Choosing Cut Points to Optimise Product Yields

R.W.Brooks, J.Drury, F.D. van Walsem[1]

Published in: Hydrocarbon Processing 1999, 78(11), 53-60

Introduction

The properties and economics of the final products produced by an oil refinery are tightly constrained by market specifications and conditions. The capability to meet all the specifications are initially set by the fractions into which the Crude Distillation Unit (CDU) divides the Crude Oil or Oils. The size or yield and properties or qualities of the fractions are determined by the Final Boiling Point or Cut-Point settings used to operate the CDU. The relationships between the set of Cut Points and the size and properties of the resulting fractions are extremely non-linear. The refinery LP planning model used to optimise production within market conditions has to be linear. The LP thus contains a simple model of the CDU which summarises operations into a number of pre-defined Modes created from tabulated values of yields and properties which are each represented by a single representative value across a 'Cut' defined by its Final Boiling Point or 'Extreme' Cut Point. The LP then selects the Modes of operation and 'blends' the 'intermediate product' outputs of two or more Modes to achieve the particular yields and qualities of Final Product that will best suit market conditions.

This paper investigates the method of selecting Cut Point values within Modes and their effect upon Final Product Yields. It combines a proprietary non-linear CDU model with a linear Mode selection and blending model built in a spreadsheet . It shows the advantage in Final Product Yields that can be obtained by optimising Extreme Cut-Point values compared to using the design-fixed Extreme Cut Point values still used by many refiners. It uses a new multi-dimensional data visualisation based upon parallel co-ordinate mathematics to make all the results of the Mode model simultaneously visible. This has considerably reduced the depth to which users need to understand how the model works before being able to use its results.

A novel visual method for CDU operators to establish operational Cut-Point values from the Extremes used by the LP is presented as an alternate multi-dimensional view of the model. This method has the advantage of separating modellers from users to the considerable benefit of both.

The paper indicates directions for further improvement in the combining of non-linear CDU models and refinery planning LP's.

The Problem

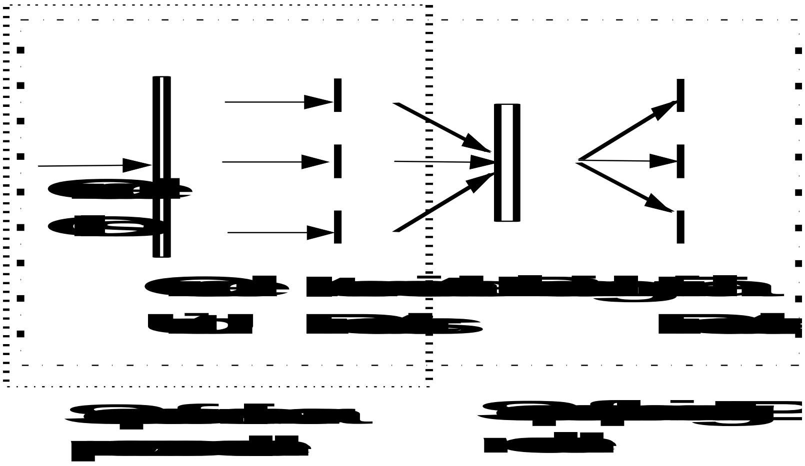
Prediction of the intermediate product yields and qualities that will be obtained when various crude oil mixtures are processed in a Crude Distillation Unit requires highly non-linear models. The results from these models are approximated by linearisation for use in the Linear Programs that are used for planning the operations of the refinery and for choosing the most economic crudes to process, the Modes and Cut-Points to use , the intermediate product qualities resulting from the Modes, the recipe with which to blend them to produce on-specification final products and the calculated Actual Cut Points which should be used when operating the CDU to achieve the same result.

---

1 [1]R.W.Brooks and F.D. van Walsem are with Process Plant Computing Limited, PO Box 43, Gerrards Cross, Buckinghamshire SL9 8UX, UK

2 J.Drury was with KBC Advanced Technology Limited, Weybridge, Surrey, UK when this work was performed.

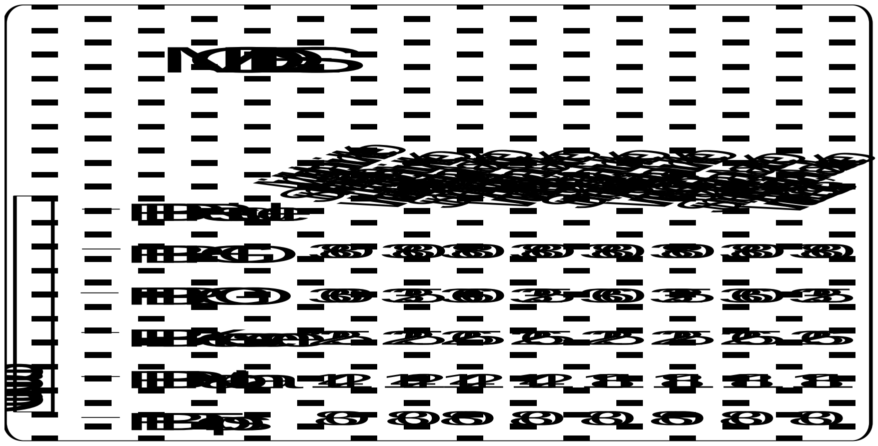
3 Address correspondence by E-mail to Robin_Brooks@ppcl.co.uk in the first instance.



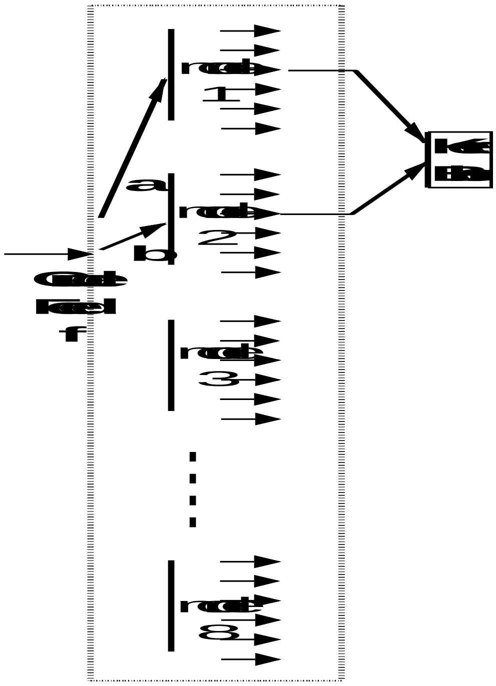
The diversity and complexity of the many inter-relationships between variables requires a knowledge of oil chemistry, process operations and refinery and market economics. Understanding has been hampered in the past in part by the inability to visualise the behaviour of more than a very small number of variables at one time. This has often led to a partitioning of the problem into smaller and more manageable segments within the domain of one individuals scope of knowledge and therefore of visualisation but with the disadvantage that this has encouraged local optimisation at the expense of whole-problem optimisation. In particular, the affects of Extreme Cut Point choices in Mode definition upon the Yields of Final Product have rarely been available to a refiner until now.

The Model

The overlap between the two models with different representations of a simplified CDU considered in this paper is shown in Figure 1. It has two main modelling areas and the scopes of these are shown. The process model is highly non-linear and can accurately calculate the Yield and Qualities of Intermediate products that will result from the use of specified Crude Oils with particular sets of Cut Points. It has 8 Modes of operation defined, each of which has a set of Extreme Cut-Point values for each crude oil that was specified when the refinery was designed. These are shown in Figure 2.



To apply LP Optimisation, the refinery planning model has to be linear or be linearised. The optimisation results in the best economic choices of operating Modes (and in the case of multiple crudes - not shown here - crude type selection). Its purpose is to produce the selection of imaginary Intermediate products that it will blend into the needed Final Product quantities and qualities. It cannot cope with the non-linearities of Cut Points vs. Yield and Quality so instead uses tabulated values of Yield and Quality of the Intermediate products produced for each Mode as its linear model of the Crude Distillation Unit. These values are generated by the CDU model and put into an LP-usable form by a separate program.



The CDU model was first used to calculate the Intermediate Product qualities and yields for each run-down stream (per Mode) from one of the sets of pre-specified (design) cut-points (Modes) of Figure 2. Crude data came from a major refiners commercially-available Assay Library. The proprietary Crude Distillation Unit model used was the one provided in the products Reference Manual. It included equipment constraints only.

A spreadsheet was then used to blend these 'streams' (Modes) pair-wise (see Figure 3) in 1% steps, to cover all possible ways to make Final Product and to calculate the properties and yields of each Final Product. Also calculated from the Extreme Cut-Points of each Mode were the actual set of Cut-Points that should be used on the real CDU to produce the same Final Product yield and qualities.

This scenario is hereafter referred to as 'the Unconstrained solution' although it is actually constrained by the equipment capabilities built into the CDU model and is unconstrained only in that no other restrictions are placed upon the intermediate product properties that it produces. It generates a wide range of Intermediate product Qualities but in practice the refinery planning LP would preferentially select Modes that provide intermediate products closest in qualities to the Final Product Specifications. This can result in a number of Modes being infrequently or never used. This is not untypical of the operations of many refineries.

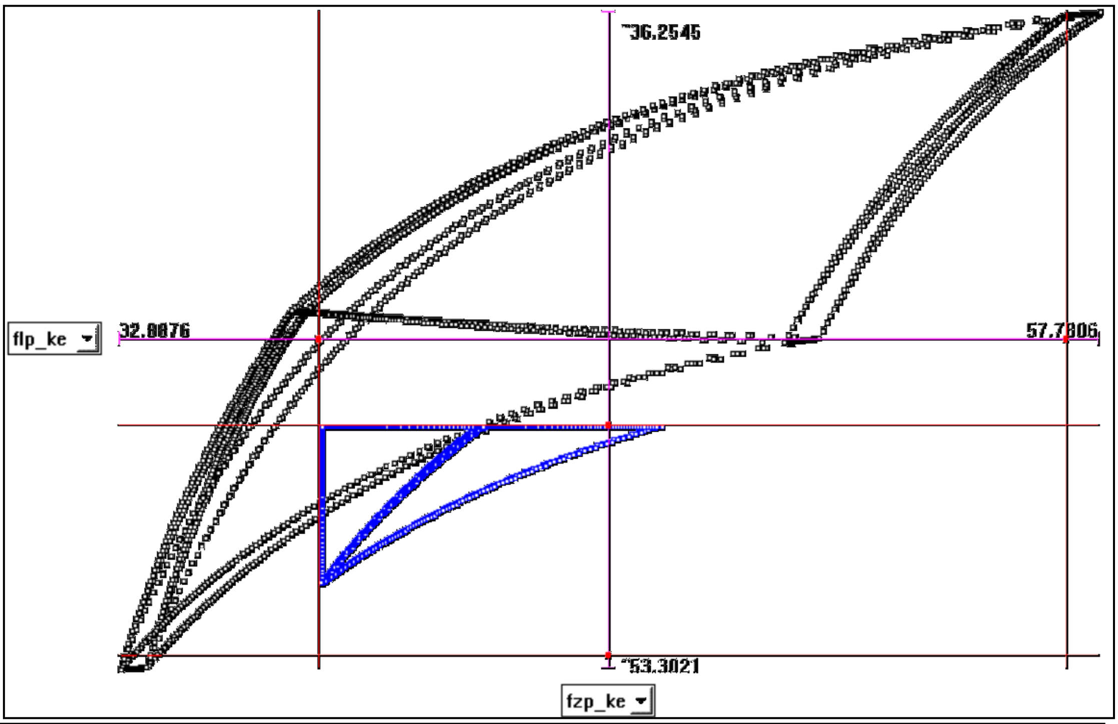


Figure 4. Kerosene Flashpoint vs. Freezepoint for Arab Light crude at calculated CDU efficiency

For the second solution the CDU model was optimised to calculate the Cut-Points needed to maximise or minimise Kerosene Yield whilst keeping Intermediate Product Qualities constrained within Final Product specifications. The intermediate product qualities and yields for the 8 streams (one per mode) produced using these optimised cut-points were then processed through the spreadsheet, as above, to blend the streams pair-wise to produce Final Product Yields. This solution is referred to hereafter as 'the Constrained Solution'.

All the results above have a use in that they all represent feasible operation regimes, and they permit an operator to alter specification bounds for any properties and backtrack - if he is able - to appropriate modes, stream pairs and their blending ratios. The solutions effectively form a look-up table where the rules for carrying out the looking-up are not defined and where the extent of the data is very large.

The Results

Kerosene Flash Point in the blended final product was plotted against Kerosene Freeze Point to create Figure 4. Each point represents the properties of the final product blended by combining the Kerosene intermediate streams from two Modes of operation in a particular blend recipe.

The larger curvilinear quadrilateral came from the Un-constrained solution and is bounded by the equipment constraints. The Constrained solution produced the smaller triangular area and is bounded by the Final Product Specifications. The part of the Un-constrained solution lying in the area bounded by the Final Product Quality Specifications is small indicating that the combinations of intermediate products able to blend into acceptable final product is low.

Figure 4 shows two of the approximately 30 variables or dimensions involved in the models. It is not simple to interpret. A full understanding of the model and the inter-relationships between all the variables requires the user to maintain a mental model of the hidden parts of the model while viewing the two variables on display in Figures 4 and even then there is the possibility of missing many of the inferences that an expert would draw.

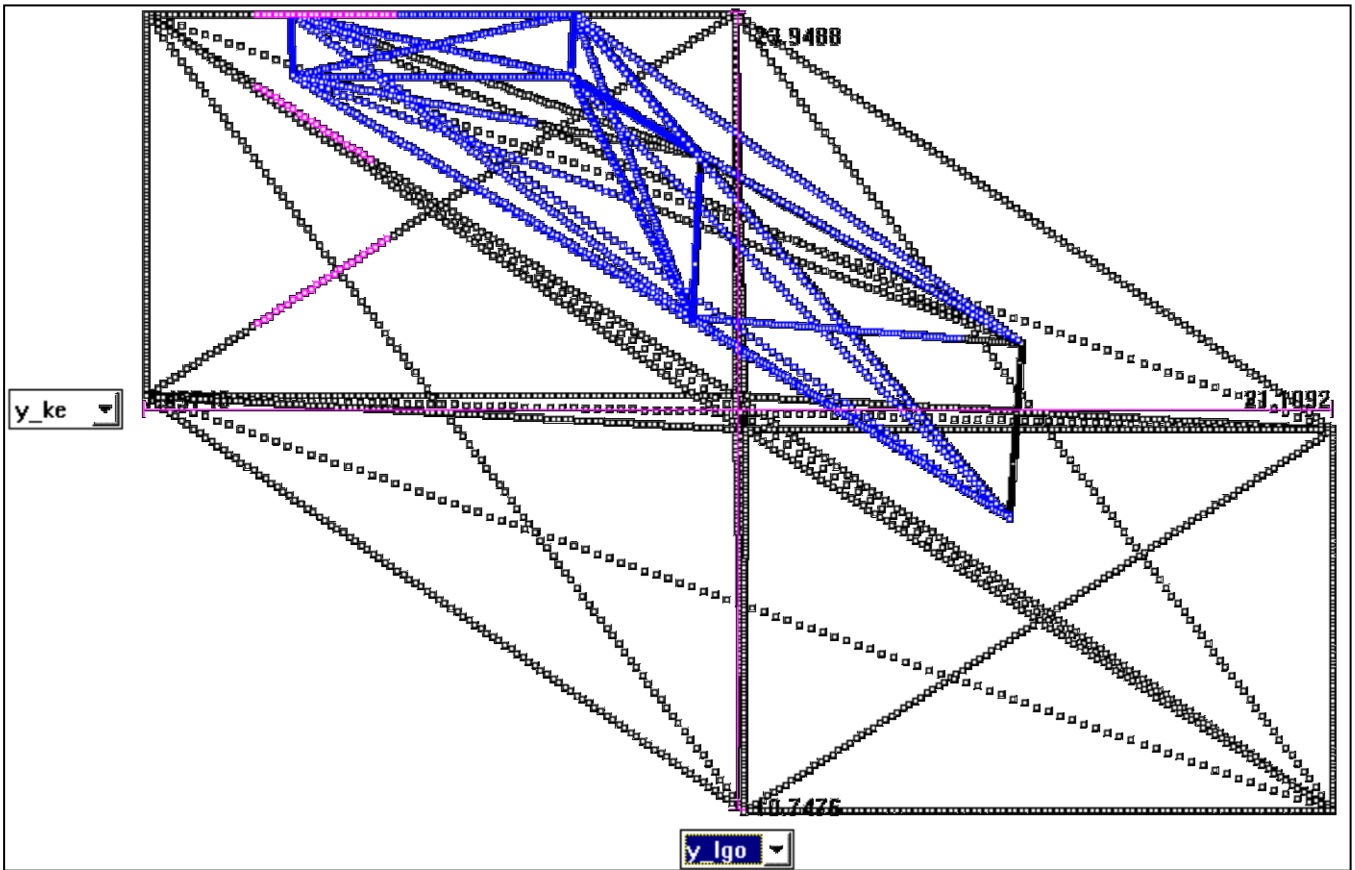


Figure 5. Arab Light. 100% CDU efficiency. Constrained and Unconstrained solutions. Yields of Kerosene vs. Yields of LGO in Final Product.

Figure 4 visually appears at first to be a two-dimensional representation of a three-dimensional slab with an unknown third variable supposed as the index of height in the slab. A little study soon reveals that the

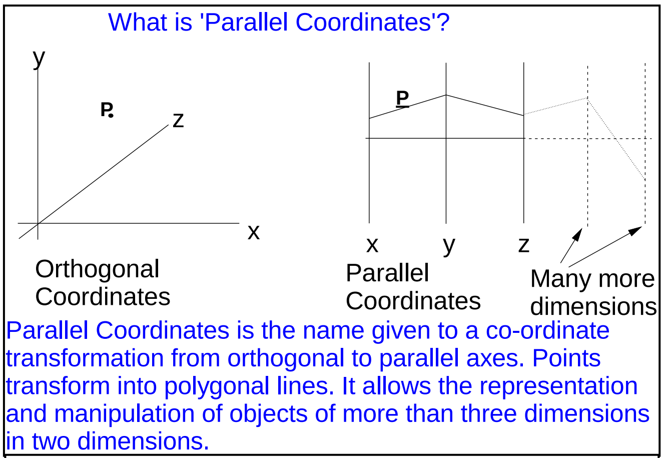


Figure 6. The basis of the Parallel Co-ordinate transformation

'slab' is in fact of higher dimensionality so that more than one hidden variable would be required to locate a position in or on it. x-y plots of other pairs of variables in the model quickly confirm its multi-dimensional nature, for instance Figure 5 which shows the Yield of Kerosene vs. Yield of Light Gas Oil (LGO) in Final Product. The dimensionality would have been even higher had we considered more specifications per Mode and blended more than pairs of Modes as a real refinery planning LP would do.

The problem was thus one of needing to use multi-dimensional data visualisation to reduce the need for the user to have such an extensive mental awareness of all the variable interactions. Parallel Co-ordinates was the technique adopted and commercially available software was used to perform the multi-dimensional visualisation and manipulations and to create the charts used in this paper.

Figure 6 shows the basis of the Parallel Co-ordinate co-ordinate transformation. By drawing axes parallel to each other the orthogonal co-ordinates limitation of 3 axes is removed. A point in orthogonal co-ordinates transforms into a polygonal line in parallel co-ordinates.

Figures 7 and 8 show in parallel co-ordinates views the whole range of possible Final Product Yields and properties resulting from blending pairs of the Modes for the Unconstrained and Constrained solutions respectively. The red triangles superimposed on the rightmost three axes of each figure are the Final

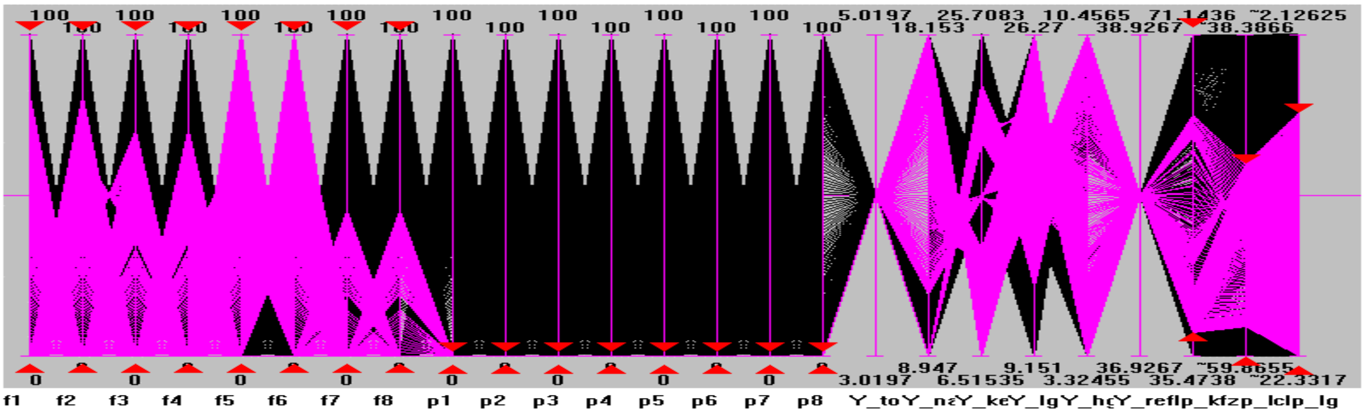


Figure 7. Arab light. Unconstrained Intermediate Qualities Blended to in-Specification Final Products

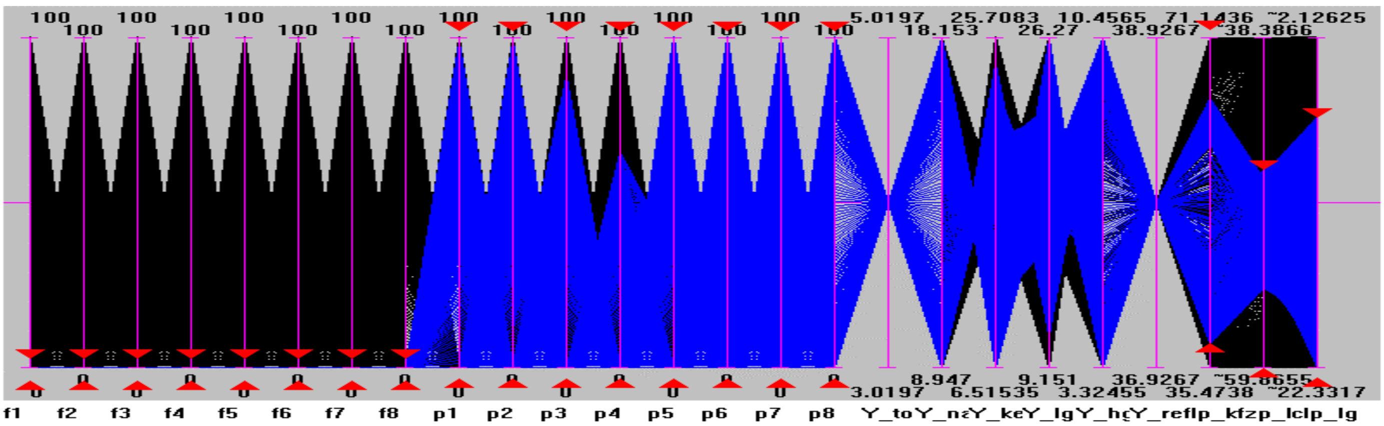


Figure 8. Arab light. Constrained Intermediate Qualities Blended to in-Specification Final Products

Product Quality Specifications for Kerosene Flashpoint and Freezepoint and LGO Cloud Point. The pink or blue areas of the charts thus show all the possible pair-wise combinations of the 8 Modes (the leftmost 8 axes in Fig 7 and the central 8 axes in Fig 8) which will produce on-specification Final Product. The black areas on the charts are unselected combinations in the tabulated data.

The axes to the right of the intermediate products and to the left of the Final Product Specifications show respectively the Yields of Tops, Naphtha, Kerosene, LGO, HGO and Residue.

Figure 9 shows the results of the graphical queries of Figures 7 and 8, superimposed for ease of comparison. The higher Yield of Kerosene available with Constrained intermediate products is clearly visible and would be recognisable to an LP too.

Figure 10 shows an expanded problem including additional Final Product Qualities, notably sulphur. The higher Yield of Kerosene obtained with Constrained Intermediates is again clearly visible.

Also clearly visible in Figure 10 is that only 4 of the 8 Modes in the Unconstrained case can be blended, and then only in restricted proportions, to make on-specification Final Products. This is not unusual. Many refineries have redundant Modes defined. They do not realise it because they focus on the

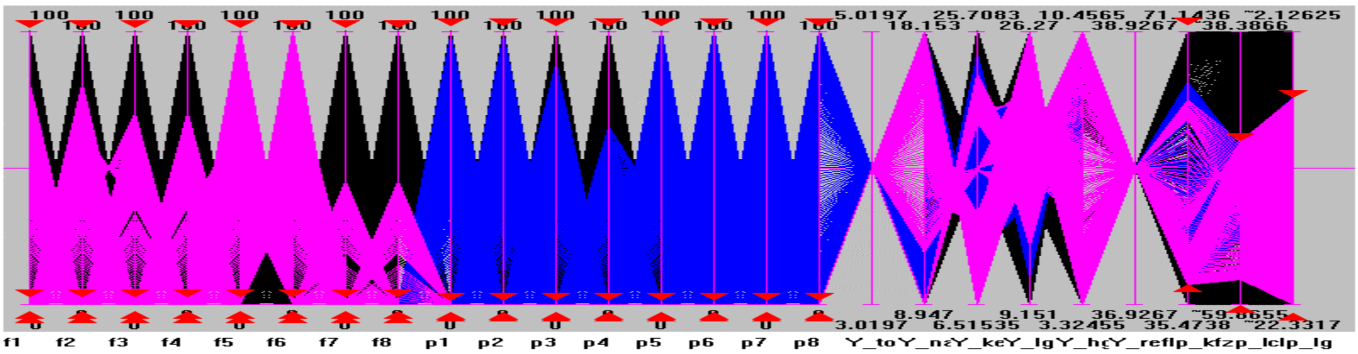


Figure 9. Arab light. Constrained (Blue) and Unconstrained (Pink) Intermediate Qualities Blended to in-Specification Final Product. Note higher Yield of Kerosene when blending from Final Product Specification Constrained Intermediate Product.

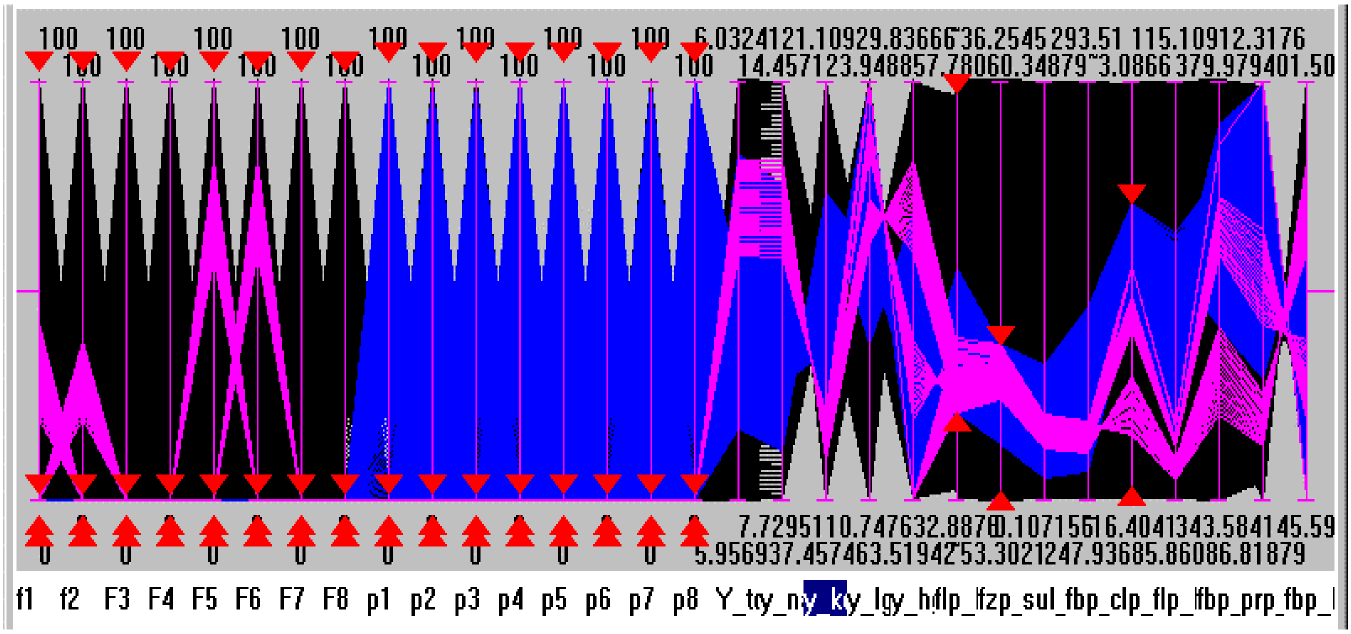


Figure 10. Arab Light. Calculated CDU efficiency with Constrained and Unconstrained Intermediate Product Qualities

Note higher Kero Yield for Constrained Intermediate Qualities cases

Intermediate Product Qualities produced by a Mode instead of on the Final Product Qualities that can be blended from the Intermediate Products produced by the Mode.

The general conclusion is that better yields are obtained when blend components are close in quality to the desired target specification. In the limit, the yield would be highest if both blend components could be identical because then no Mode blending would be required because the Intermediate stream would already meet Final Product Specifications and optimum Yield. A further improvement could therefore be obtained by iterating around the loop consisting of both the CDU and LP models until the Extreme Cut-Points calculated produce intermediate products for the cut which completely meet the final product specification and do not need blending.

Cut-Point Selection for Users

The model contained many variables not shown in Figures 7-10 notably the calculated operating Cut Points derived from the Extreme Cut Points of the pairs of Modes that were blended in a recipe to make each Final Product. A common operational need is for a tool to allow the selection of Cut Points to meet Final Product Specifications and to optimise Yield. We were able to create this very quickly by defining an alternate view into our model. It involved fewer variables so that the display was less crowded and easier to understand. It is shown in Figure 11. The calculated Cut Points or Final Boiling Points of HGO, Kerosene and LGO are shown on the first three axes followed by the predicted Final Product Kerosene Flashpoint, Freezing point and Sulphur, followed by the Yields of Kerosene and Naphtha and finally the Cloud Point of LGO. Specifications for Flash Point, Freezing Point and LGO Cloud Point are already in place. The users range of possible values are given by the blue band.

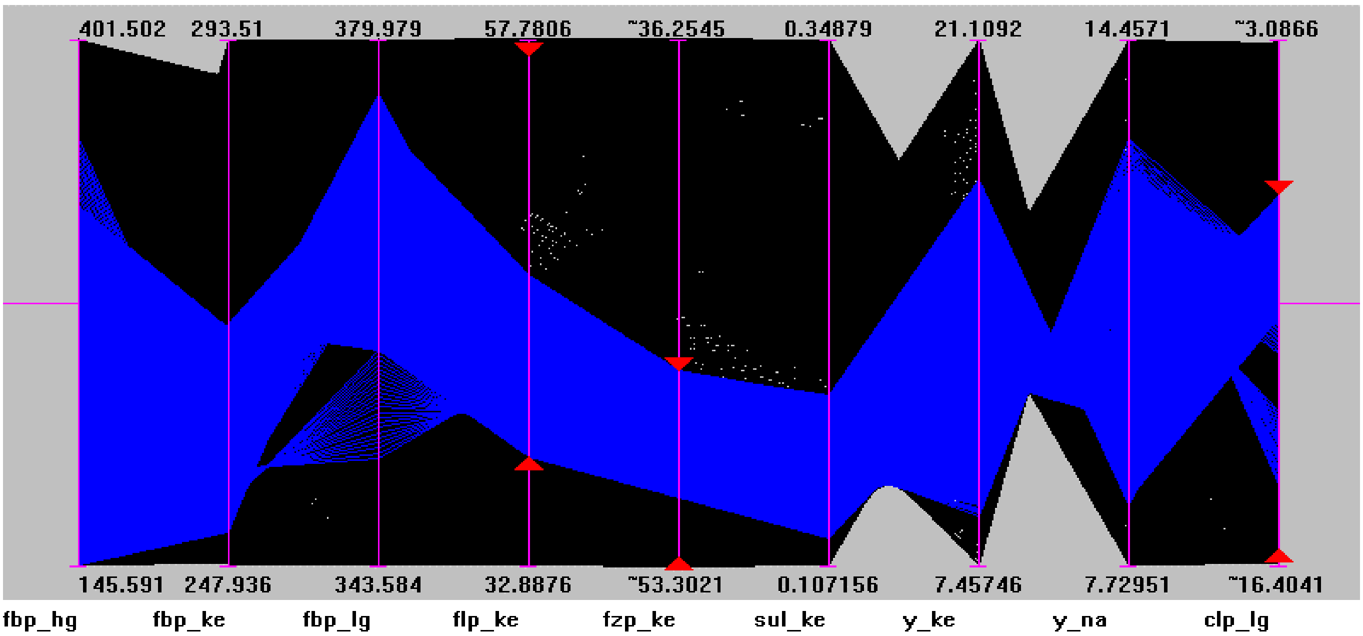


Figure 11. Arab Light. Calc. CDU efficiency
All Cut Points, Yields and Final Product Qualities that are available when Intermediate Product Qualities are constrained to:-

Kero Flash Point > 38 deg
Kero Freeze Point < -47 deg
LGO Cloud Point < -7 deg

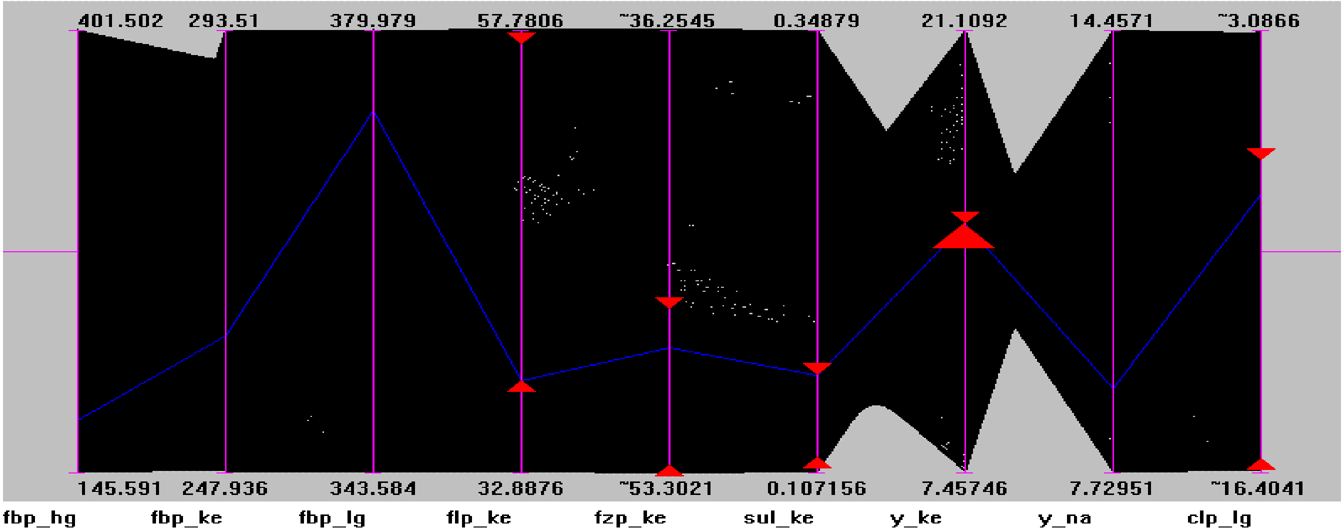


Figure 12. Arab Light. Calc. CDU efficiency
Showing Cut Points to be used to produce Maximum Kero with a maximum level of Sulphur in the Final Kero product.
Intermediate Product Qualities are constrained to:-

- **Kero Flash Point > 38 deg**
- **Kero Freeze Point < -47 deg**
- **LGO Cloud Point < -7 deg**

To use this display to find an operational Cut-Point value, the User first adds any further Product Specifications that are available such as a limit on Sulphur in Kerosene. This will narrow the blue band further. He then closes two graphic selectors around his desired objective of maximum Yield until only one multi-dimensional point (one polygonal line in Parallel Co-ordinates) is visible. He can then read off the values of Cut Point to give him the desired optimum. This situation is shown in Figure 12.

Conclusions

The complexity of refinery operations can be managed given simple access and selection from a large range of operational scenarios and accompanying data. One method (discussed here) presents the support tools of data modelling, optimisation and data visualisation to the operator, with simple selection methods to arrive at the best of a range of feasible operations. The operator then takes part in the optimisation process, and in this case, can select the Cut Points appropriate to any criteria he is given, providing his data is sufficiently comprehensive.

Acknowledgements

The authors wish to express their thanks to their colleague Dr E.M.Stafford for his extensive reviews and contributions during the performance of this work.

References

First Quartile Performers Close Their Business Loops Too. R.W.Brooks, A.D.Thomson, F. van Walsem. European Refining Technology Conference, London, June 1997. Also available from www.ppcl.co.uk

Viewing Process Information Multi-Dimensionally for Improved Process Understanding, Operation and Control. R.W.Brooks. Invited paper at AspenWorld Conference, Boston, 1997. Also available from www.curvaceous.co.uk

New Dimensions for Improving Refinery Profitability. R.W.Brooks. European Refining Technology Conference, Antwerp June 1999. Awaiting publication. Also available from www.curvaceous.co.uk