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Achievement in Operations Research

Optimizing Chevron's Refineries

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Chevron has developed a software modeling tool that its seven company-owned refineries use to select the most profitable raw materials, evaluate product options, optimize refinery processes, and promote efficient capital investments. The tool is a linear program with distributive recursion mathematics, which Chevron uses in operations and strategic planning. Over the past 30-plus years, the company has continually improved this application of operations research, and its complementary and supporting systems and business processes, and they are now deeply embedded into the fabric of Chevron's downstream business of reliably and efficiently supplying products to our customers. The value that these efforts bring to Chevron now approaches $1 billion annually. We estimate that the cumulative value to Chevron over the past three decades is approximately $10 billion.

Keywords: petroleum industry; oil refinery management; decision support; optimization; distributive recursion linear programming; successive linear programming; pooling problem.

Chevron, one of the world's leading integrated energy companies, conducts business worldwide. It is involved in virtually every facet of the energy industry. In its upstream organization, it explores for and produces crude oil and natural gas. In its downstream organization, it refines and markets transportation fuels, chemicals, and lubricants. In this paper, we describe Petro, our refinery planning tool, which has made and continues to make a huge contribution to the effectiveness of Chevron's downstream organization.

Refineries convert crude oil into products, which fuel the world. A large portion of these products are transportation fuels, including gasoline for automobiles, jet fuel for airplanes, and diesel fuel for trucks and railcars. Refineries can also produce lubricating oils and a lower-value fuel oil product used to fuel ships.

Most of the feed to our refining facilities, called crude oil, comes from oil-producing fields worldwide. Multiple crude oils, each with its own set of qualities (e.g., sulfur content, hydrogen content) go through a number of refinery process units to convert crude oil into products. In these processes, they are mixed or pooled in feed and intermediate tanks, and in pipes at multiple points in the refining process.

The proportions in which they are pooled, the process units they go through, and the conditions under which they operate subsequently determine the refinery's end products and the value of these products. To maximize the value of the refining process, Petro considers all the crude oils and quantities available, refining options (e.g., quantities pooled and process units), and current prices for the products it manufactures.

Background on Refining

One fundamental difference between crude oil, which enters the refinery, and products, which are the output from the refinery, is that crude oil contains a wide array of hydrocarbon (hydrogen plus carbon) molecules, which boil from room temperature to well over 1,000 degrees Fahrenheit (F), whereas products boil over a much narrower temperature range. For example, gasoline boils between room temperature and 350 degrees F, jet fuel between 300 and 500 degrees F, and diesel fuel between 350 and 650 degrees F. Crude oil also contains appreciable amounts of sulfur, whereas most product specifications call for very low levels of sulfur. Tracking qualities like these for each crude stream in a refinery is critical in modeling refinery processes.

Typical refinery process units include:

• Distillation units: Primary crude oil processing units separate the oil into narrow product boiling ranges via a process called distillation.

• Cracking units: The part of the crude oil that boils too high to make products is cracked (a process that breaks heavy hydrocarbon molecules into lighter ones) to the product boiling ranges. Cracking units include hydrocracking, fluid catalytic cracking, and coking.

• Treating units: In a process called hydrotreating, distilled and cracked stocks are then purified to remove most of their sulfur and increase their hydrogen content. Hydrogen is either purchased or manufactured to support the hydrotreating process.

• Reforming: Gasoline production requires a special process called reforming to meet octane specification (e.g., the 87 octane number of regular unleaded gasoline at a typical service station).

In addition, products from individual processing units are blended into final products. Specialty products, such as lubricating oils and chemicals, require additional processing.

Although most refineries contain the process units described previously, refineries differ significantly in the size and capability of their process units, and also have other types of process units not mentioned in this paper. Of the roughly 500 refineries in the world, no two refineries are alike. Some refineries are configured to upgrade difficult-to-process crude oil into products through multiple process units. Other refineries with fewer process units rely on easier-to-process crude oil to make their products. Refinery capability is a term used to describe the combination of size, number, and flexibility of process units. Moreover, the capabilities of any given refinery will change many times throughout the year as process units are idled for routine maintenance or as unplanned disruptions occur.

No two crude oil fields, which supply the roughly 80 million barrels per day of the world's oil demand, are alike. The amount of material within each product's boiling range and the amount of sulfur and hydrogen the oil contains vary considerably from field to field. These are just a few of the many qualities that influence the complexity of refining a crude oil. The price of each crude oil is a function of its quality. Crude oils that are easier to refine (e.g., have more hydrocarbon material in the gasoline, jet, and diesel boiling ranges, and contain lower sulfur) command a price premium in the market relative to crude oils that require considerable cracking and treating. These quality-based price adjustments change with market prices and are influenced by the availability of competing crudes.

Challenges

The challenge to maximize enterprise value in Chevron's crude-to-customer supply chain is multifaceted. On an ongoing basis, it involves decisions such as:

• which crude oils to buy for the refinery;

• which products (gasoline, jet fuel, diesel, lubricants, fuel oil) to manufacture; and

• how to operate the refinery to make the best use of Chevron's assets.

Information used to make these decisions is dynamic: availability of crude oil varies, demand for products change, market prices fluctuate, refinery capability changes, and product quality requirements change, although less frequently. On a longer-term basis, capital investments unlock opportunities to further maximize enterprise value, such as building a new lubricants plant.

For Chevron and our competitors in the industry, finding the best fit between crude oil and refining capability creates both a challenge and an opportunity (Klingman et al. 1987). Because crude oil costs typically represent 70–80 percent of our total costs, acquiring crudes that economically fit our ability to refine them has a great deal of value. For example, some refineries have more capacity to process high-sulfur crude than others. Given that Chevron processes almost two million barrels of crude oil per day, finding an improvement that saves just one cent per barrel is worth millions of dollars annually to the company. Finding the right answer to the crude oil optimization opportunity involves achieving a high degree of competence in all of the following areas: maintaining accurate crude oil-quality data (assays), configuring an optimization tool that accurately represents the range of capability of the refinery in a way that results in quick convergence to optimality, training and retaining skilled modelers and knowledgeable analysts, and maintaining a robust reporting system. If one or more of these challenges is not met, the value of Petro and the crude selection process is diminished.

Refinery capability and volatility in product prices create a product optimization opportunity, similar to the crude oil purchase optimization opportunity. Refineries can shift the amount of products they make by altering the operating conditions (e.g., temperature and pressure) of their process units. For example, a refinery can make more diesel fuel, but less jet fuel, if prices dictate this shift. However, prices alone are not enough to drive a shift in the products we make. Analysts must also understand the refinery's costs associated with making each product. Because diesel product specifications require low sulfur content, diesel must be hydrotreated, whereas jet fuel does not require this additional processing. The additional costs of hydrotreating must be weighed against the price difference to understand which product is more profitable. Comparing a refinery's costs to produce products relative to market prices for those products is an ongoing optimization opportunity that requires competency in many of the same areas as crude oil optimization.

Because of scheduling and transportation time, the crude oil optimization and buying processes take place two–four months before the crude oil is processed and products are sold. As we get closer to the day on which the crude oils are processed, a number of important steps take place to assure that the optimization plans, which we carried out at crude selection time, dovetail with and contribute effectively to the instructions that guide the daily operation of each refinery. During this time, we update the optimization case (a case contains the inputs, outputs, and model formulation associated with a given optimal solution) to reflect changes (e.g., in prices, refinery capability, or demand).

Given the breadth and complexity of our refining capability, covering the salient properties within a model is a challenge. Our goal is to closely model the economic impacts of all the process units to the extent that we understand these impacts, either based on measured performance or on detailed process simulation models. This includes not only the separation, treating, and cracking processes, but also the blending processes. In building a Petro model, we strive to address this complexity, while also providing timely and understandable answers for our analysts. If multiple models are required to address all the opportunities associated with refining, then close communication—either organizationally or through technology—is needed to avoid fragmented, and therefore suboptimal, management of the business.

The example in Figure 1 illustrates some of the challenges and opportunities associated with product and refinery optimization that our analysts face every day. It involves a balance between (1) the average sulfur content of the streams produced in the refinery, which are blended into gasoline, and (2) the requirement that the gasoline products stay below sulfur specifications. This is a real-world problem inasmuch as Chevron has and continues to devote a good deal of effort to determining how to best meet stricter sulfur specifications on gasoline and other products

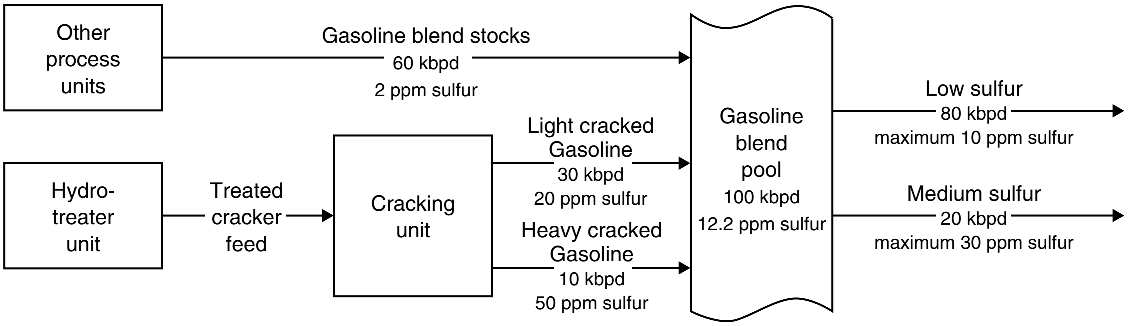

Figure 1: In this example, a refinery needs to complement its low-sulfur gasoline with some medium-sulfur gasoline to balance the sulfur in the gasoline blend stocks. Other options also exist to achieve this balance (kbpd = 1,000 barrels per day, ppm = parts per million).

associated with more stringent air quality standards. Figure 1 shows several process units and intermediate streams in a refinery. The cracking unit breaks the heavy molecules in the treated cracker feed into two gasoline boiling-range streams, light cracked gasoline and heavy cracked gasoline, which are pooled with the gasoline blend stocks. This example illustrates that several approaches are available to meet the sulfur specification, depending on how we route the intermediate streams or operate the process units.

In Figure 1, the average sulfur of the 100,000-barrels-per-day streams, which are blended into gasoline, is 12.2 parts per million (ppm). This is too high to meet the 10 ppm sulfur specification on the low-sulfur gasoline. To maintain a feasible operating posture, one solution is to produce and sell 20,000 barrels per day of medium-sulfur gasoline, which has a maximum sulfur specification of 30 ppm.

Because we sell the medium-sulfur gasoline at a lower price, we have an incentive to reduce its volume and increase the volume of the low-sulfur gasoline. Several refinery solutions exist to allow us to achieve this goal. One option might be to blend the high-sulfur, heavy cracked gasoline into jet fuel because the jet sulfur specification allows it. Another option, which reduces the sulfur of the cracked gasoline, would be to lower the sulfur on the hydrotreater product by increasing catalyst temperatures; however, this would reduce the run life of the hydrotreater catalyst. If a minimum run life needs to be maintained to achieve a preset maintenance schedule, it may be possible to reclaim the run life by buying crude oil, which is easier to process in the hydrotreater. If we cannot economically justify changing the crude oil quality to maintain a minimum catalyst life, capital investment solutions might include purchasing a more effective catalyst or investing in an additional reactor. To find the optimum solution among these options, we must design and configure our tool to simultaneously evaluate all the solutions.

Solutions Considered and Selected

In the 1950s, oil companies started to explore the use of linear programming (LP) methods for refinery crude oil selection (Garvin et al. 1957, Bodington and Baker 1990). By the 1970s, these programs were mainframe based, but their input format was not intuitive; the cases took several hours to solve and the solutions were given in thick stacks of computer paper. However, the biggest challenge was that the LP model was incapable of representing refinery processing. Because different crudes have significantly different refining characteristics, the models must track the chemical and physical changes of each crude through each of the downstream process units, even as crudes and intermediate streams are pooled in common pipes or tanks (see Figure 2). Because each crude oil contributes different qualities, the conventional LP modeler needs to create a whole new array of streams each time a new crude oil is considered. This is both impractical and inaccurate. In the example in Figure 2, low- and high-sulfur feeds are mixed and distilled,

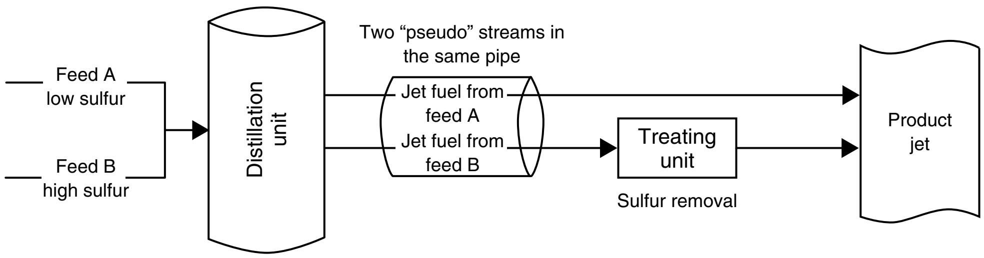

Figure 2: This figure illustrates the problem of using conventional LP for modeling refineries.

producing a single stream with a blended-sulfur quality. With conventional LP, this stream must be modeled as two pseudostreams to distinguish the sulfur quality differences of the two feed sources. The LP sees an opportunity to bypass the low-sulfur part of the stream around the treater. However, this might not be possible because the blended sulfur necessitates treating the entire stream. This failure to address the mixing of qualities is called the pooling problem.

The industry needed to solve the pooling problem. During the 1970s, a number of solutions were considered, including a technique called successive linear programming (SLP), which solves nonlinear optimization problems using a sequence of linear programs (Zhang et al. 1985, Baker and Lasdon 1985). Chevron and other energy companies, including Texaco, used SLP primarily in the gasoline blending arena (DeWitt et al. 1989, Rigby et al. 1995); however, Chevron did not use it for refinery-wide modeling.

In the late 1970s, Chevron worked with modeling industry consultants from Haverly Systems. They offered a potential solution for refinery-wide modeling by applying an iterative technique called distributive recursion LP, a technique that enabled refinery-stream modeling to be consistent with the actual stream flow. Stream properties were pooled from the sources and distributed to each destination in proportion to the amount of the stream going to that destination. Although some have argued that SLP and distributive recursion are similar (Lasdon and Joffe 1990), Chevron decided to improve its ability to use distributive recursion because of its success in using it for refinery modeling. During 1978 and 1979, Chevron modified its LP system to incorporate distributive recursion and rewrote the optimization model of its El Segundo, California refinery, applying this new method throughout the refinery model (White and Trierwiler 1980); this was the first time the industry used distributive recursion to model an entire refinery. Because the matrix architecture of distributive recursion connects the entire refinery optimization from crude oil to product, and matrix coefficient changes have a clear link to an upstream cause, the technique worked well. To get realistic answers using the recursive model, the cost or value of each quality of each stream must be linked upstream to the value of the crude and downstream through the processing units to the value of the products (White and Trierwiler 1980). Other methods did not have this capability and did not fare as well.

Accurately modeling the relationship between the stream going into the process unit and the product yields, which depend on feed qualities and process unit conditions, is critical to optimization. The relationships are captured in a delta base model for each process unit. Modelers develop these relationships from simulation models or plant data. The delta base model translates these nonlinear relationships into piecewise linear models. For each process unit in the refinery, if input streams vary from the base conditions, the delta base model calculates the resulting differences in the outputs. These delta base models are included in the LP configuration.

The LP must have initial best-guess qualities of the pooled stream to leverage the delta-base model and solve the optimization. However, the composition of the pooled stream is not known until after the solver has completed one complete iteration. This is where recursion is employed. The analyst provides a first guess at the properties of the pool, and IBM's LP CPLEX solver finds a solution for the matrix.

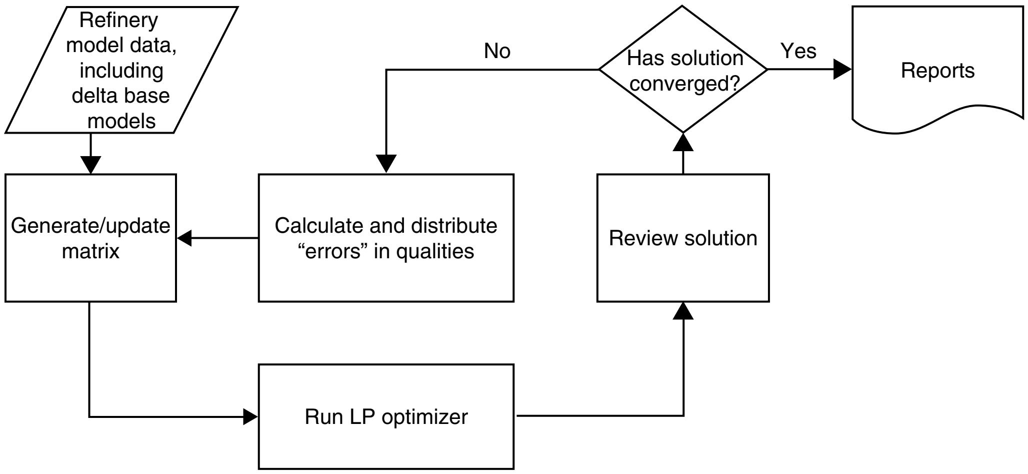

Figure 3: This diagram shows how the refinery LP model is updated based on the difference between the original composition anticipated and the composition that results from the (tentative) solution.

Petro calculates the difference between the composition of the actual solution and the composition of the guess and tracks these errors. In distributive recursion, this error is distributed to all the destinations in the refinery for that stream, the matrix is adjusted, and the LP model is solved again. This is repeated until the solution converges to within a prespecified tolerance. The appendix illustrates a simplified version of Petro's underlying LP model. Figure 3 shows the iterative process of using the LP model with recursion. Prejudging the qualities of the pooled streams enables us to model nonlinear constraints as linear, and the solution converges rapidly.

Many of the process units in refining behave nonlinearly. The ability to handle nonlinear problems allows recursive LP to replicate the results of process simulation models. Developing recursive LP modeling methods to closely represent the refinery's reactive and separation processes over a wide range of feed and process conditions has been a priority for Chevron for some time. Achieving this creates a powerful linkage between the external drivers of refinery profitability (e.g., crude oil availability, product demands, prices) and the specifics of how to best set operating conditions of process units in response to these drivers. Distributive recursion enables us to handle these nonlinearities associated with refining in a way that allows us to achieve optimized solutions in a reasonable amount of time.

Distributive recursion LP has and continues to be the dominant method used within the industry to optimize refineries. If developed and used properly, it delivers a combination of speed, flexibility, and accuracy. Models can be quickly added or updated to reflect changes in feeds, products, and refinery capability. For Chevron, combining this operations research (OR) technique with (1) our modeling techniques, (2) Petro, which facilitates modeling, case setup, interpretation, and communication of results, and (3) solid work processes and training programs allows the analysts who use Petro daily to explore planning alternatives and deliver timely answers to guide the operation of Chevron's seven wholly-owned refineries.

Implementation and Evolution of Petro

Chevron implemented a mainframe version of Petro during the late 1970s and early 1980s. Over the past 30-plus years, we have continually developed and improved Petro and its complementary and supporting systems and work processes. In the following sections, we describe how we implemented Petro and discuss its relationship to surrounding systems and work processes.

As personal computer (PC) technology improved, we moved Petro from mainframes to PCs. We also moved from bulk properties to molecule-based methods to better model gasoline and chemical processing. This improved accuracy, but also increased model sizes; however, because of advances in computing capability, solve times did not increase. In the early 1990s, we improved our recursion techniques to improve solution convergence.

In 2002, Chevron started to make extensive use of multiperiod and tank inventory modeling to optimize around refinery unit shutdowns, thanks to a steady improvement in solve times for handling the larger matrices. Using the larger multiperiod models has been routine in preparing our refinery plans for some time (Kutz 2004, Rigby et al. 1995).

A key driver for multiperiod modeling is that it provides a more accurate picture of the refinery's capabilities by including storage options. Given that our refineries may have as many as 20 process units, one or more of those units is not operating much of the time. When a process unit is not running, its feed is often stored in tanks until the unit starts back up. Before multiperiod modeling, planners used single-period optimization (Kutz 2004), a time-consuming iterative approach. Multiperiod modeling makes the plans that result from the optimization much easier for the operations personnel to execute. This match between the plans and the current state of the refinery has resulted in a closer relationship between the analysts and the operations personnel who are responsible for planning and execution.

In 2002, Chevron and Invensys signed an agreement that gave Invensys global marketing rights for the Petro refinery planning system. Under the agreement, Chevron would continue Petro's development activities, and Invensys would assume global marketing, implementation, and support responsibilities for new third-party customers. Presently, there are 10 external Petro licensees.

In 2004, we started to use multirefinery modeling, primarily for the purpose of optimizing a region, for example, our two California refineries in El Segundo and Richmond. Optimizing a region can entail transporting streams from one refinery to another or balancing regional product demands between refineries. We also use multirefinery models to evaluate capital projects that impact an entire region. Creating multirefinery cases is as easy as copying and pasting individual refinery cases into the multirefinery model, in which linkages between the refineries have been modeled. Petro's architecture allows this copy-and-paste step to happen in less than three minutes.

From 2006 to 2009, to include more of the supply chain in the optimization space, we developed a version of Petro to link refinery operations to product terminals and trading centers.

Recent innovations for Petro include developing (1) a system to share Petro results via the Web with all the stakeholders who manage the supply chain, and (2) developing a reporting system that supports advanced graphics. In addition, we enhanced Petro's models to incorporate our highly nonlinear catalyst aging correlations and improved Petro's ability to represent the real-world constraints in our hydrocracking process units. A catalyst is used up over time and its usage is based on feed rate, feed qualities, and unit temperature.

Over the past three decades, we have implemented a number of technological and organizational improvements to enhance Petro's value to our business. Some of the improvements involve Petro itself; others involve its supporting infrastructure or complementary systems. As Figure 4 shows, Petro has become more integrated with other tools and data sources. Within Chevron, people at all levels of the organization understand the need to continually improve how we address these challenges, and we will continue to make improvements to maintain our competitiveness.

Petro Support and Model Building

Today Petro has two main components of support: maintaining the information technology (IT) systems and building and updating models. Chevron staffs each with people who have specialized skill sets. The success and extent to which Petro is used can be attributed to the creative efforts of these people who have tailored Petro to meet the specific needs of refinery optimization.

A centralized team of IT employees who are conversant in programming techniques provide Petro's global system support. The IT group updates the Petro platform once or twice a year. These updates, which impact all Petro refinery models, usually involve minor changes to the existing core system. Typical updates include incorporating the latest

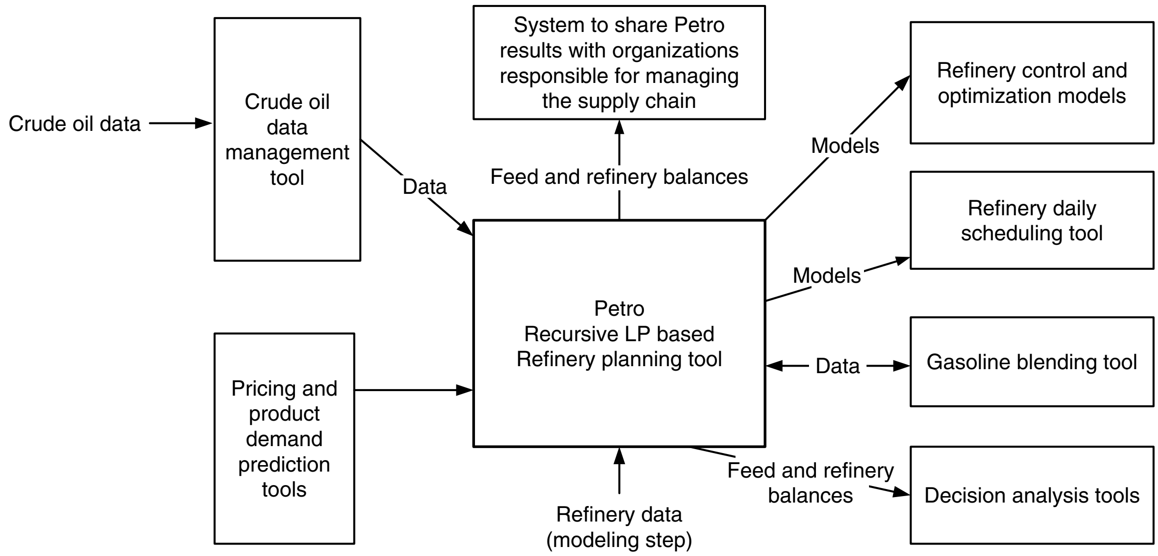

Figure 4: This diagram shows the extensive number of information technology applications and associated business processes to which Petro connects. This integration greatly enhances Petro's value to Chevron.

CPLEX optimizer or new reports and navigation features, which are usually requested by our most experienced Petro analysts.

The refinery modeling and data aspects are supported by local modelers; these modelers support the Petro analysts who address business questions. Modelers are usually chemical engineers who have worked in our engineering organization and understand the refining process.

The initial development of a new Petro model for a refinery is a significant undertaking. It typically involves a project team commissioned by management and takes several months to complete. The project team includes (1) people very familiar with the refinery processing, (2) at least one analyst who will use the model after it has been completed, and (3) an experienced Petro modeler. A detailed picture of the refinery's feeds, products, stream routings, and processing capability must be in place before modeling can begin. Once each stream is defined, modelers determine what qualities need to be ascribed to that stream for proper valuation. This is a critical step because stream qualities either determine the product mix that stream will produce when it is processed, or determine whether the stream will be suitable to blend into a final product stream. Of the 10,000 equations associated with a single-period complex refinery model, about 70 percent involve cascading stream-quality information from crude oil to finished products. Like all big projects, we conduct the initial development in stages, and thoroughly test each stage before moving on to the next stage. When developing new models, modelers leverage the existing model architecture and adhere to common conventions for standardization.

Modelers must also make periodic updates to an existing refinery model. These updates are triggered by any need to add new variables or equations. This occurs when we add a new stream destination, add a new process unit or make structural changes to an existing one, or add a new crude oil or product. Some minor structural changes may take only minutes to complete. Other changes are extensive and may be based on insights developed from intensive evaluation of the process unit data. Model updates always involve refreshing the crude oil data (i.e., crude assay).

Our modeling philosophy is to develop detailed, robust process unit models that cover a wide range of capabilities on the unit. This helps us to initialize the model over a wide range of conditions needed to reflect systematic shifts in refinery operations.

If we know that a particular process unit will change frequently and unpredictably, modelers will build unique, tunable equations, allowing analysts to make adjustments without requiring a model update. New model rollouts involve reviewing the changes with analysts, creating the multiperiod and multirefinery models (frequently a 10-minute exercise, given the architecture of the Petro system), and ensuring the connections to supporting systems work properly. To avoid supporting multiple models, we build each Petro model to serve multiple business needs. Once the rollout is complete, our goal is to have all the analysts switch to the new model as quickly as possible.

Petro Analysts

Analysts in various parts of the organization use Petro to identify the most economical mix of crude oils, product make, and refinery operations for given period(s).

Analysts who focus on optimizing our crude selection sit in our trading hubs next to crude oil traders. They perform analyses to evaluate the economics of crude cargos for 30–50 types of crude oil, depending on the refinery. A crude oil's value, which is based on the products it makes less its market price and delivery cost, results in that crude's margin. The hierarchy of highest-margin crude oils is then communicated to traders who negotiate and purchase the highest-margin crudes.

Additional analysts focus on optimizing the amount of each product to produce. For a given crude oil, the final refinery yield of gasoline, jet, diesel, and fuel oil can be altered by changing refinery operating conditions and routings. The cost to produce each product varies as a result of processing requirements to meet product specifications. In addition to working on understanding production costs, analysts work with product traders to understand product prices and the ability to buy and sell products in the market. By running Petro, the analysts generate an optimized product mix, which they communicate to product traders who negotiate and secure buys and sells on behalf of the refinery. Because refinery locations and marketing capabilities do not always align, Chevron buys products from other companies (and these companies buy from us) to minimize transportation costs. Like crude oil optimization, product optimization occurs prior to actual production to allow time for blending and scheduling.

Another group of analysts works to reoptimize the refinery in the very short term. Because crude oils have been purchased and the product mix has been set, the optimization is only internal to the refinery with fewer degrees of freedom.

Using Petro has been a good way for analysts to broaden their careers beyond the technical into the business realm of refining and the integration of the operations, business processes, and organizations.

To ensure that the plans that are developed using Petro can be executed, our scheduling tools and our online control system use the same models as our planning tool. This enables us to maintain as much consistency as possible between planning and execution. The reporting and case-sharing capabilities allow the organizations in the value chain to collaborate.

Chevron has used Petro analysis in discussions with both the U.S. Environmental Protection Agency and the California Air Resources Board to analyze fuel blends under consideration for future regulations. Analysts using Petro identified gasoline formulations that had less impact on supply and cost, while still meeting environmental targets.

In addition to optimization, Petro analysts provide key inputs into our business planning and strategic processes. The objectives of our business planning process are to forecast earnings, plan maintenance timing, and align capital projects with planned maintenance for the upcoming three years. Petro analysts generate information on the type and amount of crude oil the refineries buy and products they make (known as refinery balances) to help guide this process.

We prepare strategic plans, which include estimates of long-term capital requirements to respond to forecasted changes in product specifications or to improve the business. Petro modelers support this effort by adding the process units we are considering (e.g., a hyrdotreater to remove sulfur) to the model. Analysts then generate refinery balances with agreed-upon refinery capabilities, crude oil availability, and product demands and prices from our long-term forecasting group. Refinery balances developed from Petro are then passed to our decision analysis (DA) models that analyze uncertainties and develop probabilistic project economics. Chevron's culture supports the application of DA tools, including tornado diagrams and decision trees; in 2010, we were awarded the INFORMS Decision Analysis Practice Award (Neal et al. 2010). We have also used Petro to provide multirefinery stock balances for this analysis when proposed investments have regional implications.

More About Petro

Today, Chevron has a refinery model for each of its seven company-owned refineries. Analysts load the model from a server onto their PCs. Petro's spreadsheet interface allows them to load the data from tables and databases, set up the cases, run the model, and review the analysis. Petro utilities manage cases and allow cases to be stored or shared. Under the spreadsheet interface, *C* code generates the matrix for the linear model, which is solved using IBM's CPLEX solver. After each LP iteration, the tool compares the solution with the original "guess," distributes the differences in the qualities to downstream processes, updates the matrix, reruns the LP model, and repeats this process until the objective function converges. The *C* code then translates the output matrix into spreadsheet-like updatable reports for exporting to Microsoft Excel.

Given the size and complexity of the models and Chevron's philosophy that analysts must thoroughly understand the cases with which they work, highly developed reporting is essential for successful implementation. Petro's reporting capabilities are one of its distinguishing characteristics relative to other products used in the industry.

Reports help analysts to understand (1) how the case is set up (inputs), and (2) what message the case is delivering (outputs). Several of the reports are designed to allow the analyst to compare and understand what is happening between a base case and alternative cases. The reports help analysts identify the root cause of the elements that drive the solution. These can be interactive reports in which they review and mark up reports to define the next case or scenario. This unique feature fits naturally with the way analysts approach a problem.

Petro model sizes and solve times

Model type	Equations (thousands)	Coefficients (thousands)	Solve time (seconds)
Single-period models	5–10	100–200	5
Multirefinery models	10–20	200–400	10
Multiperiod models	25–100	500–2,000	60

Table 1: This table reports model size and typical PC solve time of the single-period, multirefinery, and multiperiod Petro models Chevron runs today.

Multiperiod models require a new class of reports to foster an understanding of what is happening from period to period in a given case, allowing an analyst to compare and understand what is happening between two cases.

Considering the thousands of stream qualities and hundreds of destinations associated with even single-period refinery optimization (see Table 1) and the nonlinear aspects of the problem, models need to be constructed and set up to achieve reasonable solutions that converge. Over the years, we have been fairly successful in this regard—most solutions converge. Modeling techniques play a key role, and most of our experienced modelers recognize and develop a work-around to any model construction that is likely to cause convergence problems. We also train analysts on how to correct the convergence problems they encounter by restricting flexibility (i.e., where refinery streams can go) in a targeted way. Stable algorithms, with fewer nonconverged cases, fewer local optima problems, and faster solve speeds, are features that distinguish Petro from other approaches to refinery planning.

One obvious challenge to implementing Petro involves managing the quality of the data that we incorporate into the model. Two key sources of data are crude oil qualities (assays) and refinery process unit performance. Over the past 10 years, we have made great strides in improving the data from both sources.

Our crude oil assay team now has a monitoring and grading system, which automatically triggers an update to the server versions of the models' crude qualities in our assay management system if the qualities of a specific crude oil fall below a specific score on a standard test. This has resulted in much more frequent updates of the crude oil qualities. These updates are passed to Petro in less than two minutes via an interface to our crude assay management system. A Petro report keeps track of needed assay updates to ensure we are using the latest information.

Other initiatives to improve the tracking of refinery performance have also contributed to refinery optimization. We now closely track our crude oil mixing in tanks, our process unit stream rates and properties, and our product-blending recipes. We also track the performance of the catalysts that promote the many chemical reactions that take place in refining. These data are readily available through Microsoft Excel spreadsheets for use in model updates and tuning.

The improved fidelity of the data has made validating model accuracy easier. It has set a higher standard for our modelers, which represents our deeper understanding of refinery processing. Fortunately, distributive recursion LP, in the hands of our highly skilled modelers, has been able to replicate the complexity of our units with remarkable accuracy, while still maintaining solve-time performance and convergence. Rigorous model validation has improved Petro's credibility with refinery engineers and management.

Organizational Capability

Petro grows its organizational capability by developing the analysts who use the program. Each day, 25–30 analysts use it routinely. Petro analysts typically stay in their positions for only one to two years; therefore, they must quickly become proficient. A working knowledge of refinery economics, gained from being an analyst, is valued in many positions within Chevron; hence, the company tries to rotate many people through the analyst position. The capability management group actively manages this rotation to ensure that enough analysts are available to meet the immediate and longer-term business needs.

In addition to training classes, analysts send Petro cases on which they are working to senior analysts, who mentor them on how to frame the problems, develop solid cases, and analyze output reports. Petro's case management architecture, which allows case sharing via email and the use of screen-sharing software, makes this possible.

Managing tool support capability is essential to the long-term successful implementation of an OR program as complex as Petro. The modeler job is a challenging position to fill. Typically, a candidate for this job has worked for several years as a process engineer in refining and as an analyst for a minimum of two years. A modeler requires about a year to learn the system well enough to make simple updates and several years to model effectively with recursive LP.

Chevron places a great deal of emphasis on developing and retaining its modelers because it believes that people with this skill provide the company with a competitive advantage. It is a strong core capability that has been developed over a long period. Chevron's modelers have a deep understanding of both Petro and the business. Its models are more granular than those developed by other companies; thus, Chevron can explore more optimization opportunities.

Benefits

Chevron estimates that Petro and OR presently provide approximately \$1 billion per year in benefits, derived from several sources, to Chevron's downstream business.

As we describe previously, Chevron uses OR to optimize crude oil selection, determine the highest-value products to manufacture in its refineries, and optimize the refinery process units. This generates ongoing earnings from operating the downstream business of approximately \$600 million per year. Our estimates are based on the following comparative calculations.

- Chevron quantifies the value of its crude oil selection process at \$400 million per year by comparing the earnings from the Petro-optimized purchased crude oil slate against a benchmark crude oil slate. We run the Petro-optimized and the benchmark crude supplies through separate Petro models and compare the resulting earnings. The benchmark slate, which Chevron updates each year to reflect changes in crude oil availability and refinery capability, consists of readily available crude oils. We have demonstrated experience running the benchmark slate in the refineries. However, if we had no crude oil selection process, we know that we could operate with the benchmark slate. We have tracked the value of crude selection with Petro for the past 10 years.

• Chevron continually uses Petro to evaluate the refinery cost of making refined products (gasoline, jet, diesel fuels) against the marketplace value of these products. Our analysis shows that using Petro for product optimization generates $100 million per year. In addition to adjusting refinery operations to produce the highest-margin products, we sell products to the market when producing them is advantageous; we buy when our cost to produce is higher than the market price. Similar to crude, we compare planned products against a base slate of products to quantify the value of production optimization.

• Chevron uses Petro to conduct ongoing and periodic analyses to determine the optimal way to run the refining processing units as crude oil prices, raw material availability, product prices, product specifications, and equipment capabilities change. The analyses have shown that using Petro to optimize refinery process units generates $100 million per year in value.

In addition to the foregoing activities, which we estimate generates about $600 million per year in benefits, Chevron uses Petro in conjunction with DA to evaluate capital projects for its refining system on an ongoing basis. Petro combined with DA results in data-driven economics so that project options are evaluated based on their contribution to the long-term economic health of the enterprise. Specifically, Petro and DA make two contributions, which provide a total of $400 million per year through capital optimization. The first involves getting better value out of the projects in which we invest. The second involves avoiding investments in expensive projects that we do not need or that we can replace with less expensive alternatives.

• We elect to invest about $1.5 billion per year in projects to improve the downstream business. For these projects, we look at alternatives to determine the projects that best meet our economic criteria, including rate on capital employed (ROCE) and net present value (NPV), which roll the discounted cash flow in future years from projects into a single number. Typically, this process allows us to achieve an additional 2–3 percent on ROCE; for our $1.5 billion-per-year base, this improves NPV by about $200 million per year.

• Annually, we use Petro and DA to reject proposed projects, which would cost approximately $200–$250 million, because our analyses show that these projects have little or no merit. We replace them with alternatives that cost between $0 and $50 million with no change in earnings potential. The net value here is (coincidentally) also about $200 million per year.

Using Petro and DA enables us to gain a deeper understanding of the implications of projects under consideration; consequently, we can make smarter investment decisions. Based on reviewing capital projects that used Petro in recent years, we estimate the value of decisions made through our capital evaluation process is currently $400 million per year.

To summarize, the $600 million value generated from ongoing earnings from operating the downstream business plus the $400 million generated from improved capital efficiency total $1 billion per year.

We calculate Petro's value today to be $1 billion per year; however, we also know that because of advances in technology, organizational capabilities, effective modeling, management support, and market conditions, its annual value has grown significantly in the past three decades, and the amount of Petro's annual value to Chevron 30 years ago is only a fraction of this $1 billion. Based on our experience, we can calculate an effectiveness factor to compare Petro's value in a previous year to its current value. For example, we estimate that Petro's value in 2001 was about one-third of what it is today; therefore, the effectiveness factor for 2001 is 0.33 (see Figure 5). In this figure, we annotate events or advances that have enabled step changes in Petro's value to Chevron, and thus can depict the increase in Petro's value over time.

We believe that the Petro licensees have business processes in place that are similar to Chevron's and that they also find its value proportional to their refinery sizes.

Observations

Petro has strongly influenced the way our downstream business approaches planning and decision making; it is now an integral part of Chevron's processes and culture.

We have learned to target model accuracy to meet our business needs. For a number of applications,

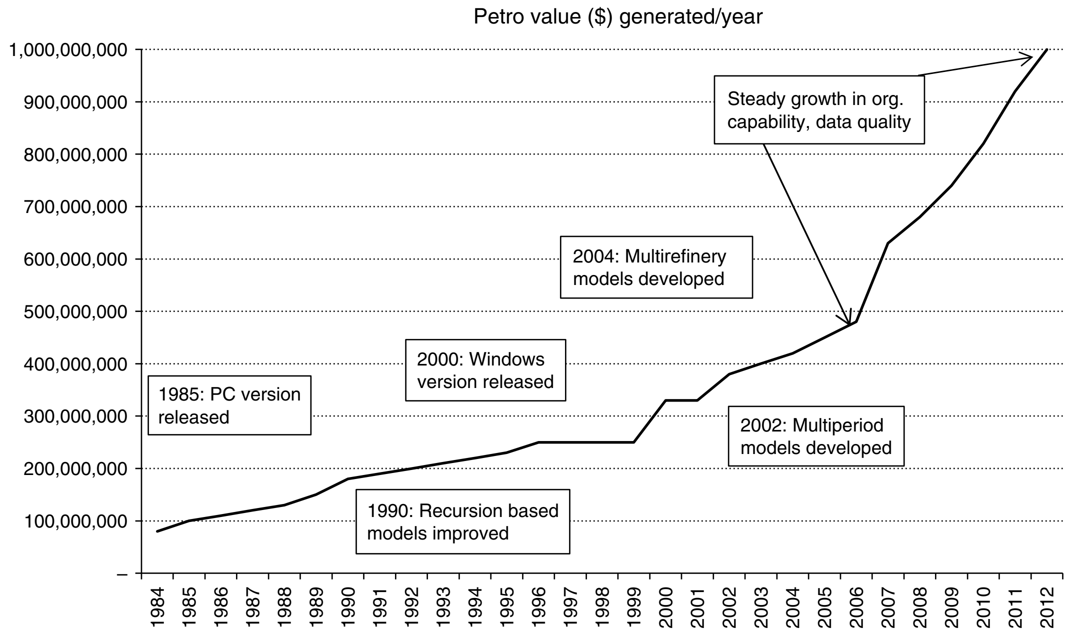

Figure 5: This graph estimates how Petro's value ($) has grown over time.

we accept a looser convergence tolerance because it significantly reduces solve times without meaningfully impacting the business. Analysts want a fast and friendly interactive tool that adds value to their analysis process.

Regular use drives continual improvement of the product. Over the years, crude oil feed qualities, product specifications, computer technology, lab analyses, and refinery technologies have changed dramatically. Petro's flexibility has enabled us to respond competitively to these changes.

Analysts will not make recommendations based on a software product that they do not understand. They will switch to simpler tools or make a judgment call to deliver an answer they can explain confidently. Reporting and training increase the understanding and confidence of the analysts.

Because one bad matrix construction can cause excessive solve time or a wildly nonconverged solution, we make and test small model changes incrementally. Bad constructions will infrequently surface for some case setups that we have not tested sufficiently.

As the number of models and modelers grew, we found that efficiency increased when we standardized the modeling style and structure.

Appendix

Single-Period Model Formulation for a Single Refinery

Figure A.1 shows the complexity of a refinery. The outputs of each process unit will depend on how the process unit is operated (e.g., temperature and pressure). We can route the intermediate streams in many ways. Our decisions are driven by cost, product specification, and product price. The following is a simplified representation of the LP model formulation used within Petro to make these decisions:

$C =$ Set of refinery feeds $c \in C$ (e.g., crude oil).

$R =$ Set of refinery units $r \in R$ (e.g., process units, tanks, pipelines).

$I =$ Set of intermediate products $i \in I$.

$P =$ Set of end products $p \in P$.

$S =$ Set of operating parameters (e.g., combination of temperature and pressure) for $r \in R$.

$Price_c =$ Unit price of feed $c \in C$.

$Avail_c =$ Availability of feed $c \in C$.

$Price_p =$ Unit price of product $p \in P$.

$Demand_p =$ Demand of product $p \in P$.

$Capacity_r =$ Capacity of refinery unit $r \in R$ (e.g., process units, tanks, pipelines).

$Cost_{rs} =$ Cost to produce one unit of product $p \in P$ or intermediate $i \in I$ by utilizing refinery unit $r \in R$ at a given mode setting s.

$F =$ Factor that converts units of volume in stream to units of mass.

$Q =$ Set of qualities (e.g., sulfur, octane) tracked, $q \in Q$ for each product $p \in P$.

$Spec_q =$ Specification for $q \in Q$.

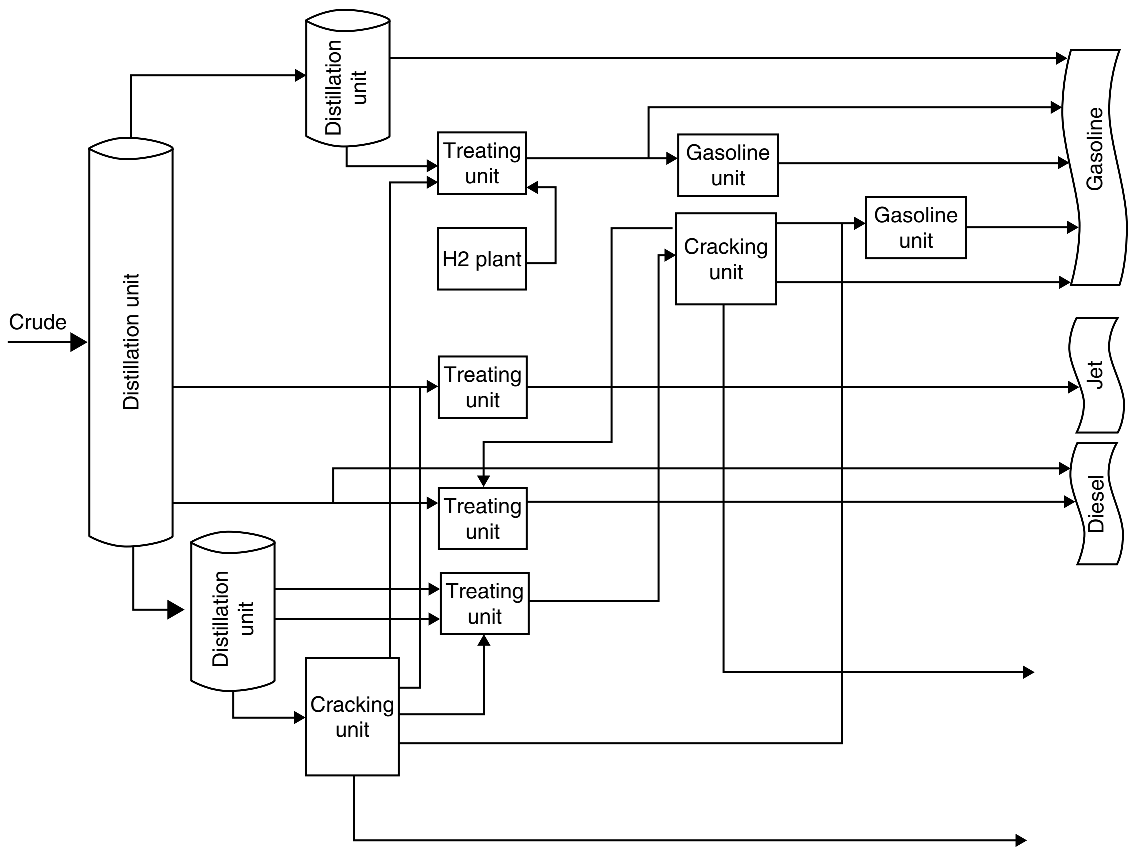

Figure A.1: This diagram of a sample refinery includes intermediate streams and products.

Decision Variables

x_{ir} = Amount of intermediate i fed into refinery unit r.

x_{cr} = Amount of crude c fed into refinery unit r.

y_{irs} = Amount of intermediate i output from refinery unit r at mode s.

y_{prs} = Amount of product p output from refinery unit r at mode s.

y_{qpr} = Amount of quality q in one unit of product p output from refinery unit r.

m_{rs} = Variable indicating the percentage of the stream resource $r \in R$ is operating at mode s (operating parameters, such as temperature and pressure).

Although m_{rs} is modeled as a percentage within the LP, in reality, resource r can only be operated at a single mode setting during the period. Consequently, the optimal values of m_{rs} are interpolated to arrive at a single mode setting. For example, if the optimal values of m_{rs} indicate operating at a temperature of 320 degrees for 80 percent of the stream and 330 degrees for 20 percent of the stream, then interpolation results in a single mode of operation temperature as 322 degrees.

Objective Function: Maximize (Revenue Less Cost)

Maximize

$$\sum_{p\in P}\left(Price_p * \sum_{r\in R}\sum_{s\in S} y_{prs} * m_{rs}\right) - \sum_{c\in C}\left(Price_c * \sum_{r\in R} x_{cr}\right)$$
$$- \sum_{r\in R}\sum_{s\in S} Cost_{rs} * \left(\sum_{p\in P} y_{prs} + \sum_{i\in I} y_{irs}\right) * m_{rs}.$$

Constraints

$$0 \le \sum_{r\in R} x_{cr} \le Avail_c, \quad c \in C,$$

$$0 \le \sum_{r\in R}\sum_{s\in S} y_{prs} * m_{rs} \le Demand_p, \quad p \in P,$$

$$0 \le \sum_{s\in S}\left(\sum_{p\in P} y_{prs} + \sum_{i\in I} y_{irs}\right) * m_{rs} \le Capacity_r, \quad r \in R,$$

$$\left(\sum_{i\in I} F * x_{ir} + \sum_{c\in C} F * x_{cr}\right)$$
$$= \sum_{s\in S}\left(\sum_{p\in P} F * y_{prs} + \sum_{i\in I} F * y_{irs}\right) * m_{rs}, \quad r \in R,$$

$$\sum_{r\in R}\sum_{s\in S}\frac{y_{qpr} * y_{prs}}{y_{prs}} * m_{rs} \leq Spec_q, \quad q \in Q,\ p \in P.$$

Note: Prejudging the qualities of the pooled streams enables us to model these nonlinear constraints as linear:

$$\sum_{s\in S} m_{rs} = 1, \quad r \in R,$$

$x_{cr}, x_{cr}, y_{irs}, y_{prs}, y_{qpr} \geq 0,\ m_{rs} \in (0, \ldots, 1).$

Company Profile: Chevron is one of the world's leading integrated energy companies and conducts business worldwide. Chevron is involved in virtually every facet of the energy industry. This includes:

- Exploring for, producing, and transporting crude oil and natural gas.
- Refining, marketing, and distributing transportation fuels and lubricants.
- Manufacturing and selling petrochemical products.
- Generating power and producing geothermal energy.
- Providing energy efficiency solutions.
- Developing the energy resources of the future, including research for advanced biofuels.

Chevron's refining resources are concentrated in North America, South Africa, and the Asia–Pacific region, and serve customers around the world. Chevron's global refining system manufactures fuels and other products sold by Chevron's marketing, lubricants, and supply and trading organizations. Manufacturing operates seven refineries that produce fuels, base oils, and other products that are marketed by Chevron under three brands: Chevron®, Texaco®, and Caltex®. These retail products are available on six continents.

In 2011, Chevron processed 1.8 million barrels of crude oil per day and averaged 2.9 million barrels per day of refined product sales worldwide. Total downstream earnings in 2011 were $3.6 billion.

Chevron maintains four trading hubs located in Houston, Texas, Singapore, London, and San Ramon, California. These trading hubs link our refineries with crude and product trading markets around the world.

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