New Dimensions for Improving Refinery Profitability

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Introduction

Oil refiners have long recognised that better information is a prerequisite to progress. They have led in the use of computers for gathering of data and especially process history data to these ends. Enormous strides have been made in the last 25 years to the point where few refineries today do not have substantial amounts of detailed process tag history data available to them. This has created an awareness of the need for equivalent progress in the methods and technologies for analysing this data to extract the considerable information that it contains[1].

The root problem of analysing process data is the sheer volume that a well-implemented process historian makes available. The immediate reaction of an engineer confronted with a large amount of numerical data is to plot a graph to summarise the details in the hope that this may reveal something of the principles. Existing types of graph allow from 2 to 7 process variables to be summarised, although the considerable added effort of using more than 3 variables means in practice that graphs of more than 3 variables are not a part of most engineers everyday toolset.

This paper describes a very different analysis technology based upon multi-dimensional geometry and made possible by a novel co-ordinate transformation that allows for a two-dimensional representation of a multi-dimensional space. It has the advantage of being easy to learn and to use. It does not require the user to have any knowledge of multi-dimensional geometry. Many process tags, up to 30 are usual and more are possible, can be viewed and manipulated simultaneously in their normal units of measurement and without the need to introduce new, artificial variables. Relationships between variables emerge visually and without prior hypothesis.

The essentials of the method are described and the method is then applied to process variable history data for a refinery Steam Boiler in order to demonstrate its utility. Considerable insight is developed into the behaviour of the boiler and estimates are derived from the operational data of the financial incentives for process improvement.

'Holes' in process behaviour have been observed and are reported here, it is believed for the first time, as a new and important process phenomenon. Black Holes are internal regions of a process variables' range where good product has never been made yet where the plant has frequently operated and continues to operate. Examples are identified in this paper during the Boiler analysis and briefly discussed in terms of their possibly profound implications for, in particular, process control and process modelling.

The Method of Parallel Co-ordinates

Parallel Co-ordinates is a co-ordinate transformation that allows a 2-dimensional view of N-dimensional geometry. It is a co-ordinate transformation in just the same way as the more familiar co-ordinate transformations between, for example, rectangular and spherical co-ordinate systems. It is based upon replacing the fundamental assumption of orthogonality between dimensions that has restricted previous co-ordinate systems to visualisation in a

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maximum of three dimensions. If dimensions are instead represented as parallel to each other then the limitation on their number (almost) disappears.

In Parallel Co-ordinates we can continue to add more axes or dimensions up to the width of our paper or computer screen and the polygonal line which represents the multi-dimensional point just gets longer, the lines combining to form patterns.

The patterns may be characteristic for regular objects such as lines or planes or may be anomalies that prompt further investigation. They can also be used in other ways that provide an intuitive and attractive human user interface.

Process Improvement

There are three major parts to the improvement of functionality or usage of an item of equipment. They are:-

1. **Analysis**
    - Is there technical or usage scope for improvement?
    - Are the economic incentives sufficient?
2. **Specification**
    - What exactly is to be changed and how is it to be done?
    - What will it cost?
3. **Implementation**
    - Implementing the improvements.
    - Proving that the forecast results and benefits were achieved.

This paper will examine the use of the parallel co-ordinates method within the Analysis phase only. This will be done using examples from the analysis of an operational high-pressure refinery steam boiler.

Boiler Analysis

The boiler from which our data came is a typical large refinery installation able to produce up to 200 tons per hour of steam on demand at 600 psi and approximately 700 degrees F. An outline flowsheet is shown in Figure 1.

The boiler is fired with both oil and gas. Feedwater purity is measured by the electrical conductivity of the water. Combustion air is provided by two Combustion Air Blowers feeding into a common Windbox which has adjustable dampers with approximately eight damper positions on each of its two inputs and approximately four damper positions controlling its output and hence its internal pressure.

The objective of the investigation was the improvement of steam product consistency to benefit the downstream consuming processes and improve environmental performance and

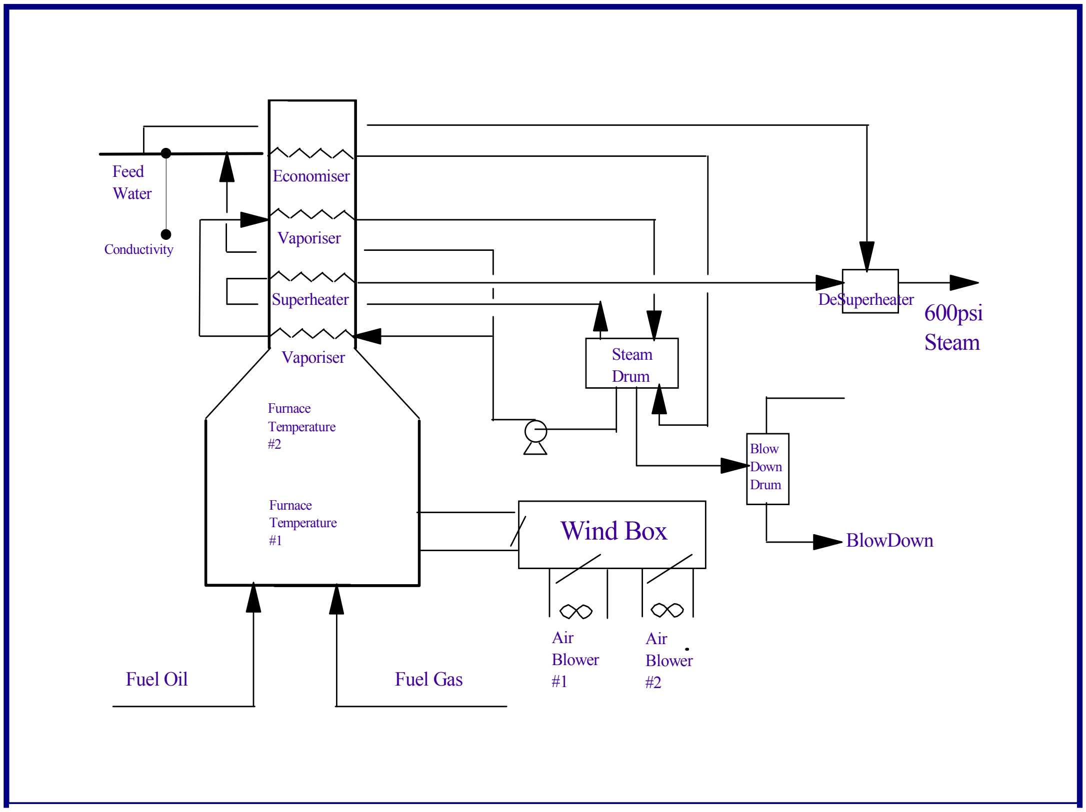

Figure 1. Flowsheet of the 200 tons/hour 600 psi steam boiler

energy efficiency. The magnitude of the potential benefit savings that could be achieved provided budget limits for improvement works.

The data available consisted of 1736 values taken every hour for a period of approximately 3 months for 16 process variables. When time was included it became a 17-dimensional problem in which all the relationships between all the variables were available for study. Figure 2 shows the data plotted in parallel co-ordinates.

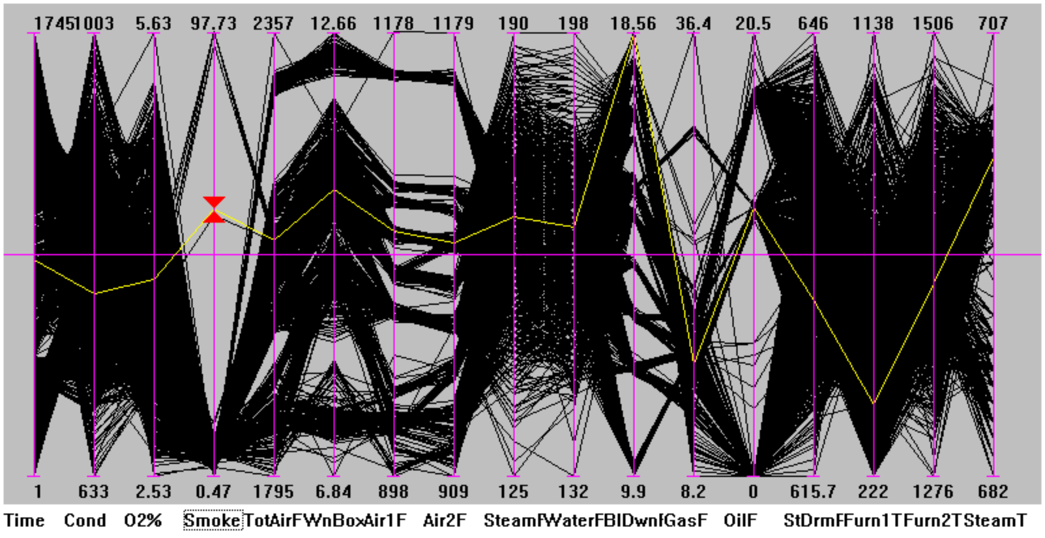

Figure 2. The Process data plotted in parallel coordinates. A single multi-dimensional point corresponding to a high-smoke situation is highlighted in yellow.

Each of the variables is plotted over its entire working range on a vertical axis from bottom to top. For instance, the % Oxygen in flue gas is plotted from its lowest value of 2.53% to its highest value of 5.63% on the third axis from the left. Each value is then joined by a line to the values at that time of those variables (Conductivity of Feedwater and Smoke Density in this case) on either side. The process then repeats so forming a single line-trace showing all the observations at one instant. A single instance of this line-trace is termed a multi-dimensional point in the parallel co-ordinates representation. A single multi-dimensional point has been highlighted in yellow in Figure 2.

Plotting the data for many points, in this case 1736 of them, produced patterns of black areas where the process had operated most often and lighter-coloured or white areas where the process operated less frequently.

The data can be seen in Figure 2 to be strongly patterned. Some of the patterns were due to the process itself. For instance, the bold bars between Air1F and Air2F indicate that both those variables had a similar small number of operating values (damper positions) and they were most often both set to the same operating value. Blow Down flow also had a small number of operating values.

Fuel Oil flow appears limited to three values. This indicates that there are two sets of oil burners each of which can be either on or off. However, the small number of points in the ‘white’ parts of the OilFlow variables axis indicate that here was some capability to add additional individual burners. Periods when they were used and their consequent affect upon Furnace Zone temperatures and Operating Costs could be worthy of further investigation.

Fuel Gas flow appears to be more continuously variable across its range than Fuel Oil Flow.

Other patterns are due to underlying relationships in the data which become visible in some way in the parallel co-ordinates representation. For instance, the vertical line of very small white holes formed between the Steam Flow and Water Flow axes indicates a planar relationship between these two variables indexed by a third variable (which is not necessarily present in the data set).

Setting Benchmarks for Comparison

There are broadly two ways to approach the analysis of process data. One is to look at the unusual events, for instance, the two periods of high Smoke intensity that can be seen in Figure 2, in order to learn by trying to explain how they occurred. The other is to look at the variability in normal operation against a benchmark of, for instance, the best 10% or 20% of production, and then to seek to understand the causes of the variability.

In this paper we selected a set of data to act as a benchmark against which to compare.

Product Quality for the boiler output was taken as steam temperature and pressure variability since Steam Demand was uncontrollable and assumed, in the absence of any demand data, to have been met. Steam pressure in this plant was regulated at 600psi. We chose values of Steam temperature very close to 700 degrees F. This was slightly above saturation temperature and a range between 699 and 701 degrees selected 64% of the total points confirming the validity of our selection. We also added more demanding specifications for Smoke of about half the observed operating range, and limited the percent Oxygen in flue gas to lie between 2.8 and 3.5%. The result of this can be seen as the yellow highlighted points in Figure 3. This 'Best Product' accounted for 16% of the total points.

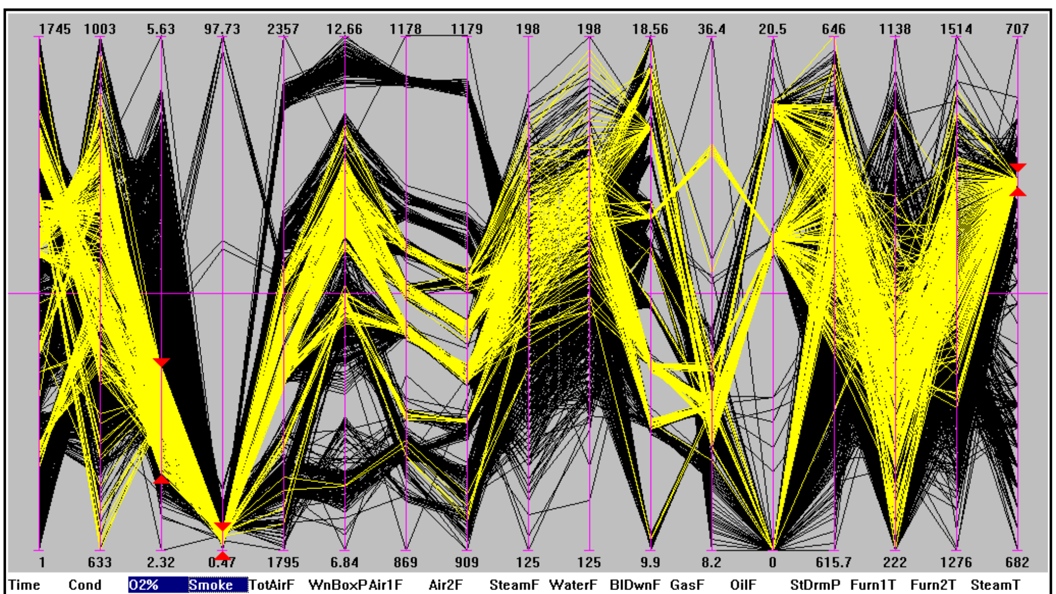

Figure 3. The Benchmark 16% defined as 'Best Product'

Imposing this 'Best Product' quality reference across the total operation immediately showed where the boiler had been operated to produce non-quality product. For instance, the two Combustion Air Blowers (Air1F and Air2F in Figure 3) feeding into a common Windbox each have adjustable dampers with approximately eight positions. It can be seen in Figure 3 that the same damper position number was most often used for both and that all positions have been used at various times. Yet, unknown to the operators, 'Best Product' was produced only when using the middle three or four of the eight positions. Better operating procedures or process controls limits could easily avoid operation in these black regions exterior to the yellow region.

Black and White Process Holes

Examples of black process 'holes' can be seen in Figure 3. Two distinct examples are visible on the WindBox Pressure axis where there are three yellow bands separated by black areas. Within the three yellow bands 'good' product is made. When the plant operates in the two black areas between the yellow bands bad product is made, but the fact that the black areas are black indicates that the plant has actually spent substantial time operating there[2].

Other black holes can be seen in Figure 3 on the Conductivity, BlowDown Flow, Fuel Gas Flow and Furnace Zone 2 temperature.

Areas in Figure 3 where the plant never operates appear white. Examples are clearly seen on the Air1Flow and Air2Flow axes. The 'White Holes' thus formed almost always indicate intentional non-operation in that range and are therefore less of a concern because they are predictable. They may still cause the control engineer and the process operator some difficulty. Theoretically, small white holes in a variables range could be an indication of negative stability of the process in that region but we have yet to observe a good example of this in an operational plant.

We have named the black areas between yellow bands 'black holes' and have found them in almost every process that we have looked at. They are a major problem for plant operations as existing process control algorithms are not able to recognise and therefore avoid holes. As yet, we do not have a general theory to explain the origin of black holes in continuous processes.

The best, perhaps only, way to deal with black holes at present is to understand the process sufficiently well that one can decide which of the yellow bands is 'best' and make that the only operating zone through rigorous implementation of operating procedures, process controls and control limits. Considerable process knowledge and process control judgement is required during the analysis process since in a complex plant it is very likely that no yellow band exists which contains no black holes and which is at the same time 'wide' enough to allow the process controls room to operate.

It can also be seen in Figure 3 that good product is produced only in the upper half of the boilers operating range (SteamF is the Steam Flow measurement). This might suggest that the boiler controls were biased towards operation in the region of the nameplate throughput and might have benefited from being less throughput sensitive. Examination of a time-trend of steam production showed that load was reasonably variable and rarely at maximum. It supported the opinion that the boiler controls effectiveness at lower throughputs might have benefited from attention. There is also a suggestion that the benchmark quality settings for 'Best Product' could be forcing the sacrifice of some peak load capability.

Referring again to Figure 3, there are two measurements of temperature inside the furnace (Furn1T and Furn2T). Good production is seen to use the lower part of the first temperature zone and the middle-upper part of the second. This may provide useful information about burner positioning and burner pattern control firing.

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[2] In mathematical terms, the black areas actually indicate that we are operating in a multiply connected region. This is a significant and fundamental problem because all process control algorithms in common use today, whether single variable or multi-variable, implicitly assume that they will be operating in a simply connected region.

Figure 3 shows that our Best Product quality definition allows wide variability in Feedwater Purity and BlowDown Flow. We therefore added a specification on BlowDown Flow to the Best Product definition and both the specification and the resulting new 'Best Product' benchmark can be seen in Figure 4. Note that the black holes on FeedWater Conductivity, Fuel Gas Flow and Furnace Zone 1 Temperature are now quite distinct. The plant should not be operated in these holes.

Economic Assessment

A new dimension is added to any interpretation when operating costs are included. Two calculated variables were added to provide a Total Fuel Cost of Steam and a Unit Fuel Cost of Steam. Both were linear combinations of fuel unit cost and fuel flow rate. These new variables, TotCost and LbCost, are shown in Figure 4.

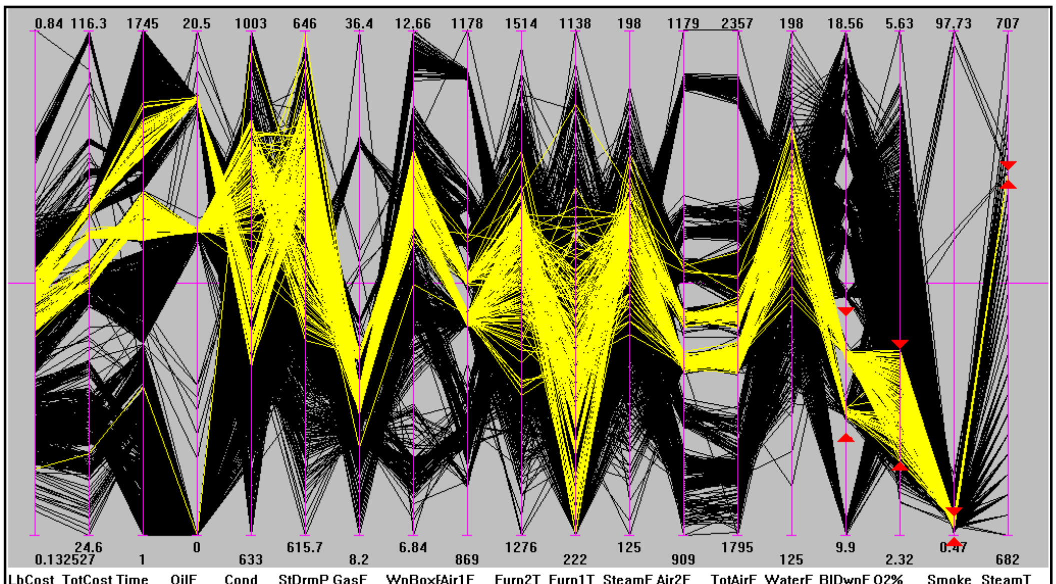

Figure 4. Best Product with Unit and Total Fuel Costs added

Three, possibly four, distinct bands emerge for Total Cost and three slightly partly overlapped bands for Unit Cost as can be seen in Figure 4. They are selected in different colours in Figure 5 for easier comparison.

It is perhaps most significant that the separation of the three cost bands in Figure 5 continues into the Cost per Pound of Steam produced. The yellow (cheapest) and green (middle) cases were similar in using the same setting for Fuel Oil and the same Total AirFlow. They differed in the quality of the feed water (Conductivity), although this was not reflected in the BlowDown flow, and in the temperatures in Zone 2 of the furnace where the yellow band was cooler than the green.

The most expensive pink band used the highest of the three Fuel Oil settings. The green and yellow did not. The pink band also had the purest feed water (lowest Conductivity) and this was reflected in a lower Blow Down rate but not, apparently, in a lower fuel requirement. This would be worth further investigation by adding the cost of FeedWater Purification treatment into the product cost calculation.

The pink band Airflow was higher but so was Steam Flow and hence total Fuel. Adding a variable to calculate air flow per unit of steam flow (since the relative stochiometry of fuel oil and gas is unknown) showed that the ratio was inline with the other bands.

Furnace temperatures in Zone 1 were slightly higher but similar to those of the green band whereas in Zone 2 the pink band temperature range was significantly lower than either the green or the yellow bands.

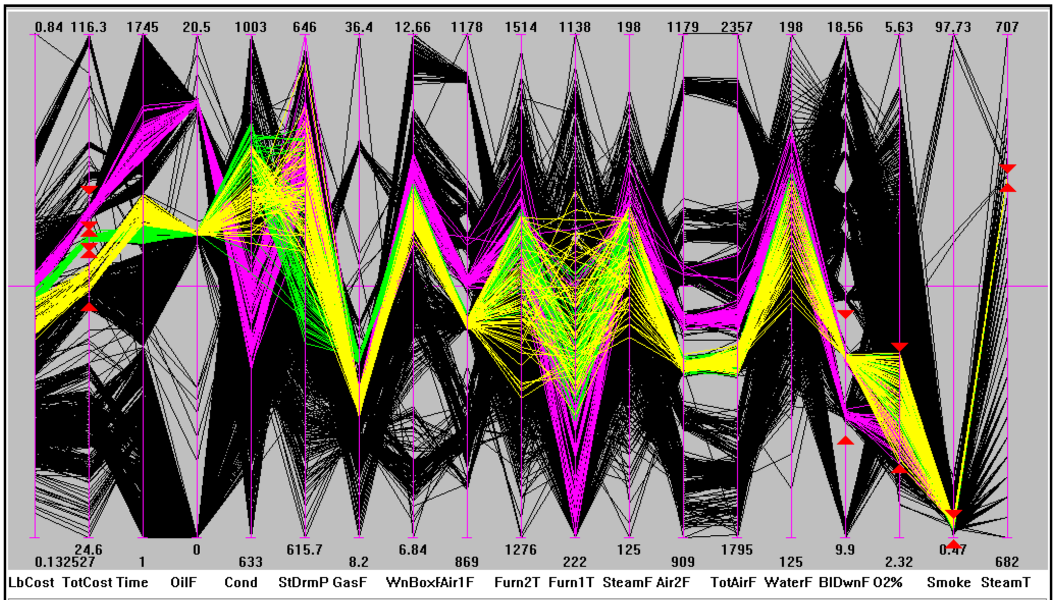

Figure 5 Three Cost Regimes

To understand the significance of the Zone 1 and Zone 2 temperatures requires more knowledge of the physical aspects of the furnace construction, the placement and control of the oil and the gas burners, and the operational state of the furnace during the one time period when the pink band was active. These are aspects of Domain Knowledge usually not available outside the plant itself.

An estimate can be made of the economic benefits that would be achieved by improving operations so that the boiler always operated in the yellow cost zone instead of 40% in yellow and 30% each in pink and green as now. The cost of operation in each of the zones can be read off as 72 money-units/hour in yellow, 78.5 in green and 84 in pink. The current average cost per hour is thus 0.4*72+0.3*78.5+0.3*84 = 77.55money-units/hour.

The saving that would be achieved by always operating in the yellow zone would be 77.55-72 = 5.55 units/hour or 7.2% of present fuel costs (since only fuel costs were included in the calculation of operating cost).

Costs can be 'optimised' for a given steam production and quality by focussing on a particular steam throughput. The process conditions that were in use at that time can then be read off as well as the Costs. An example is shown in Figure 6 for one particular steam flow rate and highlights the range of process conditions actually used over a period of several months. The three resulting cost bands have values of 72.5, 79.3 and 83.9 money units. That is a cost variance of over 15% and gives some indication of how much one could afford to spend in order to improve the consistency of process operations.

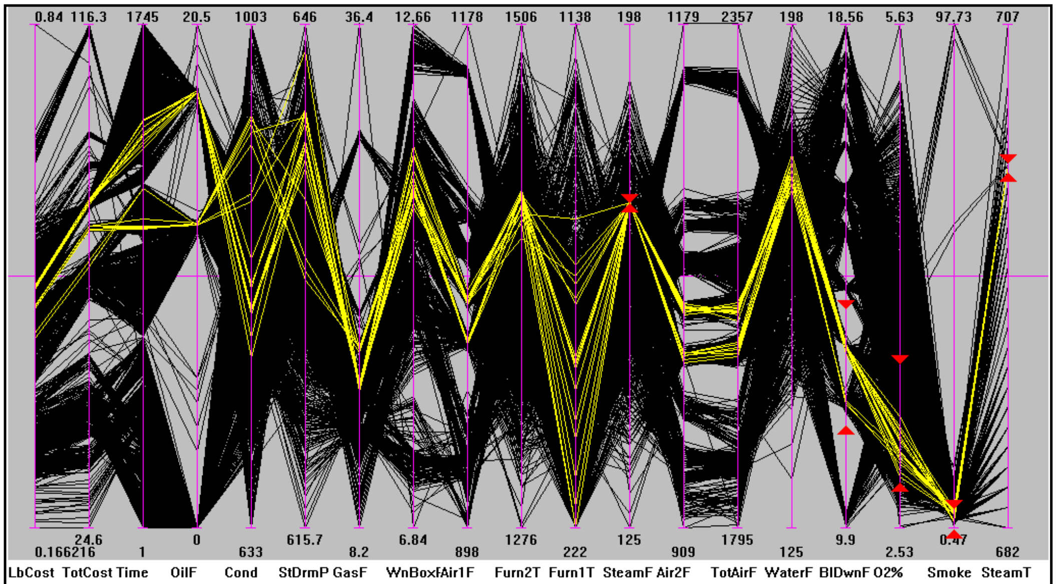

Figure 6. Cost Choices for a particular Steam Demand

Final Remarks

- Parallel Coordinates is a method for viewing the actual data – there is no theory involved – the results are exact
- There are many potential developments to come using this technique[2] – one pending paper uses the technique to separate the developers and users of complex mathematical models[3].
- Black Holes are a totally unexpected phenomenon observable for the first time with the parallel coordinates method. Work is in progress to (a) develop a general theory to explain their origin and (b) to assist plant operators to minimise the adverse effects of operating in Operating Zones that contain black holes.
- The cost/yield analysis of the boiler gives immediate, unarguable results
- The major lesson is that there is considerable value in improving not only the gathering and storage of process and laboratory history data but also in radically improving the methods of visualisation and analysis.

References

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