# Improved Swing-Cut Modeling for Planning and Scheduling of Oil-Refinery Distillation Units

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Abstract

Nonlinear planning and scheduling models for crude-oil atmospheric and vacuum distillation units are essential to manage increased complexities and narrow margins present in the petroleum industry. Traditionally, conventional swing-cut modeling is based on fixed yields with fixed properties for the hypothetical cuts that swing between adjacent light and heavy distillates, which can subsequently lead to inaccuracies in the predictions of both its quantity and quality. A new extension is proposed to better predict quantities and qualities for the distilled products by taking into consideration that we require corresponding light and heavy swing-cuts with appropriately varying qualities. By computing interpolated qualities relative to its light and

heavy swing-cut quantities, we can show an improvement in the accuracy of the blended or pooled quality predictions. Additional nonlinear variables and constraints are necessary in the model, but it is shown that these are relatively easy to deal with in the nonlinear optimization.

## 1. INTRODUCTION

Distillation or fractionation models for planning and scheduling activities serve an important role in all decision-making problems inside the oil-refining sector. As the distillation units separate the crude-oil into various cuts or distillates and then distribute these to downstream transforming and treating units, all efforts to improve their quantity and quality predictions to avoid potential inconsistencies in the targets for scheduling and/or control applications is always worth pursuing. The driving force in most separation processes found in oil refining is the volatility difference between multiple light and heavy crude-oil components, which are of course temperature and pressure dependent. Rigorous engineering calculations to represent the details of most oil-refining processes can be found in commercial simulators such as Aspen-Plus and Hysys (Aspen Techology), PetroSIM (KBC), PRO-II (Invensys), and UniSim (Honeywell). These tools provide extensive capabilities to model, on a molar basis, material, energy, kinetic, and equilibrium relationships along with embedding several physical and thermodynamic property packages.

However, distillation models in planning and scheduling problems rely on essentially mass and/or volume-basis material balances, where the crude oils are decomposed into several cuts based on what are known as true boiling point (TBP) temperature distribution curves for how yields and other qualities are distributed as a function of TBP temperature. In this way, variations in material and property flows from these distillation processes can be modeled considering the column's known temperature distribution or profile. When swing-cuts are introduced, these are used to model the fact that the temperature profile can be manipulated, controlled or optimized to produce more or less amounts of adjacent light and heavy intermediate swing-cuts before being blended into a final distillate or product-cut, which is dispatched downstream. Unfortunately this approach, albeit simple to implement in planning and scheduling models, has a serious drawback in the sense that the properties for the light and heavy swing-cut flows are assumed to be the same,[1] which is not true.

In this work we propose a novel swing-cut model enhancement, which mitigates this issue by correcting the light and heavy swing-cut properties using a set of simple flow-weighted interpolations at their interfaces, which will be described in detail. Two examples are presented, one with a crude-oil distillation unit using actual data, and the second is a planning case with different grades of diesel, where both provide a comparison between the conventional and the improved swing-cut models.

## 2. PREVIOUS DISTILLATION METHODS IN PLANNING AND SCHEDULING MODELS

Mathematical programming has been extensively used to model planning and scheduling problems in the oil-refining industry for decades.[2-4] Although more accurate results may be obtained by using rigorous models, their complexity, difficulty in reformulating them as optimization problems, and the intractability of their solution prevent them from being used in practice.[5] Commercial planning software such as GRTMPS (Haverly), Aspen PIMS (Aspen Technology), and RPMS (Honeywell) overcome this problem by using simplified process unit-operation models, which involve mostly linear, bilinear, and trilinear constraints and are solved using home-grown successive or sequential linear programming (SLP) algorithms, sometimes referred to as distributed recursion.

Previous work embedding distillation process models into oil-refining planning problems somewhat improved the simple fixed yield and properties model by considering different operational modes.[6] Moro et al.,[7] Pinto et al.[8] and Neiro and Pinto[9] proposed a nonlinear planning model considering the distillation furnace temperature as an operational or process variable, and then by experimental or through process simulations, fit delta or shift coefficients for the intermediate or final cuts or stream flows and quality values with variations. Zhang et al.[1] highlighted the conventional swing-cut model considering the existence of fractions with the same qualities swinging between adjacent cuts using a volume ratio on crude-oil feed. Li et al.[5] proposed improvements in the swing-cut model based on weighted-average cumulative yield variations of the crude-oil assay considering "weight transfer ratios" of each product-cut. The upper and lower bounds for the yields are defined by the union of different operational modes in the distillation tower. Their approach also included empirical models similar to those from Watkins[10] to predict distillate properties. In addition, Guerra and Le Roux[11,12] applied this modified swing-cut model to improve the overall oil-refinery planning modeling for a medium-scale case with several process units and product blends. Although these previous works try to improve the distillation model's accuracy without overloading the formulation, they do not deal with the issue that the swing-cut properties vary inside the light and heavy portions or fractions of the swing-cut. Instead, they use empirical correlations based on the crude-oil assay TBP curves alone without adjusting the swing-cut qualities directly, as we propose in this work.

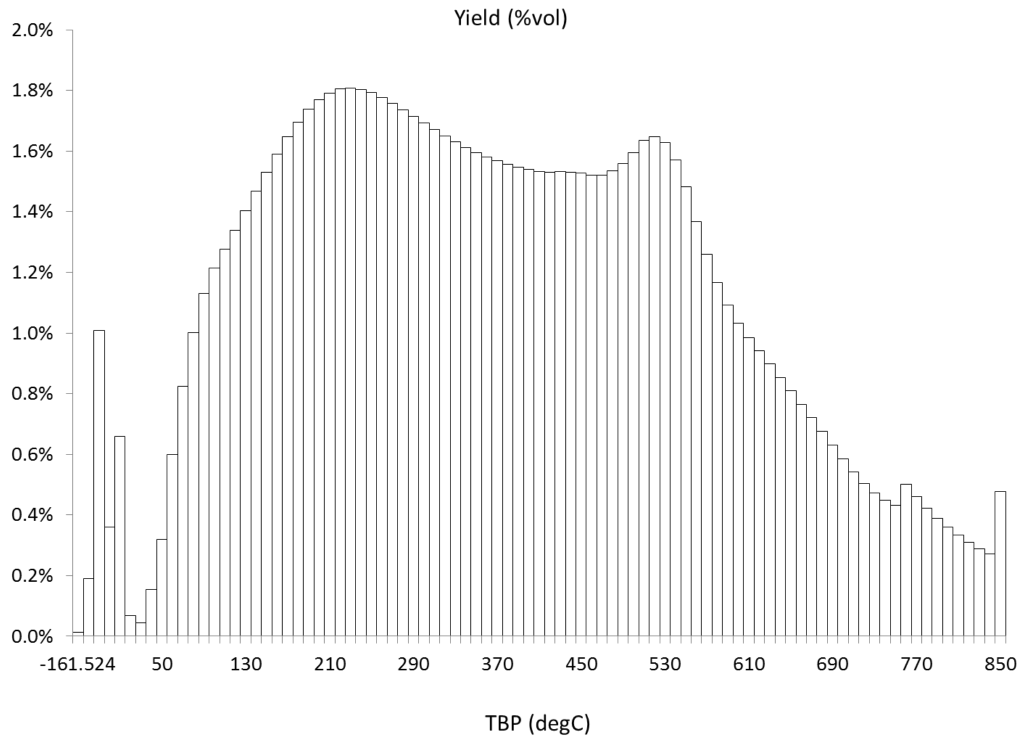
More recent and complex distillation models applied to planning and scheduling problems have been published that use nonlinear relations, as well as molar and energy balances with temperature cut-points as variables. Alattas *et al.*[13] applied nonlinear programming for a single-period refinery operational planning problem to predict yields using the well-known fractionation-index[14] showing profit increases by stressing the accuracy in the distillation process. In their work, the distillation column is considered as a sequence of flashes using pre-determined temperatures, and with both rectifying and stripping fractionation indices (FI) in each section. The nonlinear Heaviside function is used to model the fractionation-index pair within the molar balance of each flash. Extending this work, Alattas et al.[15] addresses the multiperiod operational planning problem by replacing the Heaviside function to manage the FI pair with mixed-integer constraints using convex hull and big-M formulations. In both FI models, some simplification, such as constant pressure throughout the column, is assumed. Another issue in their paper is the exponential polynomial in the equation (22), which calculates the vapor pressure as a function of reduced temperature and is highly nonlinear. This can be a source of instability during the solution.

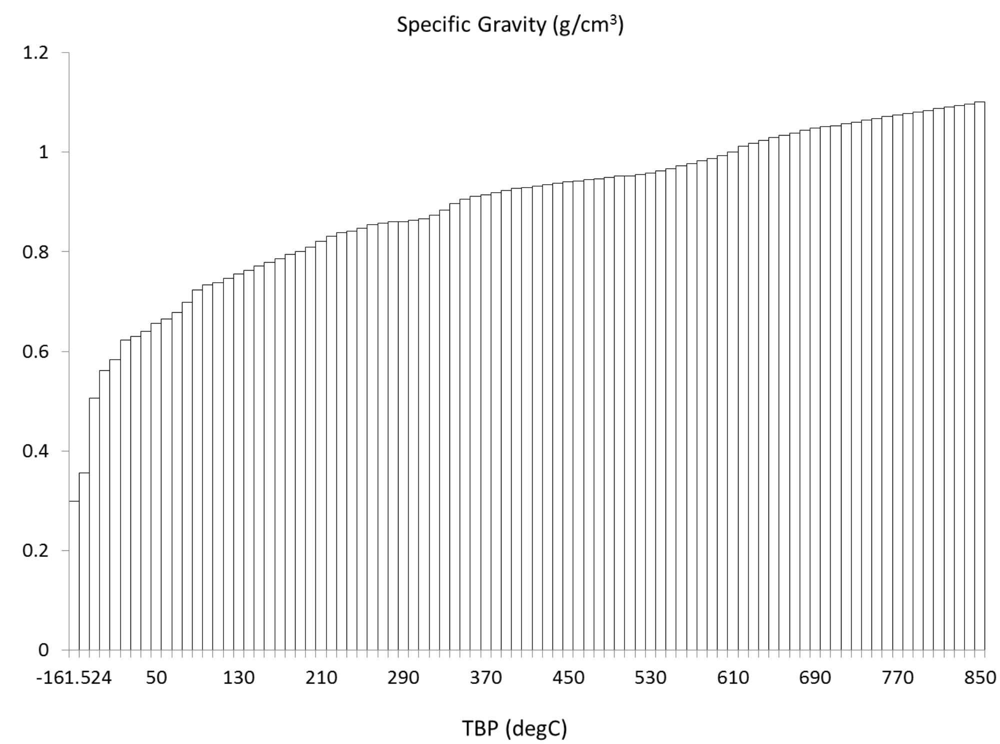
Mahalec and Sanchez[16] proposed an inferential monitoring and optimization of distillation columns via hybrid models, i.e., combining first-principles and statistical empirical correlations together. They also use molar and energy balances for the TBP changes in a tray-by-tray formulation. Their technique uses actual data from the column's operation, and/or data from a rigorous process simulator of the column to fit parameters in both the first-principles and empirical correlations. This of course requires continuous calibration to keep the models sufficiently accurate. In addition, their approach is mainly concerned with the yield or fraction of each product-cut fractionated at the initial and final TBP temperatures, and unfortunately does not consider the variations in other qualities or properties as a function of temperature.

In this paper, we focus on improving the conventional swing-cut formulation instead of reformulating it using more detailed temperature cut-points along with short-cut molar, energy, and equilibrium relationships used by the previous researchers. Our method is still flow-based (either volume or mass) and proposes a straightforward enhancement to the swing-cut formulation by correcting or adjusting the qualities of both the "light" (top) and "heavy" (bottom) swing-cut fractions, thus improving the quality predictions of the blended or pooled distillate streams as we shall show.

## 3. MICROCUT CRUDE-OIL ASSAYS AND CONVENTIONAL SWING-CUT MODELING

Crude-oil and vacuum distillation units (CDU/VDU) at the planning and scheduling levels, are typically modeled by decomposing or separating each of its crude-oil feedstocks into what are known as hypothetical or pseudocomponents, also referred to here as "microcuts". Each microcut has a predefined TBP temperature interval of approximately 5-25ºC ranging across the entire crude-oil, which usually has an overall temperature range from the boiling point of methane to 850ºC.[17] Together with the volume and/or weight yields, and a set of relevant qualities including specific gravity for each microcut, this forms what is called the crude-oil assay. Further information regarding the crude-oil assay data and the conventional swing-cut modeling can also be found in Li et al.[5]. The microcut TBP temperature interval used in this work is 10ºC. The assay data for each crude oil were generated using the process simulator PetroSIM. Volume yields, specific gravity, and sulfur content for a single crude oil is shown in Figure 1.


Yield (%vol)
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
-161.524
50
130
210
290
370
450
530
610
690
770
850
TBP (degC)


Specific Gravity (g/cm³)
1.2
1
0.8
0.6
0.4
0.2
0
-161.524
50
130
210
290
370
450
530
610
690
770
850
TBP (degC)

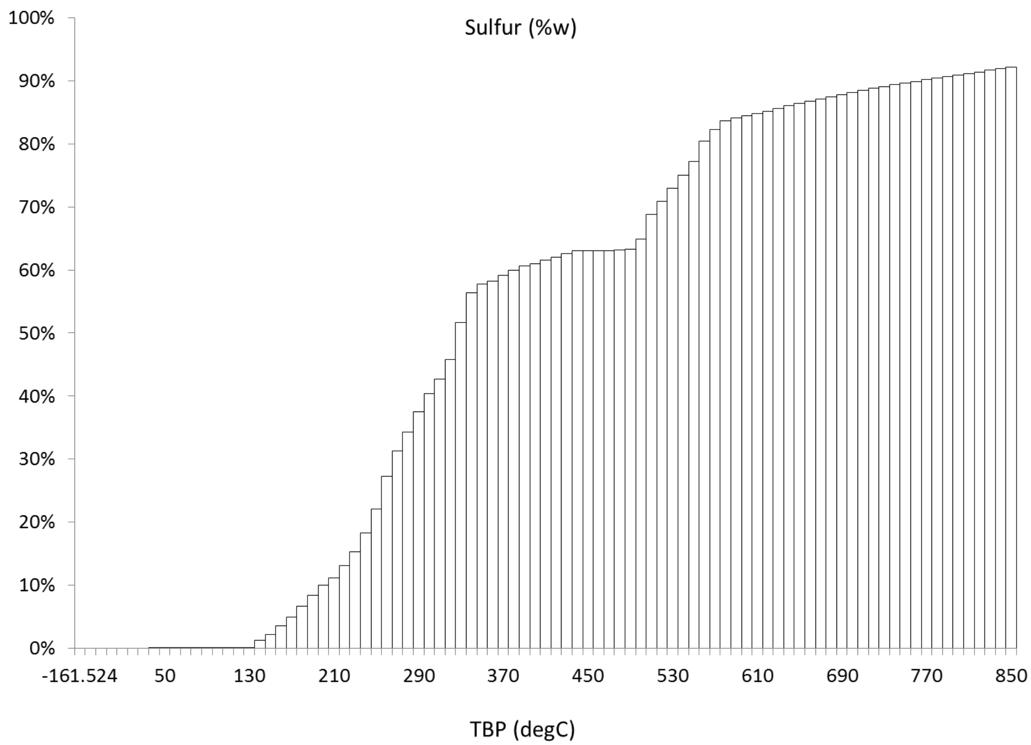



**Figure 1**. Example crude-oil assay data with eighty-nine 10ºC microcuts for yield, specific gravity, and sulfur.

Microcut or pseudocomponent yields and qualities, as well as empirically derived molecular weight, accentric factor and critical temperature and pressure, can be used by rigorous distillation models for detailed process simulation and optimization to characterize each crude oil fractionated in the distillation towers. However, for our purposes, first-principles column fractionation is not being considered. Instead, as is typical for planning and scheduling modeling, the yields and qualities for the cuts or streams leaving the distillation process are determined by mixing, blending, or pooling a predefined set of microcuts for each cut or distillate, weighted by the composition of each crude oil feeding the tower similar to a blend recipe.

The conventional swing-cut model proposed in this work uses microcuts (mc) to define the crude oil, instead of simply cuts (c) used in previous approaches where final-cuts (fc) are introduced to represent the mixing or blending of the cuts and any swing-cuts to form the final product leaving the fractionator as shown in Figure 2. The naphtha-cut, for example, is formed by blending any pure components such as isopentane (IC5) and the microcuts mc40-mc120. The first swing-cut, SW1-cut, is formed by mixing mc130, mc140, and mc150. Kerosene-cut includes mc160-mc200, and SW2-cut is formed by mc210, mc220, mc230, and mc240. The other cuts shown, light diesel-cut, SW3-cut, and heavy diesel-cut are modeled in a similar way. The four final-cuts or product-cuts, naphtha, kerosene, light, and heavy diesel, are then pools of the cuts shown. The special lines in Figure 2 with the labels "light" and "heavy" are the swing-cut split streams and will be described in more detail later.

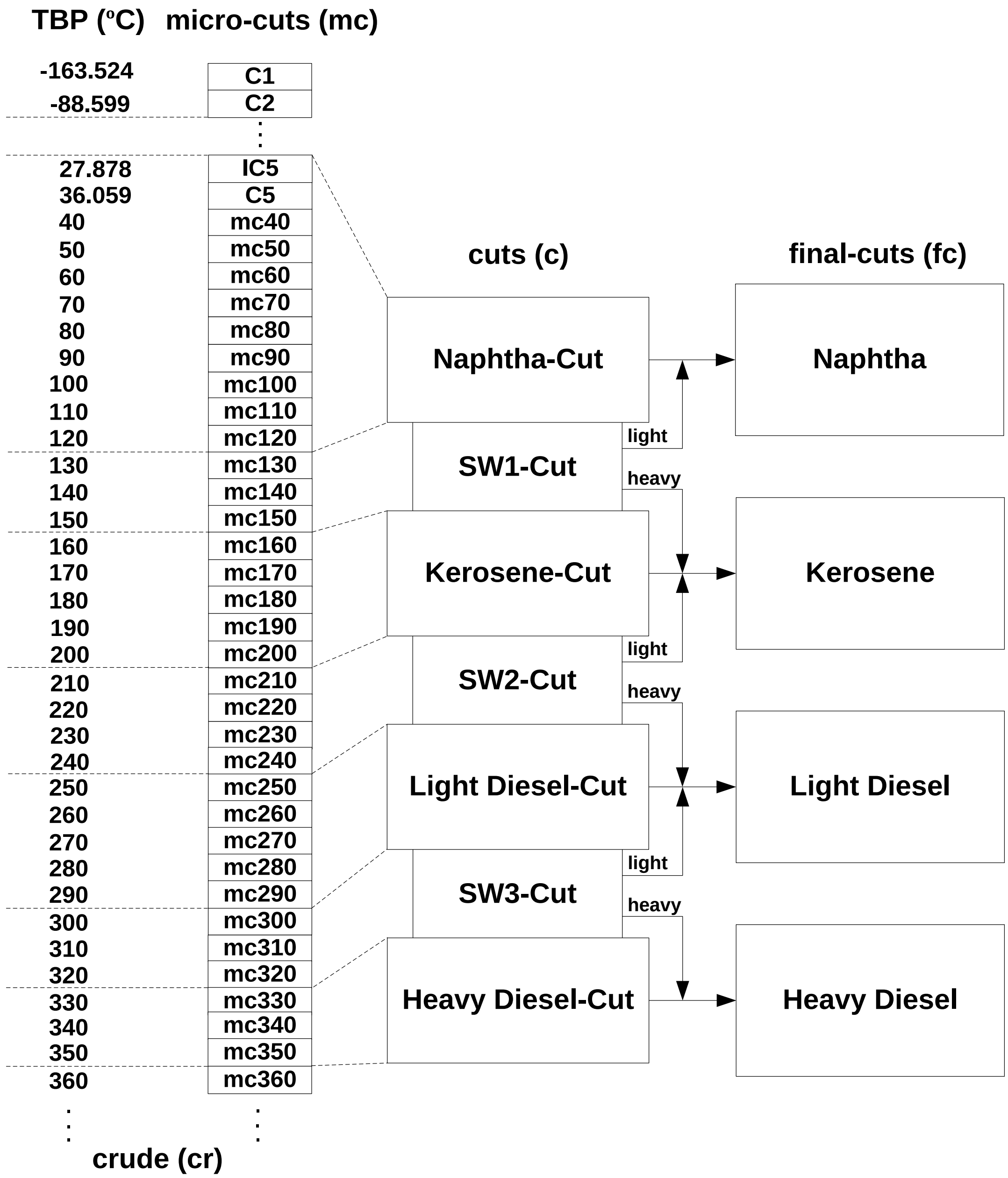



**Figure 2**. Microcuts, cuts, swing-cuts, and final-cuts.

The CDU configuration, which may have one or more crude-oil feedstocks and three swing-cuts, is shown in Figure 3. As can be seen, the swing-cuts are essentially internal modeling constructs, and they are not necessarily present physically in the tower, although they can be related to what are known as side-draw trays. The two quantity flow variables shown are taken from the general framework found in Neiro and Pinto.[9]

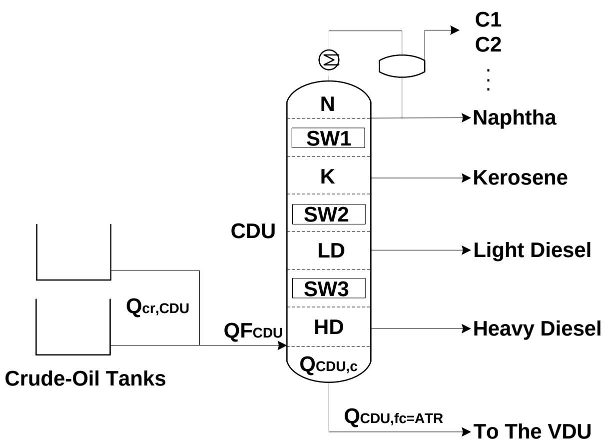



**Figure 3**. Multiple crude-oils, cuts, and final-cuts for the CDU.

The mathematical model using multiple crude oils, microcuts, cuts and final-cuts in terms of how they are combined together to model the CDU in Figure 3 is as follows. Eq 1 takes the flows for each crude oil (cr) and sums them together to form a total or overall feed flow to the CDU.

$$QF_{CDU} = \sum_{cr} Q_{cr,CDU} \qquad (1)$$

Each cut flow inside the CDU is represented by eq 2 as the sum over all crude-oils, times the sum over of each microcut's yield from its initial microcut (mci(c)) to its final microcut (mcf(c)) given by the temperature cut-points. When cut "c" is a swing-cut "sw", it is split into a “light” and a “heavy” stream where their sum is constrained and given by eq 3. Their values are variables that can be changed by variations on the final distillates quantities and qualities to match the final products demands and specifications.

$$Q_{CDU,c} = \sum_{cr} Q_{cr,CDU} \sum_{mc=mci(c)}^{mcf(c)} Y_{cr,mc} \quad \forall\ c \quad (2)$$

$$Q_{CDU,c} = Q_{c,fc=\ell} + Q_{c,fc=h} \quad \forall\ c = sw \quad (3)$$

Similar to the CDU cut flows, in eqs 4 and 5 we model the volume and mass properties or qualities, respectively. An example of a volume property $VP_c$ is specific gravity, and an example of a mass property $MP_c$ is sulfur concentration. For the mass property we require a density or specific gravity to provide the volume to mass conversion inside eq 4.

$$VP_c = \frac{\sum_{cr} Q_{cr,CDU} \sum_{mc=mci(c)}^{mcf(c)} V_{cr,mc} Y_{cr,mc}}{\sum_{cr} Q_{cr,CDU} \sum_{mc=mci(c)}^{mcf(c)} Y_{cr,mc}} \quad \forall\, c \quad (4)$$

$$MP_c = \frac{\sum_{cr} Q_{cr,CDU} \sum_{mc=mci(c)}^{mcf(c)} M_{cr,mc} G_{cr,mc} Y_{cr,mc}}{\sum_{cr} Q_{cr,CDU} \sum_{mc=mci(c)}^{mcf(c)} G_{cr,mc} Y_{cr,mc}} \quad \forall\, c \quad (5)$$

Now that we have individual cut flows and properties, we can form the final-cuts or product stream flows and properties leaving the CDU, shown in Figure 3 as the arrows to the right of the CDU. Eq 6 simply sums together the nonzero cut to final-cut flows $Q_{c,fc}$. Typically, cuts that are not swing-cuts are mapped or allocated one to one with its corresponding final-cut, i.e., naphtha-cut only goes to the naphtha final-cut. Whereas swing-cuts such as SW3-cut have "light" and "heavy" cut flows, where the "light" flow is included in the light diesel final-cut and the "heavy" flow mixes with the heavy diesel final-cut.

$$Q_{CDU,fc} = \sum_{c} Q_{c,fc} \quad \forall\, fc \qquad (6)$$

The final-cut volume and mass properties are then calculated in eqs 7 and 8 similar to the other property calculations. It is worth mentioning that the specific gravity property ($G_c$) is also a volume property and can also be computed via eq 7.

$$VP_{fc} = \frac{\sum_c VP_c Q_{c,fc}}{\sum_c Q_{c,fc}} \quad \forall \text{ fc} \tag{7}$$

$$MP_{fc} = \frac{\sum_c MP_c G_c Q_{c,fc}}{\sum_c G_c Q_{c,fc}} \quad \forall \text{ fc} \tag{8}$$

In addition, properties that do not obey ideal blending, can be easily precalculated for each microcut property using well-known blending indexes or ad-hoc blending transforms. These transformed properties then behave ideally as volume- or mass-based properties. This is also true for the blending or pooling of the final cuts. In the following section, we describe our improvement to the conventional swing-cut modeling approach just described.

## 4. IMPROVED SWING-CUT MODELING

Taking into consideration that the swing-cut can be split into two internal streams, the light going to the lighter final-cut and the heavy moving to the heavier final-cut, in our new formulation each of these internal streams has their own qualities. In contrast, the conventional swing-cut model has the same quality value for both the light and heavy streams, which are the bulk or whole swing-cut properties $VP_c$, $G_c$, and $MP_c$. In this work, we propose a new swing-cut model that adds a set of interpolations to better predict the pooled qualities of the final-cuts or products leaving the CDU or VDU. As mentioned before, we consider that both the light and heavy swing-cut streams have their own qualities, are computed as a function of their flows, and vary linearly or proportionately between the properties at their adjacent hypothetical interfaces and the whole property of the swing-cut.

The properties of the adjacent hypothetical interfaces, between the swing-cuts and their lighter and heavier cuts, can be easily calculated using the adjacent microcut pairs in the initial and final boiling point temperatures of each swing-cut. For instance, SW1-Cut in Figure 2 has its light interface property variables as $VPI_{c=SW1\text{-}Cut,\ell}$ and $MPI_{c=SW1\text{-}Cut,\ell}$, which are determined by blending the mc120 and mc130 properties identical to eqs 4 and 5. Similarly, the heavy interface properties $VPI_{c=SW1\text{-}Cut,h}$ and $MPI_{c=SW1\text{-}Cut,h}$ are computed using the microcuts mc150 and mc160. This implies that the TBP temperature range for SW1-Cut has an initial point of 130ºC and a final point of 160ºC, i.e., contains microcuts mc130, mc140, and mc150.

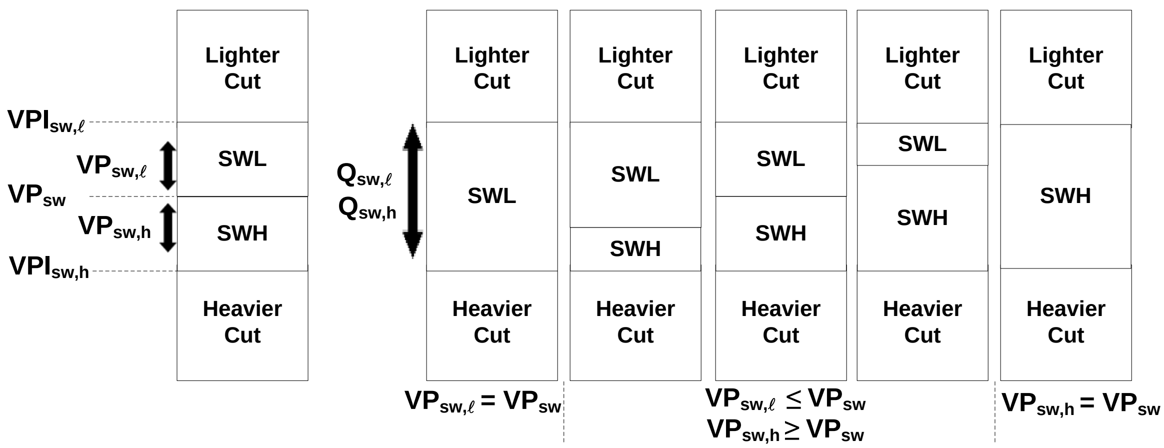



**Figure 4**. Swing-cut properties as a function of light and heavy swing-cut flows.

As shown in Figure 4, the light and heavy swing-cut portions labeled "SWL" and SWH" have their properties varying between their adjacent hypothetical interface properties, and its whole swing-cut property where the properties shown are volume-based but are the same for mass-based. If the whole swing-cut flows entirely to the lighter final-cut then $VP_{c=sw,fc=\ell}$ is equal to the swing-cut bulk property $VP_{c=sw}$. And, if all of the swing-cut flow goes entirely to the heavier final-cut, then $VP_{c=sw,fc=h} = VP_{c=sw}$. In the cases where the swing-cut is split to both the lighter and heavier product-cuts, then the properties are of course different but related to the whole swing-cut property and have simple inequality constraints bounding them, which may or may not be explicitly included in the model formulation. Eqs 9 and 10 are the equality constraints that allow us to compute the light and heavy swing-cut volume-based properties going to the light and heavy final-cuts, respectively, where eqs 11 and 12 are for the mass properties using the specific-gravity variables.

$$VP_{c=sw,fc=\ell} = VPI_{c=sw,\ell} + \frac{VP_{c=sw} - VPI_{c=sw,\ell}}{Q_{CDU,c=sw}} Q_{c=sw,fc=\ell} \quad (9)$$

$$VP_{c=sw,fc=h} = VPI_{c=sw,h} - \frac{VPI_{c=sw,h} - VP_{c=sw}}{Q_{CDU,c=sw}} Q_{c=sw,fc=h} \quad (10)$$

and

$$MP_{c=sw,fc=\ell} = MPI_{c=sw,\ell} + \frac{MP_{c=sw} - MPI_{c=sw,\ell}}{G_{c=sw} Q_{CDU,c=sw}} G_{c=sw,fc=\ell} Q_{c=sw,fc=\ell} \quad (11)$$

$$MP_{c=sw,fc=h} = MPI_{c=sw,h} - \frac{MPI_{c=sw,h} - MP_{c=sw}}{G_{c=sw} Q_{CDU,c=sw}} G_{c=sw,fc=h} Q_{c=sw,fc=h} \quad (12)$$

With these equations, whole swing-cut properties $VP_{c=sw}$ and $MP_{c=sw}$ in eqs 7 and 8 are replaced by $VP_{c=sw,fc=\ell}$, $VP_{c=sw,fc=h}$, $MP_{c=sw,fc=\ell}$ and $MP_{c=sw,fc=h}$ which enables us to predict more accurate mixed or pooled properties for the final distillates. As shown in Figure 2, each swing-cut has light and heavy streams, and therefore their properties can be corrected by this new improvement. Compared to the conventional swing-cut method for the volume-based properties, we require four new variables $VPI_{c=sw,fc=\ell}$, $VPI_{c=sw,fc=h}$ , $VP_{c=sw,fc=\ell}$ and $VP_{c=sw,fc=h}$, and two new equality constraints, eqs 9 and 10. For the mass-properties, we require six new variables that include specific gravity and two new equality constraints, eqs 11 and 12.

## 5. EXAMPLES

Two examples are presented, one with a crude distillation unit using actual data and the second is a planning case with different grades of diesel where all provide a comparison between the conventional and the improved swing-cut models. The objective is to maximize the profit obtained by sales of final products (p) to match their demands ($QF_p$) discounting the crude (cr) purchasing and hydrotreaters (HT) operation costs, as shown in eq 13.

$$\max \text{profit} = \sum_{p} pr_p QF_p - \sum_{cr} pr_{cr} Q_{cr,CDU} - \sum_{HT} \Upsilon_{HT} QF_{HT} \qquad (13)$$

The hydrotreaters severity ($\Upsilon_{HT}$) is considered the sulfur reduction percentage, and its operational costs in the objective are needed to avoid property giveaways when we have different grades of one product, as in the second and third examples. Also, a good practice is to consider one hypothetical blender for each grade; both were used in the planning examples. The CDU feed and final product specifications used in this work are given in Table 1.

**Table 1. CDU feed and final product specifications.**

| | SG ($g/cm^3$) | | Sulfur (w%) | |
|---|---|---|---|---|
| | min | max | min | max |
| CDU | 0.700 | 0.900 | - | 0.800 |
| JET | 0.780 | 0.836 | - | 0.300 |
| LSD | 0.820 | 0.850 | - | 0.001 |
| MSD | 0.820 | 0.865 | - | 0.050 |
| HSD | 0.820 | 0.880 | - | 0.180 |

The calculations were performed using GAMS[18] version 23.9.3 as the modeling system on an Intel Core 2 Duo (3.00 GHz, 16.0 GB of RAM), and the NLP solvers used in this work are CONOPT,[19] which is based on reduced gradient method, IPOPT,[20] which utilizes interior point methods, and SNOPT,[21] which is based on successive quadratic programming.

6. RESULTS

6.1. Example 1: CDU with Three Swing-Cuts

This example involves an actual CDU operation with a charge size of approximately 35 k $m^3$ per day and processes 18 different crude oils, and their compositions are known and fixed as shown in Table 2. The CDU configuration is shown in Figure 3 and has three swing-cuts (SW1-Cut, SW2-Cut, and SW3-Cut) and four final-cuts (naphtha, kerosene, light, and heavy diesel) that we are interested in.

**Table 2. Crude-Oil Diet with Volume Compositions.**

| Crude | ° API | SG (g/cm$^3$) | Sulfur (%w) | Volume Flow (m$^3$/d) | Volume Rate (%) |
|---|---|---|---|---|---|
| AGBAMI | 27.26 | 0.891 | 0.503 | 133 | 0.004 |
| AKPO | 44.96 | 0.802 | 0.066 | 2,444 | 0.069 |
| ALBACORA LESTE | 20.26 | 0.932 | 0.562 | 3,624 | 0.102 |
| BAZ | 28.54 | 0.884 | 0.271 | 2,428 | 0.068 |
| GOLFINHO | 26.91 | 0.893 | 0.152 | 339 | 0.010 |
| MARLIM LESTE JABUTI | 28.20 | 0.889 | 0.494 | 2,745 | 0.077 |
| MARLIM LESTE P-53 | 22.01 | 0.922 | 0.560 | 878 | 0.025 |
| MARLIM P-32 | 19.76 | 0.936 | 0.767 | 230 | 0.006 |
| MARLIM P-37 | 23.21 | 0.915 | 0.681 | 765 | 0.022 |
| MARLIM SUL FPSO MLS | 23.59 | 0.912 | 0.599 | 13,569 | 0.383 |
| MARLIM SUL P-40 | 22.98 | 0.916 | 0.638 | 168 | 0.005 |
| MARLIM SUL P-51 | 21.05 | 0.928 | 0.639 | 986 | 0.028 |
| MARLIM SUL P-56 | 18.01 | 0.946 | 0.727 | 565 | 0.016 |
| OKONO | 40.61 | 0.822 | 0.057 | 1,556 | 0.044 |
| PENNINGTON | 33.17 | 0.859 | 0.091 | 827 | 0.023 |
| RONCADOR P-52 | 28.30 | 0.885 | 0.580 | 2,162 | 0.061 |
| RONCADOR P-54 | 17.05 | 0.953 | 0.686 | 1,802 | 0.051 |
| SAHARAN BLEND | 43.47 | 0.809 | 0.071 | 237 | 0.007 |
| TOTAL | | | | 35,458 | 1.000 |

In Figures 5 and 6, we plot the specific-gravity and sulfur profiles for each CDU cut mentioned, where specific gravity is an example of a volume-based property. The conventional swing-cut (CSW) calculations are displayed as the solid line with triangular sample points (—▲—), whereas the improved swing-cut (ISW) values are displayed as the dashed line with square sample points

(-■-). As expected, with the conventional method, the light and heavy swing-cut properties are the same, which show as flat-lines for each swing-cut pair. As proposed by our new and improved swing-cut method, the light and heavy swing-cut properties are different from its whole or bulk swing-cut property and obey the varying proportions shown in Figure 4.

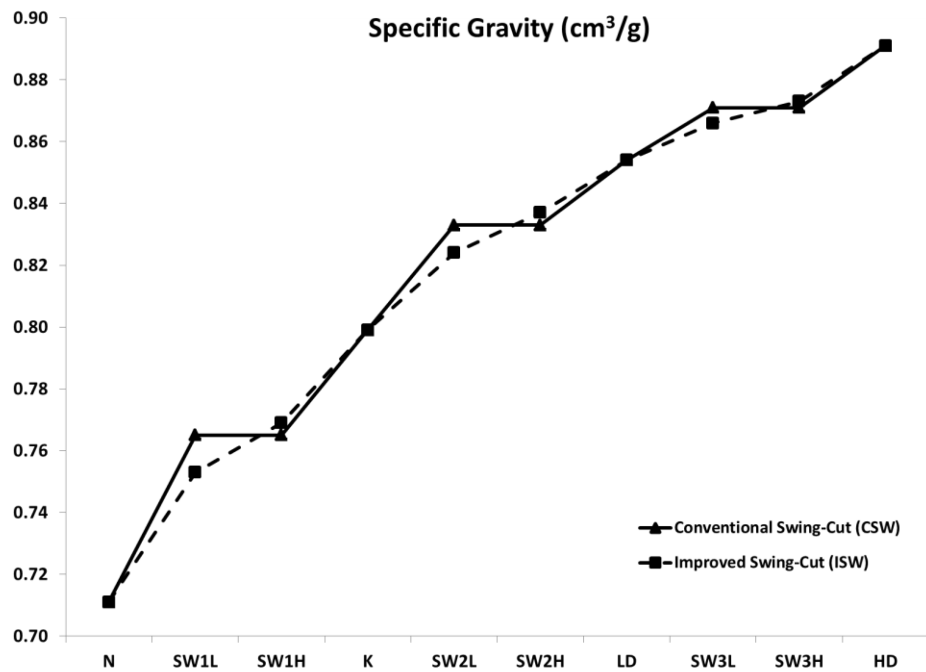



**Figure 5**. Specific gravity for each CDU cut including the swing-cuts.

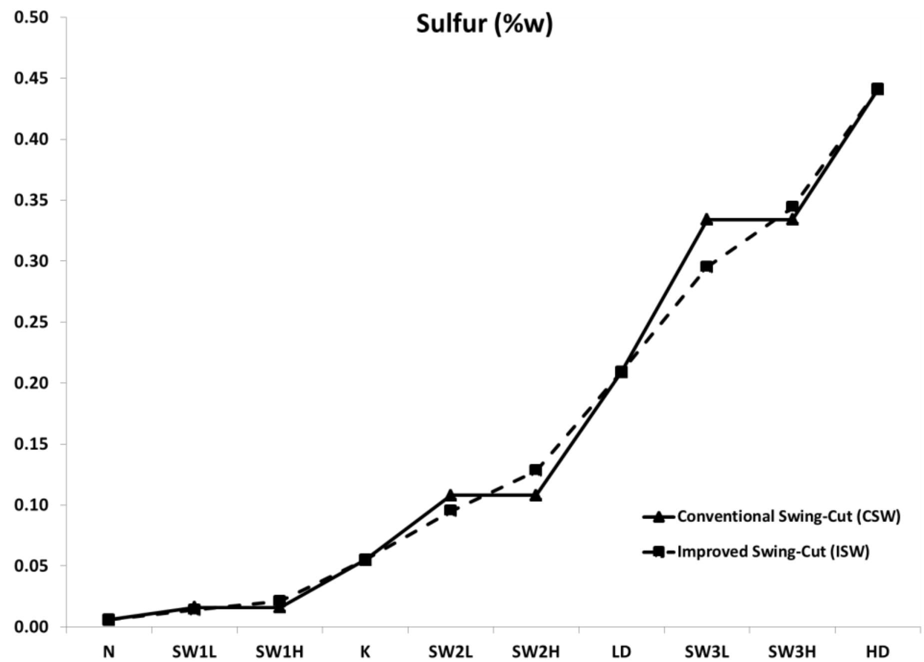



**Figure 6**. Sulfur concentration for each CDU cut including the swing-cuts.

Table 3 presents the CDU cuts volume flows determined when the charge size and crude-oil diet are fixed as the final-cut amounts for naphtha (N), kerosene (K), and light diesel (LD), which in this case are their final product demands, whereas Table 4 shows the calculated specific gravity and sulfur property values for both the conventional and improved swing-cut methods.

**Table 3. Flows for CDU Cuts Calculated and the Given Final-Cuts Used for Both Swing-Cut Methods**

| Cuts | Final-Cuts | Flow (K $m^3$/d) | |
|---|---|---|---|
| | | Cuts | Final-Cuts |
| N | N | 2.762 | 3.208 |
| SW1L | | 0.446 | |
| SW1H | K | 0.957 | 4.441 |
| K | | 2.457 | |
| SW2L | | 1.027 | |
| SW2H | LD | 1.218 | 4.597 |
| LD | | 2.444 | |
| SW3L | | 0.935 | |
| SW3H | HD | 1.564 | - |
| HD | | 2.498 | |

**Table 4. Specific Gravity and Sulfur Concentration for Naphtha to Heavy Diesel Cuts.**

| | | SG (g/$cm^3$) | | Sulfur (%w) | |
|---|---|---|---|---|---|
| | | CSW | ISW | CSW | ISW |
| N | Naphtha-Cut | 0.711 | | 0.006 | |
| NI | Naphtha Interface | 0.747 | | 0.009 | |
| SW1-Cut | Swing-Cut 1 | 0.765 | 0.753 | 0.016 | 0.014 |
| | | 0.765 | 0.769 | 0.016 | 0.021 |
| KLI | Kerosene Light Interface | 0.777 | | 0.024 | |
| K | Kerosene-Cut | 0.799 | | 0.055 | |
| KHI | Kerosene Heavy Interface | 0.817 | | 0.068 | |
| SW2-Cut | Swing-Cut 2 | 0.833 | 0.824 | 0.108 | 0.095 |
| | | 0.833 | 0.837 | 0.108 | 0.127 |
| LDLI | Light Diesel Light Interface | 0.842 | | 0.127 | |
| LD | Light Diesel-Cut | 0.852 | | 0.195 | |
| LDHI | Light Diesel Heavy Interface | 0.860 | | 0.220 | |
| SW3-Cut | Swing-Cut 3 | 0.869 | 0.866 | 0.316 | 0.278 |
| | | 0.869 | 0.873 | 0.316 | 0.343 |
| HDI | Heavy Diesel Interface | 0.882 | | 0.344 | |
| HD | Heavy Diesel-Cut | 0.894 | | 0.453 | |

In Table 5, we highlight the final-cut specific gravity and sulfur properties that are calculated using both the conventional and improved swing-cut models. These values are then compared with actual data of a run performed on the CDU with the same total crude-oil flow and diet as well as with naphtha, kerosene and light diesel final cuts.

**Table 5. Specific Gravity and Sulfur Concentration Values for Both Swing-Cut Methods.**

| | SG ($g/cm^3$) | | | Sulfur (wppm) | | |
|---|---|---|---|---|---|---|
| Final-Cuts | N | K | LD | N | K | LD |
| Conventional Swing-Cut | 0.719 | 0.800 | 0.849 | 75 | 600 | 1980 |
| Improved Swing-Cut | 0.717 | 0.798 | 0.852 | 78 | 570 | 1950 |
| Actual Plant Data | 0.717 | 0.797 | 0.862 | 105 | 503 | 2354 |

From Table 5, the specific gravity predictions using the improved swing-cut method show marginally better agreement with the actual plant data compared with the conventional swing-cut method, although the conventional method is still within experimental error. For the sulfur predictions the data is more inconclusive in terms of which method is better. As for this example, all crude oils are fixed and also for the final product demands for naphtha, kerosene and light diesel, the case is treated as a simulation because the number of variables and equations is the same, so there are no degrees of freedom. In the next examples, the difference in qualities predictions for both swing-cuts models is shown in an optimization case for the operational planning considering different grades of diesel as like as hydrotreaters operation.

## 6.2. Example 2: Oil-Refinery Planning Case

Four crude oils are used, and the CDU diet is determined considering property specifications on the final products and the processing taking place in the CDU and hydrotreaters as shown in Figure 7. The sulfur reduction provided by the hydrotreaters is a variable controlled by their severity where the bounds are given by eqs 14 and 15.

$$0.950 \le S_{D1HT} \le 0.980 \qquad (14)$$

$$0.960 \le S_{D2HT} \le 0.996 \qquad (15)$$

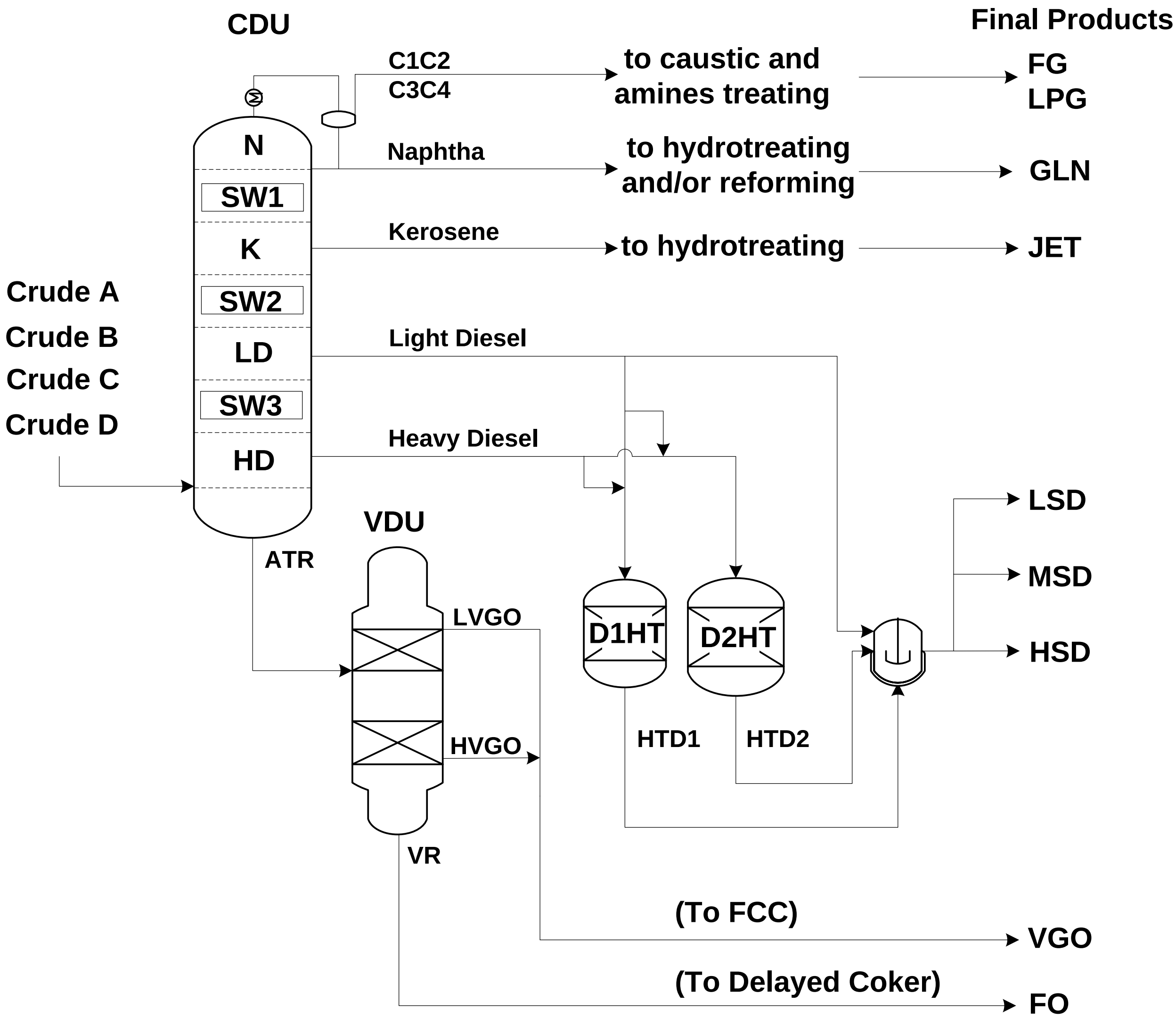



**Figure 7**. Fuels production planning case.

The final products or pooled demands are completely free or open so that the optimization problem can determine the crude-oil diet and maximize the profit considering the quality constraints for the CDU feeds and product fuels. Table 6 shows the results for the profit, unit throughputs, and final product amounts for the conventional (CSW) and improved (ISW) swing-cut models where the proposed model predicts an improvement in the profit of 3.3% (12.0 k US$/d or 4.380 million US$/y).

**Table 6. Planning Example Results.**

| Units (m$^3$/ | CSW | ISW | lower | upper |
|---|---|---|---|---|
| CDU | 18,000 | 18,000 | 14,000 | 18,000 |
| VDU | 9,960 | 9,960 | 6,000 | 10,000 |
| D1HT | 1,000 | 1,000 | 500 | 1,000 |
| D2HT | 2,200 | 2,200 | 1,000 | 2,200 |
| Hydrotreaters Severity | | | | |
| D1HT | 0.950 | 0.950 | 0.920 | 0.950 |
| D2HT | 0.995 | 0.995 | 0.950 | 0.995 |
| Crude (m$^3$/d) | | | price (US$/m$^3$) | |
| A | 2,060 | 2,060 | 720.0 | |
| B | 15,940 | 15,940 | 569.0 | |
| C | - | - | 585.0 | |
| D | - | - | 540.0 | |
| Fuels (m$^3$/d) | | | price (US$/m$^3$) | |
| FG | 8 | 8 | - | |
| LFG | 213 | 213 | 273.0 | |
| GLN | 1,970 | 1,970 | 681.5 | |
| JET | 2,214 | 2,330 | 800.0 | |
| LSD | 1,764 | 1,966 | 708.0 | |
| MSD | 1,890 | 1,349 | 693.8 | |
| HSD | 473 | 697 | 680.0 | |
| VGO | 4,721 | 4,721 | 550.0 | |
| FO | 5,239 | 5,239 | 498.0 | |
| Profit (k US$/d) | | | | |

**Table 7. Cuts Flows and Properties.**

| Cuts | Final-Cuts | CSW | ISW | CSW | ISW | CSW | ISW |
|---|---|---|---|---|---|---|---|
| | | Cuts Flows (m$^3$/d) | | SG (g/cm$^3$) | | Sulfur (w%) | |
| LN | LN | 1,478 | | 0.714 | | 0.001 | |
| SW1 | | - | - | 0.765 | 0.756 | 0.005 | 0.003 |
| SW1 | K | 679 | 679 | 0.765 | 0.765 | 0.005 | 0.005 |
| K | | 1,242 | | 0.794 | | 0.032 | |
| SW2 | | 293 | 409 | 0.828 | 0.819 | 0.074 | 0.062 |
| SW2 | LD | 825 | 709 | 0.828 | 0.833 | 0.074 | 0.088 |
| LD | | 1,490 | | 0.848 | | 0.148 | |
| SW3 | | - | - | 0.867 | 0.858 | 0.272 | 0.217 |
| SW3 | HD | 911 | 911 | 0.867 | 0.867 | 0.272 | 0.272 |
| HD | | 902 | | 0.887 | | 0.380 | |

**Table 8. Specific Gravity and Sulfur Concentration in the CDU Feed and Final Pools.**

| | SG (g/cm$^3$) | | Sulfur (w%) | |
|---|---|---|---|---|
| | CSW | ISW | CSW | ISW |
| CDU | 0.900 | 0.900 | 0.459 | 0.459 |
| JET | 0.789 | 0.790 | 0.030 | 0.030 |
| LSD | 0.850 | 0.850 | 0.001 | 0.001 |
| MSD | 0.858 | 0.861 | 0.050 | 0.050 |
| HSD | 0.877 | 0.877 | 0.180 | 0.180 |

In Tables 7 and 8, the cuts (also swing-cuts) and the final pool properties explain the different production amounts for JET and the distillates using CSW and ISW methods. Because the JET has the higher price and there are only property constraints in the model, the lower light-SW2 sulfur concentration in the ISW model permits higher flow of this stream to the kerosene final-cut and hence a higher profit is achieved.

The size of the problem is relatively small given that we are not including the entire oil refinery, and there is only one time period that has been considered. Tables 9 and 10 show the model sizes and also the results for the solvers CONOPT, SNOPT, and IPOPT.

**Table 9. Models Sizes.**

| | CSW | ISW |
|---|---|---|
| equations | 154 | 194 |
| variables | 173 | 213 |
| nonzeros | 592 | 756 |
| nonlinear | 317 | 449 |

**Table 10. Solvers Results.**

| | CSW | ISW | CSW | ISW | CSW | ISW |
|---|---|---|---|---|---|---|
| | CPU (s) | | iteration | | Profit (k US$) | |
| CONOPT | 0.219 | 0.062 | 213 | 188 | 367.8 | 379.8 |
| IPOPT | 0.156 | 0.234 | 105 | 162 | 367.8 | 379.8 |
| SNOPT | 0.047 | 0.078 | 23 | 16 | 367.8 | 379.8 |

The modest increase in the number of extra variables, constraints, and nonzeros for the improved swing-cut method should not significantly increase the computational time when embedded into larger planning or scheduling optimization problems. Good initial starting points for the variables can also be determined by first solving the conventional swing-cut model followed by the improved swing-cut model. In our opinion, the added accuracy afforded by the improved swing-cut method will more than offset the slight increase in solution time that may be required.

## 7. CONCLUSIONS AND FUTURE WORK

We have presented in this paper a new and relatively simple improvement to the conventional swing-cut modeling found in most nonlinear planning and scheduling optimization models used to plan and schedule most of the world's oil refineries. The concept is simple, in the sense that the usual assumption that the swing-cut properties flowing from the swing-cut to the light and heavy final-cuts (or product-cuts) are the same, has been extended or modified to account for the fact that they vary according to their proportions between the light and heavy interfaces. This can be easily calculated using the bilinear equations in eqs 9-12. A small but representative example, taken from an actual CDU operation with eighteen crude oils and three swing-cuts (see Figure 3), was highlighted to demonstrate the property differences for the light and heavy swing-cut streams in both methods. Also, a planning example with different grades of diesel, including two hydrotreater operations, shows that the improved swing-cut model yields higher profit because of its higher jet fuel production, provided by the lower specific gravity value for the light-SW2 flowing to the kerosene final-cut. Conceptually, the notion that the light and heavy flows from the swing-cut to its corresponding light and heavy final-cuts have different properties is sound engineering and was shown qualitatively to be acceptable with respect to the results shown. The improved swing-cut method can choose the best solution considering the more precise formulation, and even if the problem presented lower profit for a specific set of constraints, the improved method avoids the over estimation of the profit.

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ABBREVIATIONS

ATR = atmospheric residue

C1 = methane

C2 = ethane

C3 = propane

C4 = butanes

CDU = crude oil or atmospheric distillation tower

CSW = conventional swing-cut method

D1HT = hydrotreater 1

D2HT = hydrotreater 2

FG = fuels gas

FO = fuel oil

GLN = gasoline

HD = heavy diesel

HDI = heavy diesel interface between SW3-Cut and HD

HSD = heavy sulfur diesel

HVGO = heavy vacuum gasoil

ISW = improved swing-cut method

JET = jet fuel

K = kerosene

KLI = kerosene interface between SW1-Cut and K

KHI = kerosene interface between K and SW2-Cut

LD = light diesel

LDLI = light diesel interface between SW2-Cut and LD

LDHI = light diesel interface between LD and SW3-Cut

LPG = liquid petroleum gas

LSD = light sulfur diesel

LVGO = light vacuum gasoil

MSD = medium sulfur diesel

N = naphtha

NI = naphtha interface between N and SW1-Cut

SW1-Cut = swing-cut 1

SW2-Cut = swing-cut 2

SW3-Cut = swing-cut 3

SW1L = light swing-cut 1

SW1H = heavy swing-cut 1

SW2L = light swing-cut 2

SW2H = heavy swing-cut 2

SW3L = light swing-cut 1

SW3H = heavy swing-cut 3

VDU = vacuum distillation tower

VGO = vacuum gasoil

VR = vacuum gasoil

**Subscripts**

c = cuts

cr = crude-oil

fc = final-cuts (product-cuts)

h = heavier final-cut

HT = hydrotreaters

$\ell$ = lighter final-cut

mc = microcuts

sw = swing-cut

p = final products

**Parameters**

$G_{cr,mc}$ = microcut specific gravity (volume based)

$M_{cr,mc}$= microcut mass-based property

$Pr_p$ = final products prices

$V_{cr,mc}$ = microcut volume-based property

$Y_{cr,mc}$ = microcut volume yield from a crude-oil assay

**Variables**

$G_c$ = cut specific gravity

$G_{c,fc}$ = cut to final-cut specific gravity property

$MP_c$ = cut mass-based property

$MP_{c,fc}$ = cut to final-cut mass-based property (c=sw)

$MP_{fc}$ = final cut property in mass basis

$MPI_{c,\ell}$ = interface mass-based property between adjacent lighter cut and cut

$MPI_{c,h}$ = interface mass-based property between cut and adjacent heavier cut

$Q_{cr,CDU}$ = crude-oil flow to CDU

$Q_{c,fc}$ = cut to final-cut flow

$VP_c$ = cut volume-based property

$VP_{c,fc}$ = cut to final-cut volume-based property (c=sw)

$VP_{fc}$ = final cut property in volume basis

$VPI_{c,\ell}$ = interface volume-based property between adjacent lighter cut and cut

$VPI_{c,h}$ = interface volume-based property between cut and adjacent heavier cut

$S_{HT}$ = severity in hydrotreaters

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