REFINERY PLANNING AND OPTIMIZATION USING LINEAR PROGRAMMING

Introduction

Modern optimization techniques have challenged organizations to rethink the way they conduct business both internally and externally, i.e. how efficiently and effectively their entire supply chain is managed. Supply Chain Management (SCM) is one such business function that has benefited substantially from optimization software advances and solutions. The primary goal of SCM is to maximize profit by integrated management of material and transactional flows within a business and to customer and partner companies.

The petroleum refining industry has effectively embraced the software solutions to optimize the business supply chain to maximize the profit margins and create order in the chaos of numerous opportunities and challenges. The supply chain of a typical petroleum refining company involves a wide spectrum of activities, starting from crude purchase and crude transportation to refineries, refining operations, product transportation and finally delivering the product to the end user. The nature of the value chain is such that its economics are extremely complex and heavily linked (Refer to Fig. 1.0). For example, the process of selecting the right crude is linked not only to the transportation costs involved in delivering it to the refinery, but it must take into consideration the refinery configuration, capabilities and constraints in converting the crude into products, as well as the product volume and price fluctuations.

![Representation of Typical Supply Chain](image)

Figure 1: Typical Supply chain of Petroleum business

Software solutions based on Linear Programming (LP) technique have emerged as leaders among various mathematical optimization techniques available to optimize the entire supply chain from crude evaluation and selection, production planning and product logistic planning.

The objective of this article is to create an appreciation among readers about the application of Linear Programming (LP) in refinery planning and optimization as a key component of the business supply chain.

The article includes:

- Petroleum Refinery: Complexity of operations and the need and scope of optimization
- Implementation of Linear Programming for refinery planning and optimization
- Experiences in implementation and usage of Linear Programming
- The bottom line
Refinery planning and optimization is mainly addressed through successive linear programming software like RPMS (Honeywell Hi-Spec Solutions), PIMS (Aspen Technology), and GRTMPS (Haverly Systems), while more rigorous non-linear planning models for refinery planning have been recently developed. The experiences discussed in this article pertain to RPMS, as the authors have been involved in the development and application of refinery LP models using RPMS (Refinery and Petrochemical Modeling System). RPMS was developed more than 35 years ago by Bonner & Moore, which was acquired by Honeywell Hi-Spec Solutions in 1999. RPMS is used today at more than 100 refineries and petrochemical plants worldwide for operations planning, crude oil evaluation and selection, inventory management, future investment analysis and to analyze “what if” scenarios.

**PETROLEUM REFINERY: COMPLEXITY OF OPERATIONS AND THE NEED AND SCOPE OF OPTIMIZATION**

- **COMPLEXITY OF REFINERY OPERATIONS**

**Crude selection**

Modern petroleum refineries are designed to process a variety of indigenous and imported crudes. As the crude cost is about 90% of the refinery input cost, the selection of optimum crude mix is extremely important to achieve higher margins. However, the number of options for buying the crudes under a fluctuating price scenario and transporting them to refineries are so enormous that it is very difficult to evaluate all the crudes and decide on the optimum crude mix for the refinery. Refineries buy crudes both on term contracts with leading suppliers and also by spot purchases from the market. The optimum selection of term and spot crudes is extremely difficult when multiple refineries are involved and work in an integrated scenario.

**Crude transportation**

Once the crudes are selected and purchased, the focus is to optimize the transportation cost from the crude suppliers to refineries. The transportation cost can be minimized by considering the multiple options available for cargo sizes, sea routes, loading and unloading infrastructure facilities, taxes and duties, etc.

**Crude processing**

The crudes often land at refinery sites as a mix of various crudes and various options of crude blending are evaluated before it is processed. The ultimate challenge a refinery faces is processing the crudes in the best possible manner and maximize the $/bbl (dollars per barrel) for the crude input. Determining the “best possible” option is a very difficult task, as modern day refineries are built with complex processing schemes, having a combination of various technologies for heavy ends upgrading, product quality improvement, efficient fuel usage and controlling refinery emissions. The most common configuration includes catalytic cracking, hydro cracking and thermal cracking to maximize the bottom of the barrel. The other process technologies like catalytic reforming, hydro treating and sulfur recovery are a must to comply with stringent environment and product quality regulations (Refer to Fig. 2.0 for a process flow diagram of a modern refinery).
Product demands

The product demands, quality and prices drive the entire crude processing and secondary unit operations. Multiple streams with multiple blending options to make different grades of a product further make the task of refinery planning cumbersome and demanding.

Moreover, the future promises to add even more complexity through additional product specifications, environmental norms, changing feedstock, product prices, mergers and acquisitions.

- **NEED AND SCOPE FOR OPTIMIZATION IN REFINERY OPERATIONS**

Most refineries are owned by integrated oil companies having a variety of interests, from exploration and production through refining and marketing to retail sales. Within such an organization the refinery works under the direction of the Head office. The Head office negotiates long-term and short-term crude supply contracts while the product Supply and Distribution department sells products. The refinery itself typically works within the overall framework of the organization to maximize the corporate profitability. This makes the refining an extremely complex and dynamic activity. Along with the complexity of refining,
there also exists a great degree of freedom in refinery operations. For example, one of the most commonly used refinery products is fuel for automobiles, and the customer does not care about the complexity or simplicity of the refinery, what crudes it purchased, which processing technology it used, what blending or additive components it used in making the fuel. The customer is only concerned with the proper running of his vehicle and the value for the money spent. Therefore, the refiners have got both an enormous complexity and considerable freedom to satisfy the customer requirement and make profit. This requires the optimization of multiple objectives in the refinery’s business supply chain.

The table below provides a glimpse of the multiple objectives of refinery optimization:

<table>
<thead>
<tr>
<th>Objective</th>
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<tbody>
<tr>
<td>Minimize crude landed cost at refinery</td>
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<tr>
<td>Optimize refinery crude mix</td>
</tr>
<tr>
<td>Optimize black oil generation and upgradation, optimize overall product mix and dispatch</td>
</tr>
<tr>
<td>Minimize quality giveaway</td>
</tr>
<tr>
<td>Optimize fuel consumption, minimize losses</td>
</tr>
<tr>
<td>Optimize utilization of the assets</td>
</tr>
<tr>
<td>Optimize inventory management</td>
</tr>
<tr>
<td>Optimize capacity utilization and shutdown planning</td>
</tr>
<tr>
<td>Optimize unit operations maintaining highest standards of safety, catalyst life and activity, etc.</td>
</tr>
</tbody>
</table>

All of the objectives mentioned above present a refinery with a challenging problem and an opportunity to maximize the overall profitability.

In a nutshell, the need and scope for optimization is so vast in a refinery that it is essential to use software tools not only to arrive at the best plan, but also to quickly evaluate the new optimum with internal or external changes in the business scenario. However, in today’s refinery environment, data acquisition, simulation and optimization tools often reside in “silos” in different groups across the refinery. This results in various local and plant-level optimizations only, not the most profitable refinery-wide optimization. A holistic view via an integrated model of the refinery is required to give refinery planners the ability to evaluate opportunities optimally, accurately and quickly.

**MEANING OF OPTIMIZATION AND LINEAR PROGRAMMING**

Optimization means “the action of finding the best solution within the given constraints and flexibilities.” Linear Programming (LP) is a mathematical technique for finding the maximum value of some equation subject to stated linear constraints. It is commonly used in refinery planning to identify with confidence the most profitable refinery-wide operating strategy.

LP has been around since the 1940s and has now reached a very high level of advancement with the meteoric rise in computing power. The “linear” in LP stands for the algebraic aspect, i.e. all the constraints and objective functions are linear and satisfy two fundamental properties: proportionality and additivity. The “programming” in LP actually means “planning” only. The implementation of LP involves the development of an integrated LP model representing the refinery operations with all constraints and flexibilities and then solving it to determine the optimum plan.

The refinery-wide optimization using an LP model has been proven to bring economic gains far higher than unit-specific simulation models or advance process control techniques.

In short, the LP model is an excellent economic evaluation tool to drive the entire supply chain toward higher profit.

Some of the key areas for LP applications in the oil industry are:

- Grassroots refinery design/configuration
- Selection and evaluation of crude oils and raw materials
- Long-range and short-term operations planning
- Capital investments evaluation for process equipment
• Analysis of the profitability of merging and acquisition plans and the creation of ad-hoc models for joint venture refineries
• Evaluation of processing agreements and product exchange contracts
• Evaluation of new process technologies
• Control of the refinery performance
• Product blending control
• Down-time planning
• Inventory management

IMPLEMENTATION OF LP FOR REFINERY PLANNING AND OPTIMISATION

Refinery planning forms the foundation for the business decisions that have the biggest impact on refinery profitability. A refinery typically prepares the following types of plans:

• **Annual plans** for annual budgeting, term crude contracts and maintenance shutdown planning
• **Monthly rolling plans** for spot crude purchases and conducting refinery operations inline with product demands
• **Weekly plans** for finding operating strategies for units at the weekly level, i.e. the refinery knows precisely which crudes it has and must decide which crude cocktails to run, how long to do so and how it is going to meet any particularly large or difficult product demands
• **Strategic plans** for future years and expansion projects
• **Profitability improvement plans** for plant-level modifications and revamp projects

The preparation of any of the above types of plans requires a set of standard procedures and an LP model customized for the refinery configuration.

• **DEVELOPMENT OF A REFINERY LP MODEL**

Development of a refinery planning LP model primarily involves customization of commercially available LP modeling software to refinery configuration. The table below provides a list of major suppliers and the LP software.

<table>
<thead>
<tr>
<th>Supplier</th>
<th>LP Software</th>
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<tbody>
<tr>
<td>Honeywell Hi-Spec Solutions</td>
<td>RPMS – Refinery &amp; Petrochemical Modeling System</td>
</tr>
<tr>
<td>Aspentech</td>
<td>PIMS – Process Industry Modeling System</td>
</tr>
<tr>
<td>Haverly</td>
<td>GRMPTS</td>
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Development of a refinery LP model is an arduous task that demands sound, accurate and complete understanding of the refining process and planning functions. It requires compilation of enormous plant data and meticulous documentation of the same.

Major steps the in development of a refinery LP model

Some of the major steps involved in the development of a refinery LP model include:

• Mapping of the existing planning process and data collection
• Development of a future planning process inline with best practices
• Finalization of Functional and Design Specifications (FDS) for the refinery LP model building, software and hardware configuration
• Refinery model building as per FDS
• Factory acceptance test of refinery model
• Tuning of model at site and trial usage for planning and case studies
• Site acceptance test of the refinery LP model
The list of steps mentioned is not exhaustive and requires micro-level activity planning. The role of an LP consultant is very important as he has to balance the needs of the refinery planner and the intricacies involved in modeling each constraint and options. Initially, it is better to keep the model simple and understand its behavior. The complexities must be added gradually, keeping in mind what economic impact they have on refinery profitability.

**Description of a refinery LP model**

A good LP model is one that closely represents the operational reality of a refinery. A typical refinery LP model contains the end-to-end configuration of the refinery with a detailed representation of primary and secondary processing units, blending facilities, power and utilities. A model contains structural data, or fixed data, which represents the physical reality concerned, and variable data, which expresses the contingency of the particular problem. The addition of variable data like costs, prices, raw materials availabilities and products requests, process unit’s capacities and product quality specifications enables the model to set up a problem, from which infinite variant cases can be created and run to arrive at the optimal plan.

Mathematically, an LP model consists of a matrix, while for the users it can be better thought of as a set of data tables necessary and sufficient for the automatic matrix generation. A typical refinery model represents an LP matrix with 1,500 rows, 3,500 columns, 1,500 equations, 1,500 constraints and 5,000 variables. The LP software uses different optimizers like MOPS, XPRESS, OSL, etc. to solve the matrix. RPMS uses the state-of-the-art XPRESS optimizer software licensed from Dash Associates.

The model can have different time period variants to meet different planning objectives associated with Annual Planning (1X4 quarter), Quarterly Planning (1X3 months) and Monthly Planning (1X4 weeks).

Some of the **key features of a refinery LP model** include:

**Objective function in an LP model**

A refinery LP model is generally configured with a single objective function of maximizing the profit as explained below:

- To maximize \((S \text{ (Product value)} - S \text{ (Raw Material cost)} - S \text{ (Refinery Variable Costs)}\), subject to the various constraints defined in the model including the inventory value and carrying cost parameters.

**Modeling techniques and optimization features**

A refinery LP model contains modeling capabilities like Successive Linear Programming (SLP), Mixed integer programming (MIP), Implicit and Explicit Pooling, Multi-period modeling, Distributive property recursion, attribute error tracking, rigorous sulfur distribution, etc. Compared to an approach based on average values, these techniques provide very accurate estimates of yields and qualities of finished goods, all the while keeping short computation times.

Additional information can be obtained by referring to standard books on LP to understand the meaning of the LP terms used above. A good reference book is Operations Research, 7th Edition by Hamdy A. Taha, Univ. of Arkansas, and Fayetteville.

The refinery LP models use latest unit modeling techniques like swing cut modeling, delta vector modeling and mode wise modeling.

The crude and vacuum unit is modeled based on the stream TBP (True Boiling Point) cut point scheme. The crude assay manager software like ASSAY2, PASSMAN uses TBP cuts and the TBP curve of the crude oils from the various crude assay database for generating the crude wise yields and properties. It is possible to model the single physical crude unit into several logical units depending refinery specific requirement. For example, a refinery processing high sulfur (HS) and low sulfur (LS) crudes in blocked out operation can be modeled with two logical unit one for HS and another for LS crude operation.
The secondary units are modeled using delta-yield vector or mode wise yield vectors. For example, the catalytic cracker is generally modeled by setting up base yield vectors with yield controlling delta vectors for Feed UOP K, MeABP and Severity/Conversion. The static input data for determination of delta vectors can be generated from kinetic models, test runs and standard correlations. Relevant capacity and quality constraints on the feed and product side are configured. All possible blending options for unit feed and products are configured. Unit wise steam, power, fuel consumption and catalyst consumption are also built in. The rigorous recursion structure for feed and product stream properties is set up. For example, sulfur in cat cracker streams is recalculated on the basis of feed sulfur changes.

**Model Input**

Once all the static data is configured, the model is updated with the variable data in model for solving a particular problem. The common variable data required includes:

- Crude oil or any other raw material prices and minimum and maximum availability
- Selling prices and minimum and maximum demands for the different finished goods
- Available process unit capacities
- Available Inventory stocks and minimum and maximum storage limits
- Quality specifications, etc.

**User Interface**

LP software commercially available today is highly advanced with features to provide a maximum user-friendly experience. RPMS has a powerful Graphical User Interface (GUI), which provides a highly effective and intuitive interface for working with the model. It contains a model navigation window with graphical objects. The graphical objects contain information on Charge Yields, Feeds, Products, Results, etc. Data and Report factory is an integrated application of RPMS for input of static and variable data and generating standard reports in Excel (Fig. 3.0 provides a glimpse of a GUI for a refinery LP model).
The LP matrix generator transforms the input data into a great number of equations and variables. The LP optimization algorithm solves the matrix and calculates which combination of supply, processing, blending and selling activities gives the highest margin. The LP reporting system reports this optimal combination of activities, together with the financial results. The output is generated in the form of different types of text and Excel files. RPMS has a powerful report factory utility for generating various customized Excel reports. The reports contain detail output with respect to crudes quantities, product numbers, capacity utilization, power, utilities and chemical consumption levels. The outputs also provide valuable information like reduced cost, pi values, DJ values, etc.

For further information on RPMS, explore the RPMS link listed under References.

- **TRADITIONAL LIMITATIONS AND LATEST ADVANCES IN LP**

The LP modeling has changed substantially. The static yield-driven models with fixed stream properties have now been replaced by variable property-driven models using latest non-linear distributive recursion techniques. Swing cuts for cut-point optimization have been semi-automated using implicit pooling techniques. Multi-period and multi-refinery modeling capabilities have been enhanced. The linkage of crude assay data into the LP assay tables has been enhanced and automated. Process unit representations have changed from multiple “mode” type yield structures to base-delta vector yield representations.

In a nutshell, current LP systems offer embedded process simulation and other non-linear representation capabilities to provide even more accuracy and realism for refinery LP representations. The LP technique is far superior when compared to any Excel programs traditionally used for planning. However, it is worthwhile to keep in mind certain limitations of LP in order to appreciate the LP solutions:

1. **Non-linear nature of refinery processes**: The nature of the refining processes is mainly non-linear whereas linear programming - as the name already suggests - assumes that a linear combination of the provided options is valid. RPMS uses a specialized recursion technique called Successive Linear Programming (SLP) for modeling and solving non-linear problems. For most of these, engineers have developed "linear blend indices," which transform the measured qualities into index values, which can be constrained using ordinary linear constraints.

2. **Data overload**: While developing the model, providing all the possible processing options is impossible. Increasing the number of variables and constraints increases the efforts to maintain the database and the difficulty to maintain the required data consistency. It also reduces the system’s transparency, therefore increasing the chances of big errors in data and logic. RPMS has a powerful interface with Excel and tools like Fast Data Import, model comparison, etc. to minimize the data errors.

3. **LP does not consider the elements of time and storage**: It assumes that all activities occur simultaneously and that all identified components are separately available for further processing or blending (like there are separate tanks available for all individual components). A refinery may process HS and LS crudes in a blocked-out fashion, whereas an LP model mixes HS and LS crudes simultaneously. This limitation is addressed by reducing the time bucket while making the plan and using multi-period models. Weekly planning methodology can be used for making plans closer to actual operations and address scheduling issues.

4. **LP exercises no judgment**: One point must always be remembered: “LP Models are just as good as the data put in and the assumptions used to create them. Models should not replace good and sound engineering judgment.” The LP requires quality input data in order to provide workable and practical solutions. Yield and property data are based on plant measurements and rule-of-thumb calculations or estimations. Pricing data used is often based on the statistical average of past months or years. Based on the input data only, the LP model solves the problem and it exercises no judgment. A small change in one piece of data may result in a completely different solution, and
will ignore all uncertainties and risks to achieve just a minor increase in profits. This problem has been tackled by sensitivity analysis where many cases can be run using Model Modifier (MMOD) feature of RPMS and arriving at practical and implementable solutions.

**EXPERIENCES AND BENEFITS**

- **Building a refinery LP model is not a trivial exercise.** It needs clear understanding of the entire web of refinery operations and the compilation of good quality data. The model development activity is very time consuming and can take about a year for developing a good and robust model.

  The following important points need to be kept in mind while building the model:
  
  o Make sure that the crude cut strategy represents accurately the qualities (and variations) of the cuts that are critical for a site. For example, if there are issues concerning distillate 95% point or CCR values, characterize your crude cuts very thinly around the heavy gas oil/atmospheric residue cut (typically in the 330 - 390C range).

  o Obtain good representation of unit operating modes and parameters from process models. As the LP cannot work with non-linear correlations, there is a need to linearize the non-linear behavior of process units by introducing several linear “vectors.” These vectors can be generated through sound refinery process models (e.g. KBC Profimatics FCC-SIM for the FCC, REF-SIM for a reformer, etc.) for different feeds/crudes, operating conditions (severities, conversion, etc.), etc.

  o Ensure that the model has sufficient flexibility to generate feasible solutions in the first place. It is easier to start with a fairly "loose" model, which can be subsequently tightened.

- **Interpretation of LP Output:** The task of analyzing the LP output is not a simple exercise, mainly due to the limitations of the technique and the complexity of its output. It requires sustained effort in generating and analyzing the various feasible and optimum solutions and rigorous sensitivity analysis.

- **Computation Time:** Today, we solve substantially more complex LP problems in mere seconds on our desktop PCs. The running time limitations have lost much of their relevancy with the availability of desktop PCs with higher computing power. For example, solving four-period models takes only about two to three minutes on a Pentium-IV and 256 MB RAM PC.

- **Benefits of LP in refinery planning**

  LP works on the principles of pure mathematics and Petroleum Refining is more complex than the mathematics that describe it. With all the approximations and uncertainty we should not expect or even desire a “true mathematical optimum.” LP should be viewed only as a mathematical optimization technique, or as a convenient method to obtain a feasible and economic plan for the supply, processing and logistic activities of a petroleum complex, together with a description of its driving forces and constraints. In day-to-day working, an LP solution helps in achieving two key practical aspects:

  - It facilitates in the decision-making process by keeping the focus on profit under any scenario
  - It provides the targets and operating strategies for the actual operation

  LP does much more than planning for the future. LP refinery models always challenge the people and their deep-rooted rule-of-thumb approach in the refinery operations. The implementation of LP models often creates awareness among executives and management about the profit factor. LP-based planning can provide potential benefits to the tune of 15-20 cents/bbl. One of the major advantages of LP programming is that it acts as a watch dog for the refinery operations – always asking for more, the LP model helps in identifying the bottlenecks in processing more crude and directs in achieving the benchmark for operation. It clearly tells the inefficiency of operations in terms of money, and that’s where it is very close to management’s heart.

  The LP solution has not only enabled arriving at a better plan, but has also provided many valuable insights for optimizing unit operations, crude mix and product blending. The other most important benefit realized is it quantifies the impact of a change in a variable on overall refinery profitability. As a tool, RPMS provides answers to the typical questions that refinery management asks for faster decision making, including: What is optimum HS-LS crude mix?, How to maximize distillate yield and minimize the fuel &
loss?, What products to be maximized?, Which units to be run and what capacity levels?, When to plan unit shutdowns?, etc.

**Key to successful implementation of LP in refinery planning**

The output from an LP model gives us an optimal plan. In practice, the real benefit comes from implementation of the strategies and guidelines from the model. Implementing all of the LP solutions in a refinery is a difficult task. Product pricing and unit constraints often change weekly, but changing unit operating philosophy and addressing hardware constraints take time to accomplish. Even after the steps for improving optimal performance have been identified and implemented, if the pressure to improve is removed, operation tends to return to the older, more comfortable routine. The LP optimization group must continue to stress the potential savings while improving the operations until the savings are achieved.

The key to the successful implementation of LP in refinery planning is an integrated approach that addresses the following issues:

- **Regular Model updates and maintenance:** There is one human tendency of giving maximum care and attention to the thing which is very valuable or important to him. The same tendency should be kept alive for LP models, as these models provide the decision-making power (involving large amounts of money), money-related policies and future action plans. The models are continuously interacting with inside constraints and outside changes (price and product demands), making them dynamic in nature. All of these factors imply that the maintenance of these models should be carried out as regularly as possible. The type of updates can be a reduction in the yield of unit, change of catalyst, property change of secondary stream, energy consumption reduction due to application of energy conservation suggestion, etc.

- **Integrated application of different software solutions:** Refineries use a number of stand-alone software solutions like Automation Blenders, Online analyzers and sensors, APC, Scheduling software, Simulation software, RTDBMS for optimization of operations. There is a strong need to integrate the working of such software to create the maximum benefit by bringing the operations and blending close to the LP output.

- **Clear and well documented planning procedures:** There are no two opinions on using LP based software for planning. The real problem of using the LP for economic decision-making is how to interpret the LP results and how to use it for decision-making. The planning tool needs to be backed by clear cut and systematic planning procedures. The entire planning process should be carried out under the overall supervision and guidance of top management group in an integrated way. The procedures for the four key functions of plan preparation, plan implementation, plan monitoring and “what-if” case studies must be in place and working to enable the success of LP optimization.

**THE BOTTOM LINE**

Petroleum refining in the new millennium will continue to be an extremely competitive business. The application of LP methodology has shown potential margin benefits of 15-20 cents/bbl for the refineries.

The bottom line is that experienced people are the key to success: software and computers, no matter how powerful and quick, are not the substitutes for understanding and optimizing the refinery business. However, LP technique has provided an efficient and effective method to quickly evaluate and quantify the impact of internal and external changes on overall refinery profitability.

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