"Gasoline Blend Optimization via Linear & Non-Linear Programming Optimizers"

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1. Introduction and Summary

Enjoying under $2.00/gal gasoline? The United States consumes about 9 million barrels per day of the stuff, worth over a tenth of a trillion dollars a year, so every little improvement is worth billions. Optimization of the production process lowers the cost of production, and therefore is key to maximize profit. This can be done by squeezing every "angle", e.g.

- minimizing property giveaway by judicious calculation of "optimum" blending recipes,
- exploiting cheap Ethanol "octane "boost";
- maximizing the use of cheap Butane,
- using non-linear property calculations to push against specification constraints.

The tools utilized for this are linear or non-linear programming (LP, NLP) based optimizers.

The paper covers a case study using a gasoline blend optimizer to illustrate the economic impact on the US economy.

2. Gasoline and US Economy

The US produces and consumes about 9 million barrels per day (MBPD) of gasoline [1], the largest consumer in the world, out of a total global production of about 45 MBPD. Even at the current low prices, the value of 9 MBPD of gasoline is about $190 Billion/year; this comes to a gasoline-related cash flow of about $2.5 Billion/year per average size US refinery, so even small production improvements have tremendous impacts on the economics of US refining industry.

However, sloppy gasoline production operation costs money. A simple example can illustrate the "sloppiness" value, in terms of easily-understood property giveaway, that is, the gap between a spec, e.g. 87 octane, and the actual produced gasoline measured at 88 octanes.

A study undertaken by Valero in 2013 [2] indicates a US refining industry conservative octane giveaway of ~0.5 ON and RVP vapor pressure giveaway of ~0.3 psi; this is valued at about $3 billions/year. Since there are 121 US refineries, $3B/121= $25million/US refinery in property giveaway alone.

3. What is Optimization?

Simply put, it means maximizing profit, or the difference between gasoline selling price and internal cost of production.

- The selling price is set by a very competitive marketplace, so we have limited control of it.

- On the other hand, we do have "handles" to control the internal cost of production, such as the cost of feedstock, energy, hydrogen, catalysts, automation, etc.

How do we control internal costs of production? We develop simplified econometric models. For example, for an oil refinery, we develop "tiered" or hierarchical simulation models, such as Refinery LP, multi-blend planning & scheduling tools, and single blend optimizers for actual physical control of gasoline properties.

A “Refinery LP” (jargon for refinery operation planning optimization) uses simplified models of the various process units, and prices/costs for all aspects of operation, including feedstocks, energy, assumed gasoline selling prices, etc. The output of the simulation is a BUSINESS PLAN, which has operating targets for the process units, and critically, the economics of the “refining business” in terms of Gross Refining Margin (GRM), and the internal cost of production, known as “Marginal Prices”, e.g. the internal cost to make one barrel of reformate.

From a gasoline blending point of view, some of the “handles” we have are:

- How many grades of gasoline should we make? 1, 2, or 10? Only conventional or also reformulated (has environmental specs). All domestic, or also export, e.g. to Latin and South America, and West Africa??

- Reformer severity: this control the octane of a valuable, high octane, low vapor pressure blend component called reformate. We can increase the octane by increasing the severity of the reaction at a cost of increased hydrogen consumption and decreased catalyst life and run-time of the process unit, and vice-versa

- Ethanol boosts gasoline octane by 1 to 4 octane numbers, and is relatively cheap. This could help confidently lower reformer octane…It also affects the octane-barrel balance of refinery production. Is this reflected in the Refinery LP model?

- Butane is a cheap by-product, has very good octane but very high vapor pressure, which is BAD for Summer reformulated gasoline since it increase the gasoline VOC emissions. However, it is not Voodoo!!! If you have the numbers, you can precisely calculate what the effect is, and add cheap Butane without “blowing” your environmental specs. Again, is this reflected in the Refinery LP?

- Nature can be perverse….Some of the critical properties, such as the octane number, vapor pressure, and distillation temperatures are non-linear, that is, 1+1 does not equal 2, but varies with the gasoline blend composition. Why is this important? Because if we use a linear approximation, we might make an error in predicting gasoline octane, let’s say, by one octane number, so instead of making 87 octane regular gasoline, to be on the safe side, we make 87+1=88 octane gasoline, but we sell it for the price of 87. This is called octane giveaway, and could cost a refiner $10 to $20 million a year easily. By using precise non-linear models for octanes, we can calculate much more precisely and accurately the gasoline blend octane to minimize giveaway and decrease the internal cost of production. Again, are the non-linearity of expensive properties reflected in the Refinery LP?

4. Modeling Blending Optimization with Equations

A simplified Gasoline blending optimization models uses 3 types of equations:

- **1) Material/volume balance**,
  - $\sum V_{ci} = V_{batch+heel}$
-

- **2) Quality balance** (remember, there are over 38 specs!, one equation for each!)
  - $\sum V_{ci} Q_{ij} + B_j + g_j = V_{batch+heel} Q_j$
  - where: V=volume of blend component i; Q=quality of component i, B=bias for nonlinear model error, G=giveaway of quality

- If the property **Q** is non-linear, e.g. octane, $RON_i=Ri+g1(Ri-Ra)^2+g2(Ri-Ra)(Oi-Oa)+g3(Oi-Oa)^2+g4[(Si-Sa)^2((S^2)a$, then we need a non-linear LP solver

– **3) Blend Profit**, maximize $P=\text{Sell Price}-C_t$

- where: P=profit; C=total cost of blend components

The blending problem has constraints, such as:

– Inventory (no infinite supply)
– Product Specifications (38 to 40 different specs for each grade!)
– Delivery time (liftings) - Sometimes !!!

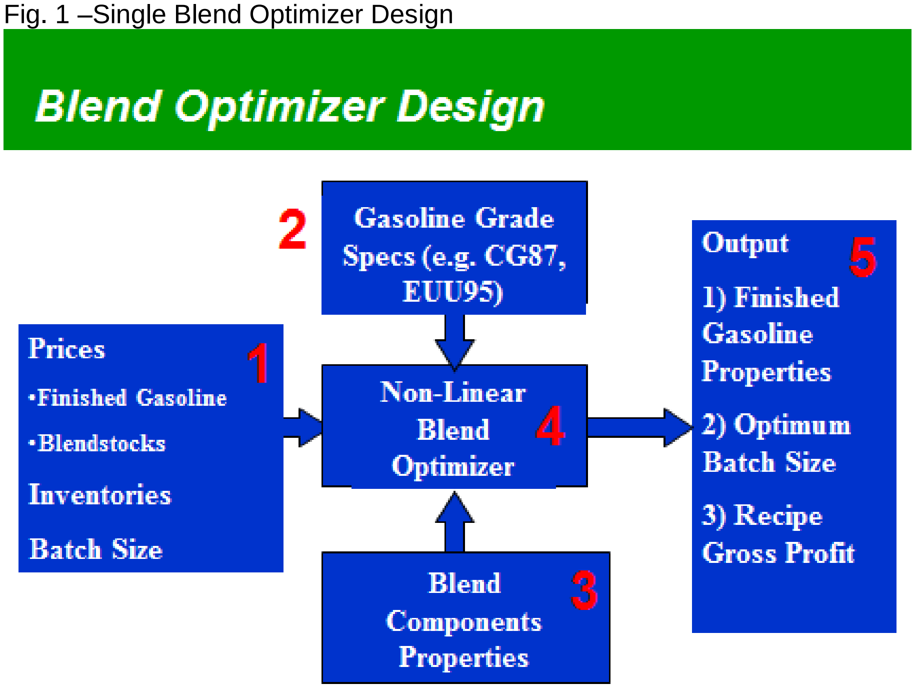
This results in a system of "n+2" simultaneous equations to be solved. If we have non-linear equations, then the solver has to be able to solve a system of non-linear equations…

– 1 for each "n" quality + volume balance plus profit equation

5. An Example of a Single Gasoline Blend Optimizer

To make it understandable, we will illustrate the design and use of a single gasoline blend optimizer. The design consists of five building blocks:

Fig. 1 –Single Blend Optimizer Design



1. Input block
   a. Prices for blend components and finished gasoline
   b. Available inventory of blend components
   c. Desired gasoline batch size
2. Gasoline specifications data base
   a. Specification of various gasoline grades, e.g. RBOB, CG, EU95, etc., up to 1023 specs
3. Blend components property data base

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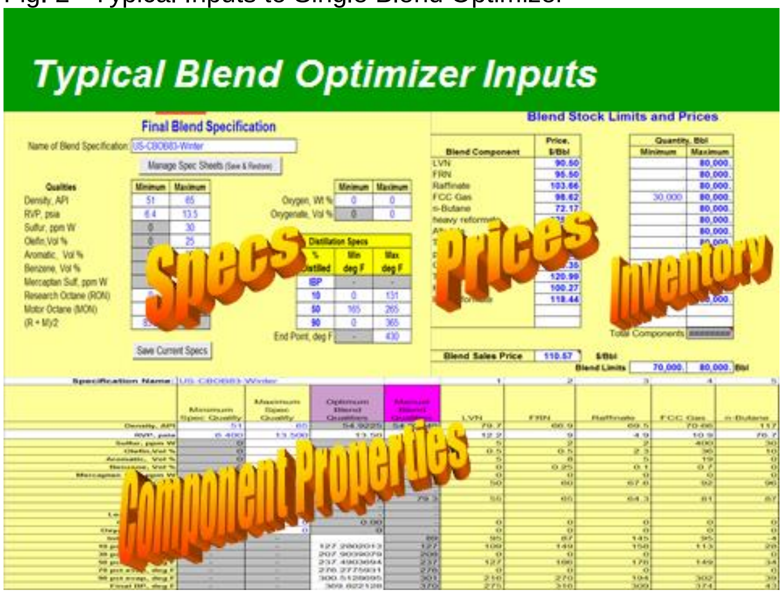
   a. Library of up to 1023 blend components and their properties
4. A Non-Linear Solver for optimization
   a. Uses MS Excel GRG2 non-linear solver
   b. Incorporates linear and non-linear property equations (e.g. octane)
5. Output block with the results
   a. Finished gasoline properties and spec constraints
   b. Optimum blend recipe
   c. Optimum or desired batch size
   d. Blend cost and profit

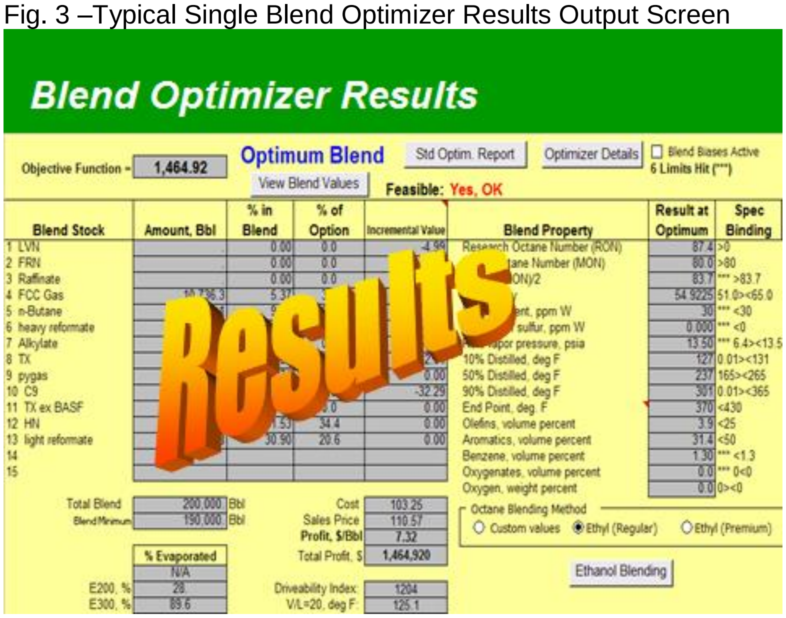
A screenshot of the input entry screens is shown in Fig. 2:

Fig. 2 –Typical Inputs to Single Blend Optimizer



The blend optimizer results screenshot is in Fig. 3

Fig. 3 –Typical Single Blend Optimizer Results Output Screen



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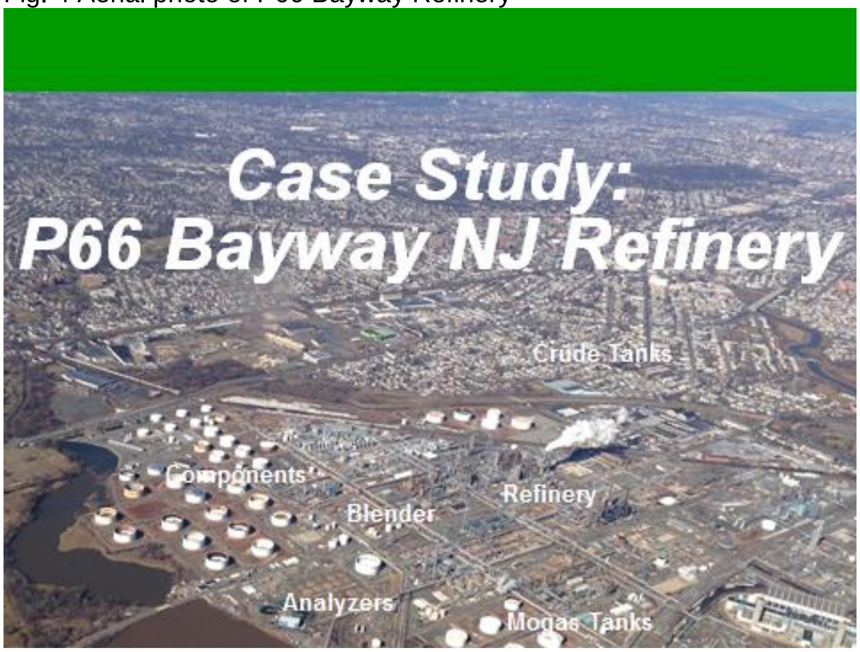
6. Case Study: US East Coast Gasoline Refinery

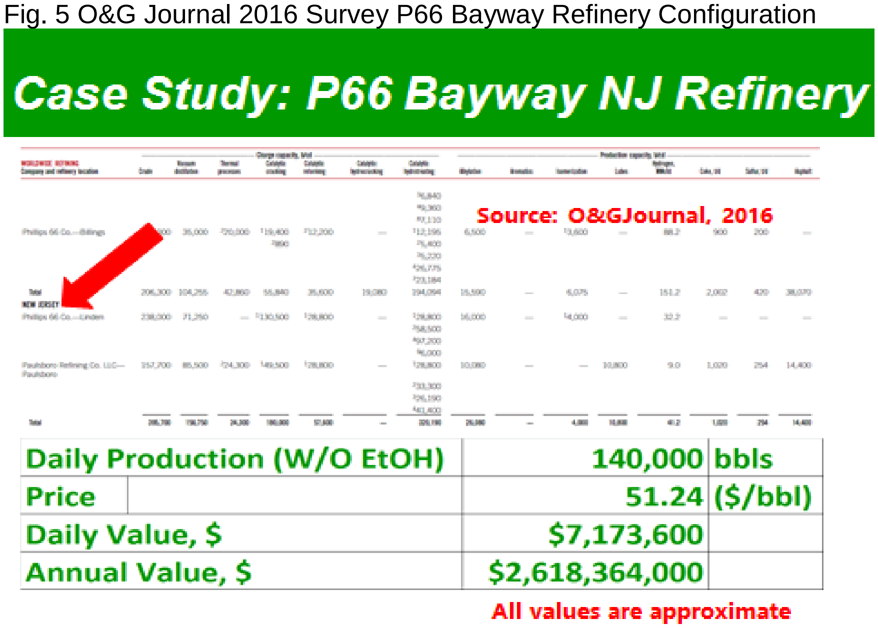
We will examine a refinery close to Rutgers University campus, P66 Bayway refinery, here in Linden, New Jersey, using public domain information from Oil & Gas Journal 2016 US refining data base [3] (www.ogjournal.com).

Fig. 4 Aerial photo of P66 Bayway Refinery



The Oil &Gas Journal annually-published world-wide refining data base shows active refinery configuration, process units and their nameplate capacity (Fig. 5). Using these numbers, the estimated cash flow of the value of gasoline produced at this particular refinery is about $2.6 Billion/year.

Fig. 5 O&G Journal 2016 Survey P66 Bayway Refinery Configuration



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The blend component production is split between use in gasoline blending and the adjacent chemical plant, and the estimated inventory available for gasoline blending is about 136-140 kBPD, without Ethanol, and about 150kBPD with Ethanol at ~10% by volume (see Fig. 6).

Fig. 6 P66 Bayway Refinery Estimated Gasoline Blendstocks Production

Component	Production-kBPD
Light Naphtha	24
FCC (Cat) Gas	65
Reformate	15
Isomerate	4
Alkylate	16
Butane	12
Ethanol	16
Total, kBPD	152

The question we ask ourselves is what is the best strategy to maximize gasoline profit given the estimated types and quantities of blendstocks produced. What choices do we have?:

- **How many grades to make**:
  - Sub-Octane Gas (CBOB's), Neat (Case 1)
  - Sub-Octane Gas (CBOB's) with 10% Ethanol (Case 2)
  - Conventional Gasoline (Case 3)
  - Premium Gasoline
  - Export Gasoline (Mexico, Brazil, West Africa, etc.)
- Adjusting reformer severity to lower octane (RON) from e.g. 105 RON to 99 RON
  - This produces slightly more reformate, decreases hydrogen consumption, and extends run length, all valuable economic impacts
  - Should we buy cheap light naphtha to make more gasoline exploiting the additional reformate?
- How can we maximize the use of Cheap Butane to make more gasoline sales?

To decide what to do, we use the blend optimizer described in section 5, and the approximate properties and prices for the blend components. This is myopic, because we cannot look at it, one grade at a time, and we need a tool like a refinery LP to look simultaneously at multiple blends of different grades over an extended time horizon, and examine the pro's and con's of the economic trade-offs….how clever we need to be on how allocate the produced blendstock streams…based on profit calculated using the marginal economics.

In the "myopic" example below, assuming that we make only conventional regular gasoline, CG87, (Fig.7) we are not using all production… so we need to find another home for surplus gasoline blendstock

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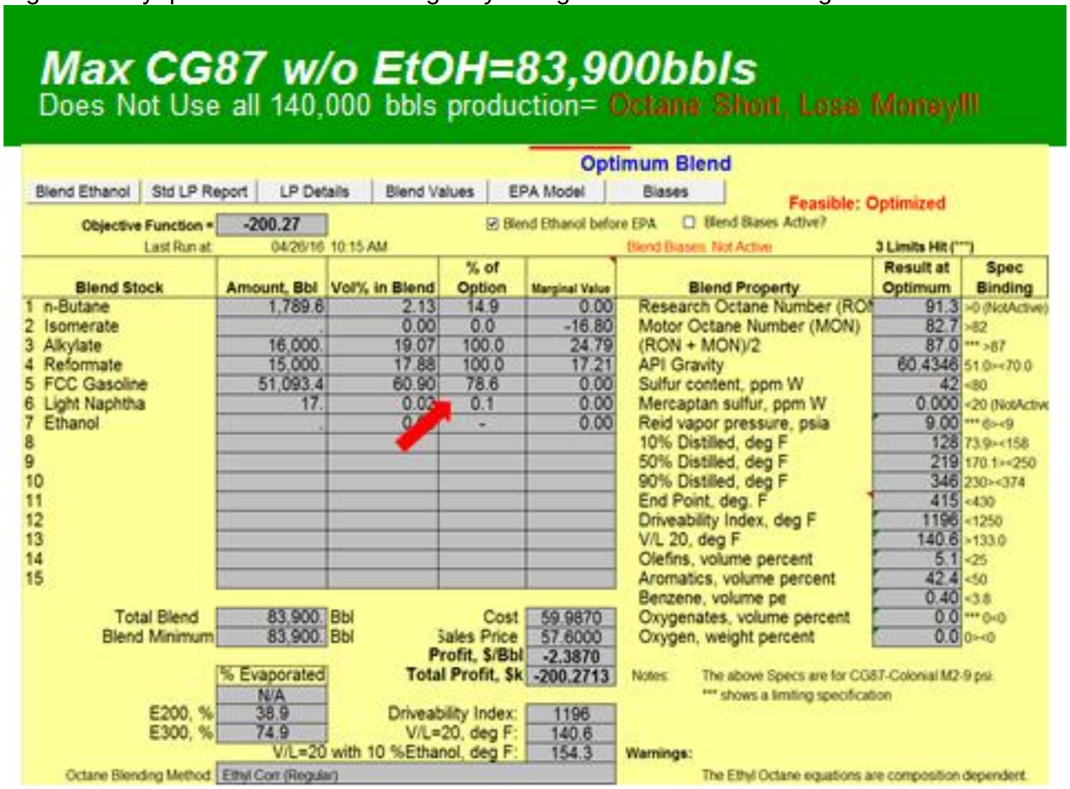
production. Choices might be selling of components, buying some components to make more gasoline, and combinations and permutations….

Fig. 7 A "myopic" case when making only one grade of conventional gasoline



Max CG87 w/o EtOH=83,900bbls
Does Not Use all 140,000 bbls production= Octane Short, Lose Money!!!

Optimum Blend

Blend Ethanol | Std LP Report | LP Details | Blend Values | EPA Model | Biases

Feasible: Optimized

Objective Function = -200.27   ☑ Blend Ethanol before EPA   ☐ Blend Biases Active?

Last Run at: 04/26/16 10:15 AM   Blend Biases: Not Active   3 Limits Hit (***)

	Blend Stock	Amount, Bbl	Vol% in Blend	% of Option	Marginal Value
1	n-Butane	1,789.6	2.13	14.9	0.00
2	Isomerate	.	0.00	0.0	-16.80
3	Alkylate	16,000.	19.07	100.0	24.79
4	Reformate	15,000.	17.88	100.0	17.21
5	FCC Gasoline	51,093.4	60.90	78.6	0.00
6	Light Naphtha	17.	0.02	0.1	0.00
7	Ethanol	.	0.	-	0.00
8					
9					
10					
11					
12					
13					
14					
15					

Blend Property	Result at Optimum	Spec Binding
Research Octane Number (RON	91.3	>0 (NotActive)
Motor Octane Number (MON)	82.7	>82
(RON + MON)/2	87.0	*** >87
API Gravity	60.4346	51.0>-<70.0
Sulfur content, ppm W	42	<80
Mercaptan sulfur, ppm W	0.000	<20 (NotActive
Reid vapor pressure, psia	9.00	*** 6>-<9
10% Distilled, deg F	128	73.9>-<158
50% Distilled, deg F	219	170.1>-<250
90% Distilled, deg F	346	230>-<374
End Point, deg. F	415	<430
Driveability Index, deg F	1196	<1250
V/L 20, deg F	140.6	>133.0
Olefins, volume percent	5.1	<25
Aromatics, volume percent	42.4	<50
Benzene, volume pe	0.40	<3.8
Oxygenates, volume percent	0.0	*** 0<0
Oxygen, weight percent	0.0	0>-<0

Total Blend 83,900. Bbl
Blend Minimum 83,900. Bbl

Cost 59.9870
Sales Price 57.6000
Profit, $/Bbl -2.3870
Total Profit, $k -200.2713

% Evaporated: N/A
E200, % 38.9
E300, % 74.9

Driveability Index: 1196
V/L=20, deg F: 140.6
V/L=20 with 10 %Ethanol, deg F: 154.3

Octane Blending Method: Ethyl Corr (Regular)

Notes: The above Specs are for CG87-Colonial M2-9 psi.
*** shows a limiting specification

Warnings:
The Ethyl Octane equations are composition dependent.

- If we make CBOB (case 1), we can use about 124 kBPD out of 140 kBPD production, and we lose about $6/bbl, or $766 k/day
- If we make conventional 87 octane gasoline blending CBOB with 10% Ethanol (case 2), we can use 139 kBPD out of 140 kBPD production, and we make about $0.42/bbl, or $58 k/day
- An alternative is to make RBOB (Reformulated Blendstock for Oxygenate Blending) with 10 vol% Ethanol. Because of tight Summer environmental specs, RBOB commands a premium price compared to conventional gasoline. We leave that as a test case for the seminar participants…
- If we make conventional 87 octane gasoline (case 3), we can use only about 84 kBPD out of 140 kBPD production, and we lose about $0.5/bbl, or $43 k/day. The loss will be greater if we cannot find a customer to buy the unused 54 kBPD production…This is a big headache…we need extra tank capacity to store the stuff, plus the cost of the inventory time-value-of-money!!!

Of course, we don't evaluate the economics myopically, one grade at a time, but we use a multi-grade multi-blend optimization model (e.g. built in a refinery LP) to decided what to make, and how much to make.

7. Conclusions

Optimization is a very powerful tool, allowing us to explicitly define profit of an industrial operation, in our example, production of gasoline, while maximizing it by manipulating variables (properties, inventory, specs) while respecting constraints, and taking into account non-linearities. It is also important not to be

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"greedy" and try to squeeze every drop, 60 to 70% is better than going overboard with complexity and never getting any results, because 100% of nothing…is nothing.

REFERENCES

[1] This Week in Petroleum; http://www.eia.gov/

[2] Seiver, D.S., "Optimized Gasoline Blending-A Standardized Approach", Valero Energy Presentation at Invensys Users Group, Jan. 2014

[3] Oil & Gas Journal; 2016 statistical surveys. http://www.ogj.com/index.html

About the author

Ara Barsamian has over 45 years of experience in the design and implementation of computer controlled gasoline blending systems around the world. He left an engineering teaching job at City University of New York for Exxon Research & Engineering Company, and never looked back. Afterwards, he worked for 3X Corporation, ABB, and Refinery Automation Institute. He loves blending, has published over 100 papers, and is a member of AIChE, ASTM, ISA, and IBIA. He can be reached at +1-973-644-2270 or jabarsa@refautom.com