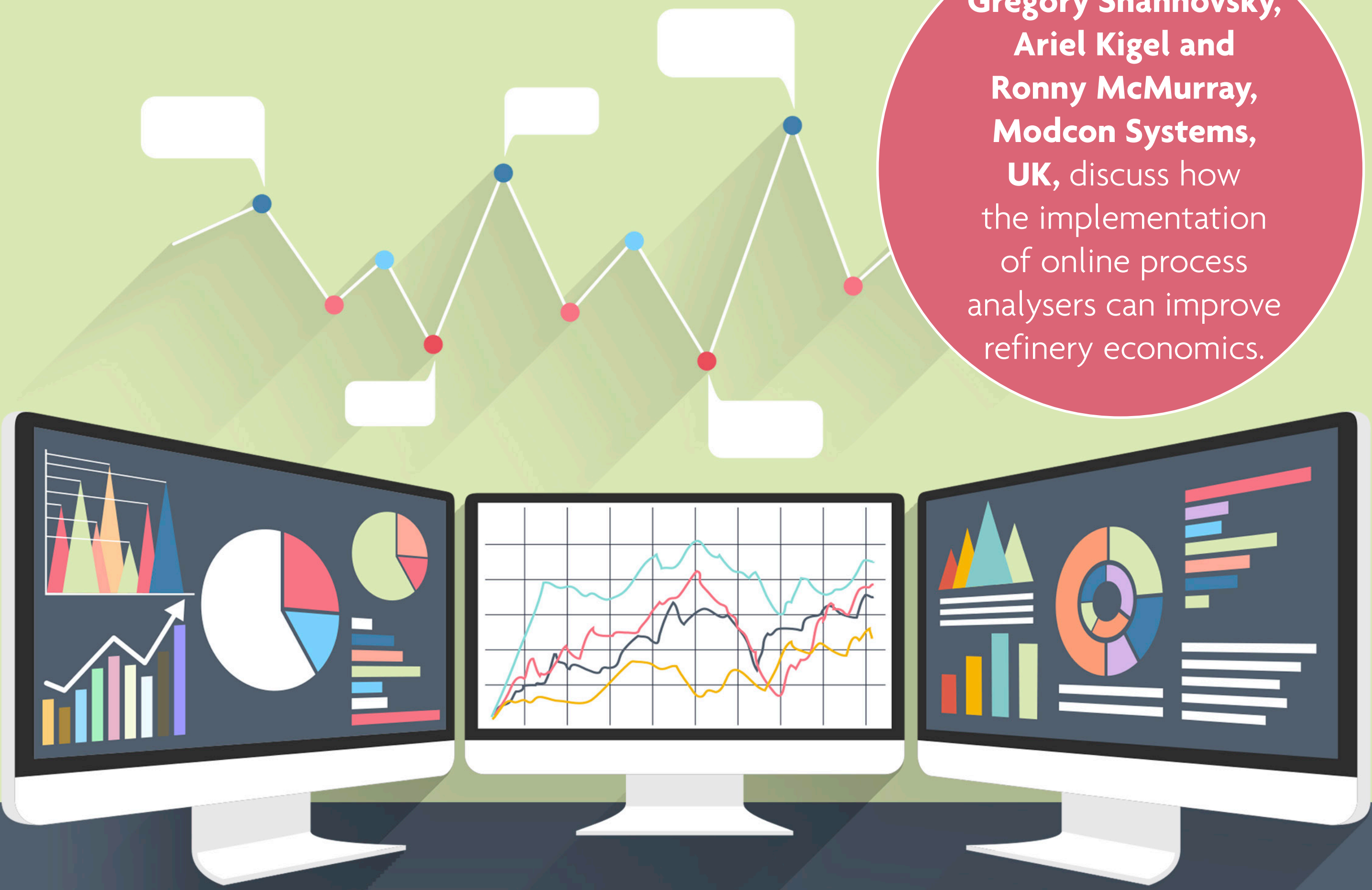
# THE ECONOMICS OF PROCESS ANALYSIS



**Gregory Shahnovsky, Ariel Kigel and Ronny McMurray, Modcon Systems, UK,** discuss how the implementation of online process analysers can improve refinery economics.

During the first decade and a half of the 21st century, overwhelming changes took place in the crude oil and fuel market. Major events that are accountable for these events include:

- The ever changing geopolitical situation in the Middle East and other oil producing countries.
- The changing demand for different fuels, and a shift towards an increasing demand of middle distillates.
- The extreme fluctuations between high and low oil prices since the beginning of the century.

To survive under these conditions, refineries must be flexible to give immediate answers to sudden changes. In previous times, most refineries were constructed according to the crude quality of neighbouring oil wells, and to bring the predominately domestically required refinery products on to the market. Today this concept has changed, and refineries must be able to distill a range of different crude oil qualities into a wide scope of different refinery products.

In the past, refineries purchased crude oil with a focus on the production of light distillates for the gasoline pool. Nowadays, the range of distillates must shift to provide an answer to the increasing demand of middle distillates, such as gas-oil. Moreover, today's fluid catalytic cracking (FCC) technology allows for the cracking of high boiling distillates for use as gasoline components.

To be competitive, refineries are obliged to maximise their refining margins, which requires a low cost of crude oil feed and high production capacity of distillates with high market values.

Often, either the crude oil price is too high, similar to Brent crudes, or the quality is too low to produce products with relatively high market values. Therefore, a compromise must be found by blending different types of crude oils to a

**Table 1. Classification of crude oils, according to API gravity**

| Oil type | °API |
|---|---|
| Light | ≥ 31 |
| Medium | 22 – 31 |
| Heavy | 10 – 22 |
| Extra heavy | ≤ 10 |

blend that provides the production of an optimised product range, at the highest capacity and lowest cost of crude oil.

## Crude oil characterisation

Crude oil is characterised by either being light or heavy, sweet or sour, or high or low in sulfur content, and is classified by its density into different types (Table 1).

In general, crude oils with a sulfur content below 0.5% by weight are identified as being 'sweet'. Heavy crude oils are rich in saturates, aromatics, resins and asphaltenes. The relatively high content of naphthenic acids, $H_2S$ and sulfur in heavy and extra heavy crudes make them sour and corrosive. The high content of sulfur containing compounds increases the sulfur content in the distillates and forces refineries to invest more in desulfurisation processes in order to comply with local and international standards, with respect to sulfur limitations in fuels.

Today's crude oil prices are determined by their chemical and physical properties, which are responsible for the additional cost of processing in comparison to conventional light crudes.

### Specific gravity and API

Heavier crude oils are more expensive to distill than light crudes. They require more energy in heating to bring the crude oil to its boiling point for distillation, and they will have a higher bottom residue for further distillation in the vacuum distillation unit.

### Sulfur content

Sulfur is of major concern in today's refineries. Crude oils with a high sulfur content cause a refiner to increase the capacity for post-treatment of the distillates for desulfurisation, to allow the products thereof to conform to the specifications required by local and international regulations – regarding limitation of the sulfur content in fuels. Secondly, sulfur poisons the catalysts in catalytic refinery processes, which forces refineries to purchase higher volumes of catalysts. Finally, when sulfur is present as $H_2S$, its sour character increases the rate of corrosion of the refinery units and pipelines.

### TAN content

Refineries are constructed from building materials that must be resistant to corrosion caused by the crude oil. The total acid number (TAN) indicates the sour characteristic of crude oils, which is directly linked to the corrosion enhancement of the crude oil during distillation in the crude distillation unit (CDU). As compared to sweet crudes, increasing the TAN content will directly result in enhanced corrosion of the CDU, increasing the cost of maintenance. These additional acids will also be distributed in kerosene, atmospheric gas oil (AGO) and vacuum gas oil (VGO), which has an impact on the final product and its ability to comply with required specifications.

### Heavy metals

The drawback of the presence of heavy metals in crude is that the bottom product of the CDU will be rich in heavy metals, especially vanadium, which is restricted in several heavy fuels as its presence endangers the catalysts used in cracking processes of heavy fuels and bottom residues.

### Viscosity and pour point

High viscosities and pour points, resulting from their elevated wax content, are characteristic of heavy and extra heavy crudes. This increases the cost of transport by needing heated pipelines, by their handling cost in terminals and ports, or by blending these crudes with compatible light or diluent crudes in order to increase their flow properties.

## Crude oil prices

Crude oil prices are defined by availability, demand and supply, and the cost of transport from the well to the terminal, but, especially, by quality. Additional discounts are given for crude oils with inferior quality, as compared to high quality crudes such as Brent crude.

Decreasing the American Petroleum Institute (API) gravity, causes a correlating increase of viscosity, sulfur, TAN and heavy metal content, impacting the fuel production processes and increasing the production cost of refinery products.

Upon comparing different crude oils, without taking into consideration the cost of transportation, the price of a crude oil is influenced by the API, TAN and the sulfur content. Vendors provide a discount according to the differential between a certain crude oil and Brent crude, where each of them – API, sulfur, TAN or heavy metals – will individually contribute to the final price. Increasing the API reduces the discount, while increasing the TAN and sulfur increases the discount given for the price of a certain crude oil, as compared to the Brent price.

A number of different mathematical approaches and models have been developed to calculate the price of crude oils, based on the differential of the API, the sulfur and the TAN content.[1, 2]

Being based on such a model, the crude price at a time ($t$) is calculated by equation 1. Where $P_{i,t}$ is the crude oil price at a certain time; $P_{Brent\ t}$ is the Brent price at a certain time and the values of API, sulfur and TAN.[1]

$$\text{Ln}\ P_{i,t} = \alpha + \alpha_1\ \text{Ln}\ P_{\text{Brent t}} + \alpha_2\ API_i + \alpha_3\ sulfur_i + \alpha_4\ TAN_i$$

(Equation 1)

Table 2 shows an example of the calculation of differentials for various crudes, expressed as the percentage (%) to be added to the cost of Brent crude resulting from the API, the sulfur content and TAN.

## Utilisation of opportunity crudes

In the past, most refineries were designed and constructed from materials according to the availability of crude oils,

**Table 2. % to be added to Brent price for different crudes, compared to Brent crude[1]**

| Crude | API° | Sulfur % weight | TAN mg KOH/l | Dollar % added to Brent price |
|---|---|---|---|---|
| Brent | 37.5° | 0.4 | 0.041 | 0.00 |
| Kumkol | 42.5 | 0.07 | 0.1 | 3.33 |
| Zarzatine | 42.6 | 0.08 | 0.23 | 3.34 |
| Brass river | 37.4 | 0.11 | 0.06 | 0.81 |
| Saharan blend | 45.3 | 0.12 | 0.37 | 4.52 |
| Qualboe | 36.0 | 0.13 | 0.26 | 0.07 |
| Azeri light | 34.8 | 0.15 | 0.2 | -0.51 |
| Bonny light | 35.3 | 0.15 | 0.5 | -0.28 |
| Cabinda | 37 | 0.17 | 0.03 | 0.45 |
| Escravos | 33.5 | 0.17 | 0.104 | -1.16 |
| Ekofisk | 38.5 | 0.19 | 0.56 | 1.09 |
| Escalante | 24.1 | 0.19 | 0.26 | -5.40 |
| Oseberg | 37.8 | 0.27 | 0.4 | 0.51 |
| Forcados | 30.4 | 0.28 | 0.1 | -2.87 |
| WTI | 40.8 | 0.34 | 0.1 | 1.71 |
| Esider | 36.7 | 0.37 | 0.01 | -0.28 |
| Siberian light | 37.8 | 0.42 | 0.652 | 0.08 |
| CPC blend | 45.3 | 0.56 | 0.06 | 3.17 |
| Syrian light | 38.0 | 0.68 | 0.05 | -0.58 |
| Forties | 38.7 | 0.79 | 0.093 | -0.58 |
| Flotta | 36.2 | 0.98 | 0.15 | -2.27 |
| Ural | 31.3 | 1.25 | 0.08 | -5.20 |
| Iranian light | 33.1 | 1.33 | 0.09 | -4.64 |
| Suez blend | 31.3 | 1.41 | 0.06 | -5.65 |
| Oriente | 24.0 | 1.59 | 0.04 | -9.24 |
| US Poseidon | 29.7 | 1.65 | 0.41 | -6.99 |
| Iranian heavy | 30.1 | 1.78 | 0.13 | -7.18 |
| Kirkuk | 34.3 | 2.28 | 0.09 | -6.74 |
| Bow River Hardisty | 20.3 | 2.96 | 0.69 | -14.28 |
| Syrian heavy | 23.1 | 4.2 | 0.28 | -16.26 |

which were easily obtained by a refinery. As a result, the versatility of many refineries to purchase crude oils of different qualities is limited. Many of those refineries, which are constructed to distill light and low sulfur crude oils, are restricted to process heavy fuels.

Quality properties determine the market value of each type of crude individually. As compared to Brent crudes, opportunity crudes are commonly characterised by an inferior quality. This, of course, has a strong impact on the price of the opportunity crudes in comparison to high quality crudes. Therefore, the consumption of opportunity crudes plays an important role in refinery profits, and is most attractive when the oil prices rise.

Due to their restricted process ability, opportunity crudes are brought into the market at very low prices. To process the opportunity crudes, the following parameters should be taken into consideration:

- The distillation unit and its pipelines should be constructed of high TAN and hydrogen sulfide resistant metals, otherwise increased corrosion will occur, which is accompanied by higher expenses of maintenance.
- Severe corrosion of overhead systems, piping, heat exchangers and vessels.
- High fouling tendencies.
- Critical differences between the physical and chemical properties make heavier crude oils more difficult to distill than light crudes. Higher viscosities, fouling tendencies and different flow streams make it more difficult to maintain stable crude charge rates, which are required for stable product yields, quality and reliability. Differences in boiling points between light and heavy crudes require different process conditions, such as preheating and different distillation temperatures, overhead, etc.
- Heavy fuels are rich in asphaltenes, metals and other contaminants, which cause a poorer desalting performance, and require post-desalting.

Today's refinery strategy is based on increasing the refining margin to its maximum. The prices for the final product are determined by demand and supply worldwide, which means that it is the objective for each refinery to maximise the consumption of 'opportunity crudes', as these crudes are far less expensive than conventional crude oils.

To overcome the limitation – that opportunity crudes in general cannot directly be distilled by available equipment in a refinery – refineries are obliged to blend the opportunity crudes with conventional crudes to such an extent that the resulting crude blend can easily be distilled by the existing CDU.

The blending of opportunity crude oils with conventional crude oils will result in the reduction of the negative influence of the API, sulfur, TAN and pour point during the refining process. It increases the production capacity of middle distillates by shifting the cut point towards them. To maximise the revenue by using opportunity crudes requires maximum incorporation of opportunity crudes into blends, whereas care must be taken to avoid precipitation of asphalthenes during blending or processing.

Another drawback is the high viscosity of many of these heavy, extra heavy and opportunity crudes. Blending with light crude oils, kerosene, or other diluents, is required to obtain flow properties to enable their transport through unheated pipelines. It is the objective for each refinery to maximise the consumption of 'opportunity crudes', since these crudes are far less expensive than conventional crude oils.

## Benefit of online process analysers

The use of advanced process analysis and control, when optimising petroleum product manufacturing processes,

**Figure 1.** Salt in crude oil analyser.

allows a refiner to achieve the required quality at maximum production capacity and minimum cost, by increasing the conversion level of crude oils into different distillates and providing the flexibility to change between different crudes at any time. Recent developments in process analyser technologies significantly increase the online utilisation factor and reduce the analyser maintenance, which is required to ensure maximum efficiency of the refinery, to produce the required range of distillates at the highest capacity and production yield.

As laboratory analyses are time consuming it is recommended to implement online process analytics in those cases, where the existence of lag-time between laboratory and process may harm the production. This makes monitoring, especially of the critical parameters such as the API, TAN, viscosity and sulfur content, highly important.

Linear programming (LP) software is in the market to calculate the ratio between different crudes in a crude blend, and the resulting physical properties in the blend and on the resulting distilled products.

It is recommended to monitor one or more critical parameters to ensure that the blend answers to its required specification. Implementation of online process analysers allows for the monitoring of the critical physical properties throughout the entire crude oil blending and/or distillation processes. Immediate process corrections can be made in real time whenever a discrepancy is observed between the product quality and its required specification, or with the LP's predicted physical properties. If not, the production unit will run in a non-optimised mode, reducing the production of valuable distillates.

It is up to the refinery or blending company to decide which critical properties it wants to monitor, by evaluating the influence of each of them on the blending properties or their impact on the distillation process, and the financial risk the company wants to take if not controlled online. In addition, fluctuations in crude oils that affect predicted values of critical properties of the crude oil and blends must also be taken into consideration.

Several online process analytical technologies exist to measure online physical properties. Density can be measured using an online vibrating element densitometer. Different technologies are available to measure the viscosity. The TAN content can be determined online by applying wet chemical titration technologies. The total sulfur content of crudes is calculated by online process X-ray fluorescence (XRF) analyses.

A total solution has been brought on to the market to measure a variety of different physical properties, such as salt content, water, API, viscosity, TAN, etc., which consists of a package of different technologies that are combined into one single crude oil analyser.

## Comprehensive CDU control by online process analysers

Online process analysers are not only beneficial in the maximisation of crude oils during the blending process, but also enable the optimisation of the CDU during operation and its protection from harmful events, such as extended corrosion, and fouling and plugging of the CDU. In particular, the incorporation of a salt in a crude oil analyser will reduce the salt content of the crude oil to a minimum before entering the CDU. The salt in a crude analyser measures the salt content, which is in correlation with the ASTM D3230 electrometric method (Figure 1).

Aside from that, additional measurements can be conducted to guard the CDU from high TAN and sulfur content, by constant monitoring of the crude feed and producing an alarm when undesired values are measured, to enable immediate crude switching.

Once the salt is controlled, for the purpose of maximising the performance of the CDU to produce distillates of highest demand and value on the market, it is also important to measure online water content and the density. The online measurement of the density indicates the stability of the crude feed to confirm with the expected crude feed.

During its transition period between two sequential crude batches, permanent changes of physical properties occur as a result of the length of the pipelines leading from the tanks to the distillation unit. By monitoring one or more critical physical properties of the crude oil feed, one can determine when all crude oil from one specific batch in the pipelines has been entirely replaced by its sequential batch, enabling an adjustment of the CDU process conditions as early as possible.

The distillation profile of most crude feeds is analysed by the laboratory before starting processing. The online monitoring of the distillation profile will not provide any benefit towards ensuring produced distillates are in compliance with their specification.

Therefore, the most important factors to optimise the CDU is to increase the capacity of the most required distillates by continuously measuring the physical properties of the distillates themselves. As physical properties of neighbouring distillates can overlap, implementation of online process analysers to measure a broad range of critical physical properties is required to guarantee the compliance of the product with its

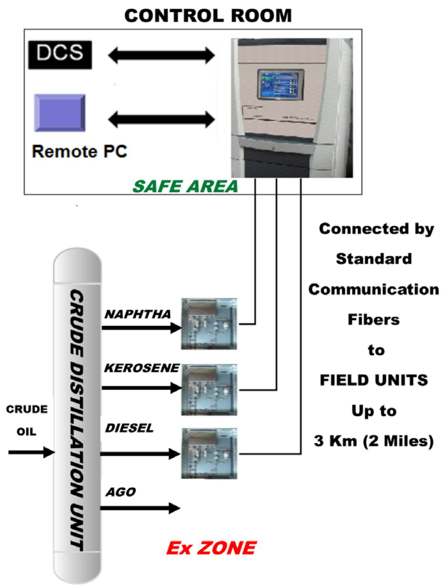



**Figure 2.** NIR process analyser measures quality properties inside the Ex Zone from a safe area.

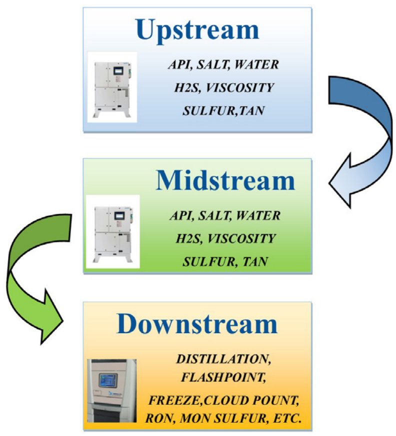



**Figure 3.** Critical quality parameter online, being measured from upstream to downstream.

specification while shifting cut points. Online ASTM-based process analysers have the advantage of measuring exactly according to the official ASTM methods, such as D86 (distillation), D97 (pour point), D664 (TAN) and D445 (viscosity). However, a large number of these analysers are required to gain a comprehensive overview of the various physical properties in the different process streams. Additionally, each analyser must be connected to a sampling system to bring the sample to the analyser(s). ASTM-based analysers are dedicated to the measurement of one single property, they are time consuming and cannot perform simultaneous analyses in different process streams. As these analyser systems are expensive, they are not beneficial to provide an entire overview of the physical properties in all process streams at once.

Correlative analysers, such as near infrared process analysers (NIR), provide an excellent solution to that. These analysers are based on the correlation NIR spectra and between physical properties of the distillates. The NIR process analyser is connected by optical fibres to a number of different measuring probes, which are located at a distance of up to 3 km (2 miles) away from the central analyser. This allows the installation of the analyser in any safe area, such as a control room, and without additional costs for an atmosphere explosive (ATEX) enclosure, while only its measuring probes are installed in the hazardous area, the Ex Zone (Figure 2).

Each NIR analyser is connected to a number of measuring probes in different process streams. Optical multiplexing allows very fast switching between the different measuring probes, to measure the NIR spectrum uninterrupted, which is further processed by means of chemometrics and online validation and calibration software into accurate quantitative analyses of multiple physical properties in the different process streams.

The concept of applying NIR process analysers for instantaneous monitoring of multiple quality parameters in each of the interlinked distillate streams provides an overall view of the quality properties of the produced distillates at any time. This enables real time adjustment of the process conditions towards the production of the most in demand distillates at the highest capacity.

## Conclusion

Today's refinery economics are based on an ever increasing refining margin to increase the profitability of the refinery. This is achieved by utilising crude oils or crude oil blends at the lowest cost to produce predominately high valued distillates and refinery products.

To achieve this goal, refineries are obliged to reduce the cost of crude feedstock by blending conventional expensive crudes with maximum volumes of low cost heavy and opportunity crudes; maximise the production capacity of high valued distillates; and control critical quality properties of crude oils, distillates and final refinery products, by incorporating online process analysers from upstream to downstream (Figure 3).

A variety of different online process analysers are on the market, which provide efficient tools to optimise process conditions maintaining critical physical parameters of the crude oil and distillates alike, that comply with the required specifications. The implementation of modern online process analysers, using technologies that are based on standard ASTM methods and correlative spectroscopy-based methods, provide refineries with the capability to perform immediate adjustments of process conditions that will result in the highest production capacity of valuable in-specification distillates from maximum quantities of low cost opportunity crudes. This will maximise the refining margins, thereby increasing the profitability and economics of a refinery.

## References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