OVERVIEW OF

THE ADVANCED REFINERY MODELING SYSTEM (ARMS)

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The Advanced Refinery Modeling System (**ARMS**) is a PC-based refinery LP modeling system independently developed and maintained by MathPro Inc. We use ARMS exclusively in studies for our clients. We do not offer it as a licensed software product.

This brief description of ARMS covers seven topics.

1. Refinery LP Modeling
2. Applications
3. Technical summary
4. Basic modeling concepts
5. Special features
6. ARMS inputs
7. ARMS outputs

1. Refinery LP Modeling

Assessing the effects of new regulatory standards or new refining technologies on refining economics calls for engineering, or *techno-economic*, analysis of refining operations.

The method of choice for conducting techno-economic analysis of refining operations is formal, computer-based modeling, employing a *refinery LP model*.

> LP stands for *linear programming*, a widely-used mathematical technique for optimization -- that is, for finding the best solution (in an economic sense) to complex problems involving the allocation of scarce resources across many competing activities. In refining analysis, the scarce resources are the production facilities of the refineries of interest and the competing activities are the various processing operations in the refineries.
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> Because it finds the mathematically best solution in each instance, LP modeling is especially useful in analyzing alternatives – such as alternative fuel standards or alternative technical responses to a given standard.

Refining companies use custom-configured LP models of their own refineries for tactical and operations planning, and for estimating the values of crude oils and other refinery inputs. Government agencies and private sector organizations use generalized refinery LP models (that can be adapted to represent various refineries or refinery groupings) to estimate the effects on refining economics of proposed fuel standards or regulations.

With a refinery LP model, experienced analysts can simulate how a refinery or group of refineries would operate – on an average day in a specified time period – to produce specified products, at minimum cost. These simulations yield not only descriptions of prospective refinery operations but also estimates of the magnitude of the associated operating costs and the capital investment requirements (if any) for new or upgraded processing capacity.

Analysis employing a refinery LP model yields three kinds of results.

- estimates of *incremental or differential refining costs* associated with a proposed standard or technology;

- estimates of *capital investment requirements* and *operational changes* induced by the proposed standard or technology; and

- estimates of the *properties* of the fuels produced, for calculating emissions and other kinds of performance (e.g., fuel economy).

These results allow estimation of the total social cost of a proposed standard or the benefits of a new technology, as well as associated changes in emissions. They also provide an indication of economic driving forces – that is, marginal refining costs – that could lead to changes in retail prices, absent any changes in market structure.

By its nature, refining analysis cannot shed light on how the structure of a fuels market or the pattern of supplies to that market would be likely to change – either independent of or as a result of new fuels standards. Such changes are driven not only by refining techno-economics (the object of refining analysis) but also by circumstances in other markets and other refining centers, and by business decisions taken by various refiners. These factors, though important to industry, government, and consumers, are beyond the scope of refining analysis.

2. Areas of Application

MathPro Inc. has applied ARMS in numerous studies to support analyses of a wide range of public policy and business planning issues involving the refining sector, including:

- Technical and economic impacts on the refining sector – and resulting social costs to consumers – of new regulatory programs for clean transportation fuels, such as federal oxygenated and reformulated gasolines (RFG1 and RFG2), California reformulated gasoline (CaRFG2 and CaRFG3), Arizona Cleaner Burning Gasoline, Tier 2 low-sulfur gasoline, and ultra-low-sulfur diesel fuel (ULSD), California's MTBE phase-out, and lead phase-out.

- Technical and economic impacts on the refining sector of proposed regulations affecting the properties and composition of transportation fuels, such as the Renewable Fuels Standard, MTBE phase-out nation-wide, a Distillation Index (DI) standard, the proposed waiver on the oxygen content of federal RFG2, and various clean-fuel programs at the state and regional levels.

- Economic impacts on the refining sector, and the attendant capital requirements, of new process technologies, including FCC naphtha hydrotreating to produce low sulfur gasoline, distillate hydrotreating to produce ultra-low sulfur diesel fuels, and distillate hydrotreating to produce premium diesel fuels.

- Technical requirements, investment requirements, and incremental costs for phasing lead out of gasoline, in various countries.

- Effects of new gasoline standards on the supply and price of petrochemical feedstocks produced in the refining sector.

- The refining values of various specific crude oils, by region and refinery type.

- The refining values of various gasoline blendstocks and additives, such as ethanol, iso-octane/iso-octene, alkylate, isomerate, and MMT, by region and refinery type.

Continuing extension of ARMS is expanding its realm of applications even further.

3. TECHNICAL SUMMARY

ARMS is a PC-resident refinery modeling system that operates under current versions of Windows®. It represents the technology and economics of refinery operations in *engineering* (not econometric) terms. It is designed specifically to support a spectrum of refinery modeling applications dealing with technical and economic responses of the refining industry (or individual refineries) to real or prospective changes in public policy, regulation, technology, and/or market conditions.

ARMS comprises a linear programming (LP) model of refining operations; a library of crude oil assays; a database of techno-economic values describing refinery operations, process-by-process; and a software suite for creating, operating, and reporting on refinery LP models.

ARMS has a *data-driven* architecture, which facilitates easy operation and easy enhancement. It embodies strict separation of the model's mathematics and data. This separation enables one to change data values and create scenarios without changing either the mathematics or any computer programs. Equally important, it facilitates continuing enhancement of the model's structure, without computer programming and its attendant costs in dollars and time.

The LP model in ARMS is expressed as a computer-readable **model statement**, specifying the model's mathematics and logic in symbolic, non-procedural form, independent of any data one might associate with the model. The database contains techno-economic and boundary values, in tabular or relational form, physically separate from the model statement.

Linking the model statement to a specific set of techno-economic and boundary values produces a distinct **model instance**, or **case**, that ARMS processes and solves. (Typical analyses of policy and planning issues may involve creating and processing hundreds of cases.)

> At present, typical model instances contain about 1200 constraints, 4000 variables, 45,000 non-zero coefficients.

ARMS has a graphical user interface and custom-designed computer programs for managing the model statement; managing data; creating model instances (cases); solving models; and analyzing model solutions. The programs form an open, flexible, easy-to-enhance system, with input and output links to spreadsheets and other external applications. ARMS was designed and developed by MathPro Inc., and is maintained and enhanced by MathPro Inc.

Because of this design and implementation approach, ARMS supports both quick-response analyses and longer-term analyses that may call for modifying or extending not only the database but also the model statement itself.

4. Basic Concepts

The ARMS LP model is a *static*, *process-oriented*, *disaggregated*, *optimizing* representation of the operations and economics of refining.

- *Optimizing*: Solutions to the LP model define optimal refining operations and economics for the specified refinery or refining aggregate and policy scenario.
- *Disaggregated*: ARMS represents refining facilities (that is, capital stock within refinery battery limits) at a user-specified level of disaggregation: an individual PADD or a group of PADDs (e.g., PADDs 1-3); a region, state, or refining center; a group of similar refineries in a refining center (e.g., coking refineries in the Gulf Coast center); or an individual refinery.
- *Process-oriented*: ARMS represents refining operations, process by process, in techno-economic or engineering (not econometric) terms.
- *Static*: ARMS represents an average day's operations of the specified refining aggregate or refinery in the specified time period (year and season), with no inter-temporal flows such as inventory build-up or draw-down.

The solution to an ARMS case defines a pattern of refining operations and a set of prices for feeds, products, and refinery process capacity that minimize aggregate refining cost or maximize aggregate profit contribution, for a given set of boundary values.

In this context, *profit contribution* is the difference

> **Product Revenues - Costs of (Crude + Other Inputs + Purchased Energy + Catalysts and Chemicals) – Capital Charges (including taxes and maintenance costs)**

where the revenues and all of the cost items are per barrel of output and input (respectively), with fixed costs not considered.

The ARMS LP model is a partial equilibrium model. That is, the solution to an ARMS case simulates refining operations such that

- the market for each refined product clears at the computed prices;
- each refinery is in competition with all others in the given region; and
- all competitors have full information about the market.

Solutions to a given ARMS case define optimal refining operations in terms of:

- volumes consumed and marginal value of crude oils and purchased blendstocks;
- compositions and qualities of finished products blended to specification;
- aggregate capacity utilization and the marginal value of new capacity, by process;
- aggregate investment in new capacity;

- volumes produced and marginal cost of each finished product;
- marginal cost of each intermediate refinery stream and blendstock; and
- marginal cost of satisfying each individual specification, by blended product.

Solutions to sequences of ARMS cases can trace out refinery supply or cost functions and indicate the impacts on refining operations and economics of prospective changes in energy and environmental policy and regulation; crude oil and feedstock quality, price, and availability; product demand and specifications; and refining capital stock.

5. Special Features

5.1 Process Representations

ARMS contains representations of not only the standard commercial refining processes but also new and prospective processes and process options. Examples include

- Olefin-maximizing FCC catalysts;
- FCC operations with residual oil feeds;
- Depentanization of gasoline blendstocks;
- Desulfurization of FCC naphtha via CD TECH and ExxonMobil processes; and
- Production of ultra-low sulfur diesel fuel via hydrotreating technology representative of that offered by Criterion Catalysts, Akzo Nobel Chemicals, and Haldor Topsoe.

Because FCC operations are the most important single determinant of refining economics in conversion refineries and because FCC units have exceptional flexibility, ARMS contains an especially detailed representation of FCC operations. The representation covers various feedstocks (ranging from distillates to residual oils), catalyst types, operating modes, and conversion levels.

ARMS allows simultaneous representations of any number of distinct, user-specified gasoline pools – for example, CaRFG3, federal RFG2, and conventional. Each pool may contain up to three grades (e.g., regular, mid-grade, and premium). ARMS honors specifications for each grade and for each pool represented.

5.2 Ratio Constraints

All refinery LP modeling is susceptible to "over-optimization"[1]. To counteract this tendency, ARMS contains a set of special structures called *ratio constraints*. These constraints minimize

1 The term "over-optimization" denotes the tendency of refinery LP modeling to indicate higher aggregate profit contributions and/or lower incremental costs of a given refining operation than could occur in practice for a given

the most important form of over-optimization – called "cherry-picking" – which has particularly important consequences in analyses of sulfur control.

Cherry-picking arises from the interaction of three factors.

- Most refineries simultaneously process a number of crude oils – each with distinct price, properties, and refining value. Because refineries commingle crude oils, the intermediate streams that refineries produce also are commingled (within each boiling range, defined by distillation cut points).

- Most refinery models represent crude oils individually to (1) capture their unique physical and economic properties and (2) allow selection of an "optimal" crude slate. But, separate representation of crude oils leads naturally – almost inevitably – to separate representation of the intermediate streams produced from each crude – even though these steams are actually commingled in the "real" refinery.

- As a mathematical technique, LP is a relentless optimizer; it always locates and selects the most attractive processing options represented in the model at hand.

Left to its own devices, an LP solution procedure will produce model solutions showing highly specific separations and allocations of the commingled streams in any given boiling range. This is cherry-picking. In a cherry-picking solution, each process unit receives as feed the streams that maximize the unit's economic effectiveness, and each product blending pool receives the blendstocks best suited to it. Unfortunately, cherry-picking separations from commingled, run-of-the-refinery streams are difficult or impossible to accomplish in most real refinery operations. Cherry-picking will occur with any refinery LP model that represents individual intermediate streams within given boiling ranges *without* special analytical techniques to represent the commingling that actually occurs.

The two most widely used techniques to address cherry-picking are recursive pooling and ratio constraints. The former is rigorous – but complicated, expensive, and time-consuming. The latter is approximate but adequate – and far less difficult to implement and use.

ARMS embodies the latter approach. The model contains a large array of ratio constraints, which establish, in the form of ratios, the relative volumes of each distinct stream in key commingled refinery streams represented in ARMS. In connection with sulfur control, the ratio constraints serve to

- Control the allocation sulfur-bearing streams to the various process units, so that each unit receives only run-of-the refinery mixtures; and

- Establish run-of-the-refinery commingled blendstocks, within specific boiling ranges or for certain sources of material, for allocation to each product pool within a given product category – such as gasolines and the distillate products.

The ratio constraints ensure that results generated by ARMS reflect no significant over-optimization due to cherry-picking.

set of refinery capital stock, product specifications, and market conditions.

5.3 Other Special Structures

ARMS contains equations representing the Distillation Index (DI) for each gasoline grade within each class. This feature facilitates presentation of DI values in standard solution reporting. More importantly, it allows easy and direct representation of proposed DI specifications inside the model.

ARMS tracks energy density for each gasoline grade within each class and for each diesel fuel class. This feature facilitates estimation of changes in fuel economy (mileage) associated with various regulatory standards.

ARMS recognizes supply functions for refinery inputs and demand functions for refinery outputs (both refined products and excess streams), in the form of volume/own-price relationships. This feature facilitates analyses involving certain economic interactions between the refining sector and its suppliers and/or its customers.

5.4 Predictive Model and Complex Model Representations

The ARMS model contains built-in representations of (i) the federal Phase 2 Complex Model (CM) for certifying federal RFG and conventional gasoline (for "anti-dumping") and (ii) the California Predictive Models (PM) for certifying CaRFG2 and CaRFG3. Consequently, in ARMS solutions, the properties of the RFG pools (if any) comply with the relevant (federal or California) emission standards. ARMS can accommodate both the Complex Model and the Predictive Model in a given model instance, such that some gasoline classes can be subject to the Complex Model while others are subject to the Predictive Model.

The CM and PM representations in ARMS are "reduced-form" models that we derived. The reduced form models are nonlinear in the gasoline properties that are their independent variables) – just as in the CM and PM themselves. We express the reduced form models as sums of *piece-wise-linear* functions, one such function for each gasoline property in the CM or PM. In LP parlance, piece-wise-linear functions are called *Special Ordered Sets, Type 2* (**SOS2**). Such functions can be embedded directly in the LP model's linear framework. We solve the ARMS model using a commercial LP solver with SOS2 capability.

This discussion touches only on the highlights of the approach. Discussion of the details, some of which are of critical importance, is beyond the scope of this document. A full discussion is in *Fuel Reformulation*; Vol. 4, No. 2; March/April 1994; pgs 64-68.

6. ARMS INPUTS

At present, the ARMS database comprises more than **100** tables of input data values that give numerical expression to the refining representation in the ARMS model. The database includes representations of about **150** different foreign and domestic crude oils, **48** refining processes, and **35** refined products - including three grades each of up to three gasoline classes.

In general, data elements in the ARMS database are in two categories: boundary conditions and technoeconomic values. The two categories have the same computer-readable (relational) format, but play different roles in analyses.

- *Boundary conditions* express assumptions about certain future conditions that refining operations must satisfy, such as regulations, crude oil availabilities, product demands, product specifications, and crude and product prices.

- *Techno-economic values* characterize the performance of refining operations, in terms of crude assays, input/output coefficients for each refining process represented, and blending properties for each blendstock represented.

Changes to boundary conditions express changes in assumptions about future conditions, and such assumptions underlie each scenario and ARMS case. Changes in techno-economic values usually express new refinery-specific process data or significant changes in refining technology. A specified set of boundary conditions and techno-economic values express a scenario for analysis and establish the corresponding ARMS cases.

Using ARMS in a given analysis involves changing elements of the boundary conditions from case to case while (in general) holding the techno-economic values constant from case to case.

6.1 Boundary Conditions

ARMS boundary conditions (scenario-specific inputs) include:

- Prices and availabilities (maximum and minimum) of crude oils
- Prices and availabilities of purchased input streams
- Prices and availabilities of purchased utilities
- Prices and demands for finished products and excess streams
- Gasoline grade splits
- Aggregate processing capacities (nameplate capacities and stream factors, by process)
- Specifications (e.g., octane, sulfur, oxygen, RVP, T_{90}, etc.) for the primary blended products, including all gasolines, jet fuels, diesel fuel, heating oil, and various grades of residual fuel
- Recipes for those products not blended to specification in the model
- Target values for regulated vehicle emissions (VOC, NOx, Toxics, CO)
- Capital investment cost (in $ per throughput barrel) for additions to capacity, by process
- Limits (if applicable) on aggregate additions to capacity, by process

Each set of boundary conditions is defined in one or more discrete tables in the ARMS database.

In most studies, we estimate these values on the basis of information drawn from public sources, such as U.S. government publications, industry trade publications, and special reports.

6.2 Techno-economic Values

For each refining process represented in ARMS, the technoeconomic values characterizing the process are stored in a discrete table in the ARMS database. Each “process table” contains technoeconomic values, specified over a set of operating modes for that process. An operating mode denotes a specific combination of process inputs and operating conditions. For each operating mode, the specified technoeconomic values include:

- Charge rates for each input stream
- Utility consumptions (fuel, steam, and power)
- Yields of each output stream
- Consumption of nameplate capacity per barrel of throughput
- Direct costs per barrel of throughput

Each operating mode is in volume balance and (for most processes) overall mass balance. In addition, each operating mode for desulfurization processes is in sulfur mass balance.

We estimate techno-ecomomic values on the basis of information drawn from industry trade publications, presentations at professional meetings, textbooks, and communications (confidential and non-confidential) with organizations that provide process technology to the refining industry.

7. ARMS OUTPUTS

Solutions to a given ARMS case (scenario-specific **outputs**) define optimal refining operations, in terms of:

- Total refinery revenues
- Total refining costs, by category (direct operating cost, capital charge, etc.)
- Volumes consumed and marginal values of crude oils, purchased blendstocks, and additives
- Compositions and qualities of finished products blended to specification
- Aggregate capacity utilization and the marginal value of new capacity, by process
- Aggregate investment in new capacity, by process
- Volumes produced and marginal costs of finished products
- Marginal cost of each intermediate refinery stream and blendstock
- Marginal cost of satisfying each individual specification, by blended prooduct

All of these outputs reside in the ARMS database, and may be viewed interactively, compared side-by-side, and printed under user control.