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## INTELLIGENT ALARM HANDLING
## IN THE STEEL MANUFACTURING INDUSTRY


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**Key words:** prediction model, multivariate statistics, reheating furnaces, thermocouples, acid regeneration, iron and steel industry


## SUMMARY


This project was carried out for the "Jernkontoret", the Swedish Steel Producers' Association. The aim of the project was to investigate the applicability of various intelligent alarm handling methods in addressing energy related condition-monitoring issues within the steel manufacturing industry.

During the course of the project two real time applications and a postproduction tool have been implemented. These applications give steel producers the ability to detect drift in analyser measurements, validate critical process measurements, and detect abnormal process behaviour and estimate waste gas emission. These capabilities offer improved control of quality and the environment and optimised energy consumption.

The technology exploited in this project can be used in many areas of the steel production industry and there are many opportunities for future work. Real-time application of the technology is foreseen to continue from strength to strength.

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# Contents

# 1 Project Background

The Swedish Energy Agency (STEM) has provided the funds for the project. Industrial applications have been investigated in two companies in Sweden, SSAB Tunnplåt and AvestaPolarit AB. The work has involved engineers from these two companies and also from Advanced Process Control Ltd (APC) and Control Technology Centre Ltd (CTC). APC have provided expertise and consultancy in the field of reheating furnace operations and related control system design. CTC, a spin out company from the University of Manchester, has provided engineering services and software to exploit advanced alarm handling technology based upon techniques in Multivariate Statistical Process Control (MSPC).

The Control Technology Centre Ltd. has been involved for a number of years in developing the software product MonitorMV, a toolbox of technologies for process condition monitoring, fault detection and diagnosis. In this project, MonitorMV has been employed in the development of several condition monitoring solutions for the steel manufacturing industry. The MonitorMV Product has been under continuous development throughout the course of this project. CTC has attracted funds from a variety of companies, from the process control industries and from the mining industries in order to fund this development. The capability of the product has been progressed in part on the basis of the various experiences gained in industrial applications in the chemical, steel and minerals processing industries.

The project commenced in January 2001 and finished in September 2003. During this period work has progressed to address three specific programmes of work each on a different process and with a different objective. These Programmes are

- Validation of thermocouple measurements in a reheating furnace (AvestaPolarit AB)

- Development of a prediction model for NOx emissions in a reheating furnace (SSAB Tunnplåt)

- Investigation of the use of Multivariate Statistics for the modelling of an acid regeneration process (SSAB Tunnplåt)

A fourth project, included in the latter stages of the overall programme, concerned the ability of multivariate monitoring techniques to detect abnormal operation across the whole reheating furnace with a view to improving operational advice in real time. This assessment involved input from SSAB, Advanced Process Control Ltd, CTC and Perceptive Engineering Ltd.

## 2 Conclusions

Two real time applications and an off-line application of the technology have been implemented. These applications give steel producers the ability to detect drift in analyser measurements, validate critical process measurements, and detect abnormal process behaviour and estimate waste gas emission. These capabilities offer improved control of quality and the environment and optimised energy consumption.

## 3 Technology Overview

The techniques that have been used in this project fall under a general heading of Multivariate Statistical Process Control (MSPC). These techniques include Principal Component Analysis (PCA) and Partial Least Squares, or Projection to Latent Structures, (PLS) modelling.

The primary objective of MSPC is to monitor a process over time in order to detect if statistically significant events, or abnormalities, occur. This technology relies heavily on the concept of cross-correlation in order to capture the underlying relationships between various process variables that exist during the normal process operation.

Principal Component Analysis (PCA) is a method of extracting the majority of information from a set of measured signals, i.e. process variables, and expressing it using a greatly reduced number of variables, known as principal components. This technique is widely used in areas where large quantities of highly correlated data needs to be consolidated and, as such, has found significant use in the process industries. In addition to reducing the dimensionality of problems prior to, for example, statistical analysis, PCA also tends to eliminate uncorrelated noise from multiple measurements.

Partial Least Squares or Projection to Latent Structures (PLS) is a method of identification that offers certain attractive features, both in providing a more robust identification approach than Ordinary Least Squares (OLS) approach and as a basis for multivariate condition monitoring. The basic approach of the algorithm is, as with PCA, to identify the principal features in the data. However, unlike PCA, PLS divides the variables into cause and effect. It then identifies the primary features in the cause variables that are able to describe the variation in the effect variables. Hence, PLS seeks to define normality in terms of cause-effect relationships that exist between various process variables.

## 4 Benefits

An on-line NOx estimator gives the process operator a real time NOx value between analyser measurements. Ultimately an on-line estimator can replace an analyser and in some industries this is standard practice, with the real time NOx estimator more commonly known as a Predictive Emissions Monitoring Systems (PEMS). The NOx estimator also compensates for drift in an analyser measurement – where a measurement is available. A threshold on the drift can be used as a trigger for carrying out a calibration check on the analyser. The estimator gives a valuable insight into understanding NOx generation and can be used to evaluate the impact of an operating point change on NOx generation.

Validation of thermocouple measurements provides an early warning of thermocouple failure. True temperature measurements are predicted by the validation model and can be substituted for faulty measured values. In the case of critical measurements used by furnace control systems, this gives an indirect energy saving by maintaining product quality – i.e. preventing lower grade production or re-processing of the steel.

Monitoring the general health of an entire reheating furnace involves monitoring a large number of process variables. Detecting abnormal behaviour in such a large number of variables is a high workload and traditional statistical process control techniques can fail to help the process operator. By contrast MSPC reduces the workload down to monitoring a single, overall, quality measure and detects subtle deviations from normal behaviour, drift in analyser measurements and abnormal events. Energy related process variables such as specific energy consumption and production rate could be included in the MSPC scheme, allowing abnormal energy consumption to be detected.

# 5 Costs and Savings when implementing Condition Monitoring (MSPC)

The cost of implementing the technology is a software license fee and engineering effort to commission an application. The engineering effort and benefits will naturally vary from process to process. As more applications are commissioned, it is expected that the experience gained will lead to the development of a standardised solution. This will help to reduce variation in project costs.

The ability to validate critical process measurements, estimate waste gas emissions and detect abnormal / energy inefficient operation will improve control of product quality and control of environmental emissions. As limits on NOx emissions become tighter, savings from avoiding penalties will be realised. Improved product quality will lead to a reduction in the amount of scrapped product, giving energy savings. For example, heating costs of up to 1200 kWh/Tonne of steel are wasted if the product is scrapped. Detecting abnormal energy consumption will improve the efficiency of production, again leading to energy savings.

# 6 Future Possibilities

The NOx estimation scheme is equally applicable to other pollutants such as CO2 and indeed any process parameter not routinely measured. A combined real-time model of NOx, energy consumption, production rate and other furnace variables would provide a powerful understanding of furnace behaviour. This would be the basis of an advisory scheme or even a closed-loop optimisation scheme to balance the requirements of NOx compliance, energy efficiency and production rate.

Monitoring rolling mill forces, predicting tapping end point in LD converters and electric arc furnaces and monitoring the integrity of hearth furnaces are just a few examples of where this technology can be applied. The principles of sensor validation are also widely applicable to many situations.

# 7 Robustness & Lifetime

The technology investigated in this project uses models derived from process data. Over time process change and evolve – either intentionally as a result of routine maintenance, capital project work, or just long term drift. The technology reported here can compensate for process drift and the MonitorMV software can adapt models on-line. These abilities improve robustness and provide the lifetime of the final technology solution. Some process modifications may require re-calibration of the models or new plant tests to be carried out.

# 8 Marketing

Promotion of this work is planned in the form of conference papers and articles in industrial journals (e.g. Iron and Steel Engineer).

# 9 Applications

## *9.1 Validation of Thermocouple Measurements*

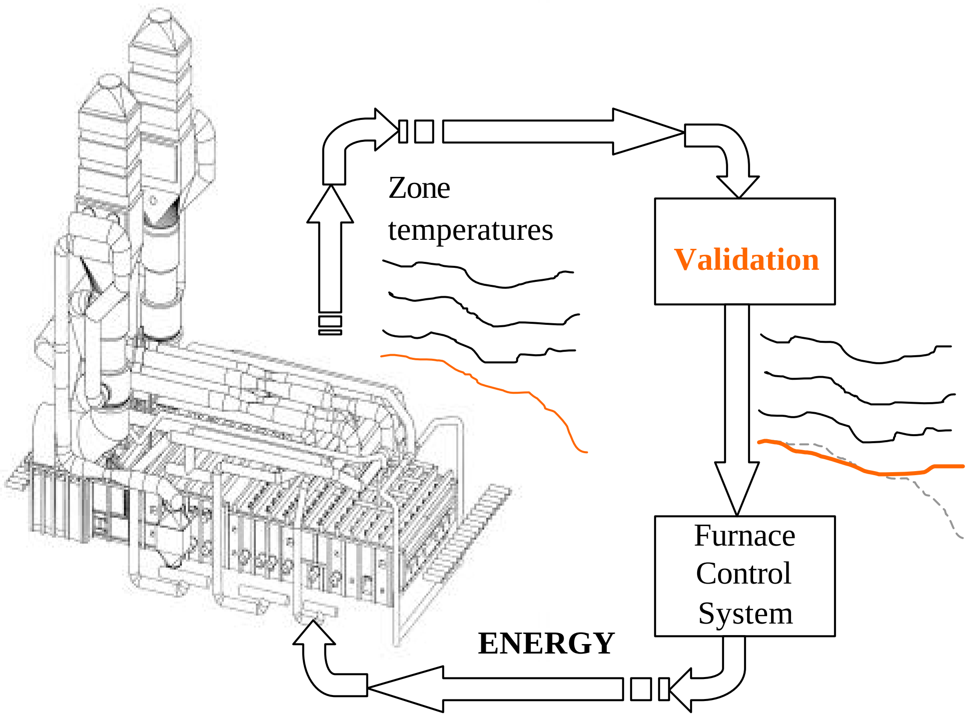
The prerequisite for satisfactory control system performance is reliable availability of feedback measurements. In fact, a control system can only be as reliable as its feedback measurement equipment. At the same time, general sensor equipment is susceptible to long- term drifts and sudden failures. As a result, key business drivers, such as running cost, productivity and product quality, can be adversely affected, compromising the economic viability of the entire processing plant. Therefore, the improvement in feedback measurement reliability has a direct and positive impact on key business drivers in any manufacturing industry.

The Fuel Optimisation Control System (FOCS) scheme, employed in the reheating furnaces of the hot-strip rolling mills, relies heavily on the accurate temperature measurements inside different furnace zones. These thermocouple-measured temperatures are used as feedback measurements in local PID- based control schemes (one controller for each furnace zone) as well as the initial conditions in slab temperature calculations.

The impact of the faulty or erroneous temperature measurement in the reheating furnace is twofold. For example, where the measured value is below the actual temperature, excessive fuel is used in the furnace burners. This in turn increases the energy consumption, which is probably the main business driver for this process. On the other hand, if the measured value is above the actual temperature then the product quality may be degraded. Hence, in either case an important business driver is adversely affected by the failure of the instrumentation to provide accurate and reliable measurements.

This programme of work is concerned with the development of a validating mechanism for thermocouples used in reheating furnaces. The presence of strong cross-correlation between different thermocouple measurements is exploited by the MonitorMV software system to detect faulty sensors and estimate the true value of the associated process variables.

A case study of furnace B at the AvestaPolarit site in Avesta, Sweden, shows the ability of the MonitorMV software to detect the early stages of a thermocouple failure. The validation scheme is presently under trial on-line on reheating furnace A.



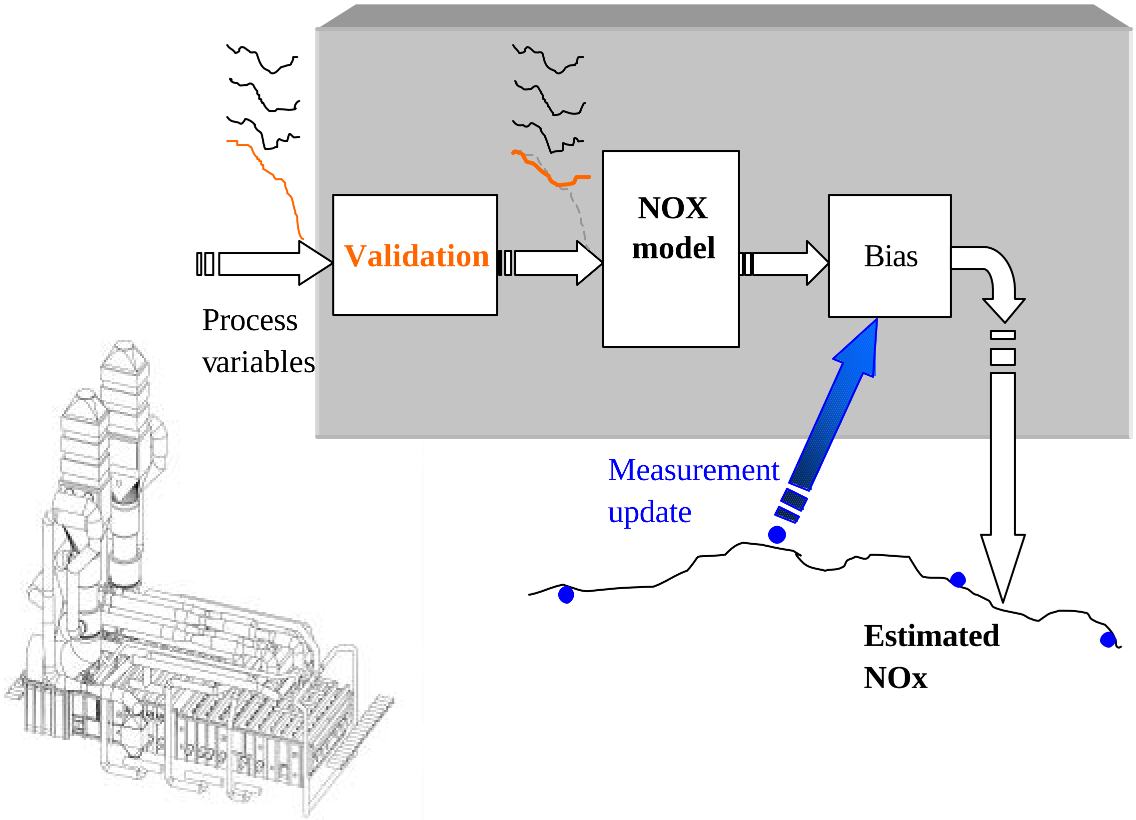
Future developments should focus on integrating these validation mechanisms into the current control systems for reheating furnace A, thereby providing accurate and reliable validation of thermocouple measurements. Also, a similar scheme could be employed for the reheating furnace B, for which the capability of MonitorMV to detect faulty thermocouples has been demonstrated in the case study. Furthermore, the concepts that are employed in the validation of thermocouples could be employed for other instrumentation around the furnace. This would ensure that critical sensors are backed up and monitored automatically, thereby shielding the control system from misinformation and potentially costly mal-operation.

## 9.2 Development of a NOx Estimation Scheme

The need to protect the environment from combustion generated emissions, such as carbon dioxide ($CO_2$) and nitrogen oxides (NOx) has led in recent years to considerable demand for improved combustion system design and operation. And while the most important business drivers in economic considerations of the reheating furnace are minimisation of energy consumption and maintenance of high throughput, it is evident that, with increasingly stringent environmental regulations and heavy penalties for non-conformance, furnace emissions are likely to become a significant, if not crucial cost driver. Such environmental considerations are forcing process plants to measure emissions and investigate methods for their cost-effective reduction.

The crucial step in attempting to address the issue of NOx emissions in a cost-effective manner is the development of an accurate cause-effect prediction model. Such a model would not only offer viable and economic alternative to costly hardware-based analysers, in a form of a ‘soft sensor’, but also provide the basis for the development of a NOx control scheme.

In this particular case a NOx estimation scheme was developed using MonitorMV Design and Online systems for reheating furnace U302 at the SSAB site in Borlänge, Sweden. This work has been carried out in collaboration with process control engineers of SSAB and APC Ltd.




In order to develop an accurate prediction model an important decision in the early stages of model design is the selection of a set of cause (input) variables. Here process knowledge provided a crucial insight into the underlying cause-effect structure of the model. In particular, the first two zones (preheating zones) were highlighted for having the greatest impact on NOx emissions. The most important cause variables from these two zones have been identified as the flow rates of air and fuel into the burners as well as the zone temperatures. Additionally, it has been found that the flow rate of the atomising steam into the burners has a significant and negative impact on the NOx emissions. In other words, increase in the total flow rate of atomising steam into the burners is found to reduce NOx emissions. Hence, the total flow rate of atomising steam could be seen as a crucial cause variable in any attempt to minimise NOx emissions.

The NOx prediction model developed in this project is a dynamic model. It is vitally important that the training data is 'sufficiently excited' in order to reveal information concerning dynamic relationships between cause and effect variables. To ensure this, numerous step tests have been performed on the flow rates of air and fuel into the burners of the first two zones of the furnace.

The NOx prediction model has been developed around an FIR model structure using Partial Least Squares (PLS) regression to identify the model coefficients. The model has shown a satisfactory level of accuracy with a normal (Gaussian) distribution of prediction error. This finding indicates that the NOx prediction model accounts for most of the structured information concerning NOx emissions. Finally, a bias filter has been used to gradually remove any steady state offset between the model predictions and the actual process measurements.

Validating condition monitors, based on Principal Component Analysis have been implemented to ensure availability of measurements for a subset of cause variables. In this way, the overall reliability of a developed solution is greatly improved in the case of possible instrumentation failure. Validation schemes have been employed for groups of cause variables that exhibit strong cross-correlations. These were found to be the temperatures in zones 1 and 2 and the combustion air temperatures from the first 7 zones of the furnace.

The developed NOx estimator, consisting of the PLS-based prediction model and the bias adaptor, as well as the associated validation monitors have been implemented online, using MonitorMV Online system, at the SSAB site in Borlänge, Sweden, providing the continuous estimation of the NOx emissions. This NOx estimator is expected to facilitate further developments of a NOx control scheme and aid in the development of a condition-monitoring scheme for a reheating furnace.

Future developments should focus on incorporating the developed prediction model into an advisory system that would indicate which cause variables should be changed and by what amount in order to minimise NOx emissions while maintaining high productivity. Also, the model should be employed in the development of the condition-monitoring scheme for the entire reheating furnace. This is especially so since sudden and rapid change in terms of NOx emissions that is not accounted for by the developed prediction model may be a symptom of an operational problem of the reheating furnace. In order for these schemes to be successful, a diagnostic rule base needs to be established by using the process knowledge, which would relate results produced by such advisory/condition monitoring schemes and the actual process.

## 9.3 Investigation of the use of Multivariate Statistics for the modelling of an acid regeneration process.

This work is concerned with investigations that relate to an Acid Regeneration process at the SSAB factory at Borlänge.

The Acid regeneration process is used primarily for the regeneration of pickling liquor, namely hydrochloric acid that is used to remove iron oxide on the steel in the pickling line. As a by- product of acid regeneration, iron oxide is created. This iron oxide has a value and is sold by SSAB as a product in the open market.

The first attempts to develop a statistical model to describe the acid regeneration process were based around the principle that if all available data is collected over a significant period, covering many days of process operation, then such data should provide a basis for representing the normal profile of the process. Subsequently, if other data is referenced against this profile then there should be a basis for determining if this other data is normal or not.

Following this theme, the PCA- based models revealed several modes of process operation, corresponding to:

- normal acid operation,
- starting up/shutting down ‘water mode’ operation, and
- periods during which the acid plant was not operational.

Although frequent changes to the process and to the process operating conditions were made in attempt to gain a better understanding of the process, the information concerning the changes was not being referenced by MonitorMV or was not in a form that could be utilised. The outcome was that, although MonitorMV could detect that the process was operating in a different regime, there was no basis for deciding the basis for the difference or if the difference corresponded to normality or otherwise.

The above considerations became clear after attempting to relate to all three modes of operation simultaneously. It was therefore decided to narrow the scope of examination to only the normal acid mode of operation. In this way it was thought that the sensitivity of the model would be increased and small-scale variations that may differ from the normal would be more clearly highlighted. However, as a result of the increased sensitivity of the principal component models, the non-stationary nature of the process became even more apparent. In particular, it was found out that the general statistical model had an extremely limited period of validity before being rendered obsolete by some change in the operating condition of the acid regeneration plant.

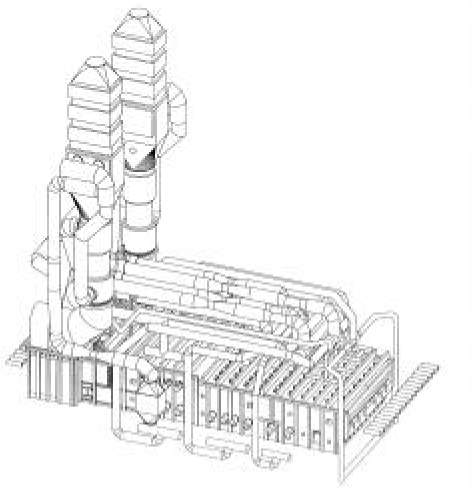
The real lesson here is that progress in statistical modelling for condition monitoring is only feasible if a process is settled in its operating conditions. Any changes must be of a consistent and observable nature and must be able to be referenced by the monitor if any progress is to be made. This, unfortunately, was and is not the case with the acid regeneration plant.

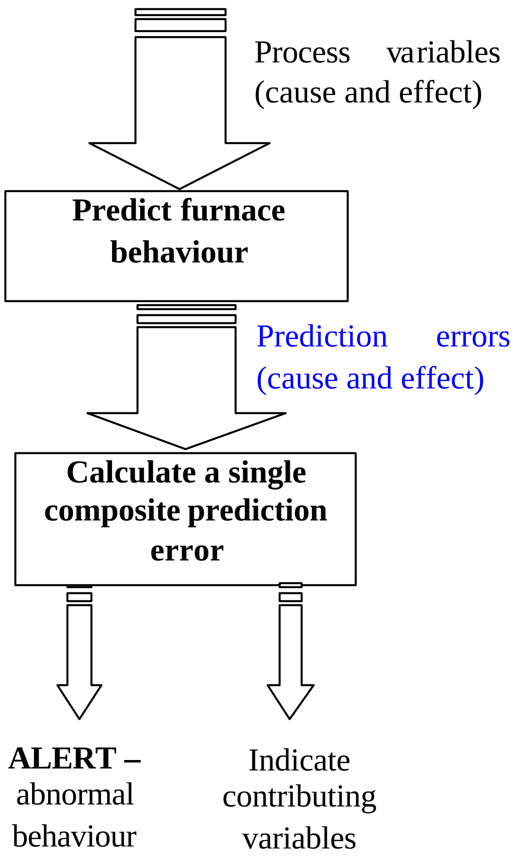
The programme of work progressed in order to try to make some headway in producing models to describe the behaviour of the acid plant. It was decided to investigate the possibility of determining a model that would relate cause signals with effect signals by employing a PLS based model. In this way, non-stationarity that was a direct result of the changes in cause signals would be accounted for and the validity of the model would be extended in time. This approach did not prove fruitful because of the lack of excitation of the various cause signals and also the lack of appropriate sensor information to indicate when cause signals were changed.

The investigations with the acid regeneration plant have proven to be less productive than those reported above for the reheating furnaces. However interesting aspects have been shown concerning the capability of the Multivariate Statistics to classify regions of process operation and to relate these regions to variations in key process variables.

## 9.4 *Reheating Furnace Condition Monitoring system for improved operation.*

It has been proposed that by using predictive condition monitoring on an industrial steel reheating furnace there will be improved operational understanding, measurement robustness, and incipient fault detection that all together will lead to increased efficiency and productivity. Part 2 of the main report discusses the initial analysis and system that has been developed to achieve a versatile predictive condition monitor.






The findings demonstrate the ability to detect abnormal process events and identify subtle deviations from normal process behaviour. A sophisticated multivariable model that gives robust predictions in the presence of highly correlated noisy production data delivers these abilities. The analysis also covered the development of on-line predictions of environmental emissions, in particular NOx, and other important economic variables such as scale loss, production rate and specific energy consumption. These estimated parameters could be used to independently backup sensors or included as part of an enhanced control system.

Accurate predictions of NOx, O2, scale loss, production rate and specific energy consumption have been obtained for Furnace 301. Where software based Predictive Emissions Monitoring System (PEMS) is used to monitor NOx (or any other environmental emission), a periodic relative accuracy test is usually required by the relevant government agency. Although PEMS are usually applied to real time data (as opposed to the averaged data analysed here), this report includes a typical relative accuracy calculation for the NOx prediction to illustrate the precision of the model, which may now be used for further evaluation.

The preliminary multivariable model developed for the furnace can be used to detect changes from normal operation. These changes may be considered as abnormal events, although more subtle changes in process behaviour and drift in analyser measurements may simply indicate wear and tear. As an example, a drift in $O_2$ measurement the weeks before summer maintenance stop 2002 was clearly indicated by the model. Else, such drifts are only possible to detect by use of parallel measurements.