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# Energy and Emissions Optimisation at Chevron Cape Town

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**Abstract:** Across the hydrocarbon processing industry today, energy and utility costs are often the largest operating expense after the purchase of raw materials. Performance of the plant fuel gas systems heavily impacts variable fuel costs, environmental emissions (like SOx and NOx release), overall complex performance and throughput. Controlling fuel gas header pressure and quality introduces the complexities of non-linear dynamics, significant self-propagating interaction and insufficient degrees of freedom to solve the combined control and optimization problem.

Chevron has installed a system to manage these complexities on their 90 000 bpd refinery in Cape Town, South Africa. The system, designed and installed by BluESP, performs plant-wide optimisation across three vaporisers in different parts of the plant and four boilers in the utilities section. The solution uses linear model predictive control with gain scheduling and an LP optimiser to operate against sulphur dioxide emission limits as well as hydraulic constraints. This paper discusses the challenges in controlling the system, the use of model predictive control to address these challenges, as well as the benefits achieved.

## 1. INTRODUCTION

Fuel gas headers are used on virtually every refinery and chemicals complex to manage the fuel gas pool. A typical fuel gas header consists of both producers and consumers of fuel gas, all connected to a common header, as shown in Figure 1.

A large number of so-called “off-gas” streams enter the fuel gas header from the different process units across the complex, typically from the overhead vapour lines of the many light ends columns. In addition, one or more enrichment gases are usually added to the header to ensure control of the fuel gas calorific value (also referred to as heating value). The enrichment gas frequently consists of liquefied petroleum gases (LPG), which is a valuable product in its own right. Natural gas is sometimes available as a make-up gas to facilitate header pressure control.

Major fuel gas consumers are the large furnaces, steam boilers, and various fired heater reboilers on large distillation columns. Finally, a flare system provides for pressure relief to ensure safe plant operation.

In some cases the furnaces and boilers on the refinery are capable of dual firing i.e. they may be fuelled with gas or oil or a combination. In this case it is almost always economically attractive to consume the maximum amount of fuel oil possible, as this is a low value product.

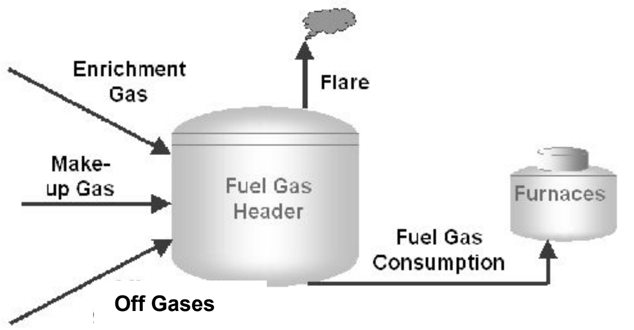


Fig 1: Schematic of a Fuel Gas System

Highly variable fuel gas header pressure and quality is a common problem throughout the industry. Fuel gas pressure has to be kept within a safe range. Suppose the header pressure is too low and dropping. If nothing is done, the pressure will eventually drop below the minimum safe limit for furnace firing, and several of the major process units may shut down, potentially leading to a refinery shutdown. In this case, make-up gas needs to be added to balance the volume in the drum and return the pressure to setpoint, but this will disturb the fuel gas heating value.

On the other hand, if more fuel gas enters the drum from the different process unit than what is consumed, pressure will rise. If this situation continues, eventually the fuel gas flare valve will have to open in order to prevent the pressure from exceeding maximum safety limits. It is highly undesirable to flare fuel gas, due to strict environmental regulations, and the economic losses caused by excessive flaring.

Therefore a control objective for the system is to maintain fuel gas pressure between minimum and maximum limits in order to ensure safe operation of the complex.

All the off-gas flows from the various columns change frequently and often continuously in terms of both flow and quality due to natural disturbances and operator actions occurring in the various process units around the complex. This means that the fuel gas quality changes continuously and apparently randomly.

Most furnaces have coil outlet temperature controllers (COT). These COT controllers are designed to keep the furnace outlet temperature as close as possible to setpoint, in order to keep the process units running smoothly. The regulatory design of the furnaces is motivated by the fact that variability reduction will lead to less variable unit operation, maximising economic benefit. Unfortunately, these designs to do not take into account the fact that what appears to be good for the process unit may not be best for the fuel gas system, and that variability in the fuel gas system will dramatically impact the stability of every process unit around the complex.

As the quality and pressure of the fuel gas varies, the COT controllers of all the furnaces will try to counteract this. Suppose fuel gas heating value has dropped. The COT controllers will open the fuel gas valves supplying energy to the furnaces, increasing consumption, and drawing down the pressure of the fuel gas header. To resolve the situation, either make-up gas needs to be added to increase the pressure, but often this comes at the cost of further upsetting fuel gas quality.

The result is that the furnace COT controllers will change fuel gas consumption in order to compensate for the changing heating value, negatively impacting the volume balance. The COT controllers struggle to maintain their set points. This upsets the various distillation columns in the process units downstream from the furnaces. The resulting propagation of these disturbances eventually impacts the cut-points of these columns. This results in changes to the quality and flow rate of the off-gas streams leaving these distillation columns and entering the fuel gas header. Variations in unit operation (because of variable fuel gas pressure and quality) eventually come back into the fuel gas system via the off-gas streams, similar to a recycle effect.

Figure 2 below is an actual data set spanning several hours from a refinery, showing the addition of LPG enrichment gas under operator control (stepped line), as well as fuel gas quality.

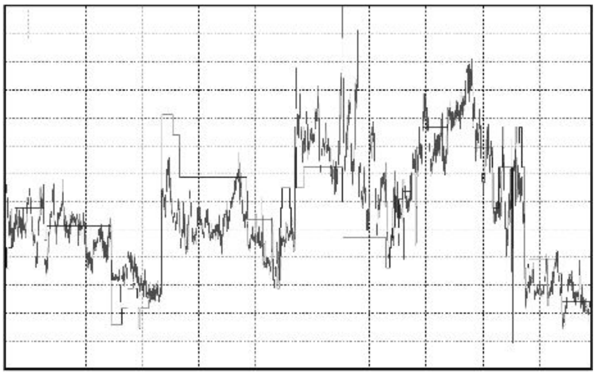

Fig 2: Effect of LPG on Quality

In the above figure each occasion when there is a fuel gas pressure spike represents an incident where the flare valve has to open to reduce header pressure. Quite often, LPG addition was being used even though the flare valve was open. This represents a very significant loss.

A further objective of any control system is to maintain the quality above some low limit.

The system shows gain sign reversals, as well as changes in gain of several orders of magnitude. Human operators cannot deal with this level of complexity, and no rule of thumb will work in this case. Neither is it possible to build a standard PID scheme that can take care of gain inversions.

It is clear that volume and quality balancing are interdependent, and that a system cannot adjust the one without affecting the other. Therefore both control objectives must be solved simultaneously. In addition any solution must also take into account environmental limits placed on the operation.

## 2. MODEL PREDICTIVE CONTROL BASED SOLUTION

As described by Dreyer and Kotze (2004) and Misra *et. al*. (2008), BluESP has developed Model Predictive Control (MPC) techniques to address this complex control problem. The solution combines a linear MPC with gain updates calculated from a rigorous blending equation formulation.

In 2013 BluESP implemented such a control system for the Chevron Cape Town refinery. This solution addresses the control issues described above, while maximising the amount of fuel oil used in the refinery boilers. This results in a reduction in the use of LPG and an economic benefit.

The characteristics of the Chevron Cape Town fuel gas network that informed the design of the system are summarized as follows:

- Many off-gas streams join to form the fuel gas pool

- LPG is added at various points as a make-up gas to maintain fuel gas system pressures
- Fuel gas is flared when the header pressure exceeds a certain value
- The main fuel gas consumers are furnaces on temperature control
- A number of steam raising boilers and furnaces that can use both fuel gas and fuel oil as fuels are installed
- There is a daily limitation on the amount of $SO_2$ that can be emitted.

The Energy and Emissions Optimisation (EEO) solution was designed to achieve the following control objectives:

- Balance volumes and quality across the complex
- Stabilise fuel gas consumption which, in turn, stabilises fuel gas pressure
- Minimise flaring
- Honour all boiler, furnace and hydraulic constraints

In cases where these objectives are competing, the tuning of the MPC is used to endure that the objectives with the highest priorities are met first. Typically the highest priority is given safety and environmental related measurements, followed by variables associated with the control systems ability to control (e.g. valve positions). The pressures in the fuel gas headers are the next priority, followed by the fuel gas quality.

The linear program optimiser that is part of the MPC is configured to minimise use of LPG by maximising use of fuel oil. This provides the economic incentive for the system.

The following was delivered as part of the project:

- MPC based fuel gas header and quality pressure controls
- MPC based boiler controls, that include steam header pressure control
- Provision for the inclusion of a large dual fired furnace in the scheme
- Inferential fuel gas quality calculation
- Inferential $SO_2$ prediction system

The solution spans three different operator stations in the refinery's central control room. This is unusual for an MPC application, since the scope of control is normally one unit. The extended reach of this application is necessary for optimisation, but poses challenges in terms of operator and engineer acceptance and training. These difficulties were overcome by involving the key people from the beginning of the project, as well as spending a significant amount of time with the operators to make sure they were comfortable with the actions being taken by the MPC.

*2.1 Solution Details*

Aspentech's DMC Plus was used as the MPC engine for this project. This algorithm employs a description of the plant in the form of finite step responses, which are generally obtained by plant testing. The plant control and optimization problem is posed as a quadratic program. Further details of the algorithm may be found in Qin & Badgwell (2003).

The models used are represented as unit step responses; the dynamic response of a particular controlled variable (CV or output) to a unit step in an MV (manipulated variable or input) or FF (feed forward or disturbance variable). The prediction of a particular output is then given by (Garcia *et al*, 1989):

$$y(k) = \sum_{i=1}^{n-1} H_i \Delta u(k-i) + H_n \Delta u(k-n) \tag{1}$$

Where $y(k)$ is an output, $n$ is the number of coefficients, $u$ is an input and $H_i$ are the step response coefficients.

The coefficients in (3) are found using plant step test data. Identification routines commonly used include Finite Impulse Response, Sub-space and ARX based tools. More detail is given in Qin and Badgwell (2003).

A simplified version of the model matrix to describe a fuel gas header is shown in Fig 3. MVs are listed down the matrix with CVs across.

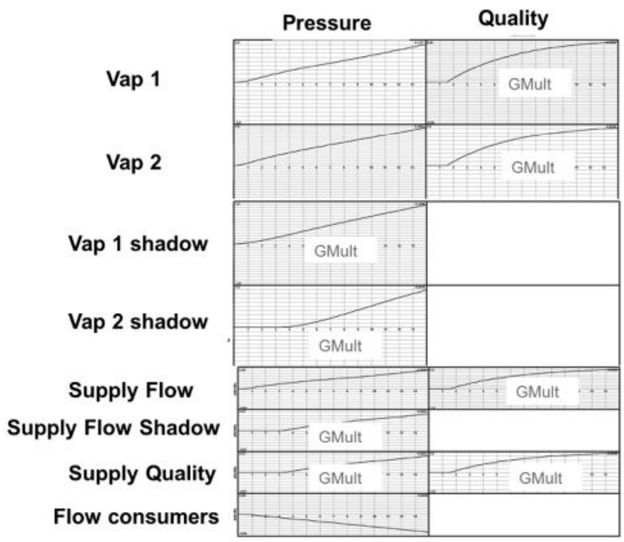


Fig 3: Header Model Matrix ("Gmult" indicates slope or gain is calculated)

Key features of this matrix are:

- the pressure models all have integrating characteristics; models to flow have a fixed slope determined from the plant tests
- "Shadow" variables are used to model the non-linear secondary effect of flow changes on quality and in turn pressure. These supplemental MVs have the same value as the associated real MV, but the CV response is that of the non-linear effect of quality on pressure.

Effectively the pressure is modelled as the sum of two responses, each with different slopes.

- Quality models have calculated slopes or gains.

The total supply (off-gas) flow and supply quality are feed-forward or disturbance variables for the system. Because these variables represent summations of various off-gas flows, the gains of the quality models are not linear. These blending equations have been discussed by Muller, Craig and Ricker (2011), who present the equations necessary for calculating the gains.

As an example of the gain scheduling used consider the effect of change of the flowrate of an individual stream on the quality of the fuel gas. The quality Q of the fuel in the fuel gas drum can then be calculated from:

$$Q = \frac{\sum_i^N Q_i F_i}{F_T} \qquad (2)$$

where $Q_i$ is the assumed quality of the offgas or enrichment gas stream, $F_i$ is the measured flow of the stream, $N$ is the number of offgas and enrichment streams and $F_T$ is the total flowrate.

Differentiating (2) with the respect to flow $F_i$ gives

$$\frac{\partial Q}{\partial F_i} = \frac{Q_i - Q}{F_T} \qquad (3)$$

The "gmults" calculated in this manner are applied to the matrix shown in Fig 3 for the sub-models of quality against any particular flow.

The other gain modifiers required are calculated in a similar fashion.

The BluESP implementation codes all the relevant equations in a database. This allows for straightforward entry and modelling of the topology of the fuel gas network.

The system models the effect of changes in flow of individual off gases on the total flow and quality. For this particular implementation the off gas flow qualities are considered constant, with values calculated by averaging a number of months of laboratory measured compositions of the stream.

In cases where the off gas compositions change significantly it may be necessary to provide a mechanism to update the compositions in the database.

A similar approach is taken to the calculation of the instantaneous production rate of $SO_2$. This calculation sums the $SO_2$ production rates from various sources:

$$SO2 = FCC.SO2 + VDU.SO2 + SRU.SO2 + SWS.SO2 + Flare.SO2 + FuelGas.SO2 + FuelOil.SO2 \qquad (4)$$

where FCC is the fluidised catalytic cracker, VDU the vacuum distillation unit, SRU the sulphur recovery unit and SWS the sour water strippers.

It is the last term representing $SO_2$ production from the burning of fuel oil that the EEO system controls in order to remain within emission limits.

All the necessary data to calculate the terms in (4) (flows and compositions) is collected in the database, validated and written to the plant control system. The calculation is checked against a daily calculation performed by the refinery's environmental team.

A simplified model representation of a boiler is shown in Fig 4.

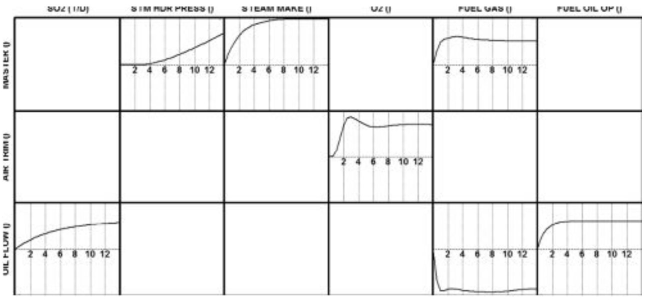

Fig 4: Part of Boiler Model Matrix

Through this matrix the system has the ability to limit $SO_2$ emission rate through use of fuel oil. In addition the system can modify fuel oil flows to help maintain the balance in the fuel gas system, and thus prevent flaring. The model also allows for control of the steam header pressure, optimisation of the flue gas oxygen, and the honouring of all hydraulic constraints.

The system is implemented as one large controller, which facilitates the plant wide optimisation necessary for this distributed system. This also allows for the formulation of an economic objective function for the controller in terms of the actual costs of fuels:

$$J = \sum C_{LPG} F_{LPGi} + \sum C_{FO} F_{FOj} \qquad (5)$$

$J$ is a cost function to be minimised by choice of MV moves, $C_{LPG}$ is the cost per unit volume of LPG, $F_{LPGi}$ are the flowrates of LPG, $C_{FO}$ is the cost per unit volume of fuel oil and $F_{FOi}$ are the flowrates of fuel oil. The inclusion of (5) in the linear program for the controller provides the economic optimisation and thus meets the need to improve refinery profitability.

The trade-offs required to manage the often competing control objectives are implemented using DMC Plus's ranking procedure for CVs. These ranks are used successively by the engine to calculate whether a feasible solution to the steady-state problem exists. If a feasible solution for a set of variables with the same rank, then so-called equal concern errors (ECEs) are used to solve a quadratic problem, which determines the limits that must be relaxed. The combination of ranks and ECEs provide an intuitive and powerful method for tuning the controller.

## 3. EEO BENEFITS

The benefits from an automation exercise are both financial and organisational. Traditionally the organisation concentrates on the revenue, but tends to downplay that the system has automated a complex business process. The financial benefit comes from doing what was previously done manually, but in a more consistent and reliable way. As people in a normal work environment, personnel cannot be available to make decisions and communicate with each other on a minute by minute basis. To even attempt do so would be disruptive and counterproductive. People cannot function like computers. What organisations need to do is leave complex and unusual situations for people to handle and unload them from doing the mundane tasks that are well suited to automation.

The financial benefits from the EEO system arise from:

- Maximising the use of fuel oil with a corresponding decrease in the use of valuable LPG, leading to a direct and measurable economic benefit
- Ensuring environmental compliance in terms of $SO_2$ emissions.
- Improved steam header pressure control
- Improved control of excess oxygen in the boiler flue gases
- Minimising flaring
- Minimising the need to reduce throughput through major process units to prevent flaring
- Creating the space for different units to run reliably closer to their real constraints.
- Reducing variability in heater outlet temperatures allowing for greater optimization capacity in terms of moving the different process units around the refinery closer to their true process limitations.
- Lowering maintenance costs due to greater stability. Examples are, less tube replacements in furnaces, fuel gas valves lasting longer, etc.
- Reducing the refinery Energy Intensity Index, which is directly related to the amount of fuel fired and flared.

A formal post audit was conducted on the performance of the system. Figure 5 shows the comparison of the LPG usage in the base case and post audit periods. Note that the scale has been removed for confidentiality reasons. The results show very clearly both a reduction in the average usage, as well as a reduction in the standard deviation of the variable.

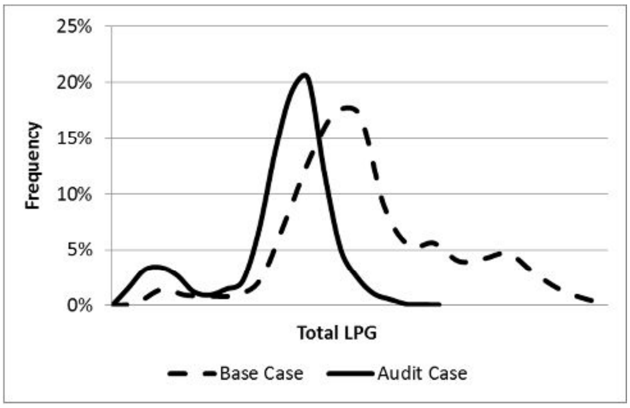

Fig 5: LPG Usage Histogram

Figure 6 shows a histogram of the daily production rate of sulphur dioxide.

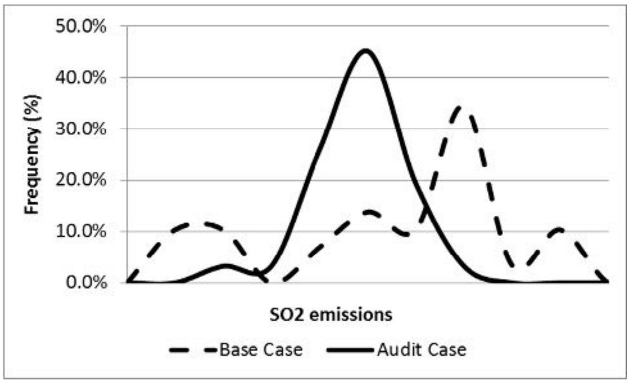

Fig 6: $SO_2$ emissions histogram

The control of the emissions has been improved and the system has met its environmental goals.

Other benefits may not be quantifiable but are nevertheless real. Organisational benefits to the refinery include:

- Ensuring consistent operation of the fuel gas and boiler systems.
- Greater visibility of environmental compliance issues, and improved co-operation between groups.
- An acknowledgement of and attention to the utility systems on the refinery, which traditionally do not get attention.

Reducing operator stress. Operators can focus on production unit operation knowing the fuel gas system is managed and optimized.
A greater awareness in the refinery of the capabilities of modern control system to perform plant wide optimization at a high frequency.

## 4. CONCLUSIONS

The implementation of the EEO system at Chevron Cape Town has been successful, both from a financial and organisational perspective. Chevron and BluESP formed a team to implement the project; the team is currently reviewing other opportunities within the refinery.

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