Closed-loop Optimization of a Solvent Dewaxing Plant

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A non-linear steady state closed-loop optimization is running at the DEA Mineraloel AG Grasbrook solvent dewaxing facility. The equation-oriented form of the model provides for speed and flexibility. Rapidly changing plant configurations and operating modes are automatically detected by the software so that the model configuration always matches the plant exactly. The model is particularly robust in the face of measurement error, noise, and non-steady state behavior.

The Solvent Dewaxing Process

The purpose of solvent dewaxing is to separate lubricating oils and paraffinic waxes from a feedstock consisting of lube oil fractions.

Although there are many process variants, all commercial solvent dewaxing plants contain common features:

- feed chilling train
- solvent injection
- rotating drum filter(s)
- solvent wash
- solvent recovery

In most plants there are a number of *stages* each of which makes an oil/wax separation. The first stage (often called a *dewaxing* stage) separates feed into wax with a high oil content (*slack wax*) and oil with a low wax content (*lube stock*). Downstream stages (eg: *Deoiling*) are fed slack wax from the first stage and produce progressively harder wax (less oil content), and higher pour point oil (more wax content).

DEA Grasbrook Plant

The dewaxing and deoiling facilities at DEA's Grasbrook refinery consist of the following major equipment (see Figure 1):

Dewaxing 1
Chilling train
Dewaxing filters (3)

Dewaxing 2
Chilling train
Dewaxing filters (4)

Deoiling
Feed heating
Deoiling filter (1)

This plant operates in one of seven possible configurations to produce one of 12 distinct products. Dewaxing stage 1 contains up to three filters in parallel. Dewaxing stage 2 contains up to four filters in parallel. The deoiler is a single filter. Dewaxing stages 1 and 2 operate in parallel, with each normally making a different set of products. The Deoiler can follow either of the two dewaxing units depending on the operation.

In a single dewaxing unit feed oil combines with primary solvent and enters the chilling train which cools it to a temperature set by the pour point specification of the filtrate product. The chilled feed then combines with secondary solvent dilution (recycled wash filtrate) and enters the baths of the individual filters. Liquid flowing through the filter cloth enters filtrate solvent recovery where solvent is stripped from the filtrate product (lubricating oil). The slurry of wax crystals entering the filter bath forms a cake along the surface of the rotating filter drum. Cold solvent (*cold wash*) washes the cake to remove residual oil from the wax.

If the deoiling unit is out of service, the wax/solvent mixture from the dewaxer enters solvent recovery where *slack wax* product separates from solvent.

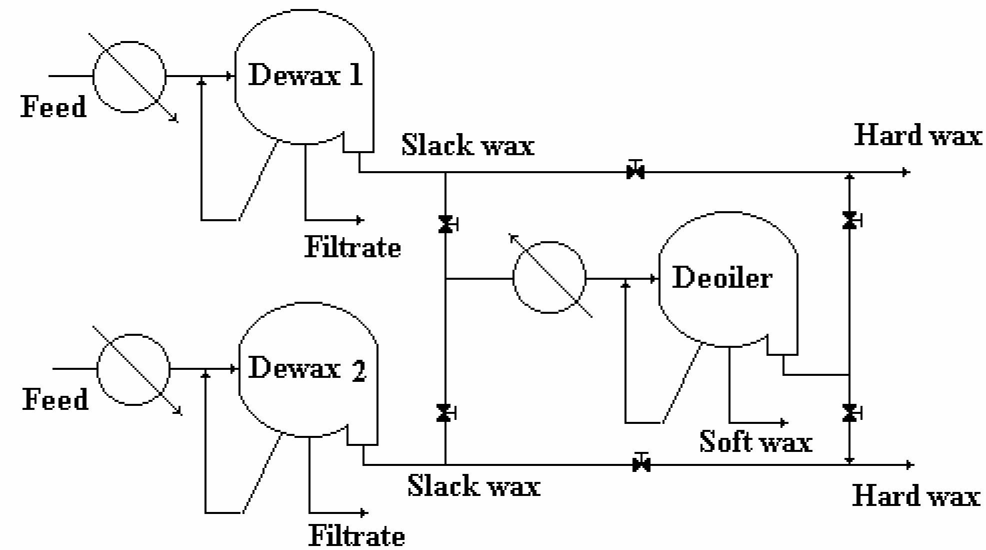

Figure 1- DEA Grasbrook Solvent Dewaxing Facilities

If the deoiler is in service, heat exchangers warm the feed coming from the dewaxing unit. Secondary solvent dilution (recycle) combines with the feed and the mixed stream enters the deoiler filter bath. Liquid filtrate flowing through the deoiler filter cloth has the solvent removed in solvent recovery and becomes *soft wax*. Cold wash sprays onto the wax cake removing residual oil to produce product wax (*hard wax*).

All recovered solvent recycles back to the process.

The laboratory analyzes product streams about once per day, and more often during a mode switch. The new lab data enter the refinery data acquisition system where they become feedback for the model.

The most important product specifications in this plant are:

- filtrate pour point
- product wax oil content.

The main operating costs in this plant are:

- feed cost
- electricity used for the refrigeration system
- steam used in solvent recovery.

Special Challenges

This plant is frequently shifting between operating modes and product specifications. On average the operation shifts every two to three days, often in a very significant way. Feed rate, feed quality, and product specifications can vary widely. Operating variables must cover a wide range to accommodate these shifts. Superimposed on the changing flowsheet is the occurrence of routine filter *hot washes* during which time hot solvent washes individual filters to unplug the filter cloth: in order to hot wash, a filter must be taken off line. Clearly these conditions complicate implementation of a closed-loop optimization system.

To deal with these complications, the optimization package routinely performs a number of important checks. First, it checks the existence of steady state by computing the standard deviations of certain key plant variables and comparing these with a maximum tolerance. Optimization occurs only when steady state exists. Next, the software automatically detects changes in plant configuration. For example, the deoiler switching from dewaxer 1 to dewaxer 2, causes the model to automatically reconfigure itself . And finally, the software checks for hot washes: when a hot wash is detected, that filter is simply removed from the model flowsheet. The net result of all these checks is that the model is constantly reconfiguring itself to react to changes in the plant flowsheet, operating mode, and dynamic state.

Model Description

A set of equations that defines the steady state behavior in the dewaxing and deoiling sections of the plant forms the basis for the model. The heart of the model is the filter which contains equations describing the following phenomena:

- temperature and composition effects on viscosity

- resistance to flow in the cloth and cake

- effect of bath level on throughput

- effect of speed on throughput

- effects of primary solvent, secondary solvent and cold wash on cake washing

- operation with excessive cold wash, or "runoff"

- pour point of filtrate

- oil content of wax

A library of reusable unit operations models is used to construct the flowsheet in a flexible way. Examples of unit operations are:

- filter
- heat exchanger
- stream splitter
- stream mixer
- feed model
- chiller

Each unit operation connects to other unit operations by *streams* containing the following set of components:

Component	Model units
Solvent	BBL/hr
Oil	BBL/hr
Wax	BBL/hr
Soft wax	BBL/hr
Total flow	BBL/hr
Temperature	F

Table 1-Model Stream Components

For a flowsheet containing both dewaxers and the deoiler the optimizer has 26 *degrees of freedom.* In control terms, each degree of freedom corresponds to an advanced controller target which the optimizer can manipulate in closed-loop. This is how the optimizer causes the plant to move closer to the economic optimum. Examples of degrees of freedom are:

- bath temperature
- bath level
- feed rate
- recycle rate
- cold wash rate
- solvent rate

The software automatically detects the number of degrees of freedom available to it by looking at controller statuses in the advanced controls. Plant operators control the active degrees of freedom by putting these advanced controllers into and out of *computer mode*. This is another example of the optimization package recognizing changing plant behavior and restructuring itself on the run.

It is important to note that the model honors constraints on all important independent and dependent variables. Constraints are enforced by the optimizer in the long-term, and by the underlying advanced controls in the short-term. This insures that the optimizer keeps the plant in a safe region, and that product specification limits are strictly enforced. Plant control engineers set constraint limits through displays in the process computer.

Technology

The model is entirely in equation-oriented form:

$$f(x) = 0$$

where $f(x)$ is the vector of equation residual values (driven to zero at the solution), and x is the vector of model variables. This formulation results in maximum execution speed and flexibility, both of which are particularly important in the closed-loop environment.

A state-of-the art sparse non-linear programming algorithm (NLP) solves and optimizes the equation set.[i] This algorithm was developed in the 1990's and contains technology which makes older NLPs obsolete. For example, the solver addresses discontinuities in the model equations using rigorous mathematics. This is critical to the success of many chemical engineering flowsheet calculations, including solvent dewaxing.

During a typical two hour solution cycle the sequence of events is as follows:

1. detect current plant configuration
2. reconfigure flowsheet, if necessary
3. collect plant data
4. detect presence of steady state
5. reconcile and update the model- fit model to plant data, insure feasibility
6. optimize- find economic optimum
7. implement optimal solution (closed-loop)
8. wait for start of next cycle

Step 5 is of particular interest. Because of the equation-oriented problem formulation it is straightforward to perform a simultaneous model parameter fit (match model to plant) and data reconciliation. The data reconciliation step is an optimization whose least-squares objective function attempts to match selected model computed values to the measured values from the plant:

Objective function =

$$\Sigma\,(meas - calc)^2/\sigma^2$$

where *meas* is the measured values from the plant, *calc* is the values as computed by the model, and σ^2 is the variance.

(Any plant measurement can be reconciled including flows, compositions, pressures, or temperatures.) This step is an efficient means of ensuring model feasibility in the face of measurement error, noise, and unsteady plant behavior. Data reconciliation results in a more robust model that solves a high percentage of the time.

Step 6 is a conventional economic optimization. The optimizer computes (within bounds) the available degrees of freedom to satisfy all plant constraints at the same time as maximizing the economic objective function stated as follows:

Objective function =
Σ product rates • product prices
- Σ feed rates • feed costs
- Σ utility rates • utility costs

The software automatically selects the feed prices and product costs based on the current plant operating mode. This makes the optimal solution consistent with the current set of refinery planning economics.

Model Results

Tables 2 and 3 contain a brief summary from a typical closed-loop optimization run of the solvent dewaxing plant. Table 2 shows the percent change of the optimal solution compared to the base case parameter update. Table 3 shows product prices relative to feed rate.

Because both products are worth more than the feed, the optimizer increased unit feed rate (see Table 2). The oil content of the wax was increased to its maximum allowable value. This saves energy and allows more wax to be sold at the filtrate price, which is higher. Bath temperature increased in order to raise the filtrate yield relative to the less valuable slack wax. At the new higher bath temperature, the pour point also increased, but remained within bounds at the solution. Filtrate yield increased and slack wax yield decreased as expected (driven by prices).

The model contains a great deal more information than was illustrated here. Throughout commissioning we exercised the model in real-time, and checked a large number of such runs in detail while running the model in advisory (open-loop) mode. In the final stages of commissioning the plant personnel had sufficient confidence in the model results to link these to the DCS system in closed-loop.

Scaled variable	Δ Optimal (%)
Profit	10.6
Feed rate	8.8
Solvent flow	2.3
Cold wash flow	4.6
Solvent recycle	0.7
Oil in wax	20.3
Bath temperature	5.3
Filtrate pour point	5.3
Bath level	-1.9
Cake thickness	-4.7
Filtrate yield	0.4
Slack wax yield	-0.4

Table 2- Example Optimization Result

Stream	Relative price
Feed	1.000
Filtrate	1.339
Slack Wax	1.326

Table 3- Relative Stream Prices for Optimization

Conclusions

A non-linear model of the solvent dewaxing operation is running at the DEA Mineraloel Grasbrook refinery. Rapid changes in the plant flowsheet are not a problem- the model simply reconfigures itself every time the operation is changed. The equation-oriented form of the model solves quickly and is flexible in many respects: of particular interest is the ability to solve the parameter estimation problem and data reconciliation simultaneously.

A complete parameter fit and economic optimization runs on a two hour cycle, the last step of which is closed-loop implementation of the advanced controller targets.

Today the entire field of closed-loop optimization is an exciting area that is currently undergoing a rapid growth. We expect that models such as the solvent dewaxing application described here will soon solve together with other plant models in real-time. Refinery-wide optimization is within the grasp of Honeywell Profimatics and we are pursuing it with vigor.

Literature cited

[i] Gallun, S. E., Luecke, R. H., Scott, D. E., Morshedi, A.M., "Use open equations for better models", *Hydrocarbon Processing*, July, 1992