Maximizing Federal Natural Gas Royalties

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I conducted research to enable the US Minerals Management Service (MMS) to maximize natural gas royalties. MMS is the agency of the US Department of the Interior responsible for managing mineral royalties. As part of managing royalties, MMS decides whether to accept royalties in value (cash payment, RIV) or in kind (physical transfer of gas, RIK). When MMS collects RIK, it also decides how to transport, process, and sell the natural gas. RIK is a fairly new program for MMS, which began continuous collection of RIK under a pilot study in 1998. As its RIK program grew, MMS sought my assistance to improve its decision processes for converting RIV to RIK and for choosing among transportation, processing, and sales options. (This is not an army matter; I worked on this project while I was a doctoral student at the Colorado School of Mines.) I provided data-processing applications to improve predictions of royalty volumes and assessments of existing royalty values. To support decisions concerning conversion of royalties from RIV to RIK, I developed a goal-price metric that accounts for a variety of market conditions. This metric compares favorably to alternatives that MMS was using or considering. I used an optimization model to evaluate conversion and contract alternatives so as to maximize total royalties. MMS began using the results of this research in 2002 and continues its use today. The first project it analyzed using these results provided a net royalty increase of $3.4 million over the first contract year.

Key words: industries: petroleum, natural gas; networks, graphs: applications.

The United States has substantial natural gas reserves. Much of this natural gas is on federal property, especially in US territorial waters in the Gulf of Mexico. On federally owned property, the government owns the mineral rights. Commercial natural gas companies produce natural gas from these federally owned reserves under leases from the federal government. They do so when they believe they can profitably produce (by drilling), transport (via pipeline), process (to remove impurities and separate the components), and sell the natural gas from these leases (most typically to energy companies). Commercial companies that drill for natural gas on leases from the federal government pay royalties based on the Mineral Leasing Act of 1920 and the Outer Continental Shelf Lands Act (OCSLA) of 1953 (Price 2000). The Department of the Interior, specifically, the Minerals Management Service (MMS), manages the mineral rights on behalf of American citizens and collects these royalties.

Most natural gas companies pay royalties in value (cash payments, RIV). After producing and selling natural gas, these companies pay MMS for the royalty share of the gas (typically one-sixth or one-eighth, depending upon the lease location) minus allowable deductions for transportation and processing. MMS, however, has the option of taking a percentage of the natural gas and selling it. This is known as taking royalties in kind (RIK). Since 1998, MMS has been taking RIK with the goal of saving administrative costs while maintaining revenue (General Accounting Office 2004). Whenever MMS chooses to take RIK from a lease, it may or may not combine the natural gas with royalties from other leases. When MMS combines natural gas from various leases, it does so at a facility measurement point (FMP). An FMP is a meter that measures natural gas flow early in the journey from the well to the sales point. FMPs comprise RIV-or-RIK decision points for MMS. Whenever MMS takes RIK, it must arrange to transport, process, and sell the gas just as if it were a commercial natural gas company (Minerals Management Service 2001).

In 1998, MMS adopted its RIK program. Under this program, it manages all RIK leases and makes decisions concerning conversion of leases from RIV
to RIK. Prior to adopting its RIK program, MMS completed the 1997 Royalty in Kind Feasibility Study. The authors of this study concluded that an RIK program for natural gas could be advantageous for both the government and commercial entities because of potential administrative savings. That is, MMS would require fewer administrators to oversee RIK (such as marketers, credit personnel, and accountants) than it requires to ensure compliance with RIV (accountants, auditors, and legal personnel). Commercial natural gas companies would save on costs primarily because RIK leases do not carry the costly audit and litigation burden associated with RIV. I accepted as given the conclusions of the 1997 Royalty in Kind Feasibility Study. I did not analyze the relative merits of RIK and RIV and the impact each has on the global economy. Instead, I accepted that MMS has an obligation to maximize royalties given producer-determined levels of production and that MMS must choose the course of action (RIK or RIV) that will return the greatest royalties to the treasury of the United States. MMS recently reiterated this obligation in its business-model extension by publishing its strategies for optimizing processing, transportation, and market opportunities for RIK (Minerals Management Service 2004).

I further assumed that such decisions have no impact on producers’ revenues. Consider a simple example: A natural gas company produces 600 million British thermal units (MMBtu) of natural gas and sells it at a net price of $10 per MMBtu, or $6,000. Assuming RIV and a royalty rate of 1/6, the company pays MMS a royalty of $1,000 and keeps $5,000. If MMS had chosen to convert this lease to RIK, the company would turn over 100 MMBtu of natural gas to MMS and sell the remaining 500 MMBtu for (one hopes) $5,000. MMS makes such decisions to convert from RIV to RIK whenever it believes it can obtain $1,000 or more in royalties (Minerals Management Service 2001). The company’s royalty payments are the same regardless of MMS’s decision. Any potential losses to the company are likely negated as it is freed from the audit burden that comes with RIV. MMS may have gained, however, by pooling the natural gas from that lease with royalty volumes from other nearby leases and perhaps gaining favorable transport, processing, or sales arrangements because of the large volume (Minerals Management Service 2004).

RIK is a fairly new program for MMS. Prior to 1998, all natural gas companies paid RIV expect for those in a few small pilot studies conducted between 1995 and 1997 (Minerals Management Service 2001). MMS continues to increase in measured increments the proportion of natural gas leases that pay RIK (General Accounting Office 2003, Minerals Management Service 2004). My research was one of several that MMS initiated to help it make appropriate decisions concerning RIK.

In response to congressional inquiries about whether MMS was receiving appropriate values for its natural gas royalties in its RIK program, the General Accountability Office (GAO, congress changed the name from “Accounting” to “Accountability” in July 2004) studied the RIK program and published its results in January 2003 and April 2004. The GAO’s mission is to provide independent evaluation of the federal government. Shortcomings identified in its 2003 report provided some of the impetus for my research.

Objective

When MMS takes natural gas royalties in kind, it contracts for the most lucrative transportation, processing, and sales arrangements that it can find (Minerals Management Service 2001, 2004).

Prior to this research, MMS did not have a systematic process for determining whether the prices it received from commercial natural gas companies were accurate or fair. Its data-processing method restricted it to examining short time periods to estimate unit prices. Because revenue from RIV can differ considerably from month to month, one needs a long period of evaluation to determine whether RIK sales can yield at least as much as RIV (General Accounting Office 2004). Also, fluctuating market conditions bias monthly price estimations. My data-processing tools enabled MMS to broaden the analytical time period, and my goal-price metric gave unprecedented fidelity to its RIV estimates. MMS can now verify a $10 per MMBtu price or determine that the price was really $9.95 per MMBtu. Five cents makes a difference in decisions about natural gas royalties.
Also, prior to my research, MMS enumerated all possible decision choices to determine its course of action. That is, it listed every possible combination of transportation, processing, and sales options for each lease it was considering for conversion from RIV to RIK. Then it compared all of these combinations to its existing RIV revenue. I used a network model with side constraints (based on the physical network of the natural gas pipelines) to determine the solution that maximizes royalties.

My objective in this study was to maximize royalties from natural gas production on federal property. Specifically, this research provides tools that

—improve the existing process for quantifying RIV lease quantity and production,

—offer royalty-maximizing decisions regarding whether to convert existing RIV leases to RIK leases, and

—offer royalty-maximizing decisions for RIK leases by identifying optimal transportation, processing, and sales arrangements.

**Data-Processing Applications**

The first step in my research was to provide MMS with tools for analyzing natural gas production and royalty information, *OGOR Calc* and *RIV Calc*.

To make proper RIV-or-RIK decisions for each lease, MMS conducts a historical analysis of the RIV at the lease. It does so to estimate future production volumes and to assess royalty values that commercial leaseholders have paid. Prior to my research, MMS performed all such analyses by manipulating spreadsheet data manually. Because this process was time consuming, MMS could examine only selected leases and had to base its analyses on examining short time periods. The tools I developed automated MMS’s process and enabled it to analyze more leases over longer periods.

These tools do not provide any earth-shattering operations research revelations, but their development and implementation was very important to the overall project:

—I gained a deep understanding of the real problems MMS faced daily, including the parameters that influenced its decisions, where it obtained data, and how good the data were. This knowledge was critical to my development of the goal-price metric and optimization technique.

—By delivering a working tool that users really needed in the first month on the job, I gained enormous credibility at MMS. That credibility was critical in gaining acceptance of the goal-price metric and optimization technique. I built these tools through daily interaction with the users so that they affected every feature.

*OGOR Calc* (oil and gas operations report calculator) enables MMS to determine the volumes of natural gas associated with various production leases (Figure 1).

*RIV Calc* converts downloaded royalty data into output tables that MMS can use for analysis and can import into the optimization model. The program accomplishes several data-processing tasks that MMS used to perform manually, including removing duplicate reports, aggregating separated reports, and correcting erroneous data. *RIV Calc* creates summarized output tables that enable users to examine sales prices and to compare them to market indices that MMS selects. Users can also examine summarized data on transportation and gas-processing costs.

Because *OGOR Calc* and *RIV Calc* have greatly reduced the time it takes to conduct historical analysis for each lease, MMS now prospects for new opportunities to convert RIV leases to RIK leases. Instead
of restricting its analyses to selected leases, it analyzes several leases simultaneously to find leases with relatively low RIV (implying that it could increase royalties with RIK) and with high enough production volumes to be good candidates for RIK.

**New Price Goal**

Before proceeding to maximize royalties using an optimization model, I examine the valuation parameter associated with keeping an FMP in RIV.

For each FMP, MMS assigns a value to RIV that is relative to a goal price. This goal price is usually a differential from a published market index price or a combination of several indices. MMS does this because it must compare the royalties it received in the past (in RIV) to potential RIK receipts in the future. Because market prices for natural gas change daily, it cannot directly compare RIV prices in the past to future RIK prices. Instead, it compares RIV to RIK by examining their differentials from some benchmark that changes with market conditions. RIK and RIV differ month to month because market prices differ from month to month and because RIV and RIK may have different market bases (General Accounting Office 2004).

To develop a goal price, I wanted to determine what portion of each month’s changes in natural gas prices leaseholders absorbed, as shown in royalty payments. I analyzed data from a random sample of natural gas royalties paid over a two-year period (details not included). Based on this analysis, I established a goal-price metric based on my estimate that, on average, leaseholders absorb 15.5 percent of total market-price changes that occur from the start to the end of the month. In months with small overall price changes (less than 12 percent of the total market price), I used the average daily market price. The average daily market price is tied to the Henry Hub index, which is the principal daily market index for natural gas from the Gulf of Mexico. The principal monthly index is the New York Mercantile Exchange (NYMEX) monthly settle price. In the equations below, $Z_t$ is my goal price metric for month $t$, NYMEX$_t$ is the NYMEX index price in month $t$, and Daily Average$_t$ is the average of Henry Hub index prices in month $t$:

$$Z_t = \begin{cases} \text{NYMEX}_t - 15.5\% (\text{NYMEX}_t - \text{NYMEX}_{t+1}), & \text{if } |\text{NYMEX}_t - \text{NYMEX}_{t+1}| / \text{NYMEX}_t > 12\% \\ \text{Daily Average}_t, & \text{otherwise} \end{cases}$$

This goal-price metric is highly dependent upon the source data. My sample data represent 20 percent of all natural gas leases in the Gulf of Mexico and are derived from examining sales in 2000 and 2001. Similar efforts should draw from data that are similar in location to the leases of interest and should draw from the most recent data available. Natural gas market prices in 2000 and 2001 exhibited a large increase followed by a large decrease but started and ended this two-year period at approximately the same value. I therefore examined the effects of market changes without an overall upward or downward bias.

I used the goal-price metric when examining royalties paid in the past (in RIV) by the leaseholders. Table 1 illustrates an analysis of one natural gas lease. For each month, I compared the goal-price metric to reported royalty values. Over a one-year period, this comparison shows the difference between the goal-price metric and the amount MMS received.

Prior to my research, MMS used the first-of-the-month (FOM) price as its primary goal-price metric. It could also use the daily average price or a goal price derived from the idea that about 70 percent of natural gas production sales are made at FOM prices and the remaining 30 percent are at daily prices (70/30). I compared $Z_t$ with these other goal-price alternatives (including arithmetic means of $Z_t$ with other metrics, Table 2) by employing a method that focuses on results of past conversion decisions. From November 1999 to November 2002, MMS converted natural gas flowing through 185 FMPs from RIV to RIK. For 61 of these conversion decisions, data are complete and differentiable enough to warrant comparative analysis (some conversions were too recent to yield complete data; some were made under earlier pilot-program policies that called for different types of data than current policies; others were not differentiable in that all of the goal-price metrics had virtually identical values). Those FMPs that earned increased royalties (relative to a goal price) following conversion from RIV to RIK I define as successful.
Lease under consideration for conversion from RIV to RIK

<table>
<thead>
<tr>
<th>Month</th>
<th>NYMEX first of the month price ($/MMBtu)</th>
<th>Henry Hub average daily price ($/MMBtu)</th>
<th>Goal: Gulf average net price ($/MMBtu)</th>
<th>Net unit price ($/MMBtu)</th>
<th>Royalty volume (MMBtu)</th>
<th>Loss/Gain ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr-01</td>
<td>5.442</td>
<td>5.199</td>
<td>5.199</td>
<td>5.184</td>
<td>651,902</td>
<td>(9,787)</td>
</tr>
<tr>
<td>May-01</td>
<td>4.891</td>
<td>4.208</td>
<td>4.741</td>
<td>4.637</td>
<td>857,966</td>
<td>(88,938)</td>
</tr>
<tr>
<td>Jul-01</td>
<td>3.397</td>
<td>3.074</td>
<td>3.074</td>
<td>3.402</td>
<td>710,445</td>
<td>233,259</td>
</tr>
<tr>
<td>Aug-01</td>
<td>3.128</td>
<td>3.008</td>
<td>2.999</td>
<td>3.184</td>
<td>333,083</td>
<td>61,570</td>
</tr>
<tr>
<td>Sep-01</td>
<td>2.295</td>
<td>2.193</td>
<td>2.223</td>
<td>2.198</td>
<td>539,879</td>
<td>(13,349)</td>
</tr>
<tr>
<td>Oct-01</td>
<td>1.830</td>
<td>2.425</td>
<td>2.043</td>
<td>1.422</td>
<td>570,057</td>
<td>(354,088)</td>
</tr>
<tr>
<td>Nov-01</td>
<td>3.202</td>
<td>2.365</td>
<td>3.065</td>
<td>2.802</td>
<td>568,450</td>
<td>(149,563)</td>
</tr>
<tr>
<td>Dec-01</td>
<td>2.516</td>
<td>2.369</td>
<td>2.369</td>
<td>2.189</td>
<td>772,124</td>
<td>(138,688)</td>
</tr>
<tr>
<td>Jan-02</td>
<td>2.555</td>
<td>2.293</td>
<td>2.470</td>
<td>2.389</td>
<td>925,650</td>
<td>(75,187)</td>
</tr>
<tr>
<td>Feb-02</td>
<td>2.006</td>
<td>2.272</td>
<td>2.065</td>
<td>2.106</td>
<td>794,569</td>
<td>32,543</td>
</tr>
<tr>
<td>Mar-02</td>
<td>2.388</td>
<td>3.019</td>
<td>2.556</td>
<td>2.755</td>
<td>829,348</td>
<td>165,429</td>
</tr>
<tr>
<td>Apr-02</td>
<td>3.472</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8,432,461</td>
</tr>
<tr>
<td>Goal loss/gain ($/MMBtu):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.058</td>
</tr>
</tbody>
</table>

Table 1: For one lease, goal and market prices varied month to month, but in January 2002, the NYMEX price fell from $2.555 on January 1 to $2.006 per MMBtu on February 1 (Column 2). The goal price of $2.470 per MMBtu accounts for 15.5 percent of the market price decline during that month (Column 4). Under the lease, MMS received a net unit price of $2.389 per MMBtu (Column 5). It received $0.081 per MMBtu less than the goal (Column 4 − Column 5), which is derived from an expectation of what an average Gulf of Mexico leaseholder should receive. Dividing the total loss or gain (right-most column) by the total royalty volume shows that over the course of one year, MMS received an average of 5.8 cents per unit below the goal price on this lease.

I define those that earn decreased royalties following conversion as failures.

I analyzed RIV data for each FMP for the 12 months immediately preceding conversion and RIK data from the first 12 months after conversion (Table 3). (A 12-month period allows me to account for seasonal differences that may occur as natural gas is used for heating and cooling in different regions.) After I determined whether the conversion succeeded or failed, I ranked the goal prices. For successful conversions, I ranked the goal prices in order of the strength of their evidence in support of conversion to RIK.

<table>
<thead>
<tr>
<th>Goal price</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOM</td>
<td>NYMEX first-of-the-month index price is the most common price MMS uses for comparison. Advantage: Because most natural gas is sold at FOM, prices are readily available. Disadvantage: Because some gas sales occur over the course of the month, the price does not reflect changes in market price following FOM.</td>
</tr>
<tr>
<td>70/30</td>
<td>70% of FOM + 30% of the average daily Henry Hub index price over the course of the month. Some believe that this price represents an accurate division of how commercial producers typically sell natural gas. Others argue that no actual contracts stipulate that gas be sold using a 70/30 split.</td>
</tr>
<tr>
<td>Z_t and 70/30</td>
<td>Mean of Z_t and 70/30. Advantages: This price provides a reasonable goal in a variety of market conditions and has less variability than Z_t and 70/30 do individually. Disadvantages: It is more difficult to calculate than other goals and has the least basis in actual sales practices among the available goal prices.</td>
</tr>
<tr>
<td>Z_t and FOM</td>
<td>Mean of Z_t and FOM. Advantages: This price accounts for market fluctuations over the course of the month and gives consideration to relationships between FOM and lease locations. Disadvantage: It has little basis in actual sales practices.</td>
</tr>
</tbody>
</table>

Table 2: This is a list of goal-price alternatives I compared to Z_t. Prior to my research, MMS used FOM almost exclusively. MMS also offered 70/30 as an untested alternative. These goal prices along with Z_t represent alternatives that MMS could use to relate RIV prices to potential RIK prices.
I ranked the goal prices from 5 (best) to 1 (worst). A low goal price implies a low value for RIV and thus provides strong evidence in support of conversion to RIK. Whichever goal price was lowest provided the lowest threshold for RIK and thus the strongest evidence in support of conversion to RIK. Therefore, I ranked the lowest goal price a 5 for a successful conversion. Conversely, for conversions that failed, I ranked the highest goal price (which gave little support for conversion) a 5.

Based on the successful conversion from RIV to RIK (Table 3), I ranked $Z_i$ as highest because it supported conversion most strongly (it had the lowest value for RIV). I ranked FOM as lowest because it was most cautious. If an estimate of potential royalties in kind were $-0.37$, for example, MMS would convert to RIK using $Z_i$ as its benchmark. If MMS used FOM prices as its standard, however, it would leave the FMP in RIV. Because this conversion was a success, I favor $Z_i$ over FOM (and the other goals) for this FMP.

To choose the best overall goal price from among the five competing goal prices, I focused on $70/30$ and $Z_i$, the two goals that performed well most consistently (Table 4).

Evaluating by FMP is the most important criterion because MMS makes conversion decisions on an FMP-by-FMP basis. $Z_i$ ranks highest on this criterion.

MMS never knows if it is making its conversion decisions in rising or falling market conditions. Thus, consistent performance in both rising and falling markets is important. Because $70/30$ ranks lowest when market prices are falling, $Z_i$ is superior over the spectrum of market conditions.

$70/30$ ranks in the middle for both successful conversions and conversion failures, where $Z_i$ ranks highest for successes and lowest for failures. MMS strives to increase the RIK program by converting leases from RIV whenever doing so provides the same or better revenue (Minerals Management Service 2001). Thus, MMS prefers to err on the side of conversion so as to increase the overall volume of gas in RIK. Also, a relatively low number of failures (18 of 61) implies that this ranking was derived from the smallest sample.

Prior to this research, MMS typically used FOM prices for its RIV-to-RIK comparisons. But comparisons of various goal prices for all previous RIV-to-RIK conversions show the inadequacy of using FOM prices. FOM prices provide a benchmark that is inferior to goal prices that account for price fluctuations over the course of a month.

$Z_i$ provides a goal price that I have shown to be more accurate than other goal prices at predicting successful RIV-to-RIK conversions. It was more accurate for previous conversion decisions, on an FMP-by-FMP basis as well as over the spectrum of market conditions, than any other tested benchmark.
Moreover, $Z_t$ provides the most appropriate balance between FOM and daily prices. MMS accepted this goal-price metric for evaluating its RIV-or-RIK decisions in 2003. (It did not use $Z_t$ exclusively, however. MMS continues to use FOM and geographically based modifications of FOM in some of its analyses.) MMS also uses $Z_t$ to quantify the relative successes of its conversion decisions after leases have been converted from RIV to RIK.

**Optimization Model**

For each FMP, MMS attempts to maximize royalties. That is, it chooses the most lucrative option from among several choices. One option is to continue to collect RIV on all of the natural gas that flows through the FMP. If instead it chooses to collect RIK, it typically has many options. The number of options depends upon the number of pipelines that are available to transport the natural gas from the production fields, the number of gas plants that are available for processing, and the number of market centers that are available for sales. Whenever MMS considers RIK for an FMP, it asks commercial companies to make separate bids to transport, process, and purchase the natural gas. Once the bids are submitted, MMS has many options from which to construct the one that will return the greatest royalties. These options involve all feasible paths through which natural gas may flow (from FMP through pipelines and gas plants to market centers).

Prior to this research, MMS enumerated all possible solutions and chose that which returned the greatest royalties (Table 5). It could keep the natural gas in RIV, expressing the net value as a differential from a market basis, such as the NYMEX index. MMS bases this differential on the amount the commercial leaseholder paid in the past. MMS assumes that the RIV differential from the market basis will not change in the future. The other options are combinations of transportation, processing, and sales options. The net value for each option is the sales revenue (measured as a differential from the same market basis as the RIV net value) less the transportation and processing costs. (Transportation and gas processing can return a net gain in some circumstances; the gain is then added to the sales revenue.)

My research enabled MMS to adopt an optimization methodology that took advantage of the underlying network of natural gas pipelines. In designing the optimization tool, I took as given the physical connectivity of the elements, as well as production volumes, RIV prices, and transportation, gas-processing, and market price parameters. The optimization tool determines from which FMPs to take RIV and from which to take RIK. For those FMPs for which RIK is optimal, it determines which pipelines, gas plants, and market centers to use (Figure 2).

One challenging aspect of modeling the network flow involves conditional costs. Transportation costs (that is, the negative profit associated with transportation) for each pipeline usually depend on the eventual market destination. For example, the operator of the Tennessee Gas Pipeline (TGP) may offer a contract at a lower price for transporting gas to a TGP market center than it does for transporting gas to the Columbia Gas market center. To account for the possibility of conditional transportation costs, I expand the network before solving it, adding paths to account for all possible costs. Adding paths to account for conditional transportation costs increases network sizes (Figures 3 and 4).

In addition to the attributes captured by the network structure, I must account for the binary nature of RIV-to-RIK conversion decisions. All natural gas that flows through an FMP must either remain in RIV or be converted to RIK. I introduce binary variables and constraints that enforce these conversion decisions. To solve the optimization model, I use a formulation that is essentially a minimum-cost-flow problem (where I maximize profit – royalties – instead of minimizing cost) with the addition of binary vari-

<table>
<thead>
<tr>
<th>Option</th>
<th>Net value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIV</td>
<td>+0.02</td>
</tr>
<tr>
<td>RIK$_1$</td>
<td>+0.03</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>RIK$_n$</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Table 5: Before it adopted my method, the Minerals Management Service listed all RIK options (1 through $n$) and compared their net values to the value associated with RIV. Each RIK option consists of a particular transportation option, a particular gas-processing option, and a particular sales option. Net values are in dollars per million British thermal units (MMBtu) and as a differential from a known market basis.
Figure 2: In this illustration of the model, I show a maximum profit network for one example system. The shaded nodes and solid arcs represent the physical natural gas network from source to market. The elements are the facility measurement points (FMPs), pipelines, gas plants, and market centers that the Minerals Management Service is considering for use in RIK. The white nodes and dashed arcs support the decision process; they model gas flow into the FMPs, account for the possibility of leaving gas in RIV, and model gas flow from the market centers to the sink.

Figure 3: In this system with two pipelines, two gas plants, and three market centers, the transportation cost for pipeline \( P \) depends on which of the three market centers the natural gas is destined for. To overcome this difficulty, we expand the network structure (Figure 4).

These projects had dozens of options and on the order of 200 variables. They were substantially more challenging to analyze than any of MMS’s previous projects. Although MMS still uses enumeration for its simplest projects (some projects are so simple that it has fewer than 10 options), it is working to integrate the model into information systems that are still in development. MMS continues to expand the RIK program in terms of quantity of natural gas and the variety of transportation, processing, and sales options it employs (Minerals Management Service 2004). MMS will continue to use this optimization model with the increasing variety of options.

First Implementation Project

To support the development and implementation of this research, I conducted an initial project in 2002–2003. Although the project was a test of the tools I had developed, it was a real project. That is, MMS implemented the results of the project, converted the leases from RIV to RIK in November 2002, and actually realized the increase in royalties predicted by my
results. The project was the most complicated (that is, it had the most options) that MMS had considered for conversion from RIV to RIK up to that point.

In the project, I examined 18 leases from three neighboring geographical areas in the Gulf of Mexico that provide natural gas to four FMPs (Figure 5). (Two FMPs are associated with Area 1, one for Pipeline White I and one for Pipeline White II.) These FMPs represented conversion decision options for MMS.

The goal differentials associated with keeping the natural gas from each area in RIV were below the market index (the RIV for Areas 1, 2, and 3 were −$0.078, −$0.152, and −$0.152 per MMBtu, respectively). The various pipelines offered transportation through six gas plants to six different market centers with different sale prices. Reaching the more lucrative markets, however, required greater transportation costs. The processing offers from the six competing gas plants ranged from $0.029 per MMBtu to $0.162 per MMBtu.

The solution from the optimization showed that converting all 18 leases from RIV to RIK would provide the maximum royalty return, an increase of about $3.5 million per year (Figure 6, Table 6). After MMS converted these leases from RIV to RIK, I tracked the results over the first contract year (November 2002 to October 2003). The actual increase in net royalties was only marginally different from the increase I had projected prior to conversion. Price variations and dropping production volumes caused the realized savings on the test project to be about $3.4 million.

Impact

MMS began using the products of my research in 2002 when it implemented RIV Calc. It later adopted OGOR Calc and incorporated the optimization model and
Figure 5: I conducted an initial implementation project in 2002–2003. Gas flows generally north (from bottom to top of the chart) from three production areas through combinations of facility measurement points (FMPs), pipelines, and gas plants, to several market alternatives. (The junctions allow natural gas to flow out of one pipeline and into another.) The market centers nearest the top had the highest sale prices, as indicated by the underlined “basis” values to the right of the markets. Selling at Transco Zone 4, for example, provided a sales basis of $0.029 per MMBtu above the market index. However, the rate to reach Transco Zone 4 on Pipeline Orange was $0.135 per MMBtu.

goal-price metric that I developed. MMS has also modified OGOR Calc and RIV Calc for use in its oil royalty program and is working to automate use of the optimization model within its information systems.

MMS now prospects for high-volume and under-valued RIV leases by examining substantial quantities of data using OGOR Calc and RIV Calc. MMS can now identify leases that were not previously under consideration by marketers. My development of RIV Calc allowed MMS to dramatically reduce analysis time and make its analyses consistent and repeatable. The new goal-price metric removes bias from changing market conditions. MMS no longer has to enumerate all RIK options to optimize transport, processing, and sales. Time savings from this are unknown but are most obviously felt when solutions are recalculated within short time periods (for example, during contract negotiations). The reduced analysis time also enables MMS to examine more difficult projects. MMS has expanded from projects with tens of options to projects with hundreds of options.

In the words of Milt Dial, the royalty-in-kind program director, “(The) contributions (of this research) have fundamentally changed the way MMS does business concerning its natural gas royalties. … (It) has had a profound impact on our operations.”
Appendix

Formulation

Indices

- \( i, j, k \in N \) set of all nodes (e.g., FMPs and pipelines).
- \( (i, j) \in A \) set of all arcs (e.g., path from FMP \( i \) to pipeline \( j \)).

Variables

- \( f \in F \) set of all FMP nodes; \( F \subset N \).
- \( p \in P \) set of all pipeline nodes; \( P \subset N \).
- \( (f, p) \in K \) set of all arcs from FMP nodes to pipelines; \( K \subset A \).
- \( r \in R \) set of all RIV nodes; \( r \subset N \).
- \( s \) source node; \( s \in N \).

Data

- \( P_{i,j} \) royalty profit from \( i \) to \( j \) ($/MMBtu).
- \( U_{i,j} \) upper bound on arc \( (i, j) \) (MMBtu).
- \( V_{f} \) royalty volume at FMP \( f \) (MMBtu).
- \( M \) a large constant, used in constraints with binary switches.

Formulation

\[
\text{Max } \pi = \sum_{(i,j) \in A} P_{i,j} X_{i,j}
\]
subject to
\[
\sum_{i \in A} X_{i,j} - \sum_{k \in A} X_{j,k} = 0 \quad \forall j \in N, \quad (1)
\]
\[
X_{s,f} = V_f \quad \forall f \in F, \quad (2)
\]
\[
X_{i,j} \leq U_{i,j} \quad \forall (i, j) \in A, \quad (3)
\]
\[
X_{f,p} \leq M * Y_{f,p} \quad \forall (f, p) \in K, \quad (4)
\]
\[
X_{f,r} \leq M * W_{f,r} \quad \forall (f, r) \in R, \quad (5)
\]
\[
\sum_{p \in K} Y_{f,p} + \sum_{r \in R} W_{f,r} = 1 \quad \forall f \in F, \quad (6)
\]
\[
X_{i,j} \geq 0 \quad \forall (i, j) \in A, \quad (7)
\]
\[
Y_{f,p} \in \{0, 1\} \quad \forall (f, p) \in K, \quad (8)
\]
\[
W_{f,r} \in \{0, 1\} \quad \forall (f, r) \in R. \quad (9)
\]

The \(P_{i,j}\) data refer to revenues or costs associated with RIV, transportation, processing, and sales. Any of these may be positive or negative.

The formulation is to maximize profit, which is simply the sum product of royalty profits times the amount of flow across each arc. The constraints accomplish the following:

1. ensure that any flow that enters a node will leave that node;
2. establish the supply of natural gas that flows through each FMP;
3. ensure that flow volumes do not exceed upper bounds;
4. activate a binary switch for flow from an FMP to a pipeline (implying RIK);
5. activate a binary switch for flow from an FMP to RIV;
6. ensure that all natural gas from any FMP is in either RIV or RIK, not both;
7. stipulate that flow amounts cannot be negative;
8. define \(Y_{f,p}\) as binary; and
9. define \(W_{f,r}\) as binary.

Some factors, including binary variables, conditional transportation costs, and continued expansion of the RIK program at MMS, cause optimization problems to increase in complexity and require longer times for computing solutions. With that in mind, I used the underlying physical network of pipelines to partition the problem by pipeline. This process allows me to identify dominated markets, remove nodes from the network, and thus to reduce the problem size. Partitioning creates several smaller problems. The set of partitioned problems contains mutually exclusive and collectively exhaustive subsets of the original set of pipelines. For example, a problem with 200 pipelines can be partitioned into 200 smaller problems with one pipeline each. Each partitioned problem may then be solved individually. The solution for each partitioned problem provides an optimal market destination (or destinations) for its pipeline. The union of market subsets from all partitioned problems provides a subset of the entire set of markets, leaving out markets that were nonoptimal in the solutions to all partitioned problems. Markets that are not chosen by any partitioned problem, then, are dominated by other markets and may be eliminated from consideration. After solving the partitioned problems, I reformulate the problem using all pipelines but disregarding any dominated markets. I examined the process by solving 10 test cases using a SunBlade 1000 workstation, AMPL Version 7.100, and CPLEX Version 7.1.0. Each test case returned optimal solutions to the partitioned problems while saving an average of 67 percent of run time.

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