Simulating optimal tank farm design

Development of a computerised model incorporating Monte Carlo operational risk simulation with the optimisation power of linear programming. The basis, structure and execution of this model are discussed

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Linear programming (LP), a technology first applied during the Second World War to help solve troop-supply problems, continues to be the premier tool for determining the optimal distribution of limited resources. Nowhere is this more evident than in the petroleum refining industry. As barriers that once separated individual refineries continue to fall in an attempt to improve overall industry health, LP is used to identify the synergies and operational improvements that result.

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Inventory disruptions

Historically, the way to alleviate product or feedstock supply problems in petroleum refining was to "build another tank". These tanks provide extra storage capacity, which effectively reduces the time element in operations planning, lessening the impact of disruptions, both planned and unplanned. Tanks allow stocks to be more readily available before they are needed, or held when their transfer is delayed. They give refiners more time to bring their contents to specification quality or to prepare for expected outages. Tanks also provide for easier stock segregations when enough exist to designate each in limited services. However, new tanks are expensive to build ($26.50–40.00 per barrel installed) and maintain, and difficult to justify both economically and environmentally. In addition, most refiners are faced with limited or no available real estate. Therefore, even though throughputs and product diversification are on the rise, refiners are challenged to operate within the same or less available inventory capacities.

So how much tankage capacity is enough? How much is excessive? Foster Wheeler (FW) recently completed a detailed tankage and hydraulic study for the Kuwait National Petroleum Company (KNPC). This assessed the adequacy of existing tank farms at all three KNPC refineries for operations through 2010, and developed an optimised solution to the refineries' tank farm needs. In addition to dealing with routine operations such as planned turnarounds, the study had to assure that the tank farm capacity would be sufficient to handle unplanned events such as ship delays, power failures, weather problems and unit outages, as well as an expected increase in refined product diversification. This would allow for optimum utilisation of the available storage capacity, while also minimising capital cost for the upgrading facilities.

Inter-refinery supply study

KNPC operates three refineries in Kuwait with a total crude throughput of approximately 900 000bpd. The refineries are Mina Al Ahmadi (MAA), Mina Abdulla (MAB) and Shuaiba (SHU). While SHU is KNPC's oldest refinery, MAB is KNPC's most modern. MAA, however, is the largest and most complex, with FCC, hydrocracker and petrochemical feedstock preparation units. These refineries have developed in stages over a long period of time, with the last modernisation completed in 1988.

Finished products from the refineries are transferred to tankers berthed at the North Pier, New South Oil Pier, SHU Oil Pier, and Sea Island. MAA products are exported to North Pier and South Pier, MAB products to Sea Island and SHU products to SHU Oil Pier. All of the refineries have been integrated for better feedstock management and product sharing through six inter-refinery transfer (IRT) lines. These include two 24in lines for black oil products, two 20/24in lines for white oil products, one 14in line for motor gasoline components and one 20in line for naphtha/kerosene. The refineries continuously exchange products for use in their various process activities or blending operations in order to create products that are ready to export. KNPC defined the objectives of the study as follows:

— Outline an interim solution for tankage deficiencies in KNPC refineries before anticipated upgrading and expansion projects are completed in 2008/2010

— Carry out a simulation study to assess the future tankage requirements for KNPC

— Check for each refinery, and for KNPC in general, the adequacy of existing intermediate and finished product storage capacity, number of tanks, IRT systems, unit charge systems, blending and dispatch facilities, and identify any modifications required

— Check the adequacy of the hydraulics and flow metering systems to ensure efficient operation of the refineries and export operations

— Identify the additional storage capacity, tankage requirements and

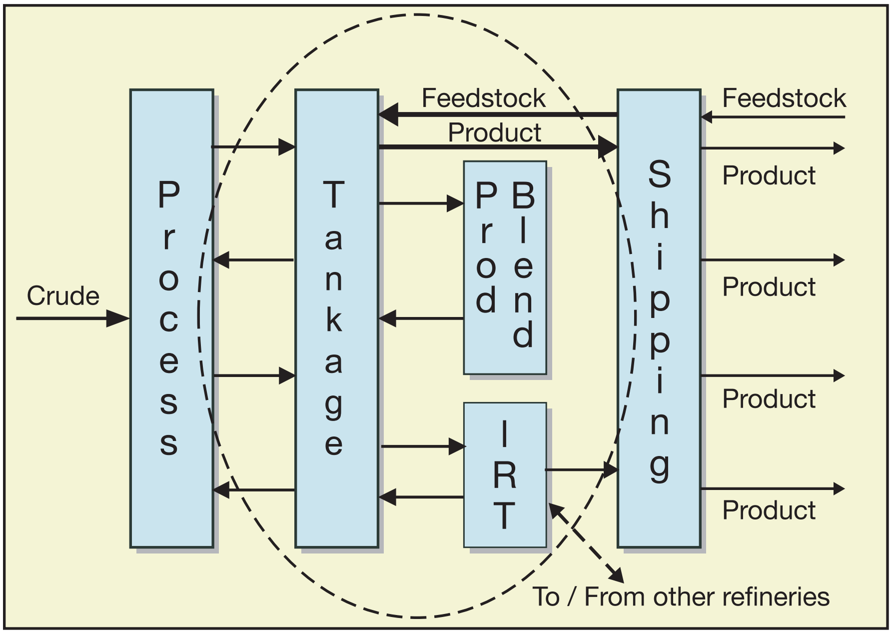

Figure 1 *Typical refinery block flow diagram*

other associated facilities required to meet overall objectives
— Assess the benefit of on-line blending and industry best practices for storage and handling
— Prepare process design packages for any new tanks and identified modifications, with budgetary cost estimates for implementing such recommendations.

To accomplish these objectives, FW performed the following tasks:
— Collected all pertinent inventory and refinery data/documents
— Prepared a study design basis
— Developed an appropriate tank farm simulation model
— Simulated the refineries' existing mode of operation in the 2008/2010 time frame
— Assessed alternative tank farm system improvements
— Performed preliminary hydraulic/flow analysis
— Issued a final report with recommendations for tank farm system improvements.

Tank farm simulation model

A simplified block diagram of a typical single refinery configuration is shown in Figure 1. The tank farm simulation model must adequately address the issues contained in the area indicated by the dashed oval line.

The tank farm simulation model served as the basis for identifying the bottlenecks, additional storage capacity and modification required in product receipt, blending, and unit charge and dispatch facilities. It was used to answer the question, "What is the adequate tank storage capacity required for anticipated refinery operations?" To effectively answer this question, the model incorporated statistical risk techniques to best reflect the realities of refinery off-site tank farm operations. In addition to dealing with routine operations such as planned unit or plant turnarounds, the model accounted for unplanned events including ship delays, power failures, weather problems and unit outages.

Operating any industrial facility involves risks. Some risks are fairly common but have a low consequence. Others may have a low probability but can be quite serious. Whatever the risks, they can be quantified and easily understood. This field of study is known as probabilistic risk assessment and helps companies and government departments to assess whether they have adequately identified the risks and potential consequences involved with operating these facilities. The concepts were developed over 40 years ago, but recent advances in computing software and power have increased both the use of such analysis and the confidence in them.

The concept of probabilistic risk assessment is that simulation can help determine the chances of a particular outcome, or set of linked outcomes, based on what is known or estimated about the smaller variables that lead to these outcomes. Historical data is used to estimate the relative frequency of those variables and then applied in random order to models to determine the impact. By defining the known linkages within a system, the simulation model is unconstrained by complexity and quite accurate.

This statistical modelling method (also called stochastic simulation or discrete event simulation) is a powerful and accurate method for solving systems engineering problems. It is not constrained by simplifying assumptions as with more traditional analytical modelling, but instead runs many "histories" concurrently, each with a different stochastic behaviour, and aggregates the results. In other words, it is a method that fairly accurately predicts expected system behaviour and variation. The Monte Carlo simulation effectively overlaid and adjusted the LP model to reflect events such as emergency unit outages, unplanned unit maintenance and shipping complications.

Such use of LP in probabilistic modelling was impractical until recently. Attempts to integrate it with technologies such as Monte Carlo simulation often produced uncontrollable models, which were exceedingly large, fragile and slow, difficult to interpret, and overwhelming in terms of their data consumption and production. However, with technical advances both in the hardware abilities of computer processing and the software abilities of LP solvers and data management tools, larger problems are solved faster, from better-managed data, to produce more stable, understandable results.

The LP model for this study was developed using Haverly System's proprietary generalised refining-transportation-marketing planning system (GRTMPS). This model represented the planned refinery operations in 2010 with current tankage condition at all three refineries. It incorporated all current interconnections between the refineries, and was initially populated with current tankage constraints, planned unit outages, planned tank maintenance and pumping limitations.

The focus of the LP model was on the tank farms, blending and shipping operations within the KNPC refineries, and not on specific refinery process unit operations. As such, it retained the ability to blend to final product specifications from material in the inventory, although it was limited to the major blend specification properties (for example, sulphur, gravity, octane for gasoline, diesel index for gas oil/diesel and viscosity for fuel oil).

Model execution

A simplified depiction of the overall model structure is shown in Figure 2. The multi-period/multi-refinery LP model was run over a total of five years (five years corresponding to the maintenance planning cycle for the refining system). To achieve sufficient resolution for proper analysis, this time frame was broken down: first, into five annual models of 52 time periods each; and second, into 260 one-week single periods. One week was chosen as the minimum resolution time required for evaluating inventory utilisation within the tank farms of the refineries and still providing reasonable run-times for the model.

The 52-week models were run with all planned outages and conditions to establish a baseline for each year, with closing inventory from one year passed on as opening inventory in the following year. Then, the 260 one-week models were run numerous times to record the effects of unexpected outages and shipping. A special utility was written to automatically apply the Monte Carlo simulation results to the one-week models and define the cases. The cases were then stacked and automatically run using the GRTMPS Evaluation Wizard.

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An interesting side note concerns the speed at which the 52-week models ran. Initial solution attempts required in excess of 40 minutes per run, which was unacceptable given the number of runs needed to establish a good baseline. However, a change in the LP solution technique, from Simplex to the Barrier, or interior point, technique, brought the run-times down to just under four minutes. Although the Barrier technique has been shown to perform better than Simplex on very large, sparse LP models, an improvement of this size was quite unexpected.

A multi-period/multi-refinery LP model alone would have been sufficient to perform the study if plant operations were predictable and steady. However, due to the nature of unplanned or emergency process unit outages and shipping delays, a more dynamic aspect was needed. The randomness provided through the Monte Carlo simulation created this dynamic representation of real-world events.

Also, the nature of LPs themselves is such that they do their best to anticipate and prepare for upcoming circumstances. This feature had to be overridden to deal with unplanned events. By applying the unplanned element of the study to the one-week, single-period models only, any preparation behaviour was eliminated, restoration time minimised and tankage forced to deal with any upsets caused by the disturbances. Final inventory positions from each one-week, single-period model were then passed onto the next week, so imbalances were worked off over several weeks when necessary. In addition, inventory capacity was modelled so that some specific limits could be violated at a cost, but total inventory capacities were firm. Modelling these specific limits as "soft" allowed the model to indicate where and when it could be advantageous to consider changing the service of tanks.

In the course of execution, the model produced a tremendous amount of data that had to be compiled and analysed.

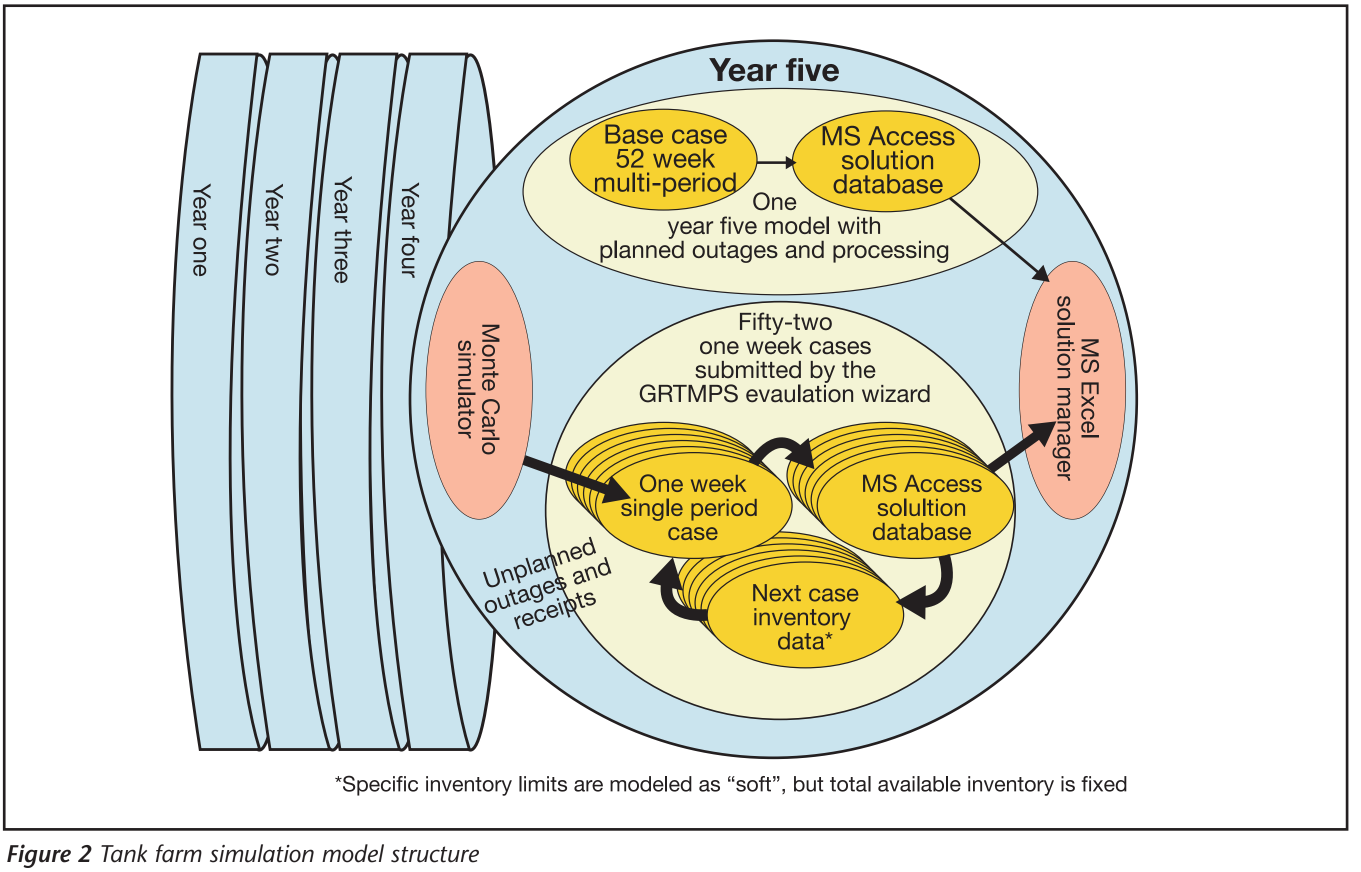

Figure 2 *Tank farm simulation model structure*

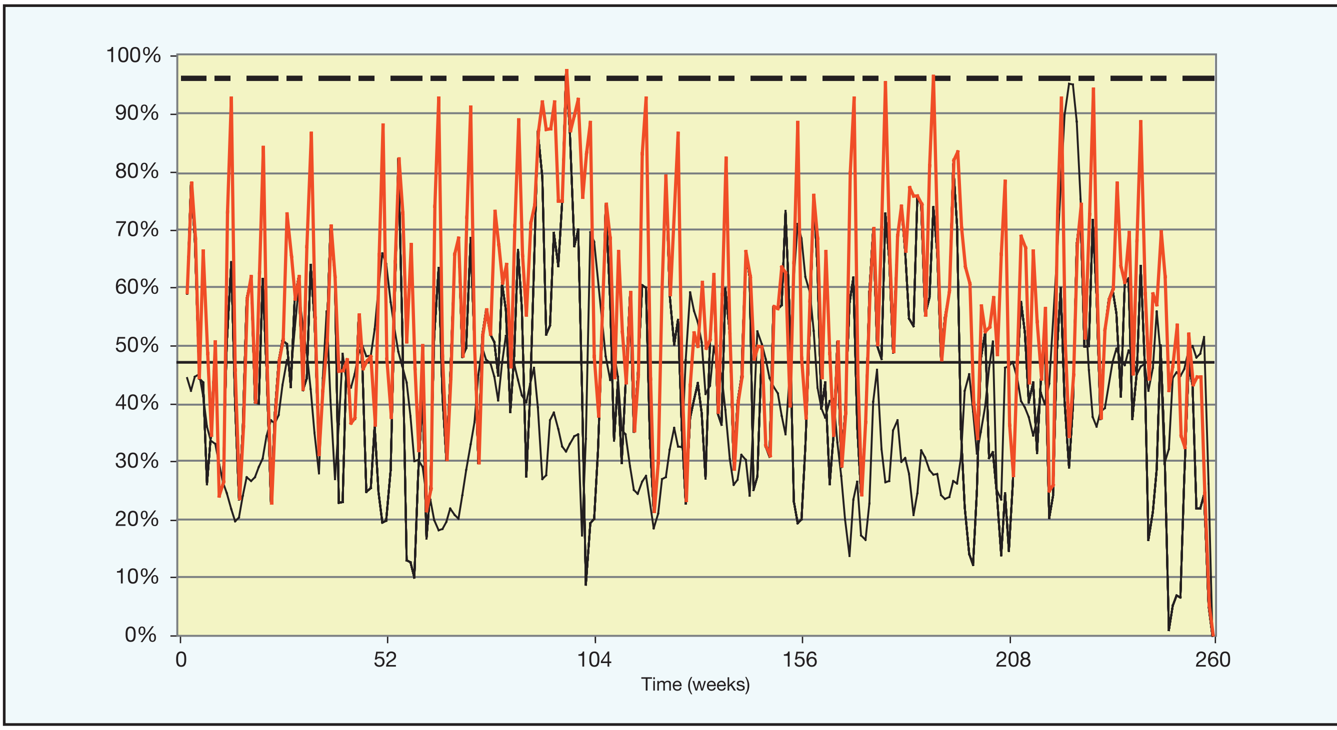

Figure 3 *Typical model output for a tank group (current tank farm operations)*

With Haverly's assistance, FW modified the report-generation feature of GRTMPS to capture the relevant information related to tank farm inventory management and download it into Microsoft Access. The raw data was then exported into Microsoft Excel for numerical analysis and graphical presentation.

Case summaries

FW used a stepwise approach to analyse the tank farm operations, with a stated goal to keep recommended capital investments to a minimum. A series of simulation model runs was performed for each case scenario to assess facilities utilisation. The scenarios that were examined include the following:

— **Base case** Current operations: the current refineries' tankage, blending and shipping configurations were examined, given planned 2010 operations. This model represents the

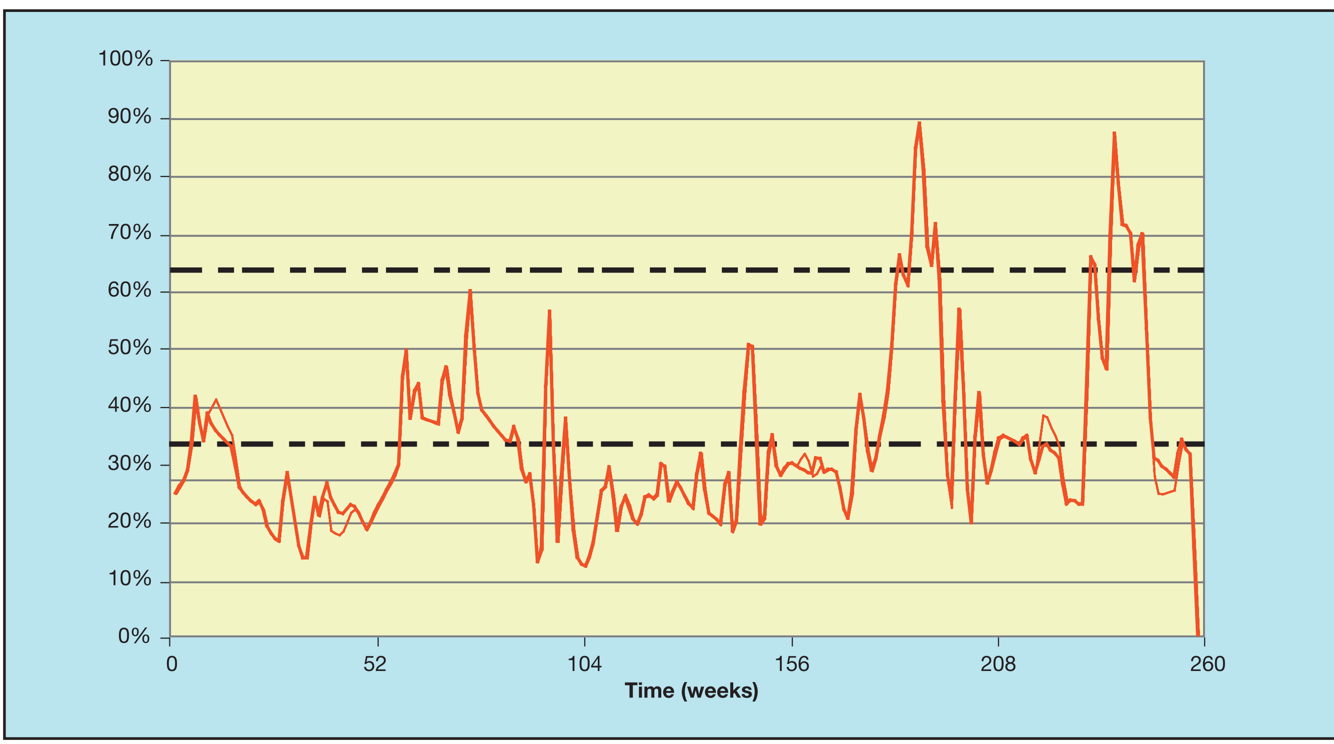

Figure 4 *Typical model output for a tank group (after implementing all proposed recommendations)*

current tankage condition at all three refineries and incorporates all current interconnections between the refineries, based on data collected during FW's site visit and output from KNPC's own LP model. The model is initially populated with current tankage, planned unit outages, planned tank maintenance and pump limits

— **Case 1** Re-allocation of existing tankage: based on constraints identified in the base case runs, existing tankage is reallocated to allow reasonable levels of utilisation within tank groups

— **Case 2** In-line finished product blending: automated, in-line blending facilities allow finished products to be blended as required, rather than the current practice of building a full batch of inventory prior to shipping release, thus reducing hold time in tankage

— **Case 3** Inter-refinery transfers of finished products: by permitting transfers of finished products between refineries (ie, tank-to-tank transfers), distribution system flexibility is improved

— **Case 4** Elimination of dual-port product loading: this is similar to Case 3, except finished products from one refinery can be shipped directly to the loading port of another refinery without going through finished product tankage first

— **Case 5** Addition of new tankage: if reasonable system utilisation cannot be achieved by the changes in facilities, practices and procedures previously identified, additional refinery tankage will be considered.

Model results

The base case model output shown in Figure 3 is for a typical tank group before any system configuration changes have been made. Figure 4 shows the improvement after implementing all recommendations. Individual lines represent specific Monte Carlo simulation runs. The bands indicate the statistical average and standard deviation for all runs.

Methods other than visual observation of the resulting charts were used to analyse tankage utilisation. For analysis of tank group capacity utilisation, the mean tank group utilisation ($\tilde{u}$) and the standard deviation (δ) of the data set are calculated and displayed on the charts. Assuming normal distribution of probability, lines are then drawn on the chart to represent $\tilde{u}$ and $\tilde{u}+2\delta$, which indicates that 95.45% of tank group utilisation fits below the upper band line.

If the upper band line exceeds 100% capacity utilisation, this would indicate that available tankage capacity is not sufficient and hence a potential restriction to tank farm operations. Conversely, a band line that falls below 100% capacity utilisation indicates that there is sufficient tankage available to deal with normal tank farm operations.

The following results were captured from the tank farm simulation model, measured and trends recorded:

— Process unit capacity utilisation

— Tankage utilisation as a percentage of working capacity

— Frequency that tank filling is constrained by maximum working capacity

— Product properties and transfer flow rates within the refineries, via inter-refinery transfers and to final product shipping facilities

— Ship movements as a result of two-port loadings

— Product movement operating costs

— Final product blend values

— Improvements in all of these as a result of defined system modifications and expansions.

For each case, FW identified, quantified and compared the benefits to the base case. Estimated capital costs for recommended system improvements as well as expected revenue increase and/or cost savings were used to determine a project payout period.

Weekly operating costs, as determined by the tank farm simulation model runs, were aggregated into annual average costs over a five-year period. Annual credits for each case were the difference in the average annual operating costs vs the base case. FW estimated capital costs for each case from in-house data and previous experience with similar projects and equipment.

Implementation of the recommended system improvements resulted in a project payout period slightly in excess of two years. The total overall project cost was reduced due to the early decision to minimise installation of any new tankage.

The results of the aforementioned analysis were presented to KNPC as well as the economic benefits for upgrading the tank farms at the three refineries. Consequently, KNPC is now implementing the upgrading project based on the system improvements as defined in Cases 1 through 4, confident that the optimal capital investment strategy has been chosen. This project also allows for future expansion and upgrading of the refineries without being constrained by tank farm operations.

Conclusion

The primary conclusion of the KNPC study was the determination that no additional tankage would be required for them to operate comfortably into the next decade. Additionally, sufficient cost savings have been identified that can pay back the cost of system improvements within two years.

As demonstrated by this project, stochastic studies such as the one presented in this article can now be effectively and confidently conducted using today's LP tools. Coupling statistical modelling methods with LP is an approach promising great returns, not only in inventory studies such as this but also in studies involving price and quality sensitivities, feedstock selections, market place dynamics, and investments of capital.

References

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