Advanced Optimisation – Coal Fired Power Plant Operations

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by

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DTI P140:
ADVANCED OPTIMISATION OF COAL-FIRED POWER PLANT OPERATIONS-
FINAL PROJECT REPORT

prepared for
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SUMMARY

In recent years the efforts to reduce nitrogen oxide (NOx) emissions from power stations have resulted in operational modifications including the fitting of low – NOx burners. These modifications are expensive and generally have an adverse effect upon plant performance, resulting in an increase in unburnt carbon. To reduce these adverse effects, on-line optimisers have been developed as an enhancement to the power station's digital control system (DCS).

The success of the boiler optimisation models has suggested that on-line optimisation can be used in other parts of the power station, eg thermal efficiency, electrostatic precipitator (ESP). Although each local optimiser is able to perform its task well individually there will be occasions when the individual packages will provide conflicting advice.

The purpose of this unit optimisation project is to develop an integrated approach to unit optimisation and develop an overall optimiser that is able to resolve any conflicts between the individual optimisers. A substantial demonstration project has been conducted at Southern Company's Plant Hammond over recent years.

Financial support for the project has been provided by the UK DTI, US DOE and EPRI together with some participant companies. Considerable effort has been put into the project by staff in E.ON UK, URS Corporation, Energy Technologies Enterprises Corporation, Tennessee Technological University, SCS Engineering and Syngenco engineering

Unit optimisers provided by E.ON UK and Synengco have been considered during this project together with the following individual optimisers:

On-line thermal efficiency package
GNOCIS boiler optimisation
GNOCIS steam side optmisation
ESP Optimisation
Intelligent Sootblowing System (ISBS)

There has been a substantial amount of software development during the Unit Optimisation project at Plant Hammond. Access to the results of this large project has been very valuable in showing the level of detail and complexity of the optimiser models. The project has also focussed thinking in the UK ahead of actually running multiple optimisers on a single unit.

There has been substantial development of individual optimisers during the project and in several instances the development of the individual optimisers has been difficult. This has meant that the evaluation of the unit optimiser has not progressed as much as originally hoped.

SCS have installed the Synengco Sentient software as the unit optimiser. Use of this software together with Excel has resulted in the individual models being quite remote from the DCS making closed loop installation difficult. It is not clear that this approach will be used in the future since it would seem preferable to keep the individual optimisers close to the DCS.

Potential conflict between optimisers can be reduced by either prioritising the objectives of different optimisers (eg environmental objectives achieved ahead of efficiency ones) or adding rules to optimisers (eg including a steam temperature model within the boiler optimiser, GNOCIS).

The limited feedback on the performance of the E.ON UK unit optimisation algorithm was favourable. Convergence was usually obtained in about 5 iterations and the algorithm proved stable and reliable.

Prepared by	**Approved for publication**

Master copy signed by D M Turner & P J Turner
Dated 3/9/04

D M Turner	**P J Turner** **Manager** **Systems & Modelling**

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1 INTRODUCTION

In recent years the efforts to reduce nitrogen oxide (NOx) emissions from power stations have resulted in operational modifications including the fitting of low – NOx burners. These modifications are expensive and generally have an adverse effect upon plant performance, resulting in an increase in unburnt carbon. To reduce these adverse effects, on-line optimisers have been developed as an enhancement to the power station's digital control system (DCS). GNOCIS (Generic NOx Optimisation Control Intelligent System) is the main optimiser used within the UK. This is a neural network based optimiser that takes various control parameters such as mill feeder speeds, excess oxygen, burner tilt and load as inputs and predicts the resultant NOx emissions and carbon-in-ash levels. In fact the models are usually used in reverse with boiler control settings being provided by the model to optimise the emissions.

The success of the boiler optimisation models has suggested that on-line optimisation can be used in other parts of the power station, eg thermal efficiency, electrostatic precipitator (ESP). Although each local optimiser is able to perform its task well individually there will be occasions when the individual packages will provide conflicting advice. The purpose of this unit optimisation project is to develop an integrated approach to unit optimisation and develop an overall optimiser that is able to resolve any conflicts between the individual optimisers.

Southern Company Services (SCS) have a long track record of using on-line optimisers on power plant. It seems likely that in the future more on-line optimisers will be used on UK power stations. This is an extremely large demonstration project in the USA and information from the project should provide valuable knowledge for UK stations.

2 PROJECT MEMBERS

Financial support for the project has been provided by the UK DTI, US DOE and EPRI together with some participant companies.

Considerable effort has been put into the project by staff in the following organisations:

E.ON UK – David Turner and Ian Mayes
URS Corporation – Jim Noblett and George Warriner
Energy Technologies Enterprises Corporation – Stratos Tavoulareas
Tennessee Technological University – Sastry Munukutla
SCS Engineering – Steve Logan, Mark Faurot, Kerry Kjline and John Sorge
Syngenco Engineering – Don Sands

In the UK the main participant is E.ON UK with funding from the DTI. The demonstration of the software in this integrated approach to optimisation is at Southern Company's Plant Hammond in Georgia, USA on a 500 MW coal-fired unit.

3 INDIVIDUAL OPTIMISERS

The following individual optimisers have been considered during this project:

On-line thermal efficiency Package
GNOCIS boiler optimiser
GNOCIS steam side optmiser
ESP Optimisation
Intelligent Sootblowing System (ISBS)

ESP refers to Electrostatic Precipitator that is used to remove particles from the air-flow before being released to the atmosphere up the stack. Pulverised coal is burnt in modern coal-fired plants and this can collect on the tube banks in the boiler. These tube banks are cleaned on-line by high-pressure jets of steam in an operation called sootblowing.

These optimisers are briefly described below.

4 ON-LINE THERMAL EFFICIENCY PACKAGE

This package is a detailed on-line efficiency calculation for the power unit. The process being modelled is shown in Fig 4.1. The two fans, forced draft (FD fan) and induced draft (ID fan) are shown on the left of the diagram. These large fans provide most of the air flow through the unit. Pulverised coal is added to the air in the mills and then burnt in the boiler. The combustion heat is used to produce steam in the superheaters and reheaters. The flue gases are released to the atmosphere up the stack after the ash particles have been removed from the flow in the ESP and heat has been recovered from the waste air by warming fresh incoming air.

The main difficulty with providing a real time heat rate calculation is the accurate measurement of both the amount of coal and its heat content entering the boiler. The calculation procedure is shown in Fig 4.2 and it starts with a detailed (ultimate) coal analysis that is generally not available in real time. Substantial work has been done by EPRI in the past on a real time heat rate calculation, see Gadiraju et al 1989, however all this previous work assumed the ultimate coal analysis is available. A more recent EPRI study, see Munukutla et al 1995 suggested that the coal composition can be determined from an on-line analysis of the flue gas composition. This work was done on a test combustor at the Southern Research Institute Birmingham Alabama. Since all values are available in real time, the heat content of the coal can be calculated in real time. The revised calculation process for the on-line method is shown in Fig 4.3.

The on-line heat rate calculation was compared to the original method during 4 days of testing, 4-7th October 2000 at Plant Hammond. There was good agreement between the on-line coal analysis and the ultimate analysis as shown in Fig 4.4.

The heat exchangers between incoming and out-going air involve leakage of the incoming air into the flue gas. This leakage can be determined by measuring the gas composition before and after the heat exchanger.

There are two methods of determining the amount of coal entering the boiler at Plant Hammond. Plant Hammond is equipped with Stock Gravimetric feeders that provide a real time estimate of the coal delivered to the furnace. Alternatively a coal weight is available from the conveyor belts delivering coal to the storage bunkers. This however is only viable over a long period of time while the unit is operating at a steady load. During the testing both these measurements of coal flow have been compared to the coal flow estimated from the gas analysis and ash collection rate. In general there was slightly better agreement between the belt and feed estimates than the emissions, Fig 4.5 shows some typical results for a variation in electrical load of the unit.

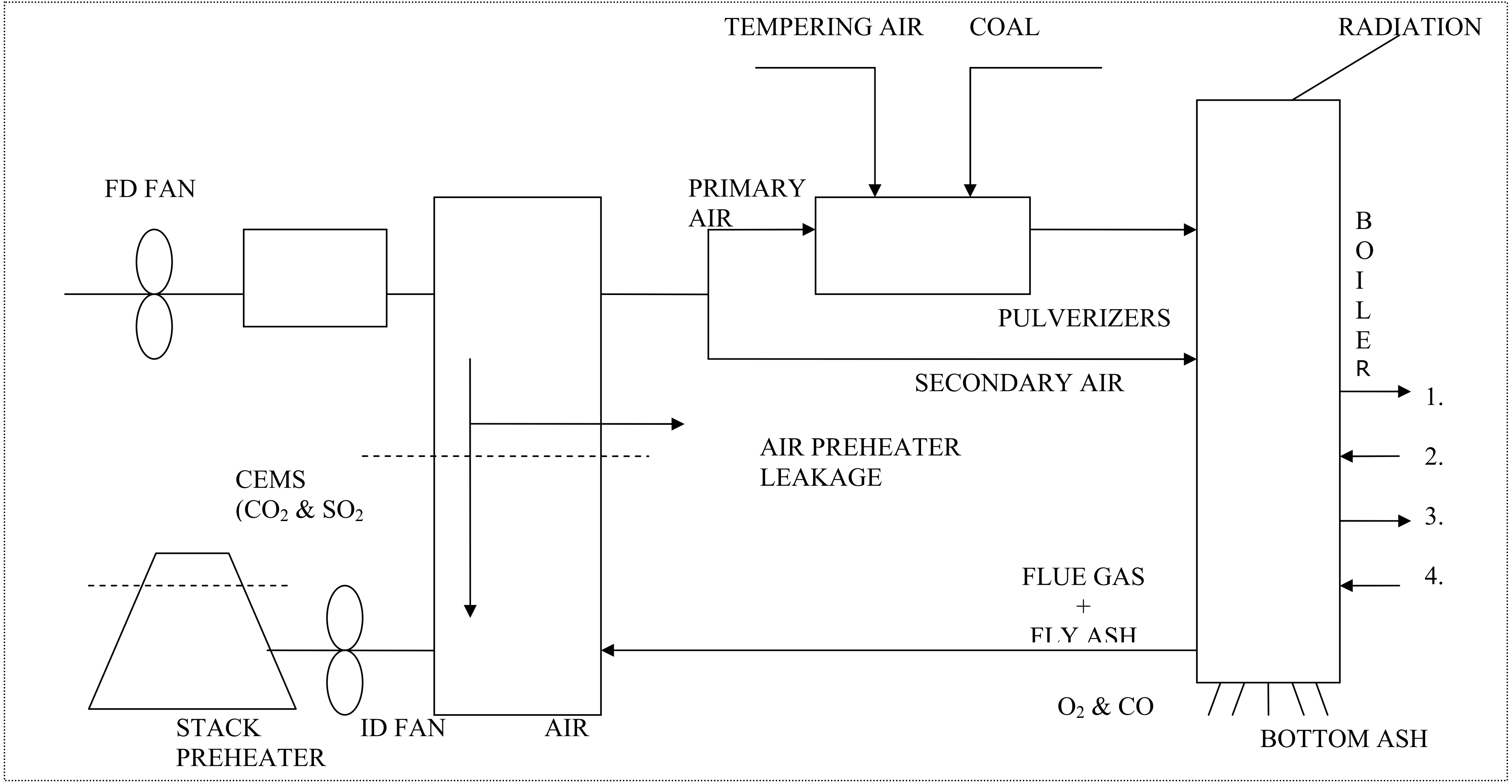
This on-line heat rate calculation uses 16 off-line data values and 29 inputs from the operating unit to predict the following four quantities:

Air heater leakage
Coal Flow rate
Heat Rate (Net)
Stack flow rate

Currently this package is not an optimiser and thus does not recommend settings for any of the on-line inputs that will optimise the heat rate. Changes though to any of the 29 inputs by any of the other optimisers will affect the plant efficiency. This provides a detailed calculation of the effect upon the plant efficiency.

A comparison of a daily calculated on-line heat rate to an accurate assessment is shown in Fig 4.6. It can be seen that the on-line calculation does not exhibit the same variability as is expected for plant operation during that day.

It is clear that a significant part of the project has been devoted to developing the on-line heat rate calculation. Development of an on-line heat rate calculation is an ambitious target though it would seem from the results shown in Fig 4.6 that the model predictions are not yet satisfactory.



INDEX OF NUMBERS USED:

1.	HOT REHEAT	3.	MAIN STEAM
2.	COLD REHEAT	4.	FEED WATER

Figure 4.1 - Schematic Of Air Flow Through The Boiler Used By The Heat Rate Calculation

Constants	Inputs	Outputs
Relative Humidity Percent	Fan Inlet Temperature (Temp)	DIRECT:AIR_PREHEATER_LEAKAGE
LOI Percent	Prim Air From APH Temp	DIRECT:CYCLE_HEATRATE
CO PPM	Sec. Air From APH Temp	DIRECT:GROSS_HEATRATE
Fly Ash (Percent of Total Ash)	Coal Air Temp	DIRECT:NET_HEATRATE
Air Heater Leakage Percent	Gas to APH Temp	DIRECT:OUTPUT_LOSS_EFFICIENCY
Boiler Leakage Percent	Gas From APH Temp	DIRECT:PTC_4_EFFICIENCY
Coal-Air (Air/Fuel Ratio)	Feed Water Temp	DIRECT:COAL_FLOW
Maximum Continuous Rating of Boiler	Feed Water Press	INDIRECT:CARBON_PERCENT
Percent Carbon From Ultimate Analysis	Feed Water Flow	INDIRECT:HYDROGEN_PERCENT
Percent Hydrogen From Ultimate Analysis	Main Stream Temp	INDIRECT:SULPHUR_PERCENT
Percent Sulphur From Ultimate Analysis	Main Steam Press	INDIRECT:OXYGEN_PERCENT
Percent Oxygen From Ultimate Analysis	Main Steam Flow	INDIRECT:NITROGEN_PERCENT
Percent Nitrogen From Ultimate Analysis	Hot Reheat Temp	INDIRECT:MOISTURE_PERCENT
Fuel Moisture	Hot Reheat Press	INDIRECT:ASH_PERCENT
Percent Ash From Ultimate Analysis	Hot Reheat Flow	INDIRECT:HIGHER_HEATING_VALUE
HHV From Ultimate Analysis	Cold Reheat Temp	INDIRECT:COAL_FLOW
Blowdown, Percent Of Feed Water	Cold Reheat Press	INDIRECT:CYCLE_HEATRATE
Unknown Loss, Percent of HHV	Cold Reheat Flow	INDIRECT:NET_HEATRATE
CO2 Correction Factor	Outside Air Temp	INDIRECT:BOILER_EFFICIENCY
SO2 Correction Factor	Fan Room Air Temp	
HSTM Correction Factor	Barometric Press	
	Econimiser Out O_2	
	Generator MW	
	Auxilliary MW	
	Stack Flow	
	Stack Temp	
	Coal Flow	
	Stack CO_2	
	Stack SO_2	

Figure 4.2 – Variables Used in the Detailed Heat Rate Calculation

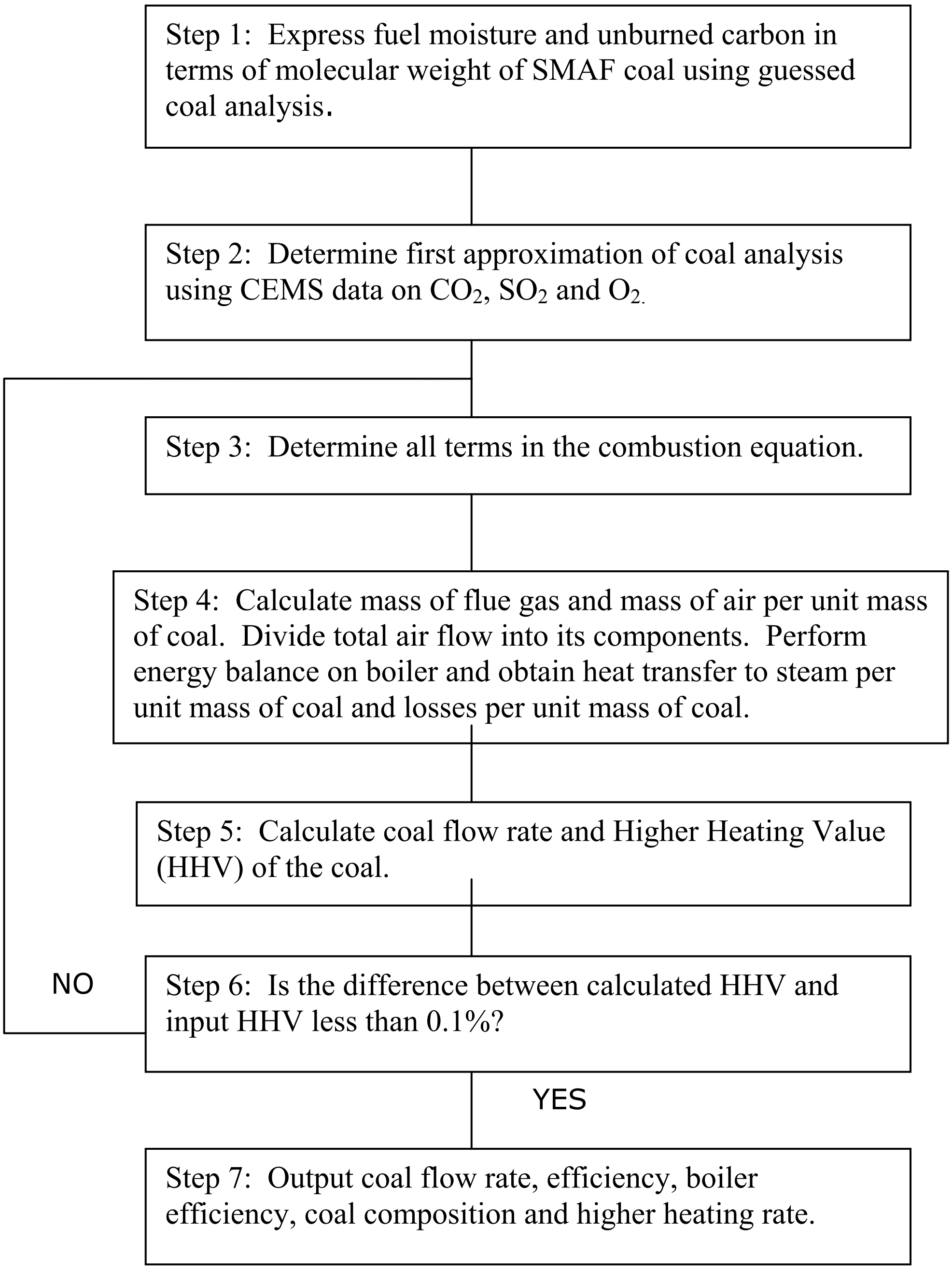


Figure 4.3 Procedure for the On-Line Heat Rate Calculation

Constituent	Hammond Provided Coal Analysis (%)	Real-Time Average Coal Analysis (%)	Real-Time Coal Analysis (Standard Deviation)	Difference Between Provided And Real-Time Coal Analysis
Carbon	70.65	70.91	0.72	0.26
Hydrogen	4.58	4.37	0.79	0.21
Sulphur	0.76	0.68	0.07	0.08
Oxygen	5.41	5.43	0.06	-0.02
Nitrogen	1.31	1.31	0.01	0.00
Fuel Moisture	7.88	7.88	0.00	0.00
Ash	9.41	9.41	0.00	0.00

Figure 4.4 Comparison of Detailed and On-Line Heat Rate Calculations

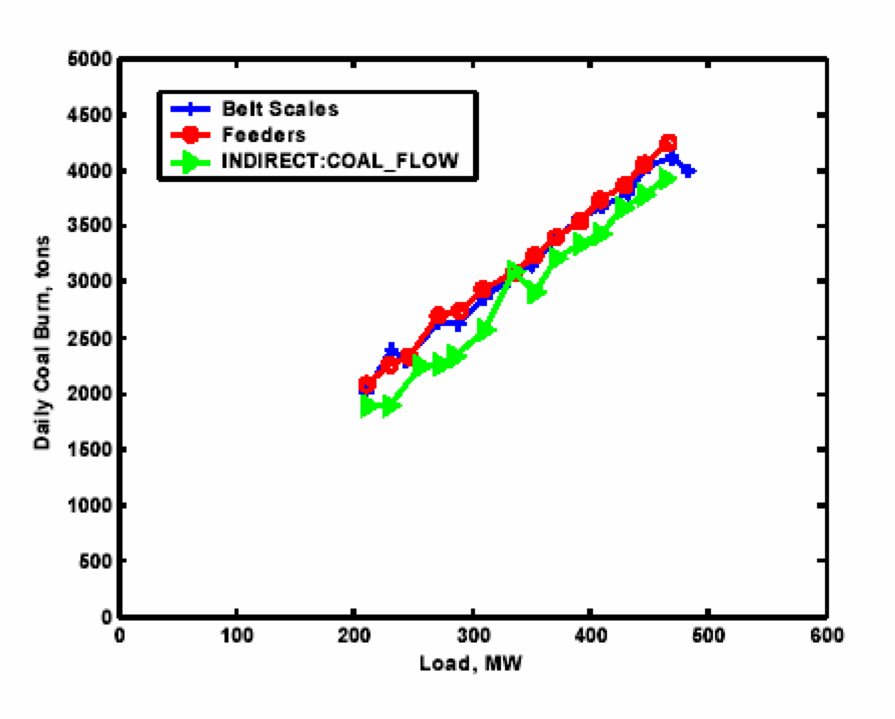


Figure 4.5 Comparison of different coal flow estimates at Plant Hammond

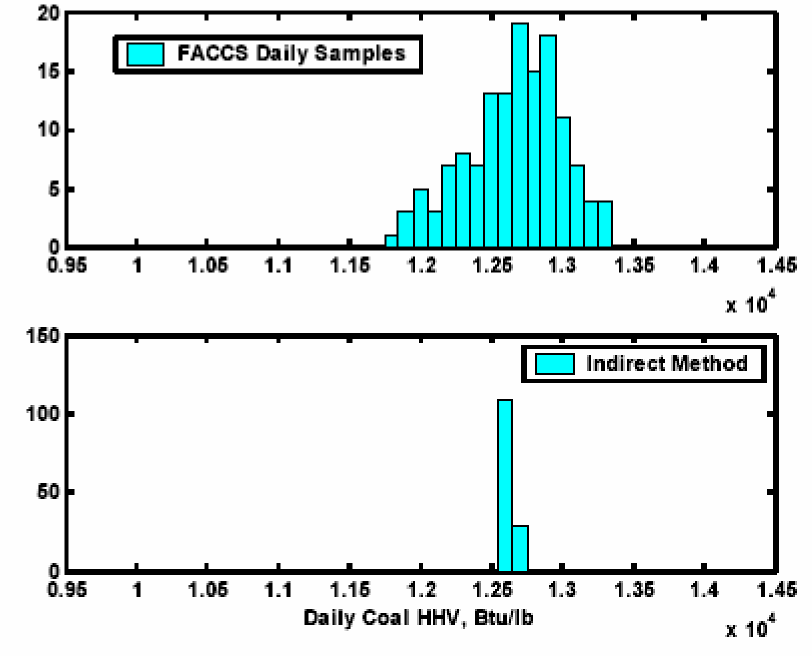


Figure 4.6 A comparison of daily calculated heat rate to the on-line heat rate calculation

5 GNOCIS BOILER OPTIMISATION

The GNOCIS/ Boiler optimiser is SCS's standard GNOCIS model using the Pavillion neural network and on-line error correction. The control variables at Plant Hammond changed by GNOCIS are coal flows to individual mills, excess and over fired-air flow. The US GNOCIS models have been used with a variety of outputs including NOx, boiler efficiency, carbon-in-ash, reheat temperature. The GNOCIS model can make predictions for any of these outputs and by changing the upper and lower limits for each output the model can optimise for any combination of the outputs. NOx optimisation is however predominantly used in practice.

Implementing the GNOCIS advice could involve changing the excess oxygen that will affect the heat losses up the stack and also the performance of the ESP. It is known that the performance of the ESP is sensitive to the air velocity though the ESP performance degrades as velocity increases. It is possible that as the excess air increases then the carbon-in-ash will decrease having a beneficial effect upon ESP performance. Experience with ESPs in the UK though suggests that the former mechanism is dominant and ESP performance reduces with increasing excess air.

The excess air within the boiler is an important operating parameter. It is possible that a recommendation for the excess air level is provided from both the GNOCIS boiler model and the ESP optimisation model. This is a typical conflict to be resolved using the unit optimisation software.

The bulk of the work on the GNOCIS boiler model within the project has been related to the on-line error correction capability. The GNOCIS model at Plant Hammond is however quite old since Hammond was one of the original test sites. The on-line error correction will not be discussed here since it has been superseded in the most recent version of GNOCIS by on-line re-training.

6 GNOCIS TURBINE OPTIMISATION

One part of the Unit Optimisation project was always to identify another process within the power station for optimisation. Within the project an optimiser for the turbine has been developed.

6.1 Throttle and Reheat Temperature Control

Between the boiler superheaters and the turbine there is a valve, referred to as the throttle valve and usually boilers are operated with a set point on steam conditions (superheater (throttle) temperature and reheat temperature). The set points are generally design values set by the boiler and/or turbine manufacturer.

For Hammond 4, superheat temperature is controlled at two different locations in the boiler. First, the division wall inlet superheat temperature is controlled by the use of the left and right hand lower attemperating sprays. The set point for these control loops is 10ºC above the minimum of drum saturation temperature of 370ºC. The final superheat temperature is controlled by the use of the left and right hand upper attemperating sprays. The set point for this loop is normally 540ºC and can be set by the operator.

Reheat temperature at Hammond 4 is controlled through modulation of the bypass dampers in the furnace backpass. The set point for this loop is normally 540ºC and can be set by the operator. Although configured in the DCS, reheat attemperating spray as a reheat temperature control method is not currently used at Hammond 4 due to its known adverse effect upon efficiency of plant operation.

6.2 Pressure Control

Main steam flow and hence generated load is effectively controlled by setting the steam pressure. This can be achieved by either (1) throttling the steam flow by modulating the governor (or throttle) valves of the turbine while maintaining constant upstream conditions; (2) varying the steam pressure ahead of the turbine; or (3) some combination of the above. For the latter two, the pressure set point is adjusted so that the throttle valves operate at valve points, i.e. where no valve is partially open.

6.3 Constant Pressure Operation

At Hammond, the Unit Master Station (UMS), when in automatic mode, will always try to control turbine throttle pressure to set point (at Hammond 4, normally set to 2400 PSIG). The UMS will normally control throttle pressure by adjusting the fuel firing rate (boiler follow mode) or, in unusual circumstances, by modulating the turbine governor valves (turbine follow mode).

6.4 Sliding Pressure Operation

In sliding pressure operation, the throttle pressure set point (and therefore throttle pressure) is varied to achieve load demand while the turbine throttle valves are controlled to wide-open position (VWO - Valves Wide Open). The primary advantages of this mode of operation are:

- Reduced throttling losses from the governor valves increases turbine efficiency.
- Boiler feedpump power consumption is reduced at lower loads.
- Higher superheat temperatures at reduced loads improves turbine cycle efficiency.

A disadvantage of sliding pressure operation is slower response time for the unit.

At Hammond 4, the DCS has been configured to allow sliding pressure operation but testing has not been conducted to develop the necessary set point curves and it is not utilised.

6.5 Turbine Optimisation

It was recommended that the main steam temperature, main steam pressure and reheat pressure be included in an optimisation. These controllable parameters operated on average, below the design set points, particularly at mid-to-lower load categories. The cumulative financial impact of these deviations is significant and for Hammond 4 over a year was estimated to be $250,000.

Although this optimisation is called Turbine Optimisation, the model is actually controlling the steam side of the boiler. Thus the spray flows are controlled to maintain the throttle temperature, the backpass damper position is controlled to maintain the reheat temperature and the fuel firing rate is controlled to maintain the steam pressure.

This new optimisation is really just the normal boiler controls. If performance can be improved by maintaining set points then this requires a modification of the control system. Improved performance will be obtained be re-designing the control loops. In general when other plant optimisers are designed care is taken not to fight the control system and thus avoid providing recommendations for normal boiler controls. For example the sootblowing model uses the spray levels to indicate when the sootblowers should be used; it does not make recommendations for the level of the spray flows and thus avoids a conflict.

There is a suggestion that the set points cannot always be achieved at Hammond 4 and this leads to the reduction in performance. Given the financial impact of not achieving the set points it will clearly be worth reviewing the operation at other stations to see whether improved control of the boiler steam side is required.

When control systems adjust the fuel flow they do so by spreading the adjustment across available mills. The GNOCIS boiler model maintains the total mill flow though may distribute the coal differently among the mills. In some plants the top mills are required to achieve the steam temperature. In these GNOCIS applications a steam temperature model is included within GNOCIS so that the model knows how redistributing the coal flow among the mills will impact upon steam temperatures. Model conflict is avoided by adding this extra knowledge into the GNOCIS boiler model.

6.6 Installation at Hammond

The GNOCIS package was modified to make recommendations on turbine steam inlet conditions to maximise cycle efficiency. This modified package is referred to as the Turbine Optimisation model and was installed at Plant Hammond as part of the UOP.

Insufficient testing was performed though during the UOP to properly quantify the performance of the system. Open-loop testing with an interim model was conducted during January 2002, but the results were not positive in part due to the unit being under economic dispatch during the testing and resultant load changes. As the result of this testing, the model structure was revised. Further testing needs to be performed to determine the benefits of this system.

Areas of possible future work include:

Testing to confirm performance
Integration with DCS to enable closed-loop control
Interface with the plant's recently installed plant information network
Confirmation of performance with the unit optimisation package.

7 ESP OPTIMISATION

Electrostatic Precipitator (ESP) performance such as measured by outlet opacity, particulate removal rate, and energy consumption is greatly dependent on precipitator inlet conditions. These conditions are in turn a function of boiler operating conditions and possibly other post-combustion emission control technologies. Given the dependence of ESP performance on upstream operating conditions and the importance of its operation on environmental performance, it was felt that the ESP should be brought into the optimisation envelope.

EPRI's ESPert (see ESPert 1994) was installed on Hammond 4 as part of this project. The ESPert package, originally developed in the 1990s, is a diagnostic and predictive model for ESPs designed to evaluate and predict ESP performance and diagnose problems. Initial expectations were to use the ESPert software as an optimisation platform; however to date, it has been used only as a predictive model.

ESPert is an ESP monitoring and troubleshooting program that continuously receives and interprets data from the ESP control system, CEM system, and boiler controls [EPR94]. The program continuously estimates ESP performance, including opacity, based on these input and diagnoses the probable causes of any divergence between measured and predicted opacity. The core model used for the basic performance calculations is the Southern Research Institute ESP performance model whose development was funded by the US Environmental Protection Agency [FD84].

Although ESPert provides ESP performance estimates that can be compared with test results, its primary intended use is as an aid for plant staff to diagnose ESP operational, mechanical, and electrical problems. At least for the purposes of this project, perhaps a more important feature of the tool is that it allows for "what-if" analyses where operational scenarios may be tested before actually implemented in the plant. ESPert also provides some capability for trending and archiving data. ESPert requires considerable plant and ESP data to effectively model the performance of the ESP and predict the outlet conditions. A summary of the required parameters is provided in Fig 7.1. As can be inferred from this table, the effort involved in setting up ESPert is considerable even if the information were readily available. Note that ESPert requires an analysis of the coal and as indicated previously with regard to the on-line heat rate model this is often not available.

The ESPert model was installed on Hammond 4 in October 2000. Since then there has been substantial software development of the model to improve the predictions of opacity. To date the ESPert model has not been used as an optimiser. The results would suggest that a black box modelling technique like neural networks or expert systems will allow better modelling of the ESP. The modelling within ESPert would seem to be too fundamental, requiring a coal analysis as input, rather than utilising black box modelling techniques. Since this model has not been used as an optimiser within the current project, the obvious conflict between the ESP and GNOCIS boiler recommendation for the excess oxygen has not been resolved. The excess oxygen is an important parameter in both models and thus it is not obvious that the conflict can be removed by omitting a recommendation for the parameter from one of the models.

E.ON UK is currently developing an ESP optimisation model under DTI Project P330. This model will not require a coal analysis as input but will use readily available plant and ESP data to optimise the performance of the ESP in terms of flue gas additive, power and opacity.

Operating Data
Coal Properties (up to nine coals) - analysis
Ash properties – Ash mineral analysis Electrical data for each T/R set Volts, amps, sparking, arching, T/R status
Boiler / Opacity data
Load, heat rate, opacity, flue gas conditioning, ESP gas inlet temperature, soot blowing
Dust cleaning Rapping cycles, hopper evacuation
Test data
Inlet and outlet ash loading, particle size, gas sneakage, gas flow, water, or oxygen, pressure, resistivity, ESP efficiency
Configuration data Boiler data Heat rate, additives, number of sootblowers, gas recirculation, burner type ESP design data Manufacturer, number of fields and gas paths, plate height, ESP pressure, ESP type, passage width, emissions, efficiency. Field data Field length, ESP voltage, T/R set in field, T/R configuration, primary voltage, primary current, wave form Duct layout – layout, flow per duct Ash cleaning – rapper types, rows, number of rappers/row/gas path Ash removal – number of hoppers, removal periods

Figure 7.1 Data Required By ESPert

8 INTELLIGENT SOOTBLOWING SYSTEM (ISBS)

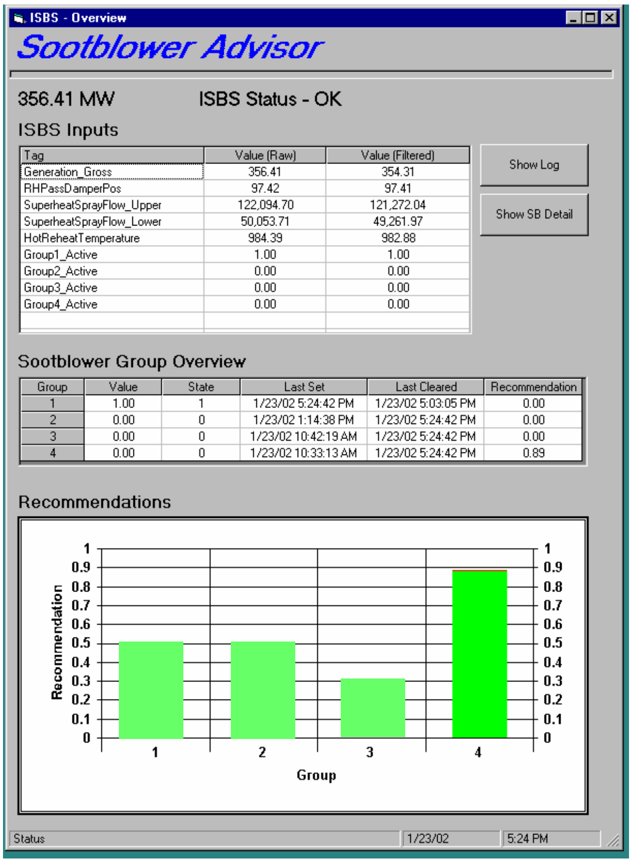
As part of this project E.ON UK developed an ISBS that was installed at Plant Hammond, see Sorge and Turner 2002. The ISBS work within the Unit Optimisation Project was funded entirely by EPRI. The ISBS provided advice on when to blow any of four groups of sootblowers. The advice was based upon a few readily available plant parameters like superheater spray flows and the backpass damper position since this plant is unusual in that the steam temperature is kept constant whilst the spray flow varies. Sootblowing is often used to maintain operational flexibility and is generally employed before performance is affected.

The main cost of the sootblowing is related to the frequency with which it is used. This model was well received by the operators at Plant Hammond and showed that the plant could be operated with only 50% of the sootblowing that was normally used. Use of the sootblowing model will thus improve the performance of the unit. The ISBS screen is shown in Fig 8.1. For this model to fit into the current unit optimisation framework then it will need to be extended to make predictions of the spray flow and damper position after sootblowing so that its advice can be compared to the demands of other optimisers.

To predict the effect of sootblowing then information is required from the DCS on the actual sootblowers that will be operated within a group. If an operator picks up some sootblowers that have not been used for a while then there will be a big effect upon the cleanliness of the plant. The ISBS model indicates when sootblowing is required but the cleanliness of the boiler following sootblowing depends upon the individual sootblowers used within a group. The information about the actual sootblowers available is not within the current model.

There was some discussion during the project on how to measure the effect of the ISBS advisor. This is probably best done in looking at the change in the spray flow after sootblowing or the change in the position of the backpass damper. If these change significantly after sootblowing then the cleaning has been substantial and the sootblowing effective. Another measure will be to look at the total steam used by the sootblowers over a period of time. It will clearly be beneficial to obtain the most cleaning from the steam used by the sootblowers. If the ISBS was further developed as an optimiser then maximising the ratio of the boiler cleanliness divided by the steam used by the sootblowers will probably be the appropriate objective function.

On other units the steam temperature varies rather than the spray flows. This steam temperature is an important variable in an efficiency model. Thus on a unit where sootblowing is triggered by steam temperatures there may also be conflicts with an efficiency model on the same unit. An ISBS model would be a useful addition in the future models for units where the steam temperature varies with boiler fouling since it will enable optimisation of the sootblowing activity.



356.41 MW ISBS Status - OK

ISBS Inputs

Tag	Value (Raw)	Value (Filtered)
Generation_Gross	356.41	354.31
RHPassDamperPos	97.42	97.41
SuperheatSprayFlow_Upper	122,094.70	121,272.04
SuperheatSprayFlow_Lower	50,053.71	49,261.97
HotReheatTemperature	984.39	982.88
Group1_Active	1.00	1.00
Group2_Active	0.00	0.00
Group3_Active	0.00	0.00
Group4_Active	0.00	0.00

Sootblower Group Overview

Group	Value	State	Last Set	Last Cleared	Recommendation
1	1.00	1	1/23/02 5:24:42 PM	1/23/02 5:03:05 PM	0.00
2	0.00	0	1/23/02 1:14:38 PM	1/23/02 5:24:42 PM	0.00
3	0.00	0	1/23/02 10:42:19 AM	1/23/02 5:24:42 PM	0.00
4	0.00	0	1/23/02 10:33:13 AM	1/23/02 5:24:42 PM	0.89

Recommendations

FIGURE 8.1 OPERATOR SCREEN FOR ISBS SYSTEM AS INSTALLED AT PLANT HAMMOND

9 UNIT OPTIMISER

The unit optimiser is the new software that was developed within the project to resolve potentially conflicting advice from different individual optimisers. The unit optimisation process was developed by E.ON UK's Dr I Mayes.

If several local optimisers give conflicting control settings for the unit then the total unit costs need to be considered to optimally resolve the situation. Whereas each local optimiser has it's own cost function to minimise and only has knowledge of it's own local restricted environment, the unit optimiser has to integrate the advice from all the local optimisers to produce an overall control strategy. In order to do this some means of compromising individual advice must be found. Since the objective functions for the local optimisers involve different high-level plant variables a common factor needs to be found to enable appropriate recommendations to be made. This factor must be the total unit costs and a unit cost function has to be defined in terms of high level plant variables such as NOx, carbon in ash, boiler efficiency, etc. It is important that costs can be associated with the high-level plant variables otherwise it is not possible to fully define a unit cost function.

9.1 Implementation of the unit optimiser

There are many common functional requirements for plant optimisers regardless of detailed differences. This suggests using an object orientated programming paradigm. With this approach an object is a specific piece of code whereas a class is a more general template which can be tailored to specific requirements. The concept of inheritance is used in this context, an object can inherit functionality from another object or class. This functionality has two forms known as properties and methods. Properties are values of parameters of the code whereas methods are actual functions belonging to the object. Access to the object's internal values are via methods, thus providing a clear boundary between the objects functionality and the implementation of this functionality. Object orientated methodology has another feature which is very useful for implementing the optimiser simulations, namely function overloading. This allows methods to be defined at the class level but the method implementation to be changed when an object is defined from the class. Different objects can inherit from the same class to carry out different detailed processing with the same named method. Thus an object's RUN method could calculate a different formula for different object yet the calling syntax is the same.

There are a number of programming languages that support object orientated programming but the one chosen for this project is the proprietary product MATLAB. This allows rapid prototyping of mathematical constructs and has a number of specialist toolboxes which enhance its capabilities in different specialist areas. One such toolbox is the optimisation toolbox which provides a sequential quadratic optimiser package. The object orientated aspects of MATLAB are limited compared to other languages but are sufficient to allow the concept to be exploited for this project. One of the advantages of MATLAB is that it uses a workspace where variables, including objects, exist, and can be interrogated at will. This is particularly useful for testing the different objects, as they are stand alone entities whose methods can be tested independently.

A general class *optimiser* was defined. This is the template or base class for all the plant optimiser objects.

This base class has the constructor OPTIMISER which sets up the following fields :

opt.input=[ ]	this field is for the inputs to the function. These inputs will contain both controllable and independent variables.
opt.output=[ ]	this field is for the output.
opt.inputlimits=[ ]	these fields contain the upper and lower bounds on the controllable inputs.
opt.inputtypes=[ ]	this field contains the input type, whether control or not, c or nc.

opt.optimuminputs=[ ]	this field contains the inputs that result from the optimisation process.
opt.optimumoutput=[ ]	this field contains the output from the optimisation process.
opt.maxchange=[ ]	this field contains the maximum reduction the optimiser can make.
opt.reachedmin=0	this field contains 0 if the limit in maxchange can be reached and 1 if the minimum is obtained before maxchange is obtained.

There are two classes derived from the optimiser class, the NOx class and the Eff class (which is meant to be boiler efficiency). The NOx class has three additional methods than the base class, namely the constructor NOx, an optimise and a run method. The run method calculates the NOx given an input data whilst the optimise method carries out a constrained optimisation, (assumed to be minimisation), of an objective function. Similarly the Eff class has three extra methods, the constructor eff, an optimise and a run method. Again the run method calculates the function Eff, whilst optimise carries out an optimisation.

The original formula used for the NOx run method was

$$\mathrm{NOx} = \frac{\sqrt{\mathrm{Load}} \times \left(\mathrm{coalflow} + \mathrm{airflow}^{1.5}\right)}{10^{4}}$$

and for the efficiency

$$\mathrm{Eff} = \frac{\mathrm{Load} \times \left(\mathrm{airflow} - 300.0\right)^{2} + \frac{1.0}{\sqrt{\mathrm{coalflow}}}}{10^{6}}$$

These formulae were subsequently modified to a seven input linear model for testing of the main optimisation algorithm.

The syntax for creating and running an object is:

nox1 = Nox()	This creates object nox1

nox1=loadinputs(nox1,inputdata)	This loads the object nox1 with inputdata
nox1=run(nox1)	This runs the nox formula given above
getoutput(nox1)	This retrieves the calculated nox from within the object

A feature that is required by the main unit optimiser algorithm is the ability to constrain the change in the output to be less than or equal to a specified amount. The other constraints on the optimisation are upper and lower bounds on the control variables. The MATLAB optimiser used is **fmincon.** This function solves the following problem:

> *FMINCON solves problems of the form:*
>
> *min F(X) subject to: A*X <= B, Aeq*X = Beq (linear constraints)*
> *X   C(X) <= 0, Ceq(X) = 0   (nonlinear constraints)*
> *LB <= X <= UB*
>
> *X=FMINCON(FUN,X0,A,B,Aeq,Beq,LB,UB,NONLCON) starts at X0 and finds a minimum X to the function described in FUN, subject to the linear inequalities A*X <= B, the linear equalities Aeq*X=Beq, and the nonlinear constraints C(X) <= 0, Ceq(X) = 0. X0 may be a*
>
> *scalar, vector or matrix. The function FUN should return a scalar function value F evaluated at X*

The change in output constraint is a non-linear one (in terms of the model inputs) and is defined in a MATLAB file. There is the possibility that the minimum will be reached before the output constraint is reached. In this case the *getreachedmin* variable is set to 1 otherwise it is set to 0.

Before the optimise method is used the input types must be defined. There are two types of input that have been used in this simulation, namely defined inputs and controllable inputs. Defined inputs are variables such as electrical load, ambient temperature etc which are not under the control of the optimisation process and control variables such as coal flow, damper settings etc, which can be adjusted by the optimiser. Variables identified as control variables have to have upper and lower bounds specified before optimisation is carried out. This is essential as in many cases the optimum control settings are on a control boundary value. Note that only the control variables are manipulated by the optimiser to achieve the optimisation and that the vector **X** referred to in connection with **fmincon** is either equal or smaller in dimension than the input data vector for the optimiser objects.

As an example the following values were used:

X = [500 340 245]

control types = [notcontrol control control]

lower limits = [100 50]

upper limits = [600 400]

The output value for the chosen x value was 9.3353, the optimised output being 1.0142. The optimal inputs were [500 100 50] which clearly demonstrates the need for upper and lower bounds on the controllable variables.

The demonstration Unit Optimiser was written in MATLAB by Dr I Mayes and the algorithm has subsequently been copied into other systems by SCS to use within the Unit Optimisation project. As indicated above there have been problems with some of the individual optimisers and thus only a couple of the models have been used together. In January 2003 some results using the E.ON UK optimisation scheme were reported. The optimisation software was proving very stable and convergence was obtained in typically 5 iterations.

9.2 Alternative unit optimisation schemes

A recent addition to the system has been the Sentient Software offered by Synengco (see www.synengco.com) and URS. This software would seem to be a general framework that is now at the heart of the unit optimisation software. Sentient communicates directly with the DCS and the individual optimisers. It also supports several optimisation methodologies, namely:

Simplex algorithm
Quasi-Newton method
Line-Search using Newton Conjugate Gradient
Genetic Algorithm
Sum of squares of M equations in N unknowns
Bounded minimisation of a scalar function
Custom algorithms

It is quite clear that SCS want to use Sentient as the unit optimiser with the E.ON UK algorithm as a custom option. No results have been produced as yet to show how the E.ON UK algorithm compares to any of the other optimisation methodologies available within Sentient.

The Sentient system will also provide a wide range of graphs that can be selected by the operator to provide a visual display of the power plant operation.

10 SOFTWARE IMPLEMENTATION

Although the basic operation of the unit optimisation model and the individual optimisers was outlined by Mayes 2001, it is worth reviewing how thinking has developed during the project. The information flow is summarised in Fig 10.1. It can be seen that goals or constraints are passed down from the higher level optimisers. The individual optimisers then perform their task within the constraints and pass back costs in terms of the optimum achieved.

Fundamental to this approach is the need for the individual optimisers to have a predictive capability. If the higher level optimisers don't specify all the required inputs for a given optimiser then the model is allowed to vary the unspecified parameters within limits to obtain an optimum.

It can be seen from the above that during the unit optimisation project there has been a substantial amount of development of the individual optimisers and also a huge array of software interfaces have been produced that enable different packages to work together. Details of the software interfaces for each package have not been included separately in the above discussion. Instead general comments about the interfaces are given in this section.

There are several points to note:

1. Excel was never designed as a real time interface and it is unlikely that this approach will be adopted in the UK.

2. This Unit Optimisation model is understood to currently run in open loop. It is unlikely that the system will be developed into a closed loop installation. This may be due to the use of software like Excel within the current system or just simply the huge amount of data required to enable all the optimisers to work.

3. The actual optimisers are now very remote from the DCS and this makes closed loop operation very difficult.

4. The use of the Sentient System means that unit optimisation is now much more central than originally anticipated. The important variables within the individual optimisers are passed through Sentient rather than directly from the RTDS.

5. Our idea of the original concept of the Unit Optimisation project was that the individual optimisers would retain the main role in plant controls and the unit optimisation would be a relatively small piece of software reconciling conflicts when they arise. There was only expected to be a few conflicts and this justified the approach of keeping the individual optimisers as the main software.

6. The Sentient system provides SCS with many options for the unit optimiser. As yet there are no details about how different options compare.

11 HANDLING CONFLICT AMONG OPTIMISERS

The description of the individual optimisers above has highlighted several possible sources of conflict. Although these optimisers are similar to UK models there are significant differences between the optimisers currently used in the UK and USA. This section thus focuses on the expected conflicts between typical optimisers that may be used in the UK.

For corner fired boilers with burner tilt, then lowering the tilt may reduce the steam temperature and thus affect the plant efficiency. Lowering the burner tilt is generally beneficial for both NOx emissions and reducing carbon-in-ash and thus is something that GNOCIS may advise. GNOCIS models for these corner fired-units now take in steam temperature data and if the steam temperatures become too low then they are designed to raise the tilt until the temperature recovers. If the GNOCIS model did not include a knowledge of steam temperature behaviour then there would be a clear conflict between the GNOCIS advice and the recommendation of an efficiency package. The effect upon steam temperature has thus been built into the GNOCIS model so that the advice from the individual optimiser is very much closer to the advice that a unit optimiser will provide. Making the individual optimiser more sophisticated is a good way of reducing the conflict between different optimisers.

In some cases GNOCIS will increase the excess air in the boiler to achieve better NOx or carbon-in-ash results. The increase in excess air however may increase the re-entrainment of dust within the ESP and thus its collection efficiency may be reduced slightly. The GNOCIS recommendation would clearly conflict with the recommendation of an ESP optimiser that is designed to reduce emission levels. It is however easy to input the emission signal into GNOCIS and reduce the excess air to meet the emission levels. GNOCIS is thus constrained to find an optimum with less excess air. This is another example where a simple constraint within the individual optimiser can reduce the conflict between optimisers.

In both the above cases objectives have been prioritised. In the first case it was decided more important to maintain steam temperatures rather than achieve the optimum GNOCIS recommendations. In the second case it was also decided that the emission limit must be met ahead of the GNOCIS objectives. Thus recent developments in individual optimisers have reduced conflicts between optimisers with rules of this type. This reinforces the view that only a few conflicts will remain to be resolved by the unit optimiser and thus it should not be the main interface between the DCS and the individual optimisers. The conflicts identified so far have been resolved by relatively easy addition of constraints to the individual optimisers. At this stage it is unclear whether all model conflicts will be resolvable by the addition of simple constraints. It certainly seems quite easy to tidy up many boundaries of the individual optimisers and reduce possible conflicts.

The Unit Optimisation algorithm was based on a unit cost function involving high-level plant variables. The task of the unit optimisation software was to minimise this unit cost function by setting constraints for the individual optimisers and then running them. The results of the individual optimisations are fed back to the unit optimiser and the process repeated until convergence is achieved. This approach is appropriate when there is no distinction between high-level plant variables other than cost. However there are many situations, as mentioned above, where high-level plant variables are distinguishable by other means and priorities can be assigned to these variables. In this situation it could be more sensible to use a rule based approach rather than a gradient based optimisation algorithm. Of course it is also possible to put a higher cost on these prioritised variables and use the gradient based method, but this is at the expense of increasing the complexity of the system for no tangible benefit.

In general it is easiest to avoid the conflict by either building some knowledge of the requirements of one model into another or by omitting a variable from a particular model. Only in a few cases is a parameter important in more than one model and will require reconciliation to obtain an optimum for the unit.

12 ON-LINE POWER PLANT OPTIMISERS IN THE UK

For many years the GNOCIS boiler optimisation model has been the main on-line optimiser on UK power stations. Several other optimisers are currently under development and in the near future units will be operating with several optimisers. Information from this Unit Optimisation project in the USA has been very valuable in focussing our thoughts on unit optimisation well ahead of actually running several optimisers together.

Recent work is developing a damage limitation model that will take thermocouple readings from around the boiler and provide advice on boiler settings to reduce overheating, thus extending the life of the boiler.

A neural network based optimiser for an ESP is being developed under DTI project, P330, see Turner 2003. This optimiser will adjust selected parameters from around the boiler to obtain the best ESP entry conditions for the ash so that the ESP can then minimise emissions. The carbon-in-ash has a big effect upon ESP performance, in general higher carbon-in-ash values reduce the ESP performance. If GNOCIS is minimising carbon-in-ash then there will be no conflict with the ESP model however if GNOCIS is minimising NOx with a limit on carbon-in-ash then there may be a conflict with the ESP model. It remains to be seen whether this boundary between the models can be resolved easily as in the examples above.

In recent years power plant operators within the UK electricity market have focussed on plant reliability, availability and emissions rather than small improvements in efficiency. There are signs however that this is now changing and efficiency is being given more attention. It has been accepted for many years that power plants have a lower efficiency when only operating at part load. The work here with the turbine optimisation is a useful reminder that gains in this area may be substantial and are worthy of re-evaluation.

Unfortunately the operation of the central unit optimiser system (Sentient) has not been demonstrated as yet within the UOP. If a central unit optimiser is required then this will have a big impact upon how we approach Unit Optimisation. We will need to identify a suitable system for use in the UK. Many stations in the UK now use the PI database for storing plant history. The PI database is equipped with graphical tools for visual displays. It would seem sensible to use the PI system for displays rather than introducing another software package. The PI database was not developed for real-time control. Thus if PI is included in a Unit Optimisation system then the individual optimisers will retain the main interface with the DCS.

We must ensure that in developing a unit optimisation strategy unnecessary complexity is avoided The intention is still to develop a closed loop unit optimisation and in this case the individual optimisers must continue to operate in closed loop. Thus the checks in place to ensure that the individual optimisers can run safely in closed loop must not be compromised by the introduction of the Unit Optimiser.

We must be careful not to perform too much software development in packages that were never intended for real time use.

Although the Unit Optimiser will require a GUI for use by station staff, its optimisation function should be written in a real time operating system. We must be careful how interrupts of the individual optimisers are handled. Interrupts are probably best avoided by passing all communications through the real time (ADN) database that is the interface between the optimisers and the DCS. In this way the individual optimisers remain close to the DCS and the communication between the different software packages remains simple.

Within a unit optimisation system there should be an audit of settings controlled by the individual optimisers to ensure that conflicts are identified. At present it is not clear whether this should be a function of the unit optimiser or whether it is better to use the ADN database to identify the source of the data supplied. This will easily indicate if a particular data item is being provided by more than one package and thus should be provided by the unit optimiser itself. A schematic of the software structure is shown in Fig 12.1.

13 RECOMMENDATIONS

It is now time to demonstrate the operation of the unit optimiser on a UK coal fired plant. A typical demonstration would include three separate optimisers, namely:

Emissions Minimisation – GNOCIS minimisation of NOx and carbon in ash
Boiler Optimisation – On line thermal efficiency model using PROATES
ESP Optimisation – Optimisation of SO_3 injection rate

It is clear that there are major conflicts among these optimisers. In particular GNOCIS and PROATES both include burner tilt level in their optimisations with obvious conflict. GNOCIS also advises on the excess air level in the boiler. As the excess air level is increased then the volume flow through the ESP increases and again there will be a clear conflict between the optimisers.

All three of the UK optimisers mentioned here are at an advanced state of development and a unit optimisation study could now be done on a UK coal fired plant using the methodology described here.

The use of an on-line neural network model for resolving combustion instability problems with a gas fired plant has been demonstrated. Thus the GNOCIS technology has been demonstrated on an instrumented gas turbine test rig. An on-line efficiency model using PROATES has been installed on some UK gas turbine plant. Gas turbine components are both very expensive and capable of causing significant subsequent damage within the gas turbine if they fail. Another optimiser looks at maintaining the integrity of these components. Good operation of a gas turbine thus requires balancing several objectives, namely maintaining combustion stability, thermal efficiency and plant integrity. There is thus a complex multi-objective function problem to be solved by the unit optimiser when it is applied to gas turbines.

14 CONCLUSIONS

1. There has been a substantial amount of software development during the Unit Optimisation project at Plant Hammond. Access to the results of this large project has been very valuable in showing the level of detail and complexity of the optimiser models. The project has also focussed thinking in the UK ahead of actually running multiple optimisers on a single unit. In several instances the development of the individual optimisers has been difficult.

2. The substantial development of the individual optimisers during the project has meant that the evaluation of the unit optimiser has not progressed as much as originally hoped. If several optimisers are installed on a unit then there should be an audit of the variables controlled by each individual optimiser.

3. SCS have installed the Synengco Sentient software as the unit optimiser. Use of this software together with Excel has resulted in the individual models being quite remote from the DCS making closed loop installation difficult. It is not clear that this will be repeated in the future due to the desire to keep the individual optimisers close to the DCS.

4. Potential conflict between optimisers can be reduced by either prioritising the objectives of different optimisers (eg environmental objectives achieved ahead of efficiency ones) or adding rules to optimisers (eg including a steam temperature model within the boiler optimiser, GNOCIS).

5. The limited feedback on the performance of the E.ON UK unit optimisation algorithm was favourable. Convergence was usually obtained in about 5 iterations and the algorithm proved stable and reliable.

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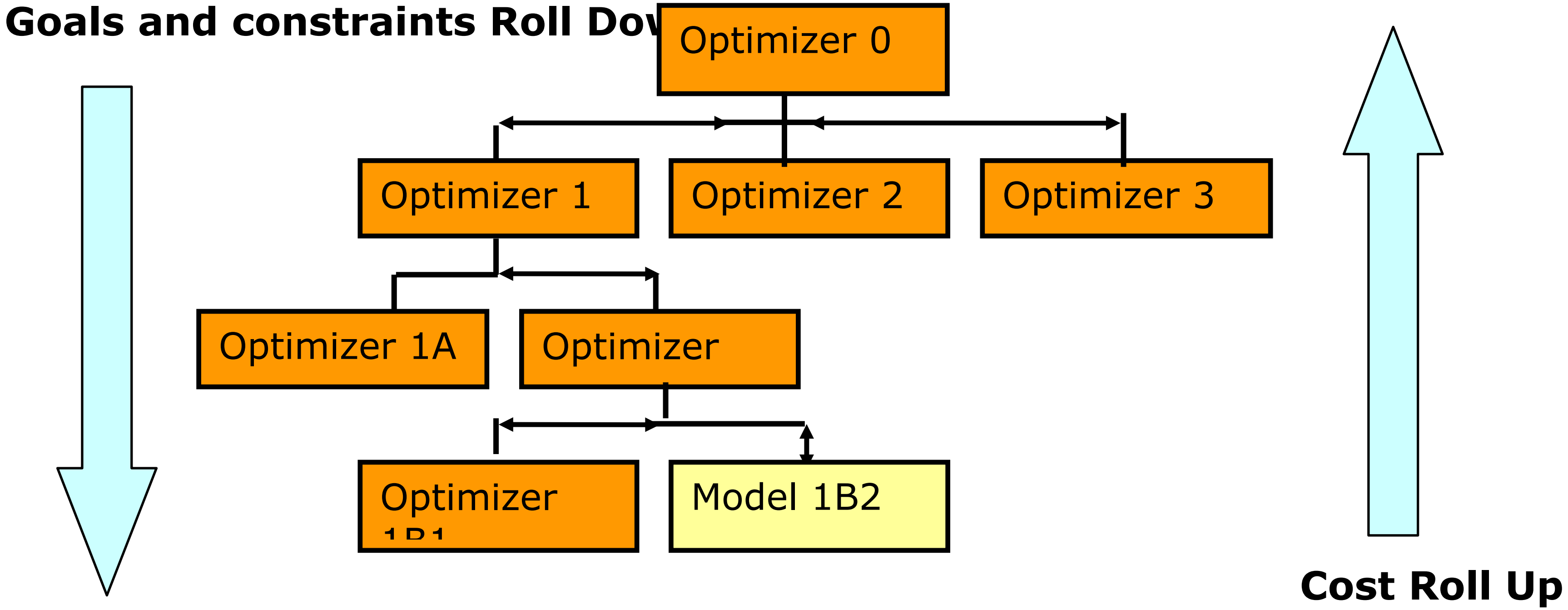

Figure 10.1: Schematic of information flow among a hierarchy of optimisers

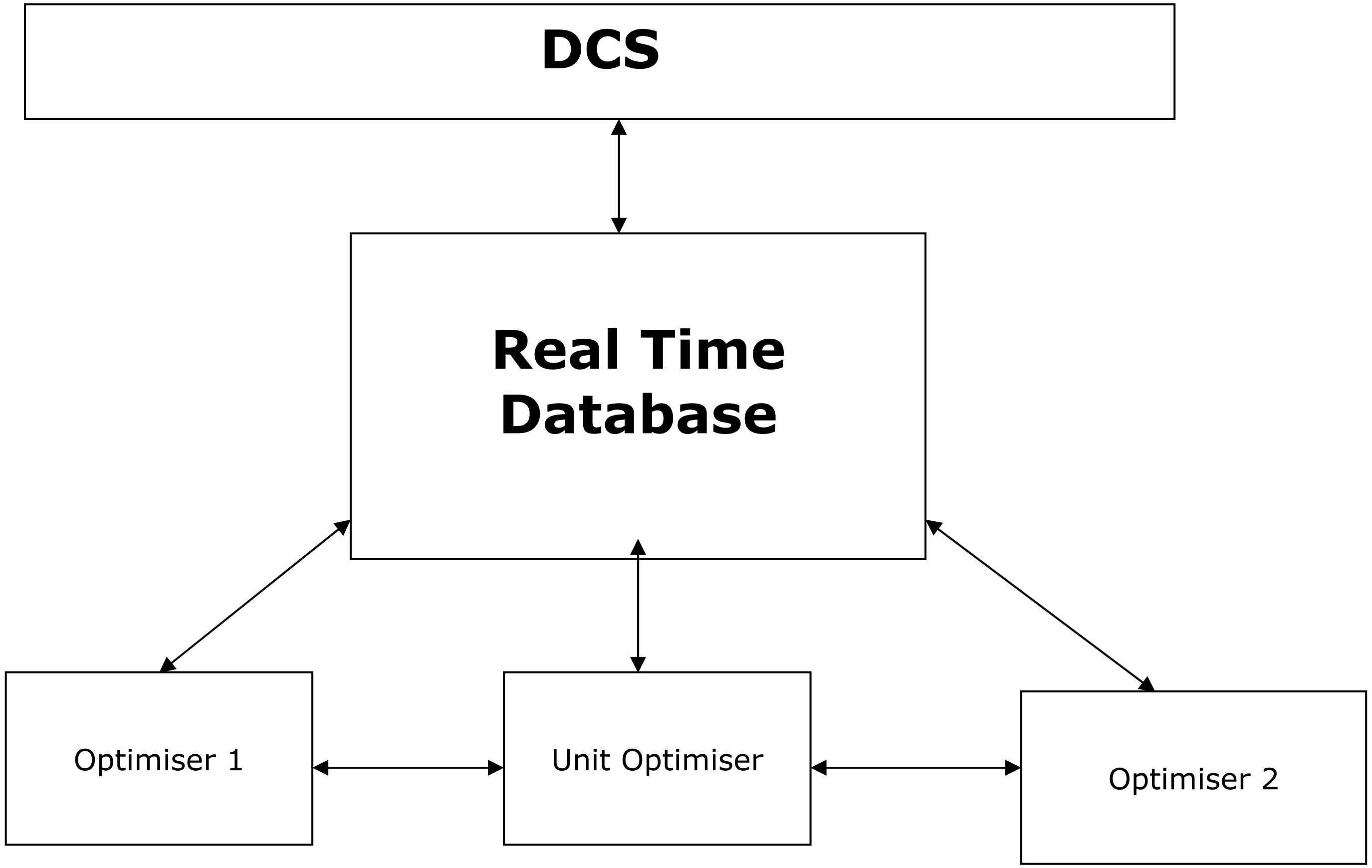

Figure 12.1: Suggested model structure for an implementation of a minimal unit optimiser that maintains the proximity of the individual optimisers to the DCS.

GLOSSARY OF COMMONLY USED ABBREVIATIONS IN THE POWER INDUSTRY

APH	Air Pre-heater
CEMS	Continuous Emission Monitoring System
DCS	Digital Control System
ESP	Electrostatic Precipitator
FD Fan	Forced Draught Fan
HHV	Higher Heating value
ID Fan	Induced Draught Fan
ISBS	Intelligent Sootblowing System
LOI	Loss on Ignition (unburnt carbon in the ash)
MW	Megawatts
NO_x	Mixture of NO and NO_2 in flue gas
T/R	Transformer / Rectifier