Best practice for refinery flowsheets

Refinery-wide flowsheets can demonstrate the true representation of changes in key operating variables and their associated impact on refinery operation

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Due to the integrated nature of process units within a refinery, change in key operating variables has an impact on overall refinery operation and product blending as well. Refinery-wide flowsheets demonstrate the true representation of this effect as all process units are linked together. Non-linear kinetic or equilibrium models in the flowsheet represent the conversion units. Fractionation models capture the efficiency of separation between different cuts or components.

KBC (A Yokogawa Company) has developed and used refinery-wide flowsheets for more than 30 years. Developed in the 1980s, Petrofine was a FORTRAN based tool capable of refinery-wide flowsheeting. In 2004, KBC launched Petro-SIM with additional features to simulate refinery process units. These standalone models are combined to create a complex-wide flowsheet which includes all process units within the refinery.

Petro-SIM is KBC's process simulator used for rigorous modelling of the entire refinery and petrochemical complex, from crude to finished products. Since each unit, including conversion units, is modelled meticulously, the overall simulation suitably reflects the non-linearity of petroleum refining which enables sensitivity analysis over a wide range of operating variables and feedstocks.

The conversion units are based on comprehensive kinetic models that predict the unit yields and product qualities. The kinetic models are calibrated specifically to match the available plant data for a particular unit. This allows the simulation to be representative of the specific unit's operation, independent of the licensor.

Product separation is simulated using fractionation technology that represents current operation and heat balances. Heat-and-material balanced distillation models which use a section-by-section approach rather than simulating each tray are calibrated to plant data.

KBC and the company's clients around the world have developed numerous refinery-wide flowsheets. Petro-SIM based flowsheets are being used for identification and evaluation of margin improvement opportunities which include optimisation of stream routings, blending strategies, molecular management, throughput maximisation, feedstock selection, and improvements in the unit operating conditions. Refinery-wide flowsheets have also been used for configuration studies for grassroots and revamp configurations.

Flowsheet development

Standalone models for the process units are the main building blocks for the refinery-wide flowsheet. Detailed kinetic and equilibrium based Petro-SIM models are calibrated using test run data. Unit configuration, operating parameters from historian and laboratory data are used to calibrate standalone models for the process units. The data are reconciled to close mass, sulphur, nitrogen, carbon, and hydrogen balance. A calibrated process model mimics the performance of the process unit. The models are valid over a wide range of operation as they are based on first principles and are non-linear in nature.

To understand overall refinery operation, a base month is selected. Base month operation provides an insight into marginal mechanisms in the refinery. The data used for standalone models are based on test run operating conditions and these test runs may have been conducted at a different time period. Due to this, it is essential to prepare a consistent basis for operating conditions of all process units.

The following guidelines are used to select the base month for the flowsheet:

- Crude blend for the month represents the typical crude blend used by the refinery
- Crude throughput should be close to the typical crude throughput of the refinery
- Most of the process units in the refinery should be operating at typical capacities and at normal operating conditions
- Most of the process units should operate continuously in stable conditions
- Changes in the inventory of intermediate streams should not be significant.

One of the major challenges is with regard to inventory. Inventory changes are not simulated in the flowsheet as it represents steady state operation of the refinery. Inventory changes in feed and product are used to estimate the net feed processed and net products produced in the refinery. Inventory changes for intermediate streams affect throughputs of the process units and hence it is essential that the base month operation has minimum inventory changes for the intermediates.

Mass balance for different process units may be inconsistent for refineries which do not use data reconciliation tools, for instance, the throughput of a delayed coking unit measured by the feed meter may not be the same as the vacuum residue production measured in the vacuum distillation unit. Validating consistencies for a product which is routed to more than one process unit and blending is more challenging. Due to these issues, data for the base month also requires reconciliation.

To build a refinery-wide flowsheet, all standalone models are combined. Crude blend for the crude distillation units (CDU) and throughputs are updated so that the flowsheet feed represents base month operation. Routing strategies used by the refinery are replicated in the flowsheet. During the flowsheet development phase, refinery strategies are used for routings rather than using optimum routings. Sensitivity analysis to validate optimum strategies is performed after completing the base case which represents 'as-is' refinery operation.

Understanding refinery stream routing strategy can be a difficult task if the refinery has multiple trains or two to three process units for a purpose, for instance more than one diesel hydrotreating unit. In this case, routings are fixed based on the feedback from planning engineers and base month data.

Petro-SIM's blending unit operation allows flexibility of optimising refinery blends based on prices, product demand, product specifications, and other constraints. Marginal mechanisms used by the refinery must be reflected in the flowsheet product blenders. The flowsheet must hit key specifications for each blend, such as octane for gasoline, flash for diesel, viscosity for fuel oil, and so on. The marginal streams used by the refinery should be reflected in the flowsheet as well.

The refiner also needs to identify major changes which are planned

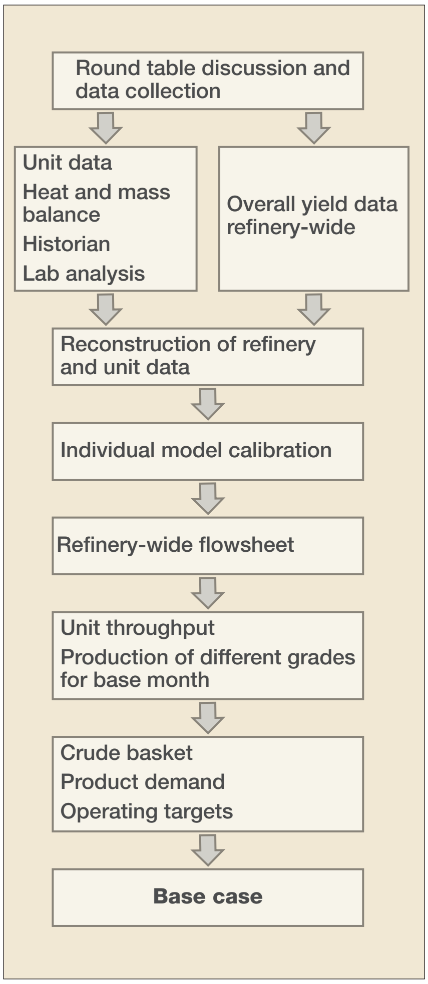

Figure 1 Work process for refinery-wide flowsheet development

in the near future including the revamp of a process unit or a significant shift in the crude basket. The refinery-wide flowsheet may be updated with these changes after which it represents the base case operation of the refinery.

The work process to develop the refinery-wide flowsheet is shown in **Figure 1**.

Flowsheet complexity

Before building a model, it is crucial to recognise its purpose. Refinery-wide flowsheets are used to understand the interaction between different process units and the impact on product blending. Including too many details in the model increases the time to build the refinery-wide flowsheet and efforts required in analysing the results.

Process engineers still need to build rigorous standalone models for various analyses, including heat integration, column hydraulics, identifying constraints for throughput maximisation, and so on. It is recommended to simplify the standalone model as much as possible before using them in the refinery-wide flowsheet. The refinery-wide flowsheet usually includes a kinetic and equilibrium based reactor model followed by 'section-by-section' fractionation columns. Simulating heat exchangers, pumps, compressors, valves, and other items is not recommended for refinery-wide flowsheets.

Scenarios or problems which can be evaluated using the refinery-wide flowsheet are different from those which require detailed standalone models of the process units. The following should be evaluated using the refinery-wide flowsheet:

- Optimum feed selection of the process units
- Incentive of debottlenecking a process unit
- Trade-off between unit throughput and conversion
- Optimum product distribution from a process unit
- Molecular management of naphtha components between different process units and blends
- Estimation of the optimum unit operating target.

The following should be evaluated using detailed standalone models of the process units:

- Identification of constraints to achieve optimum conversion or operating target
- Required changes in the process unit for achieving targeted throughput vs conversion trade-off
- Investment required for unit debottlenecking
- Detailed analysis of the equipment in process units which includes unit hydraulics, heat integration, and so on.
- Troubleshooting and root cause analysis.

Models in the refinery-wide flowsheet should still be able to monitor key operating constraints. Petro-SIM reactor models allow monitoring of major operating variables in the process units such as main air blower limitation in catalytic cracker or gas/oil ratio in hydroprocessing units. If the constraints are specific to any equipment such as fired heater tube metal temperatures, this equipment may be simulated in the refinery-wide flowsheet.

Petro-SIM Workflows provide a technique for monitoring key constraints in a complex flowsheet. Workflows can be configured by the user and key constraints in the refinery process units, blends and product logistics can be added in the flowsheet. With Workflows available in the flowsheet, quality checks of the results can be performed quickly. Hand-over of the flowsheet from one process engineer to another can be done fast. Workflows ensure that the results are always consistent and constraints have not been overlooked.

For most cases, including extra equipment increases the time required for building models and troubleshooting but has minimal impact on the time for flowsheet convergence. The time required for the convergence is a function of logical ops, recycle and adjust ops. Equipment or process units within a recycle loop increase the

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time necessary for convergence. Few of the recycles include process units and product blending as well, such as light cycle oil used as cutter stock and processed in a diesel hydrotreater, heavy naphtha used as low flash blending component, and feed for a naphtha hydrotreater (NHT).

The hydrogen network is one of the recycle loops which may consume a significant amount of time for flowsheet convergence. Kinetic based models for hydroprocessing units in the flowsheet estimate the hydrogen demand. Kinetic based models in the flowsheet estimate the hydrogen available from the producers. Using the supply-demand gap, the required throughput for the hydrogen generation unit is estimated in the flowsheet. If the refinery uses low purity hydrogen in the make-up for hydroprocessing units, the convergence of the low purity recycle also increases the time for flowsheet convergence.

Nesting is one of the techniques available in Petro-SIM which can reduce flowsheet convergence time. Using nesting, users can set the preference for the process unit convergence. One of the best options is to give preference to atmospheric and vacuum residue processing units followed by middle distillate processing units and then naphtha processing units. Vacuum residue processing units produce naphtha due to cracking which affects naphtha processing units whereas vice-versa is occasionally possible.

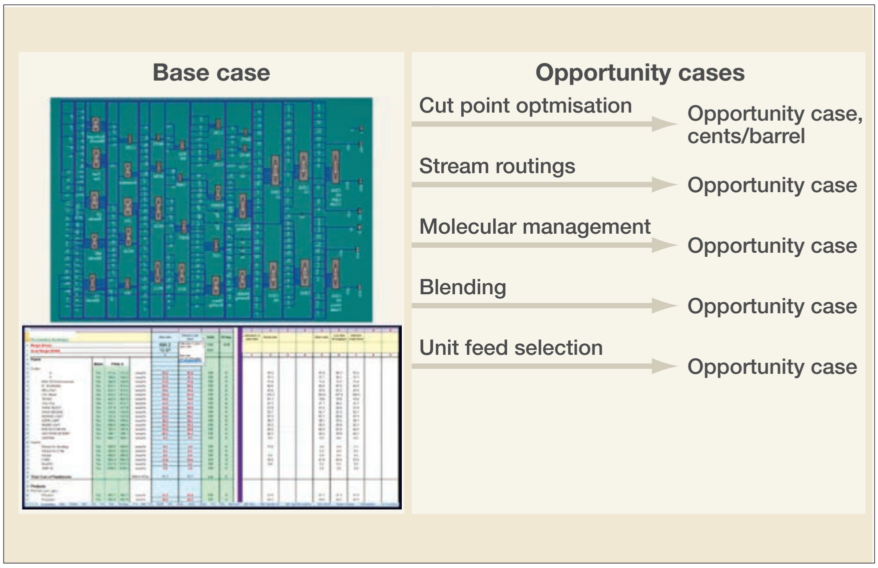

Figure 2 Opportunity evaluation using refinery-wide flowsheet

Flowsheet utilisation

KBC and the company's clients have used Petro-SIM refinery and complex-wide flowsheets for numerous objectives. The refinery-wide flowsheet is one of the main tools used to evaluate opportunities under the company's margin enhancement programme (Profit Improvement Program, PIP). KBC uses the methodology shown in **Figure 2** to evaluate identified opportunities.

The refinery-wide flowsheet (the base case) is used to assess the impact of a change in operating conditions, routings, blend management, and so on. As it is difficult to analyse results when all independent variables are optimised at the same time, only one opportunity is assessed at a time using the base case. This approach is used to identify improvements in operating strategies rather than achieving optimum numbers from a simulation. The flowsheet provides a quantitative analysis of an opportunity, but it is essential that the focus is on identifying improved strategies rather than targeting specific numbers. The absolute value of the KPIs may change in an operating refinery due to various changes such as different crude basket, varying product demand, and catalyst change-over. The improved strategy identified using the flowsheet is usually valid for all these changes but the values of KPIs are different.

Petro-SIM is capable of generating an automated Excel interface. The Excel interface is linked with Petro-SIM flowsheet and provides mass and volume balance for the overall flowsheet and for each process unit as well. Properties of streams within the flowsheet and all operating variables of the reactors and fractionation are also available in the Excel interface. The Excel interface can be tailor-made based on user preferences.

Flowsheets can provide an in-depth analysis of changes in the product slate with upgradation of bottom of the barrel and its impact on existing units

Mass or volume balance estimated by the refinery-wide flowsheet along with the price set are used to assess the economics of each opportunity. Using this methodology, techno-economic analysis is performed for each opportunity. KBC's clients also use this approach to identify and evaluate opportunities for improvements. One of the user case studies is discussed later in this article.

KBC has also used refinery-wide flowsheets for configuration and reconfiguration studies. Flowsheets can provide an in-depth analysis of changes in the product slate with upgradation of bottom of the barrel and its impact on existing units. Non-linear equations used for kinetic and equilibrium models of the existing units are essential for reconfiguration studies in which considerable changes are expected in feed for the existing process units. The flowsheet linked with the Excel interface along with capex and opex estimation tools provide inputs for financial analysis.

Users have applied the refinery-wide flowsheet to evaluate different feedstocks available for the refinery and petrochemicals complex. Petro-SIM allows seamless propagation of detailed naphtha components available in the crude assays. Evaluation of feed for an aromatics complex requires rigorous simulation of the reformer, trans-alkylation, isomerisation, and component based fractionation which includes extractive distillation. A case study for feedstock evaluation at an aromatics complex is discussed later in this article.

Refinery engineers usually perform quality give-away (QGA) analysis on a monthly basis. QGA analysis focuses on the properties which are constrained in the blends, such as RON and RVP for gasoline, or flash point and recovery for diesel. One of the main inputs for QGA analysis is a loss of margin per unit of give-away in key constraint, for instance gasoline RON of 92 compared with a spec of 91. The loss of margin can be easily estimated for some of the constraints, for instance gasoline RON if naphtha is used as the low octane blending component. Estimation of the loss of margin for some of the properties requires rigorous simulation, say diesel recovery which can be corrected by increasing the cut point of heavy gasoil (HGO) in the CDU which affects feed for the diesel hydrotreater and fluid catalytic cracker (FCC). KBC has used the refinery-wide flowsheet to estimate the impact of QGA reduction in numerous PIPs.

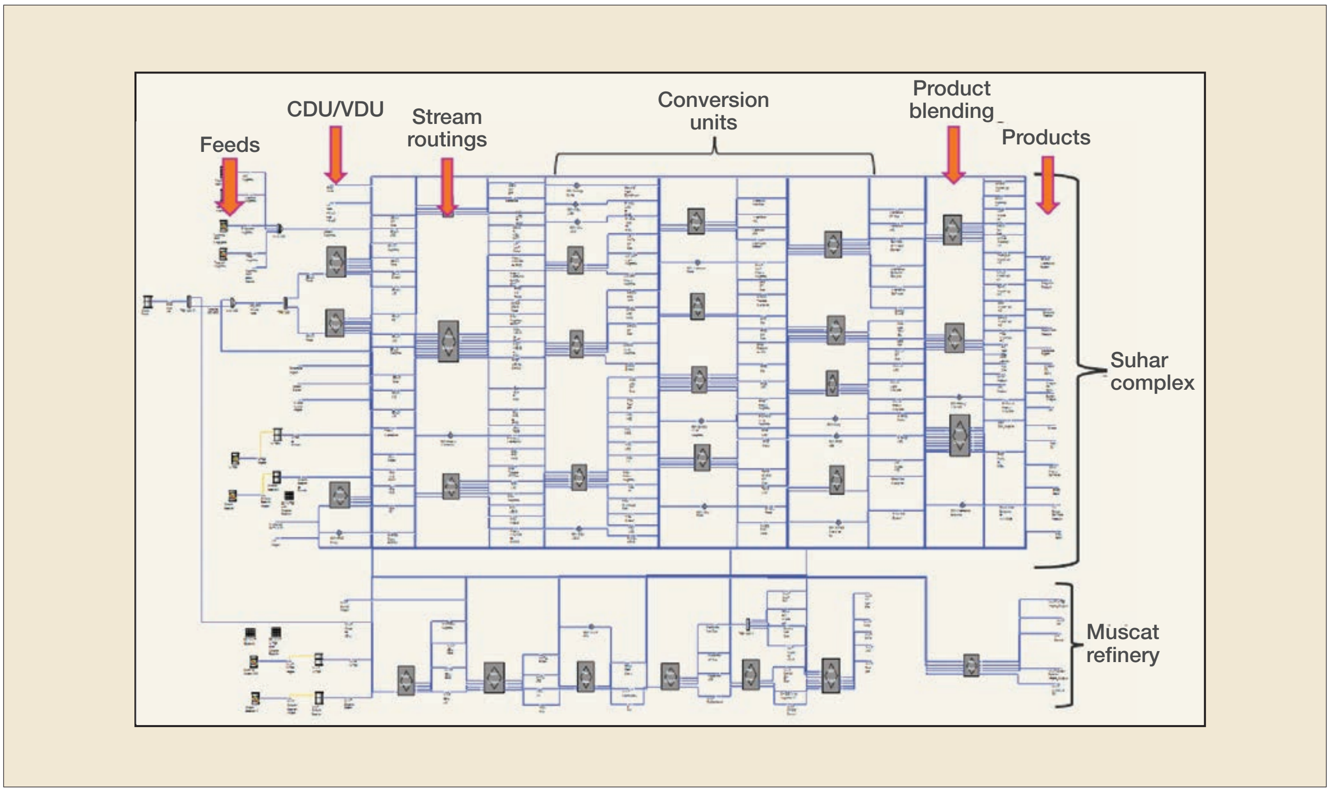

Figure 3 Orpic complex-wide flowsheet

Flowsheet maintenance

Maintenance of the flowsheet is as important as developing it. Results from the flowsheet may deviate from actual operation if changes are not made in the flowsheet on a regular basis. Refinery routings, marginal mechanisms, blending strategies, and so on do not change on a frequent basis. Changes in the infrastructure of process units, catalyst replacement, and under-performance of major equipment affect the overall performance of the refinery. Due to this, the main changes are usually made in the standalone models which need to be updated in the flowsheet as well.

Recalibration of the standalone models is required for replacement of the catalyst. Catalyst deactivation in fixed bed reactors usually does not require recalibration. If users can provide the age of the catalyst, then Petro-SIM can predict the status of the catalyst and its impact on the yield distribution from the unit. If few items of equipment are underperforming, say damaged trays in a column, a model may need to be recalibrated for these changes.

KBC uses Petro-SIM's collaboration functionality to update kinetics and fractionation models in the flowsheet using updated standalone models. Collaboration can be used offline or through a common server which connects standalone models with the flowsheet.

Case study

Orpic is one of Oman's largest and most rapidly growing businesses. Orpic's refineries in Suhar and Muscat, as well as the aromatics and polypropylene production plants in Suhar, produce fuel, plastics, and other petroleum products.

In a collaborative effort, KBC and Orpic developed a complex-wide flowsheet which includes the Suhar and Muscat (MAF) refineries. The complex-wide flowsheet also includes an aromatics plant. The snapshot shown in **Figure 3** provides an overview of the complex-wide flowsheet.

The envelope of the flowsheet starts at the feeds for the complex and the finished products produced by Orpic are the final products from the flowsheet as well. Crude to the CDUs is defined using the crude assay, and few of the import streams are defined using the required properties and detailed composition.

Stream routings in the flowsheet represent the routing strategies used by Orpic. All conversion units in the refinery and aromatics complex are simulated using Petro-SIM reactors which are based on non-linear kinetics and equilibrium. The process units in the flowsheet include fractionation models as well.

Petro-SIM blenders are used to optimise product blending based on prices of different products, market demand, and specifications. Petro-SIM workflows configured in the flowsheet ensure that the major constraints of the refinery and process units are not violated.

The flowsheet provides a detailed understanding of the interaction between the different refineries and the petrochemicals complex. As all process units are interlinked, the impact of change in the operating condition of any process unit affects all process units in the downstream, recycles, and product blending as well.

The Orpic flow sheet has been utilised for many studies. One of them was to utilise the excess amount of condensate stream from the MAF complex to the aromatics (AP) complex to maximise the Suhar isomerisation unit (ISOM).

In normal operation, OLNG condensate is imported feedstock used as the main feed in MAF NHT to maximise PENEX feed since it comprises approximately 65% of light naphtha components. In some cases, and mainly when there is a limitation in MAF NHT, the agreed amount of this condensate is not fully processed in the unit so the excess amount of it is shipped to Suhar and then sold out as light naphtha stream or blended in the Suhar gasoline pool.

It was found that processing of this stream to the AP NHTs will increase light naphtha feed to the isomerisation unit, so it will be recovered as gasoline with RON of 91. The current throughput of ISOM unit ranges from 80% to 100% and it can increase to 110%.

On the other hand, in some cases the availability of AP imported feed in the market contributes to AP NHT utilisation which affects ISOM feed. Processing OLNG condensate in the AP NHT in this case could recover reduction of the light naphtha stream and sustain isomerisation throughput in the higher side.

Conclusion

Refinery-wide flowsheets can demonstrate the true representation of changes in key operating variables and their associated impact on overall refinery operation and product blending. They are being used for identification and evaluation of opportunities for margin improvement which include optimisation of stream routings, blending strategies, molecular management, throughput maximisation, feedstock selection, and improvements in unit operating conditions.

Detailed kinetic and equilibrium based models for process units are the main building blocks for a refinery-wide flowsheet. These are connected and calibrated using test run data, and operating parameters from historian and laboratory data.

Development of the flowsheets is critical as including too many details increases the build time as well as the efforts required in analysing the results.

Adding the price set data of the complex allows for techno-economic optimisation of opportunities, whether this is part of a large improvement programme or just part of troubleshooting solutions.

To ensure top performance, workflows and regular check-ups are required. Changes in the infrastructure of process units, catalyst replacement, under-performance of major equipment, and so on affect the overall performance of the refinery and therefore need to be reflected in the refinery-wide flowsheet as well.

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