OMEGA: An Improved Gasoline Blending System for Texaco

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Gasoline blending is a critical refinery operation. In 1980, Texaco began developing an improved, optimization based, decision support system for planning and scheduling its blending operations. The system, OMEGA, is implemented on personal computers and on larger computer systems. It relies on refinery data bases and on-line data acquisition and exploits detailed nonlinear models of gasoline attributes. Texaco uses OMEGA in all seven US refineries and its Canadian and Welsh refineries. Its benefits include an estimated $30 million annually, better quality control, improved planning and marketing information, and the ability to conduct a variety of what-if studies.

In the late 1970s, the oil companies began to experience downward pressures on profitability due to rapid and continuing changes in the external environment. Contributing factors included large variations in crude oil prices, lower quality crudes, and changing gasoline specifications mandated by new government regulations and by the changing requirements of automobile engines. Partially in response to these pressures, Texaco's computer and information systems department (now the information technology department or ITD) developed an improved on-line interactive gasoline blending system called OMEGA (optimization method for the estimation of gasoline attributes).
This new system consists of a data acquisition and query module, linear and nonlinear equations that predict output blend qualities given input stock qualities and volumes, the GRG2 nonlinear optimizer [Lasdon and Waren 1978], and an interactive user interface. The system enables a user to retrieve a variety of data from up-to-date refinery data bases and to interactively examine and modify the data after it is inserted into the OMEGA data base. This data include information on stock qualities and availability, as well as on blend specifications and demands. Furthermore, the user, by selecting appropriate menu options, can construct and solve a nonlinear optimization problem that determines how much of each stock to allocate to each blend so that all quality specifications are met, stock availability and blend demand constraints are satisfied, and the selected objective is optimized.

OMEGA was first installed in 1983 and is now used in all seven Texaco USA refineries and in two foreign plants. We chose the initial site, the Convent, Louisiana plant, because of its intermediate complexity and well-established data acquisition and in-line blending equipment. As OMEGA use was extended to other refineries, we encountered some resistance from users who had developed their own blending models or had noted differences between the blends recommended by the system and existing blending practice. Analysis showed that these differences were due to the increased accuracy of the OMEGA input data and model formulation, and to the improved robustness and accuracy of its optimizer. To promote its acceptance, we made trial runs of OMEGA using the existing blend compositions as a starting point. OMEGA's final solutions consistently showed a much higher profit. Subsequent blending and testing in the laboratory verified that the predicted blend qualities were more accurate than those generated by the older methods.

The economic benefits attained by using OMEGA are difficult to measure since market conditions and refinery configurations have changed since its installation. However, taking the compositions of blends used prior to OMEGA as initial values for OMEGA's optimizer, we have observed increases in gasoline profits of up to 30 percent for some batches. Using more conservative and refinery specific estimates of per batch benefits, Texaco estimates total ongoing economic gains stemming from OMEGA to be more than $30 million annually.

**Gasoline Blending**

Figure 1 is a simplified diagram of a refinery. The incoming crude oil contains a wide range of materials, from light ones, such as gasoline, to the heaviest ones, such as industrial fuel oil and asphalt. The crude oil is split into various component streams by distillation, which separates the components by boiling point ranges. Only a small portion of the distillate can go directly to gasoline blending. Most of the output streams from the distillation unit are sent to other processing units where the molecules are reformed to improve their quality or are cracked and recombined into lighter, more valuable ones. These resulting products, of widely different qualities, are then sent to

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Figure 1: Illustrated above is the flow of gasoline stocks through a refinery. Crude oil enters the crude units and is refined by the various processes into high quality gasoline stocks. The stocks are then blended to yield one of four grades of gasoline: regular leaded, unleaded, unleaded plus, and premium unleaded.

intermediate storage tanks from which they are blended into gasoline.

Refining involves many complex processing steps. Some of these activities are batch operations, and others involve continuous processing to transform crude oil into components that have greater value in the marketplace. Gasoline blending is primarily a batch process. It must, however, be synchronized with other batch processes and with continuous processes to maintain a balanced and profitable ongoing plant operation. In addition, the entire refinery operation needs to be coordinated with parallel activities in crude supply, marketing, and product distribution. Linear programming was applied to refinery scheduling and gasoline blending problems as early as the 1950s. See, for example, the books by Manne [1956] and Charnes and Cooper [1961].

Generally, Texaco develops aggregated plans at a wide functional horizon and decreases the horizon and increases the rigor of the analysis as the operating time frame draws closer. For example, it creates a monthly operating plan for the entire downstream operation of a regional subdivision of the company. This plan is based on simplified representations of each operating function. A linear programming model for the refinery is used as part of this process. The blending portion of this LP model is usually linear. On the other hand, the company supports the day-to-day scheduling of blending operations by a rigorous representation of the blending dynamics in the form of a nonlinear blending model.

Gasoline blending involves mixing a
variety of available stocks, along with various additives, to produce a set of required blends in an optimal fashion. The required blends are leaded regular, unleaded regular, unleaded plus, and super unleaded gasolines. The stocks are the intermediate products from the refinery, such as straight run gasoline from a distillation column, reformate from a reformer, and catalytic gasoline from a catalytic cracker. Lead and other octane enhancers, such as MMT, are some of the additives. Stocks are produced by one of the refinery process units and are stored in intermediate storage tanks. The selected stocks are blended together, either by an in-line blender or in a blend tank, to create the blends. The in-line blender periodically samples the blend and automatically tests the properties of the samples on-line. This information is used to adjust stock flow rates so that the blend will meet its quality specifications in spite of unanticipated fluctuations in the properties of the stocks. On occasion, as many as 15 stocks are blended to yield up to eight blends.

The qualities of the blend are determined by the qualities of the stocks. The blend qualities are the various blend attributes or properties that must be controlled for each blend. The optimization problem is to calculate the volume of each stock to be used in each blend, subject to availability constraints on each stock and demand and quality specifications for each blend, so that an appropriate objective function is optimized. As many as 14 different characteristics may be involved for each blend.

Typical stock properties include Reid vapor pressure, percent sulfur, percent aromatics, the temperatures at which various fractions of the blend boil off, octane indices including research, motor, and road octanes, and lead content (Figure 2). Equations relating blend qualities to stock qualities and volumes are presented in more detail in the appendix. Blend volatilities and octanes are nonlinear functions of the input stock qualities, whereas most of the other qualities are assumed to blend linearly with respect to volume fractions.

<table>
<thead>
<tr>
<th>STOCK QUALITIES</th>
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<tbody>
<tr>
<td>SELECT THE STOCK NUMBER WANTED: 1</td>
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<tr>
<td>PRESS H FOR HELP</td>
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<table>
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<th>STOCK NAME: HOBG</th>
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</table>

Figure 2: The stock qualities screen is a typical OMEGA input screen. The user selects the stock desired by entering a stock number. If the refinery has data acquisition facilities, the properties will be filled in automatically and the user can review the properties modifying any erroneous readings. Without data acquisition capabilities the user enters the correct properties.
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For a problem with \( l \) stocks and \( j \) blends, there are \( J(l+3) \) decision variables and approximately \( 16J + I \) constraints. For an analysis involving seven input stocks and four output blends, the optimization problem will consist of 40 variables (most with bounds) and 71 constraints.

Currently, blending models that incorporate nonlinearities are single period ones. Those models used for operations planning include the blending requirements for an entire month in the problem definition. In this case, neither the sequence of the blending operations nor their impact on intermediate inventory is considered. This type of run is generally

**OMEGA is now used in all seven Texaco USA refineries and in two foreign plants.**

made once a month, or more often if there is a marked departure of the boundary values (stock production, blend off-take) from the values assumed in the previous analysis. Those models used for actual blending consider only a single blend at any one time, but the model may be used in this mode on a daily basis.

**The Evolution of Blending Models at Texaco**

By the early 1960s Texaco had installed computers in some of its refineries. These computers were used primarily for accounting, data acquisition, process control, and refinery modeling. During this period, gasoline blend compositions were provided by a combination of trial and error, experience, and the use of average response tables. As computers became more readily available, mathematical models were developed to aid the gasoline blender. These mathematical models attempted to predict the characteristics of each blend based on the properties of the stocks available and on the blend proportions suggested by the blender. They were quite useful for case studies to augment the blender’s intuition and experience.

During the 1960s, computer hardware and software advanced significantly. Refinery engineers began to use linear programming to solve large planning models that included linearized blending submodels. In 1965, IBM introduced POP II, their process optimization program for nonlinear optimization, which used a successive linear programming algorithm to solve nonlinear programming problems [Smith 1965]. Shortly thereafter, Texaco developed a gasoline blending optimization system, GOP, which used the POP II program.

Investigation of the blending process at Texaco in the early 1980s revealed that the GOP system was not being used routinely by all refineries. Further study uncovered several problems that inhibited its use. The blending model used in GOP was not sufficiently accurate, and therefore the actual blends frequently did not meet their specifications. The FORTRAN code was also difficult to maintain. In addition, during the optimization process, the POP II algorithm would often stop at an infeasible solution. Moreover, not only was POP II very slow but its results appeared inconsistent as it would often stop at different values if started from different
starting points. This reduced confidence in the results.

The refining industry had also changed significantly during the 1970s. The average qualities of the crude oils available for refining were different than for previously available crudes (that is, they were heavier and had a higher weight percent of sulfur). This led to changes in refinery processing and to gasoline stocks with inferior qualities. At the same time, automobile manufacturers modified automobile engines so that they required higher octane fuels. The greatest impact, however, came from new government regulations. For example, the EPA mandated that lead use was to be reduced from 1.7 grams per gallon of total gasoline produced in 1975 to 0.8 grams in 1978. Since adding lead to the blend increases its octane, other means for meeting octane specifications were required and they typically increased the cost. These changes resulted in blend specifications being more difficult and more expensive to meet.

These more restrictive blend specifications, together with the changes in input stock qualities, resulted in POP II being even more unreliable. As a result, in 1980 Texaco began looking for other nonlinear optimization packages. Experience with POP II indicated that a method that first tried to satisfy all constraints and then maintained feasibility while improving the objective would be desirable. This suggested that reduced gradient algorithms might be effective.

One of the authors (Brenner) had attended a TIMS/ORSA meeting in 1981, at which Lasdon presented results on the performance of the generalized reduced gradient algorithm, GRG2, developed by Lasdon and Waren [1978]. This presentation led him to test GRG2. Test results verified that the algorithm was very robust and reliable. The ability to imbed it within a larger system by calling it as a subroutine was also important, since Texaco planned to build a new interactive blending system around the optimizer. Based on these factors, Texaco decided to use GRG2 as the foundation for a new and improved gasoline blending and optimization system.

The Development of OMEGA

Texaco began developing their new nonlinear gasoline blending optimization system, OMEGA, early in 1982. The first phase in this development was to replace POP II with GRG2 as the optimizer. The second phase was to improve the accuracy of the mathematical blending model being used. This model is used to calculate the output blend properties, other constraint values, and the value of the objective function. The equations in the new model were obtained from several sources: the GOP model, literature in the public domain, and internal Texaco studies. The software that generates the model was developed by Texaco's information technology department (ITD), using structured programming techniques. ITD is also responsible for maintaining the software. Interfacing the model to the optimizer was such a straightforward process that it was not regarded as a separate phase in the OMEGA development.

The next development phase was to design and implement the user interface. Texaco defined ease of use as a top
priority. Hence, OMEGA was developed as a full screen, menu-driven, interactive system. All inputs and options are entered through the menus.

Because of the large amount of input data, we also developed automatic data acquisition capabilities. We designed the system to interface with Texaco's refinery data acquisition systems, which automatically record tank inventories and production flow rates and identify stock volumes available for blending. OMEGA can also access laboratory test results on stock properties, which are also recorded in the data acquisition system. This ability to access the data acquisition system has proven to be a useful feature for the day-to-day blending of gasoline.

Once OMEGA was running, the next development phase was to tune the GRG2 optimizer and the model. Prior to tuning, OMEGA was occasionally starting-point dependent. We adjusted the GRG2 parameters, made minor modifications to GRG2, and scaled the OMEGA model. These actions effectively eliminated the problem of starting-point dependency. During this phase, we also extended the system to allow the user to start from the previous optimum solution. In practice, however, the stocks available for blending vary so much from day to day that the blender usually enters a new set of starting values for each run.

**Installation**

The next phase in the OMEGA implementation program was its installation at an actual refinery. It is very important that the first installation be successful in order to promote acceptance at other sites. Much thought went into selecting the first site. A refinery with in-line gasoline blending was desirable since this gives the user better control over the blend qualities during the blending process. Texaco felt that the initial refinery needed to have engineers and nontechnical personnel (the blenders) who were familiar with computers so that the we

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would not have to deal with problems associated with introducing computers in addition to the problems of installing a new blending system. Automatic data-acquisition facilities were also desirable to take advantage of OMEGA's automatic data-capture capabilities. In addition, we chose a refinery that was neither the most complex nor the simplest so that it would be truly representative.

The first installation of OMEGA was successful. Texaco then began installing OMEGA in all of its refineries in the United States. We encountered some resistance from various engineers and blenders. Many of the refineries had developed and maintained their own models, and the engineers argued that they already had a tool that worked for their purposes (the "not invented here" syndrome). Another perceived difficulty was that the OMEGA output blends differed in composition from the products that they were blending. The blenders had obtained the recipes for these output blends from the GOP system, from case
studies using other models, from trial and error, or from experience.

Comparative analysis of OMEGA blend compositions and the compositions predicted by the plant personnel led to the identification of several factors that contributed to their differences. One factor was that the OMEGA model is more accurate than the GOP model. Another is that the OMEGA optimizer finds optimal solutions more often than the POP II algorithm did and also gives more accurate results, so it responds well to small changes in stock composition. Another factor adding to the difference in blend recipes is that, in the past, POP II would stop at an infeasible point due to the inaccuracies in the model or because the POP II algorithm would go infeasible during optimization and would not become feasible again. This made it more difficult for the blenders to determine a feasible recipe that satisfied the required specifications. As a result, blends would often have to be rebled. During the reblanding process, stocks were manually added until the specifications were satisfied, leading to blends that were more costly than necessary.

Identifying these factors contributed to the gradual acceptance of OMEGA. However, it took three years before OMEGA was widely accepted. As the engineers used OMEGA more frequently, they gained more confidence in it. Personnel at the first refinery installation were extremely helpful in answering questions and providing aid to engineers at the other refineries. Furthermore, OMEGA was very easy to use and significantly more flexible than the other procedures, and this also contributed to its increasing popularity.

One of the features that promoted the use of OMEGA was the inclusion of a quality giveaway objective. Usually this quality is octane. Prior to using OMEGA, the finished blends would often overshoot or exceed some of their specifications. For example, a blend specification might require a minimum of 87 MON (Motor Octane Number) whereas the actual blend might have an 87.5 MON. This excess octane in the output blend increases costs over what could be achieved with no giveaway. Since most of the components do not have well-established market prices, it is very difficult to obtain an accurate cost or profit objective. Such objectives, therefore, tend to be used for planning studies, and other objectives are used for daily blending.

Previously the giveaway had not been considered to be very significant. However, as governmental regulations lowered the amount of lead allowed in regular gasoline, octane specifications became more difficult to meet. The government also required new automobiles to use unleaded gasoline. With these new regulations, the higher octane stocks with good volatility qualities were in more demand. The value of the higher octane blending stocks began to increase greatly, and the price of gasoline varied a great deal during this period of time. Giveaway had
become a significant factor in determining blending profitability.

To convince the blenders that the previous method of blending was not economical, we made a trial run of OMEGA at these refineries to show what additional profit could be gained. The composition of the last batch of gasoline blended at the refinery without using OMEGA was fed into OMEGA as the starting point. OMEGA was then run in optimization mode, typically giving a much more profitable final blend recipe. The blender was encouraged to blend, in the laboratory, a sample of gasoline following the optimal blend composition reported by OMEGA and to test the sample to verify that the blend did indeed meet its specifications. The successful outcome of this process provided convincing evidence of OMEGA’s value.

OMEGA is now installed in all seven of Texaco’s domestic refineries and in its refineries in Pembroke, Wales and in Nanticoke, Canada. It currently runs on IBM mainframes, on Data General supermini computers, and on IBM personal computers. CPU times vary greatly from case to case. A typical planning problem with 40 variables and 71 constraints run on a IBM 3090 computer takes about five seconds, and as an operational problem run on a Data General MV8000 in a refinery takes about two minutes.

**Maintenance**

As mentioned earlier, OMEGA is maintained centrally by Texaco’s information technology department. It is constantly being updated and extended. When new governmental regulations are invoked, modifications are made to OMEGA to reflect these regulations. In recent years, for example, the EPA required a lead phasedown for regular leaded gasoline. This made it necessary to modify the OMEGA model so that it would be more accurate for these lower levels of lead.

The new model also reflects the fact that the laboratories are now testing the octane response of blend stocks to lead at lower levels. This phasedown also led to the use of other octane improvers, such as MMT and oxygenates, which had to be incorporated into the model.

Other business changes also led to model modifications. For instance, refinery upgrades and the refining of different crudes (heavier crudes with higher sulphur contents) have resulted in blend stocks with significantly different properties than those previously encountered. The quality equations in the model had to be extrapolated to predict the resulting blend qualities.

OMEGA is continually modified to reflect changes in refinery operations. Even during the installation phase, as new refineries began to use OMEGA, differences in refineries required changes to the system. For example, some refineries needed to account for the effects of heels. A heel is the blend left in a blend tank after pumping out all of the blend that is normally pumped from the tank. Hence, the composition of the next blend to be added to the tank should take into account the qualities and quantity of the heel. In addition, some refineries required that special consideration be given to mix stocks. Mix stocks occur when several stocks are fed into the same storage tank prior to blending. Modifications were made to
OMEGA to accommodate both heeds and mix stocks.

When Texaco began installing OMEGA in their foreign refineries, we had to make additional changes to handle the different requirements for each country appropriately. Furthermore, enhancements to OMEGA are constantly needed to enable it to answer the new and unanticipated what-if questions refinery engineers ask.

The User Interface

Simple interactive input makes OMEGA very easy to use. All input data can be entered manually. However, OMEGA can interface with the refinery data acquisition system to retrieve blend specifications, stock-flow rates, stock inventory, and stock qualities. The user specifies a file name for input data when he or she first enters the system, and this name is displayed in the lower left-hand corner of the main menu. The main menu allows the user to choose any of seven input screens or one of the two automatic data selection screens. The user can access stock qualities, stock availabilities, blend specifications, blend requirements, starting values and limits, optimization options, automatic stock selection, automatic blend specifications selection, and several other options from this menu. Figure 2 shows the stock qualities screen, which is typical of most of the Omega screens.

Several features aid the user in performing planning functions. By choosing option 7 from the main menu, the user obtains the optimization options screen. From this screen, the user can select one of the following objective functions: maximum profit per barrel, maximum profit, minimum octane (quality) giveaway, or a weighted linear combination of profit and quality giveaway. The objective function chosen depends on the problem that is being solved and the characteristics of the refinery. If the stocks available in the refinery have relatively low octane numbers, then the octane giveaway objective function would be desirable for daily blending. If superior quality stocks are prevalent, then profit would be used. The

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profit objective is usually used for planning studies.

One of the more difficult problems encountered while blending gasoline stocks is how to ensure that the holdover stocks will be easily blendable. Holdover stocks are those input stocks that are left over after blending all of the products actually required by Texaco's current blending plan. Since OMEGA looks at only one time period, if the objective function is solely to maximize profit then the holdover might contain only stocks with inferior characteristics. To counter this tendency to use all of the higher grade stocks in the required blends, the user can select quality giveaway as the objective function. The user can also place limits on the amount of a particular stock that can be used in a blend and on the amount that can be left in inventory.

Another option is available to ensure that the leftover stock will be blendable.
The user specifies that all of the leftover stock must be blended into holdover blends with specified qualities. This allows the objective function to be optimized subject to both the quality constraints for today's required blends and the quality constraints for future blends (the holdover blends). Of course, this option can sharply increase problem size. The user can also specify the maximum amount of any specific holdover blend based on marketing information for the next time period.

Each refinery uses a different set of features depending on the stocks it has available for blending. These vary depending on the refinery configuration and on the particular crudes being refined. The availability and ease of use of the many features in OMEGA has provided the engineers and blenders with a powerful and very useful tool.

The Uniqueness of OMEGA

Many companies in the process industries have used nonlinear programming to perform on-line and off-line optimization. Applications vary in scope from individual sections of equipment within a process unit to plant-wide optimization including many interconnected units. Organizations reporting such experience include Shell [Gochenour and Preston 1987; Cutler and Perry 1983] and Chevron [Justice 1985]. In particular, Chevron has developed an interactive nonlinear blending system called GINO (Gasoline Inline Optimization) and is using it in several refineries. To the best of our knowledge, no one has developed a dedicated blending system with OMEGA's scope and features nor has anyone integrated such a system so thoroughly into their blending operations both for medium-range planning and short-term scheduling. Recently, Texaco has begun licensing OMEGA for use by other companies.

OMEGA Usage

Each refinery uses OMEGA to varying degrees and for various purposes depending on the needs, complexity, and configuration of the refinery. We will describe how the system is typically used, starting from medium range (monthly) planning, and proceeding to real-time blending.

On a monthly basis, refineries use OMEGA to develop a gasoline blending plan for the month. The plan is generated five to 10 days before the first of the month. Planning is performed on a monthly basis because the overall refinery planning models, which select the refinery crude slate and determine the anticipated gasoline stock volumes and stock qualities that will be produced, are run monthly, and because tax considerations make it desirable to minimize refinery stock inventories on the first of the month.

The refinery planning model's projected blending stock volumes are input to OMEGA. The stock qualities used in OMEGA are either the stock properties projected by the refinery-planning model or the actual average stock properties from the previous month. This varies among the refineries depending on which approach the planner believes is the most accurate.

The blending planner typically calculates three to eight blends in a single OMEGA run. Each blend is one of the four grades of gasoline that Texaco
manufactures. Often the blender will create two blends for each grade, a blend for the fixed volume of the grade that has been committed during the planning process, called a "required" blend, and a blend for any additional amount of that grade that the refinery can make, a "holoover" blend. The blender may also create a blend for each method by which a grade of gasoline is to be transported. For example, the blender may create one unleaded regular blend for the pipeline and another for truck pickup at a terminal. This separation gives the blender a better conceptual view of the blending operation, and it is often required: a pipeline may deliver the gasoline grade to a geographical region that has different quality specifications than the region being supplied by truck or barge.

The refinery planning model's blend compositions are input into OMEGA as starting values. OMEGA is then executed with a 'blend-all' feature for all stocks except butane. The blend-all feature requires that all of the available stock must be blended into some blend. Butane is excluded because it is such an economical blending stock that as much will be blended as is allowed by the quality constraints and more will be purchased if refinery volumes are not adequate. The blend-all feature minimizes end-of-month stock inventories and prevents OMEGA from using all the high quality stocks and leaving only the low quality stocks behind.

OMEGA then creates a monthly blending plan. This blending plan displays the grade splits, that is, the proportion that each blend constitutes of the total gasoline output. This plan is reviewed to determine if it is reasonable (not all of the possible real-world constraints are part of the blending model). If not, additional constraints are placed on the blend compositions or the blend volumes, and OMEGA is rerun.

Once a reasonable blending plan has been developed, the marketing department is contacted to discuss the resulting grade splits. Marketing takes into account the current state of the gasoline market and the production by alternate refining sources and may make suggestions for modifying the grade splits. A finalized blending plan will then be developed for the month. The refinery uses the blending plan grade splits to determine gasoline production targets for the month.

Individual blend compositions are determined by running OMEGA with the current actual stock flow rates and stock qualities. The grade splits for OMEGA may either be fixed according to the monthly blend plan or may be allowed to vary from the plan by a small percentage (usually five percent). Low stock percentages, however, are not permitted because of in-line blender limitations. The resulting compositions are then given to the scheduler or blender. As the month progresses, these blend recipes may have to be recalculated because the availability and qualities of stock may deviate from what was expected. Normally this recalculation occurs every seven to 15
days.

The scheduler determines when each of the grades will be blended. This scheduling must take into consideration when specific blends are to be delivered, current actual stock and blend tank inventories, and the in-line blender capacity. If a particular stock inventory is low, the scheduler may rerun OMEGA, restricting the use of this limited stock and allowing the others to vary from the blend recipe by plus or minus some small amount, typically five percent.

The scheduler gives the blender the daily blend recipe(s). The blender uses the recipe(s) to determine the flow rates for the input stocks. During blending, these rates must be adjusted to account for variations in stock properties as well as any minor inaccuracies in OMEGA’s model. Many factors can account for variations in stock qualities. For example, if stock is being withdrawn from a stock tank and added to the tank at the same time, stratification can occur in the tank, causing different levels to have different characteristics.

For batch blending after the blend is completed, quality assurance personnel take a sample and test it in the laboratory. If the blend does not meet a particular specification, additional stock(s) must be added, perhaps two or three times. This process can take one or two days.

With in-line blending, product qualities are measured automatically by on-line testing equipment. The testing interval ranges from seven to 20 minutes, depending on the specific attribute under test. If some property specifications are not met, the stock rates are adjusted. In most refineries with in-line blenders, a single stock will be adjusted for each unsatisfied specification. The scheduler or planner will tell the blender which stock rate, the so-called trim stock, to adjust for each quality.

In Texaco’s Nanticoke (Canada) refinery, the in-line blender has a process control computer associated with it. The partial derivatives of the objective function and of the active constraints are downloaded from OMEGA to the process control computer. This linearized model is used to adjust the stock flow rates on-line to meet the quality specifications while minimizing quality giveaway.

Benefits

OMEGA has now been installed in all seven of Texaco’s US refineries, as well as in its refineries in Pembroke, Wales and in Nanticoke, Canada. Over the last three years, these refineries have steadily increased their usage of OMEGA. This commitment to installation and expanded use of OMEGA is clear evidence that OMEGA is perceived as contributing to overall profitability. However the extent of this contribution is very difficult to measure. Even ignoring indirect and nonquantifiable benefits, its direct contribution to profit is not clear since there are so many changing factors involved in profitability. Market demand, profit margins, and even the refineries themselves have changed. Some refineries, for example, have added in-line blenders and stock tank mixers that are used to help minimize stratification. These continuing changes make it difficult to determine the actual dollar benefit directly attributable to daily blending with OMEGA.
In an effort to get the best possible measure of actual benefits, we tried several different methods. The first method, a comparison of the blend compositions that the blenders used without OMEGA to those used with OMEGA, was carried out at three refineries prior to installing OMEGA. The blenders were asked to collect information about all of the blends that they blended during a one-week period. This information included stock availability, stock qualities, blend-quality specifications, blend demands, blend values, and the blend compositions that were used.

This information was input into OMEGA. The blenders' blend compositions were used as starting values and OMEGA was allowed to optimize. The resulting profit for the OMEGA blend was compared to that obtained by the blender. In some batches OMEGA achieved as much as a 30 percent increase in profits. The average increase in profit was approximately five percent of the gross gasoline revenue.

In late 1984, in an attempt to verify these results, we asked each refinery that was using OMEGA heavily to provide its own estimates of the benefits achieved with OMEGA. The refineries estimated the benefits as a direct increase in profit. The profit estimates ranged from two to five percent of gross gasoline revenues, with some of the refineries specifying a range within this interval. These estimates correspond to a range of 1.0 to 2.5 cents per gallon in benefits.

However, recognizing that all of the theoretical benefits from an optimization system cannot be realized in real life, we have taken half of the most conservative estimate, reducing the benefit to 0.5 cents per gallon. Applying this to all of Texaco's domestic gasoline production, six billion gallons of gasoline annually, we estimate the benefits at 30 million dollars per year.

More difficult to quantify are the intangible benefits. If OMEGA is used to calculate blending recipes, fewer blends fail to meet their quality specifications. OMEGA's more reliable gasoline grade split estimates provide significant aid to those developing marketing strategies and refinery production targets. They also provide good octane blending index estimates for the linear programming refinery planning model.

Another source of intangible benefits is the use of OMEGA for what-if case studies. These studies are performed for various reasons, such as economic analysis of refinery improvement projects and analysis of how proposed governmental regulations would affect Texaco. No attempt was made to quantify the benefits for such case studies, although some refinery and manufacturing headquarters personnel believe that these benefits are as significant as those for daily blending.

In addition, OMEGA's features have provided Texaco with capabilities to do things that were not possible with the previous blending system. One feature allows the user to deal with mix stocks. This is useful in refineries with complex piping or in plants that have a large number of stocks. The excess blend feature enables the refinery to consider new grades of gasoline, such as unleaded plus and 10 percent ethanol gasoline, to
determine whether they are profitable to produce. The ability to specify a minimum and maximum volume of stock and blend inventory, along with the blend-all feature, gives the user substantially more control of inventory. With OMEGA the user can easily incorporate lead/MMT premixes and other future additives. OMEGA’s features make it easy and quick to explore new avenues of profitability for a refinery; such exploration was difficult or essentially impossible without OMEGA.

Acknowledgment

The authors acknowledge the significant contribution of Mr. B. J. Purinton to OMEGA. Mr. Purinton was involved in the development of GOP (OMEGA’s predecessor) and was responsible for developing OMEGA’s model. In addition, he was the project leader in charge of OMEGA from its conception until he retired from Texaco in 1985.

APPENDIX

The qualities of a blend are determined by the qualities of the stocks used in the blend. The optimization problem is to determine the volume of each input stock in each blend so that the objective function is optimized subject to the output blends satisfying their quality specifications, stock availability constraints, and blend demand constraints. Most of the blend quality equations are of the following form:

\[ V_{f_{ij}} = \frac{X_{oi}}{\left( \sum_{i=1}^{I} X_{oi} \right)} \]

\[ Q_{j,k}(x) = \sum_{i=1}^{I} (S_{ik} \cdot V_{f_{ij}}) \]

where

- \( X_{oi} \) are the independent variables, the amount of stock \( i \) in blend \( j \);
- \( S_{k} \) is the \( k \)th quality index for stock \( i \);
- \( Q_{j,k} \) is the \( k \)th quality index for blend \( j \);
- \( V_{f_{ij}} \) is the volume fraction of stock \( i \) in blend \( j \);
- \( x \) is a vector with \textit{ith} component \( X_{oi} \).

Such weighted averages of stock qualities have been used in linear specification blending models for many years. However, the distillation and octane blending equations have more complex forms. There are many published forms for these qualities, usually containing exponentials, logarithms, and quadratic and other interaction terms. Two commonly used equations follow:

**Distillation Blending**

\[ D_{j,k}(x) = b_k + c_k \ln \left( \sum_{i=1}^{I} (S_{ik} \cdot V_{f_{ij}}) \right) \]

where \( b_k \) and \( c_k \) are constants, \( S_{ik} \) is the \( k \)th distillation point for stock \( i \), \( D_{j,k} \) is the \( k \)th distillation point for blend \( j \).

**Octane Blending**

\[ \text{Oct}_{j,k}(x) = a_k \left( \sum_{i=1}^{I} (V_{f_{ij}} \cdot b_i) - \sum_{i=1}^{I} (V_{f_{ij}} \cdot c_i)^2 \right) + d_k \left( \sum_{i=1}^{I} (V_{f_{ij}} \cdot e_i) - \left( \sum_{i=1}^{I} V_{f_{ij}} \cdot f_i \right)^2 \right) + g_k \sum_{i=1}^{I} \{ (V_{f_{ij}} \cdot h_i) - (V_{f_{ij}} \cdot j_i) \cdot (V_{f_{ij}} \cdot k_i) \} \]

where

- \( a_k \), \( d_k \), and \( g_k \) are constants,
- \( b_i, c_i, e_i, f_i, h_i, j_i, \) and \( k_i \) are quality indexes for stock \( i \);
- \( \text{Oct}_{j,k} \) are the various octane indexes for blend \( j \).
The optimization problem then becomes

\[
\begin{align*}
\min \text{ or } \max f(x) \\
\text{subject to} \\
Q_{j,k} & \leq Q_{j,k}(x) \leq \overline{Q}_{j,k}, \text{ for all } j; k = 1, \ldots, 7; \\
D_{j,k} & \leq D_{j,k}(x) \leq \overline{D}_{j,k}, \text{ for all } j; k = 1, \ldots, 4; \\
\text{Oct} & \leq \text{Oct}(x), \text{ for all } j; k = 1, 2, 3; \\
\sum_i X_{ij} & \leq \sum_i \overline{X}_{ij}, \text{ for all } i; \\
Bv & \leq \sum_i X_{ij} \leq \overline{Bv}, \text{ for all } j; \\
X_{ij} & \leq \overline{X}_{ij}, \text{ for all } j; i = \text{the index for grams of lead in blend } j.
\end{align*}
\]

Symbols with underbars (overbars) are specified lower (upper) limits and $Sv$ and $Bv$ are the limits on stock and blend volumes, respectively.

References


Mike Killien, the acting vice-president of Texaco USA, describes OMEGA as "A state-of-the-art blending system, which includes the unique GRG2 nonlinear optimizer, an online database, and an interactive user interface. OMEGA was first installed in 1983 and is now used in all seven of Texaco's refineries in the United States and in two international refineries. Texaco estimates the total ongoing economic benefits from OMEGA to be more than thirty million dollars annually.

"In an effort to measure the benefits, before OMEGA was installed, a comparison of the blend compositions used by the blenders without the help of OMEGA was made to those suggested by OMEGA. In some batches the resulting profit for the OMEGA blend was as much as 30 percent greater. The average increase in profit was approximately five percent of the gross gasoline revenue or about 2.5 cents per gallon. If this calculation were applied to all the gasoline manufactured by Texaco USA last year the profit increase would be approximately 150 million dollars.

"In late 1984 refineries that were using OMEGA heavily were asked to provide their own estimates of the benefits achieved with OMEGA. Two refineries gave an estimate of the increased value of the product blended. The Louisiana refinery estimated this increase in value to be between two and four percent. This gives
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a range of from 1.0 to 2.5 cents per gallon in benefits. However recognizing that all of the theoretical benefits from a computer optimizer cannot be realized in real life, we have taken half of the most conservative estimate, reducing the benefit to 0.5 cents per gallon. Applying this to all of Texaco’s domestic gasoline production, six billion gallons of gasoline annually, the benefits are 30 million dollars per year.

"With OMEGA fewer blends fail to meet their quality specifications because the blend property predictions are better. OMEGA's more reliable gasoline grade split estimates result in better marketing strategies as well as better refinery production targets. The result of these better planning numbers are fewer late trading changes and better control of inventories. OMEGA also provides good octane blending index estimates which are used in the refinery LP planning models thus improving those models. Another source of intangible benefits is the use of OMEGA for "what-if" case studies. No attempt was made to quantify the benefits for such case studies although some refinery and manufacturing headquarters personnel believe that these benefits are as significant as those for daily blending."