove sufficient; in others, a more sophisticated approach will be needed. Advanced techniques are often required where the process:

- is very integrated
- has significant time delays
- is significantly non-linear
- operates in different 'modes', eg produces different products, operates at different throughputs, processes different grades of raw material, etc.

In this Section, a selection of conventional and advanced solutions are discussed to help you to find the best, most appropriate solution.

3.2.1 Simple feedback control

PID control is ideal for many control applications

Simple feedback control is the most basic type of control, and is normally implemented using a Proportional-Integral-Derivative (PID) controller. PID controllers calculate the change to be made as the sum of up to three elements:

1. the magnitude of the error (proportional control (P))
2. the sum over time of the error (integral control (I))
3. the rate of change over time of the error (derivative control (D))

Typically for flow control only the P and I elements are used. For level control, P and I elelments are used, or even just P. For temperature and pressure control, all three elements, P, I and D, are generally used.

3.2.2 Level controls

If the flow out of a vessel is changed, the level will continue to change until another adjustment is made. In many cases, the precise level is not important, as long as it remains within limits. In these cases, the volume of the vessel can be used to absorb any disturbances: this is sometimes referred to as averaging level control.

Averaging level control can be used to 'absorb' disturbances

Averaging level control can be achieved using PID controllers with suitable tuning, but model-based level controllers give better performance. Model-based controllers use a model of the vessel (based on its dimensions) to:

- estimate the size of a mass balance disturbance affecting the level
- predict the smallest change in flow out of the vessel that will stop the level breaching either the high or low limit
- make (or suggest) changes to stabilise the level, and then calculate the smallest change in flow needed to return the level to a reasonable operating point (eg mid-way between the high and low limit) over an engineer-defined period.

3.2.3 Close control of slower responses

On process plants there are often variables which respond relatively slowly, for example temperature and quality. Where a flow might complete its response within 30 - 60 seconds, a temperature might take 5 - 20 minutes to respond completely to a disturbance.

In a process with slow-responding variables, several techniques can be applied to achieve close control.

Cascade control can be applied where there is a slow response to a change in conditions

- Another controller can be used in **cascade** with the one controlling the slow-responding variable, to help eliminate some of the disturbance. The slow-responding variable controller adjusts the set-point of the fast-responding variable.

  For example, it is common to cascade the outlet temperature of a furnace to a fuel flow controller (Fig 10). In this arrangement, the fuel flow controller maintains a constant flowrate of fuel to the furnace and prevents changes in the fuel header pressure causing disturbances in the temperature. The controllers used are usually PID devices (in PI mode).

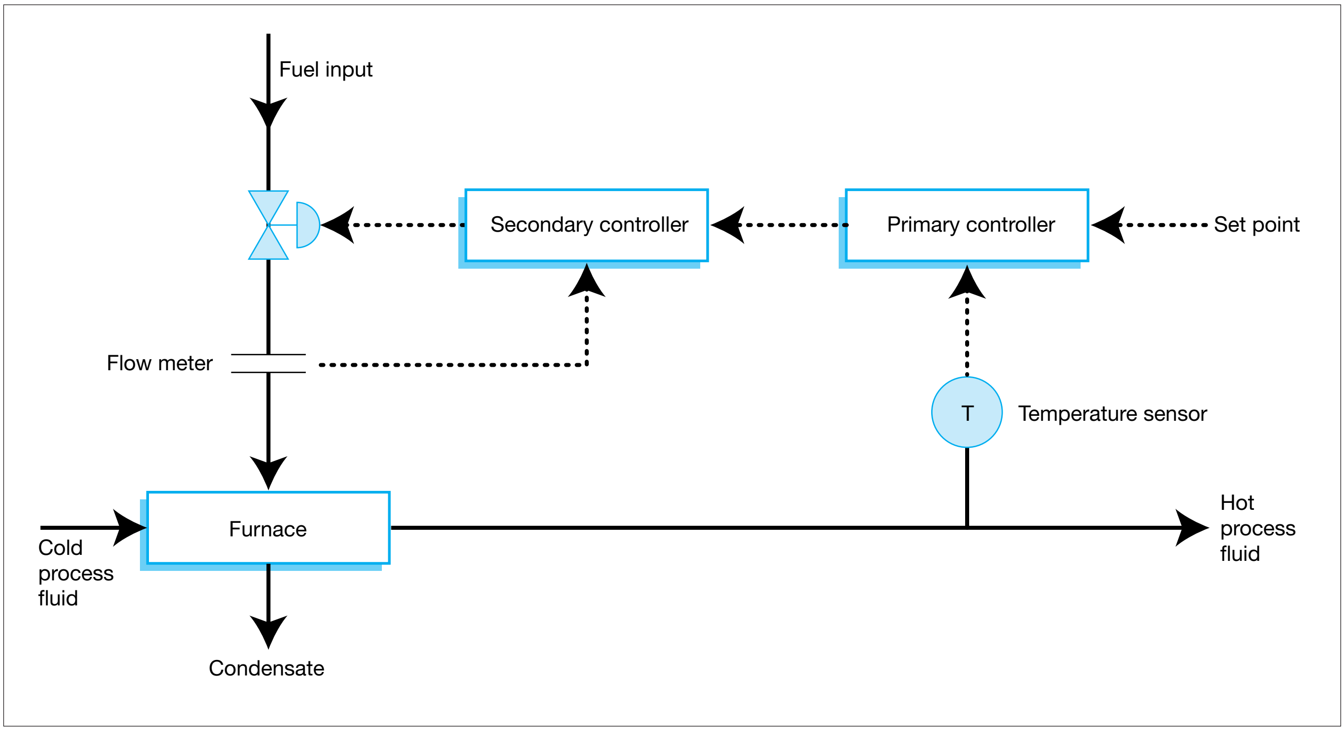


Fig 10 Example of cascade control in a furnace operation

- **Feedforward control** can be applied, whereby a disturbance is measured and action taken ahead of time, to minimise the effect on the variable(s) being controlled. For example, in the furnace operation shown in Fig 10, the process feed flow, temperature and fuel calorific value may all be used to detect disturbances, and the fuel flowrate can be adjusted accordingly to avoid disturbances in the furnace outlet temperature. In feedforward control the following algorithms are commonly used:
  - dead-time and lead/lag, to delay and filter the measured disturbance so that any changes are made at a time that will exactly cancel the effect of the disturbance
  - ratio or bias, to set the process adjustment
  - dead-time compensation, in cases where there is a significant amount of delay between process adjustment and the response. In these cases, a dead-time compensation algorithm will give better control than a PID controller.

3.2.4 Multi-variable control

Multi-variable control needs to be applied if one or more manipulated variables affect several controlled variables

There are often situations where the control problem is multi-variable, ie one (or more) manipulated variable(s) affects several variables to be controlled.

A good example is a two-product distillation column, where:

- changing the reflux flow affects both top and bottom product qualities
- changing the reboil duty affects both top and bottom product qualities.

Model-based predictive control (MBPC) (Fig 11) is the most common approach to multi-variable control. The technique involves two parts

1. a dynamic model of the process that can predict future process behaviour and the value of the controlled variables based on adjustments made in the past
2. a controller that uses the dynamic model to calculate the best set of process adjustments to bring it back to desired operation.

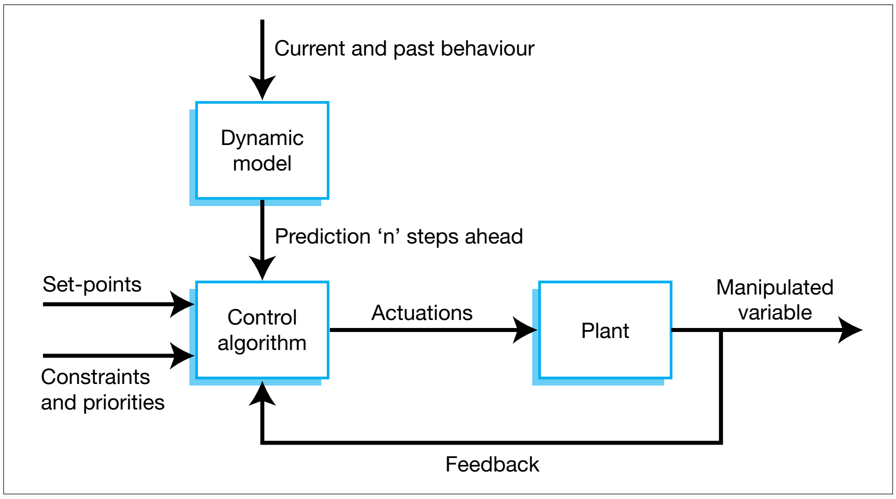


Fig 11 Schematic of a model-based predictive control system

Multi-variable control is widely used for the more 'profitable' processes, such as distillation and other separation processes (liquid/liquid extraction, evaporator), reactor systems, boilers and furnaces, and heat exchange systems. Case Study 3 illustrates a typical application of MBPC.

To build a model-based predictive controller, it is necessary to identify a model of the dynamic behaviour of the process, which usually involves plant tests. Where this approach is not possible, a number of other approaches can be used:

- cascaded PID controllers can be used and tuned by trial and error
- rule-based controllers can be built: for example, 'Rule 1: if quality 1 and quality 2 are 1% above set-point, increase reflux flow by 1%', etc.
- fuzzy control (see Appendix B) can be applied.

A rule-based approach has been very successfully applied to control steam use in the sugar beet refining process[2]. In this complicated, integrated process, rules are used to control the timing of process operations and the selection of plant configurations.

A *fuzzy logic* control system has been successfully implemented on cement kilns. The controller consistently and accurately applies the expertise of the best cement kiln operators, thus realising energy savings of 5% to 7%.

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[2] Full details of this project are given in Future Practice Profile 85, available through the Environment and Energy Helpline on 0800 585794.

Case Study 3 Model-based predictive control applied to a crude oil distillation process

A crude oil preheat train, preflash tower and main fractionator from a refinery in Spain is shown schematically in Fig 12.

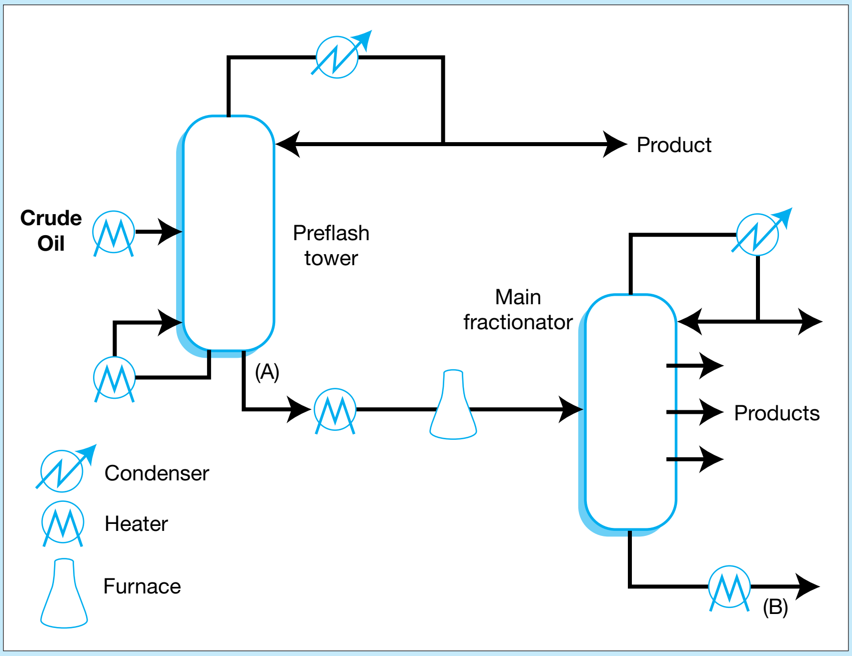

Fig 12 Crude oil distillation process

The unit preheats crude oil in a heat exchanger train before first separation in the preflash column. The liquid product from the bottom of the preflash column (A) is heated further and then distilled in the main fractionator, producing a range of products.

The installation already had a comprehensive DCS which maintained the process in a steady state. However, further improvements in product quality control were desirable.

The distillation process is complex with multiple interactions and time delays. Therefore, two advanced techniques were applied:

- models were developed from first principles to infer distillation column product qualities
- model-based predictive control of product quality and other key parameters was implemented.

The new controls reduced the amount of heavy residue product from the bottom of the main fractionator (B), resulting in a 5% reduction in energy use downstream of the distillation process. In addition, there were significant increases in the yield of more valuable distillates.

The payback period for the project was three months.

Case Study 4 Fuzzy and model-based predictive control to improve operation of a carbonisation oven

Carbonisation is one step in the manufacture of carbon composites. The carbon-epoxy composite is heat treated in a furnace, and a pre-determined time-temperature schedule is used to avoid heating the part too quickly and causing damage.

In this project, no direct measure of part temperature was available and process dynamics were known to alter significantly during the heating cycle.

After careful analysis, it was concluded that part temperature could be inferred using a variety of measures, including change in weight of the part, acoustic emissions, water vapour pressure and furnace temperature. A model-based predictive controller was then implemented to control the part temperature. This included an allowance for changes in furnace dynamics, as the furnace heat transfer mechanism changes from conduction to convection and radiation.

A fuzzy controller was also used to define the temperature ramp rate during each phase of the carbonisation cycle. This made use of ‘rules’ developed in conjunction with process engineers.

The new controls reduced the oven cycle time and energy costs by 30%, and the project had a three month payback period.

3.2.5 Minimising the impact of process changes with time

On process plants, the way a process responds to changes may vary with time. Where this is very severe, it can adversely affect the control performance. In these cases an adaptive controller may be beneficial. Adaptive controllers monitor the dynamic behaviour of a process while they are taking action and make adjustments to allow for variations, thereby providing better control.

A good example of using adaptive control to save energy can be found in refrigeration. An adaptive controller has been developed to ensure that the best vapour superheat set-points are selected for different plant operating conditions. This maximises refrigeration efficiency by minimising superheat temperature, while at the same time ensuring that the vapour leaving the evaporator is free of liquid droplets which could destroy the compressor.

3.2.6 Non-linearity

Most process controllers depend on the response of the process being approximately *linear*. In other words, if a change in fuel flow of 1 tonne/hour at one particular feedrate causes furnace outlet temperature to change by 1°C, then at another feedrate the same change in fuel flow causes a 1°C change.

Linear controllers can often be used successfully because the extent of non-linearity is small.

While most processes do not behave in this way, linear controllers often work well because the extent of non-linearity is small.

In some cases, however, non-linearity is so severe that any control system must make allowances for it. A number of approaches are available to control non-linear systems:

- **transformation**
  Variables used by the controller are transformed to make the process control problem more linear. For example, controlling the logarithm of quality on a ‘superfractionator’ gives a more linear response than that of the quality itself.
- **gain scheduling**
  The controller settings are modified to allow for the changes as the process varies.
- **fuzzy or rule-based control**
  Rules can be built which accommodate non-linear behaviour.
- **adaptive control**

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- **full non-linear control**
  Here a non-linear model that predicts process dynamics is used as part of the controller. This type of control is relatively rare.

3.3 Optimisation and scheduling

On multi-variable processes, there is often an opportunity to increase profitability using optimisation.

A variety of optimisation techniques exist.

- **Direct search methods**
  For some simple problems, a direct search method may work. Here, an on-line calculation of process profitability is provided as the optimiser changes the process. If changes made increase the measured profit, further changes in that direction are made; otherwise the change is made in the opposite direction.

- **Linear optimisers** (in model-based controllers)
  Many model-based predictive controllers also include process optimisers. The controller predicts the expected steady state of the process, while the linear optimiser calculates the most profitable steady state and the adjustments needed to reach it. These systems are cheap to install and maintain, and normally capture the majority of savings.

- **Non-linear optimisers**
  In some cases, linear optimisers are inadequate because the non-linearity in the process provides additional opportunities for profit improvement. In these cases:

  - a model of the process is built that reflects non-linear steady state process behaviour. Usually this will involve chemical engineering principles, although neural networks and similar *data modelling* techniques can be used instead of, or as well as, these models

  - when the process is at steady state, the model is updated to reflect the actual process behaviour

  - an optimisation case is run to find the most economic operating conditions for the process

  - the results of the optimisation case are passed to the controls.

  Non-linear optimisers are generally only cost-effective on higher throughput or high value product plants where there is a high level of process complexity.

- **Rule-based approaches**
  Expert systems can be used to capture expertise from engineers and operators, so that the process operation is held closer to the most profitable point as changes arise.

3.4 Performance monitoring and management

The goal of process performance monitoring is to enable management to detect opportunities for profit improvement. This requires two aspects:

- a supporting integrated infrastructure

- decision support applications.

3.4.1 Supporting Infrastructure

The key to performance monitoring and management is that all data needed for monitoring profit performance are available for analysis and reporting with minimal human intervention. To achieve this:

Effective performance monitoring and management requires readily available performance data

- the majority of data which impact profitability are collected automatically

- data from different management areas are integrated into a data warehouse, including, for example data from the process, laboratory, sales, planning and economics, maintenance, warehouse, product storage and shipping, personnel records, financial and product accounting

- the control system has facilities to help engineers and managers to build ad hoc applications using the data, eg for customised reports.

3.4.2 Decision support applications

One danger is that information systems provide only data and not knowledge

One danger of information systems is that they can produce very large reports that overwhelm decision makers with data instead of helping them. The systems must guide managers and engineers to opportunities for control and process improvements. This requires the following general features.

- **Data validation**
  All data used for decision support must be validated. Validation can be rule-based, but more complex approaches can be applied when justified:

  - complex process models can be compared with process data and used to detect when measurements do not match the model with sufficient precision (data reconciliation)

  - the fact that two measurements are related (eg two temperatures in a distillation column trend together) can be used to detect failure of one sensor.

- **Performance calculations**
  It is necessary to calculate performance measures that are indicative of business performance at various levels in the organisation, for example yield, energy use per tonne of feed, capability index, process unit profitability and site profitability. Many of the calculations involved are relatively simple, but some are complex and may require the predictive capability of technologies such as neural networks.

Targets are an essential element of a performance monitoring system

- **Targets**
  To monitor performance it is necessary to have targets. Targets are generated in a number of ways:

  - from planning and scheduling systems - these systems will generate quality and production targets, as well as inventory and operating cost levels. Common approaches are linear programming for optimal planning and scheduling, and constraint-based reasoning used for complex scheduling

  - from contracts (eg quality targets and amounts to be shipped)

  - from legislation (eg emission levels)

  - from historical data (eg energy use for boiler A is x). Here a combination of *data visualisation*, data mining and modelling techniques is useful.

- **Comparison of targets with actual**
  Information systems must help to identify situations where target performance is not met. This can be achieved by comparison of actual performance with target:

  - ensuring that statistical process control approaches are used to define the minimum limits based on natural variation in the process

  - allowing for economic value in those defining limits which are raised as problems for management

  - ensuring exception reporting approaches are used to identify and highlight key areas of opportunity.

- **Identification of changes that will affect performance versus plan**
  Usually these changes will be events in the process. The most common approaches for event detection are statistical process control and process alarm systems, but a wide range of other approaches are being investigated.

- **Root cause analysis**
  Where problems, opportunities and events occur, it is desirable to detect the root cause. This often requires the provision of various tools integrated with the information system, such as:
  - data visualisation and trending systems
  - data mining
  - data modelling
  - process modelling systems.
- **Action planning**
  Once an opportunity or problem is identified, it is necessary to define actions to take advantage of the situation. Simple systems are often useful here and the provision of standard tools, such as data mining, process modelling and spreadsheets, is of use.
- **Action tracking**
  An information management system to track the progress of actions will show progress and encourage further action.

4

THE CONTROL IMPROVEMENT JOURNEY - AN ACTION PLAN

Modern computing and control techniques can reduce energy costs significantly. Most organisations in the sectors targeted by this Guide can reduce costs by at least 10%. The steps identified in this Section and in Fig 13 will help you to make a start on implementing improved control in your organisation.

4.1 Identify priority areas

The first step is to identify priority areas, ie a process (or part of a process) or utility system where the effort and expense of applying more advanced computing and control techniques is justified. Priority areas will have one or more of the following characteristics:

- high operating costs
- low energy efficiency
- variable performance
- a major impact on business profitability.

Identifying these areas involves auditing/reviewing energy and operating costs, and investigating process performance over a period of time.

4.2 Find opportunities

Studying the opportunities will usually prove cost-effective

The second step involves studying the opportunities to improve performance. This work can either be carried out by in-house staff or by consultants, depending on available skills, and will usually reveal opportunities that can be **implemented immediately for little or no capital cost**. More often than not, the savings available from these opportunities easily outweigh the costs of conducting the study.

Opportunities for improvements are available in most organisations

A study at a food processing company revealed that a frozen product was being overcooled by 5°C, with a significant impact on energy use. Once this become known, action was easily - and cheaply - taken to raise the set-point by 5°C and save energy.

In another, similar circumstance, it was found that overcooling was a necessary *comfort margin* for a control system that could not reliably remain within 5°C of the set-point under all conditions. In this case a more advanced approach was warranted.

Once the low- and no-cost opportunities have been implemented, attention can be turned to the more advanced opportunities.

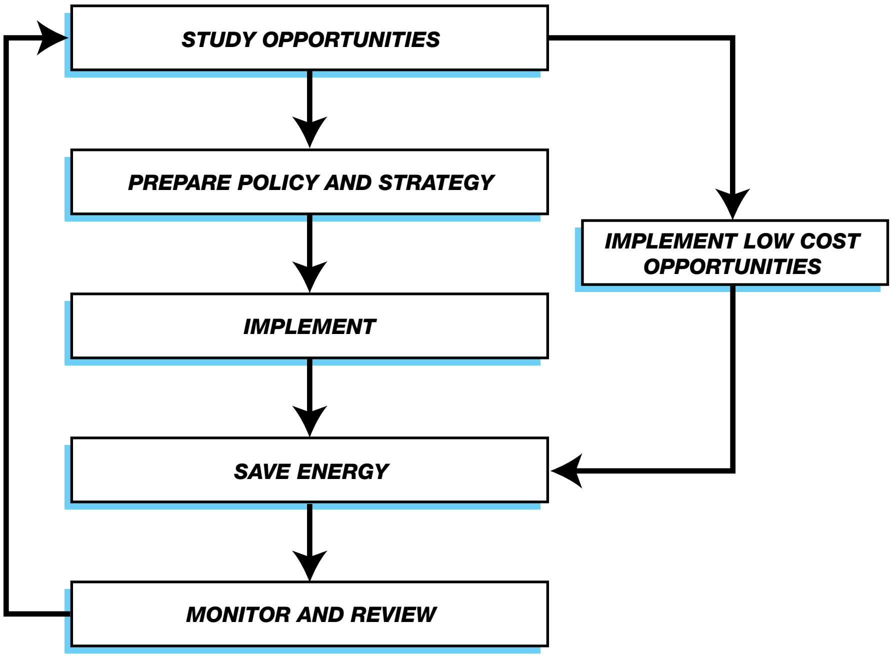
Fig 13 on page 24 provides step-by-step help to identify the opportunities.

4.3 Quantify benefits

Computing and control projects can be complex, and their success depends on bridging the gap between the technology and the application. It is important that:

- computing and control projects focus on solving real business problems and bringing benefits, and not just using the technology for its own sake
- applications are properly integrated into the environment for which they are intended, ie the business, the organisation, its procedures and practices, and the prevailing culture
- there is an awareness of the strategic significance of computing and control techniques: where this is absent, steps must be taken to raise it.

The success of an advanced computing and control project depends on bridging the gap between the technology and the application



With most computing and control projects, it is not possible to calculate energy and other savings with total accuracy in advance, although it is normally possible to produce a reasonable estimate after a feasibility study has been completed. **A 'best estimate' of potential savings is essential if a project is to be approved**.

A good first step is to **learn from experience**. Case studies showing what other organisations have achieved are available from a variety of sources (eg UK Government Programmes, professional bodies, journals and suppliers). In many circumstances, examples will be available that closely match your proposed project.

Ultimately, a more detailed estimate will be required before senior decision makers will commit to capital expenditure. Ideally, this requires an understanding of both the techniques to be applied and the process concerned. Useful approaches include the analysis of historical information and process simulation.

In some cases it may be justified to run a pilot project, as this will allow savings to be proven before significant capital expenditure is committed.

Computing and control projects often produce intangible benefits, such as improved customer care, as well as tangible benefits, such as a reduction in energy costs. A value should be placed on these intangible benefits to strengthen the case for investment.

4.4 And finally ...

This Guide has attempted to demonstrate that modern computing and control techniques can be applied effectively to reduce energy costs and improve process performance in general.

Fig 13 can be used to help you spot the initial opportunities at your own site.

If in doubt contact the Environment and Energy Helpline on 0800 585794 for more information on control techniques and their application. **ACT NOW - you may be missing an opportunity**.

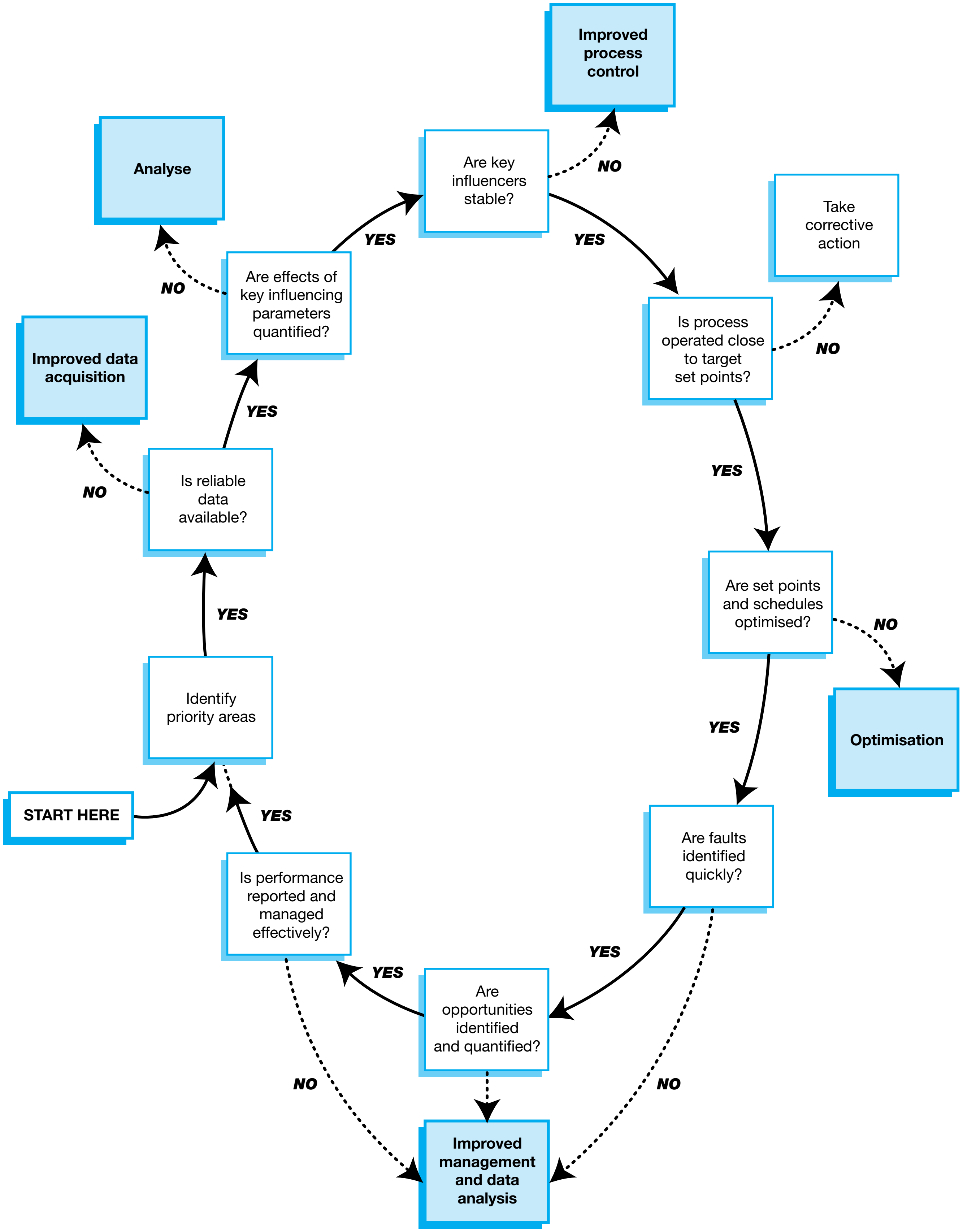


Fig 13 Can modern computing and control techniques improve performance?

APPENDIX A

GLOSSARY OF TERMS

Adaptive control

The control algorithm or parameters are altered on-line to cope with changes in process dynamics.

Artificial intelligence (AI)

A group of advanced techniques that have been developed as a result of research into human intelligence, including neural networks, expert systems, rule induction, genetic algorithms and fuzzy logic.

Case-based reasoning

An artificial intelligence technique where problems are solved on the basis of past case histories.

Comfort margin

The operation of systems away from the ideal set-point to allow for inadequacies in the control system.

Connectivity

The issue of integrating computer software applications, databases and hardware.

Constraint solving

An artificial intelligence technique for finding solutions to complex problems with multiple constraints.

Data acquisition

The process of collecting data, usually automatically.

Data mining

A data analysis technique to find patterns in data, also known as knowledge discovery in databases.

Data modelling Building models of processes and plant from historical data, using techniques such as linear regression, rule induction and neural networks.

Data reconciliation

The process of verifying that data is complete and free of errors. Data visualisation Showing data graphically to reveal patterns.

Dead-time

A delay in the response, ie the output of a system, to a disturbance or change in the control setting.

Distributed control system (DCS)

A computer-based control system where the computing power is distributed as opposed to centralised.

Expert systems

Often known as rule-based systems or knowledge-based systems, these are computer programs that can capture human expertise that can then be consistently and quickly applied.

Fuzzy control

A control system using fuzzy logic.

Fuzzy logic

An extension of expert systems, where the rules are expressed in an imprecise manner (see Appendix B).

Genetic algorithms

An evolutionary optimisation technique.

Hybrid system

A solution that involves more than one artificial intelligence technique.

Influencing factor

A factor that has a significant effect on process performance.

Intelligent sensors

Sensors with in-built computers that can improve data quality.

Knowledge-based System

See expert systems.

Linear

This refers to a process where the relationships between the variables can be expressed by linear equations.

Linear regression

A technique for fitting a set of data to a linear equation.

Management information system

A computer system that provides management with useful, timely and comprehensive data to assist with the management of the business.

Model-based control

A control system where the control actions are based on a model of the process.

Model-based predictive control

A control system where actions are based on a model of the process that can predict future behaviour.

Neural network

An artificial intelligence technique for building models from data.

Non-linear

Systems that cannot be represented by a set of linear equations.

Open system

A computer system that can easily transfer data to and from other systems.

PID control

The most common form of controller, PID stands for proportional, integral and derivative action.

Programmable logic controller (PLC)

A microprocessor with control capabilities used to control many processes, typically linked to a SCADA system.

Predictive control

Control systems that predict future behaviour and act accordingly.

Regression

See linear regression.

Rule-based control

Control actions based on rules.

Rule-based system

See expert system.

Rule induction

A technique for inducing rules (or patterns) from data.

Simulated annealing

An artificial intelligence-based optimisation technique which mimics the way that perfect crystals are formed.

Soft sensors

Software to calculate a parameter that cannot be measured directly.

Supervisory control and data acquisition (SCADA) system

A computer system (usually PC-based) that communicates with PLCs and other control systems, providing an effective user interface, data storage and connectivity to other software.

Targets

Expected values for key parameters, used as the basis for performance monitoring systems.

B

APPENDIX B

Artificial intelligence techniques

Some of the more advanced techniques are described in this Appendix. The information is intended to assist readers not familiar with the topics and does not imply that these techniques are more or less suitable than the other approaches mentioned in the Guide.

Neural networks

Neural networks are a technique for building models from data. The models may be used:

- to improve understanding and decision-making
- as the basis for a model-based (predictive) control or optimisation system
- to set targets for performance
- to predict the future behaviour of parameters
- to recognise events (eg faults).

Neural networks are analogous to the human brain in that they consist of interconnected **neurons**. Inputs to a neuron cause a signal to be sent to the next neuron and so on. The way neurons respond to signals is adjusted during the learning process until the neural network model accurately fits the data.

Neural networks are powerful, as they can:

- generalise
- deal with noisy and uncertain data
- be developed without programming
- handle complex, non-linear relationships.

Many low-cost neural network development tools are available. These can be seamlessly integrated into modern DCS and SCADA systems.

Rule Induction

Rule induction is a technique for interpreting patterns in data. These data can be values in a database or examples, such as faults and their symptoms.

The rules provide an insight into the data and their associated process, and can also be used to create a rule-based model. These models can be extremely accurate and may be used:

- to support decision-making
- as the basis for a control or optimisation system
- to set performance targets
- to predict parameters (future behaviour, missing parameters, etc).

The key benefits of rule induction are that:

- patterns can be *automatically* discovered (this is termed data mining)
- models produced are understandable (in contrast to other techniques such as neural networks, where the workings of the model are largely hidden)
- complex non-linear systems can be handled
- huge volumes of data can be analysed
- it can facilitate the development of *knowledge-based systems*.

Modern rule induction tools are readily available at a reasonable cost and can easily be integrated into modern control, monitoring and information systems.

Genetic algorithms

Genetic algorithms are one technique to find optimum solutions, so named because their operation mimics the evolution of plants and animals.

The key steps are:

- a population of random solutions to the problem is selected (1st generation)
- the fitness of the solutions is assessed according to some criteria, eg energy use
- a new generation of solutions is produced by combining the better solutions and discarding the rest (survival of the fittest). The hope is that the new solutions will be fitter than their parents
- the process is repeated until an acceptably fit solution is found.

The approach:

- makes no assumptions about the nature of the problem, handling non-linearities for example
- can combine continuous and discrete variables
- produces good solutions effectively
- does not require expert mathematical knowledge to apply.

Tools to implement genetic algorithms are readily available and can easily be integrated into SCADA and DCS systems.

Expert systems (knowledge-based systems) and rule-based systems

Expert systems are computer programs designed to capture human expertise, allowing this expertise to be applied consistently, quickly and accurately.

The first generation of expert systems contained expertise expressed as rules which were separated from the algorithms used to interpret those rules - the inference engine. This approach is still widely useful, but the systems tend to be referred to now as rule-based systems.

Alternatives to rule-based reasoning include:

- case-based reasoning
- model-based reasoning
- constraint-based reasoning.

The term expert system is now generally used for a *hybrid system*, for example one that incorporates expertise not only in the form of rules, but also procedures, models, past examples and so on. A modern expert system may incorporate rule-based reasoning, rule induction, neural networks, genetic algorithms, *case-based reasoning, constraint solving*, fuzzy logic and more.

Such systems are widely used for:

- intelligent monitoring
- fault diagnosis
- configuration of equipment
- advisory systems
- rule-based control
- planning and scheduling.

Major benefits of developing and implementing rule-based and expert systems include:

- preserving corporate knowledge
- making knowledge more widely and readily available
- transferring expertise from the skilled to the novice
- improving knowledge even of experts through the development process.

Expert system development tools that can easily be integrated into modern control and monitoring systems are readily available.

Fuzzy logic

Fuzzy logic is an extension of expert systems (rule-based systems) allowing rules to be expressed in an 'imprecise' manner.

For example, a liquid does not suddenly change from being 'warm' at 39°C to being 'hot' at 40°C. Instead, the concepts of hot and warm are imprecise.

For example, it could be said that anything above 38°C was definitely hot (truth value = 1), and anything below 25°C was definitely not hot (truth value = 0). A temperature in between would be hot to a degree (truth value between 0 and 1). Similarly, warm and cold could have spreads of truth values, depending on the temperature. This idea is shown graphically in Fig 14. The relationships between temperature and truth value need not be straight lines.

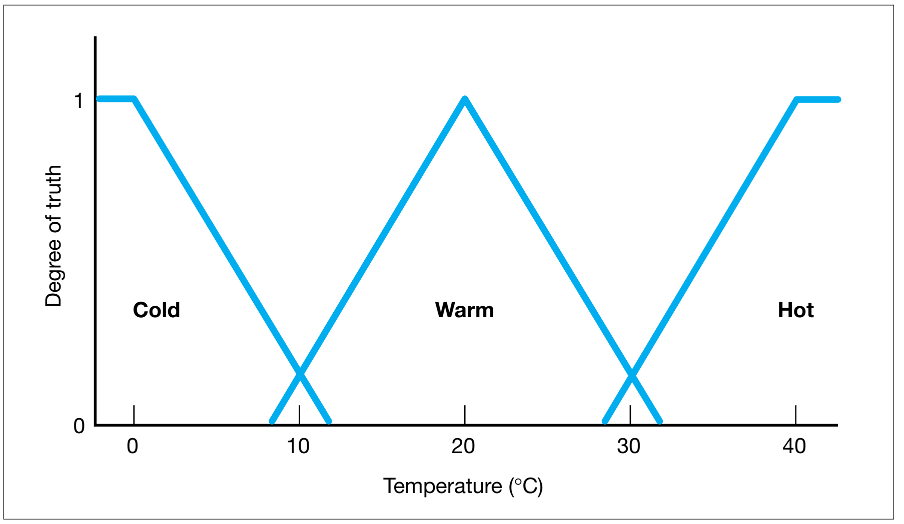


Fig 14 Relationship between temperature and truth value for a fuzzy logic system

It is clearly also possible to provide similar definitions of 'very', 'nearly', 'almost' and so on. Having done so, rules can be expressed as follows, for example:

IF vapour-temperature is very hot

AND level-of-vessel-A is almost empty

THEN decrease pressure by 15%

This rule represents a sophisticated function relating the temperature of the vapour, the level of vessel A and the pressure. The complexity is hidden in a number of places:

- within the definitions of *hot, empty, very* and *almost;* within the reasoning mechanism that combines fuzzy truth values (ie how AND and OR operate on fuzzy truth values)
- how the reasoning mechanism deals with the action part of the rule (eg working out to *what degree* the pressure is decreased by 15%).

The strength of fuzzy logic is that a very complex relationship can be represented by a rule that is simple to express and very easy to understand. Just a few rules of this nature can be used to cover all ranges of temperature and level. Together they would constitute a complete control system for pressure adjustment that is intuitive, comprehensible and could be developed without needing advanced mathematical skills. Furthermore, it could be implemented using 'low power' microprocessors, allowing it to be implemented at low cost.

Fuzzy systems have proved to be effective in many control applications. Their benefits include:

- they can deal with noisy and uncertain data
- application knowledge can be directly encoded into the rules
- no programming is needed
- their operation can be intuitively understood - as opposed to being a 'black box'
- development times can be very short
- they can operate quickly
- they can be implemented in hardware for even greater speed of operation and cost-effectiveness.

As well as control applications, fuzzy rules can be used for decision support applications. In these cases, the technology is very similar to rule-based expert systems but with the added feature of being able to represent and reason with fuzzy concepts.

Constraint solving

Constraint solving is a technique for finding solutions that satisfy multiple constraints. It is similar to genetic algorithms, since it addresses problems involving assigning a set of values to a collection of variables.

The solution technique involves keeping track of all possible values of all variables. As it cycles around applying the constraints, it reduces these possible values. If, at the end of the process, one or more variables does not have a unique value the overall problem has more than one solution.

The technology is particularly suited to scheduling, resource allocation and planning problems.

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