Are Oil Refineries Ready for Non-Linear Control and Optimization?

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Abstract: Refinery business and process optimization is complex and challenging. Characterized by uncertainties, large scope, complex equipment connectivity relationships and a large number of optimization handles, the refinery optimization problem is solved by a hierarchy of optimizers. The focus of this paper is non-linear control and optimization. A view of the readiness of oil refineries for non-linear control and optimization is presented. Factors to consider before embarking on closed-loop non-linear optimization are discussed.

Keywords: Non-linear Control and Optimization, Petroleum Refining, Real-Time Optimization, Model Predictive Control, Advanced Process Control and Optimization

1. INTRODUCTION

The U.S. refining industry is a mature commodity business, therefore improvements in technology or efficiency are passed mostly to consumers through lower prices. Refining gross margins are low and continue to fall, even with refinery capacity utilization nearing 90%. In this environment ensuring the most efficient utilization of assets and lowest operating cost are important for refiners to stay competitive.

During the last ten years, there has been an increased focus on Refinery Business Optimization. There are several levels of optimization within the broad areas of Business Optimization. The purpose of this paper is to provide a view of the readiness of oil refiners for closed-loop, real-time, non-linear control and optimization.

2. REFINERY OPTIMIZATION PROBLEM

The primary optimization objective for a refiner is to maximize the gross margin from operation in the light of current and forecasted market prices within the constraint envelope created by equipment capabilities and contracted feed and product obligations. Important price variables include:

- Price and quality relationships between different crude oils
- Price differentials between products
- Price differentials between product grades such as: high or low octane gasoline, high or low sulfur diesel, high or low viscosity lubes, etc.

Refinery optimization is a large and complex problem. A hierarchy of optimizers is currently used to solve the optimization problem. The general trend in the last decade has been integration of optimization applications and sharing of information between different optimization levels. Some of these efforts include:

- Integration of yield accounting with SAP for inventory management and order fulfillment and allocation
- Integration of planning and scheduling software
- Integration of Real Time Optimization (RTO) with the planning LP
- Building RTO for multiple units and connecting them together
- Integration of RTO with Model Predictive Control (MPC)

A key component in the integration of business optimization applications is to represent the refinery processes in an accurate model. The behavior of refinery processes is complex and non-linear. Therefore, a non-linear model of the refinery can provide the framework for such an accurate representation. Online control and optimization using non-linear models will play a key role in the maximum utilization of assets.

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3. REVIEW OF THE STATUS OF LINEAR MPC APPLICATIONS

Linear MPC controllers are now installed on all major units, at most refineries in the US. An MPC controller refers here to a steady-state LP or QP optimizer integrated with a linear dynamic controller.

However, many MPC applications do not perform adequately or deliver the potential benefits of this technology. MPC controllers that perform well have the following characteristics:

- The scope of the controller covers all key process constraints
- All key equipment, process and product specification constraints are active and are controlled at the limits
- The economic optimizer pushes against the correct combination of constraints
- Dynamic controller performance is good over a wide operating range
- Intervention from operators occurs only to handle rare conditions that were consciously not included in the controller design

Truly successful MPC applications that meet the above criteria over their lifespan are surprisingly rare in industry. Some applications are implemented poorly and others have degraded because of inadequate maintenance. It is no exaggeration to report that many applications have declined to a level where the benefits are at or near zero. The application success rate is not well represented in either the public or proprietary refiners' literature because only success stories are publicized and even those are not always justified by the control-room reality known only to a few.

The most common problems leading to poor performance are:

- Model inaccuracy
- Poor LP/QP optimizer tuning
- Lack of operator training
- Lack of maintenance

Model inaccuracy can result either from poor plant-test execution or from process changes over a period of time that invalidate an initially good model. Problems may also arise because of non-linearities in process behavior that have not been addressed in the model. Better project execution and tools that make plant testing and model identification more efficient will help to improve initial model quality. Performance monitoring tools that identify the problematic models and quantify the degradation of controller performance are necessary. Such performance monitoring tools could assist the control engineer to better maintain MPC controllers and to prioritize problem areas. Unfortunately, the currently available tools produce complex data that is confusing to most practicing engineers.

Complex LP problems contain a large number of possible active constraint sets. In these cases, encountering particular constraint trade-offs that were not considered in the MPC design can cause the application to drive the process in the wrong direction. Also, uncertainty in the empirical MPC models can create poorly conditioned LP matrices that result in highly undesirable controller behavior. Poor understanding of this issue is the norm, so these ill-conditioned problems are rarely fixed and application benefits suffer.

There are significant benefits available in industry from better implementation and maintenance of current linear MPC controllers. Justification of non-linear control and optimization should not be based on capturing benefits already accessible to current linear MPC technology. In fact, a well-maintained MPC controller is a pre-requisite for successful implementation of non-linear optimization.

4. CURRENT PRACTICE OF NON-LINEAR CONTROL AND OPTIMIZATION

4.1 Technology Overview

The general classification of technologies implemented in refineries is as follows:

1. RTO based on a nonlinear steady-state model sending steady-state targets to a linear MPC controller
2. A nonlinear steady state model setting the gains of an Adaptive MPC
3. Nonlinear empirical dynamic models (Neural-Networks) for control and optimization on small problems

In refineries, RTO has been applied to several process units in the last 8-10 years and has the highest installed base among the nonlinear control and optimization technologies. RTO typically sends target values to MPC controllers for implementation. MPC controller model gains are not usually changed by the RTO in this implementation.

Adaptive MPC, with an equation-based, steady-state, simulator setting the model gains in a MPC controller, is under development by at least one company. Here, the functionality of an RTO and MPC are combined and solved as a single problem. Model gains for an adaptive MPC are obtained from a steady-state simulator using automatic differentiation, and the dynamics are synthesized. The success of this technology is highly dependent on the accuracy of the steady-state simulation, which, for reasons stated later in this paper, may be inadequate.

RTO with linear MPC and adaptive MPC both use non-linear, steady state models. The difference between the two technologies is that in adaptive MPC the model gains in the dynamic controller are regularly modified and the dynamic constrained control problem is solved simultaneously with the steady state optimization problem. Adaptive MPC is a relatively new technology with no on-line application known to the authors, so benefits from actual applications are not available to compare against the RTO with linear MPC case. Intuitively, the concept of adaptive MPC is appealing as the objective function includes the economic optimization and dynamic control. However, combining steady state optimization and dynamic control into a single problem creates a very complex application, with a difficult tuning problem. Maintaining linear MPC with RTO is already a challenge for most refiners; combining the two into a single application would make maintenance all but impossible.

Non-linear empirical models (like neural networks) are a "black box" modeling approach. There is no suitable model form for non-linear processes and models do not extrapolate in a predictable way. Model fitting does not utilize physically meaningful parameters such as equipment design factors and kinetic constants. There is generally too little emphasis on the quality of data used for model fitting, and it is sometimes claimed that plant historical data is sufficient for development of dynamic model. As a result, these models' transparency and accuracy are both typically poor. This technology is difficult to apply to large scope problems and to use for integrating models into a refinery-wide optimizer. Significant benefits are unlikely via this approach.

4.2 Real-Time Optimization (RTO)

RTO solves the following optimization problem: "Given the fixed arrangements and sizes of equipment, the quality and cost of feedstock, utilities costs, and product specifications, values, and market demands, what are the best operating conditions to give the most valuable products at the lowest operating costs?" (Cutler and Perry).

RTO execution typically involves five main steps:

- Steady state detection
- Data reconciliation
- Parameter estimation
- Optimization
- Sending optimum targets to MPC controller

RTO uses an equation-based simulator to model the process. Open equation-based models are well suited for real-time, on-line applications since the same model form can be used for data reconciliation, parameter estimation and optimization. A Successive Quadratic Programming (SQP) solver is used to solve the model.

4.3 RTO Benefits

An RTO is successful if the application produces a measurable improvement in production, product yields or properties, or production cost. Quantifying and measuring any difference between pre- and post-RTO installation is always a challenge.

RTO can deliver value over an MPC controller when the optimization variables have a nonlinear relationship with the profit function and are not currently used to control constraints or specifications. Linear MPC controllers do not have the capability to determine optima for variables that have significantly non-linear behavior. Current practice is to have a set of LP costs to mimic different rule based solutions that are fixed *a priori*. Example of these include:

- Trade-off between feed rate, preheat temperature and riser temperature in fluid catalytic cracking (FCC) Units
- Setting pump-around flows in complex distillation towers
- Optimizing operation over the entire run-length for hydrocracker reactors and semi-regenerative reformers
- Optimizing FCC feed hydrotreater and FCC using feed quality variables that are not usually part of a MPC controller (like metals, sulfur, etc)
- Optimization of FCC, FCC gas plant and Alkylation unit when constraints in the Alkylation unit determine FCC operation

With a detailed process model a unit's overall economic performance can be better optimized.

Having an RTO has several potential side-benefits:

- An "always fresh" process model that can be used for "what-if" studies, feed selection, unit de-bottlenecking, catalyst selection studies, etc. This benefit assumes that the optimization software used has features that make the model easily available for off-line use.
- Tracking model parameters updated by RTO can help in scheduling equipment/unit outages and in making catalyst replacement decisions
- Data reconciliation has proved to be useful in identifying faulty measurements
- Gradients from an RTO model are used in refinery LP models recursively to have a more accurate representation of the assets

RTO has been applied on crude and vacuum units, FCC, reformers, hydrotreaters and hydrocrackers, alkylation units and complex distillation towers. By far the most successful refining applications reported have been on crude and vacuum units. Limited success has been achieved with FCC and hydrocracker RTOs.

4.4 Challenges Posed by RTO Projects

An RTO project involves building an equation-based model of a process unit or a process area (several units) and using the model online for optimization. The main challenges and issues in implementing a successful optimizer are:

- Selecting RTO scope
- Building high-fidelity, accurate models
- Transparency and usability of the models
- Difficult to maintain

4.4.1 Selecting RTO Scope

RTO applications with scopes covering multiple units result in higher benefits, if they can be kept on-line. Typical RTO applications cover only one major process unit, or at most a couple of units. This scope is often the same as the MPC controller scope. The scope is kept narrow due to several factors:

- The high costs and long development time for RTO projects
- The demanding maintenance requirements of a larger application
- The high computation time needed to solve large problems

Many process units offer only small incremental benefits from RTO over MPC on the same scope.

On the other hand, the refinery planning LP optimizer has a very large scope but lower fidelity. Process constraints, yield data, and equipment performance are not accurately captured in these LP models. Limiting the RTO scope, results in the “big” and “difficult” decisions being made using the inaccurate LP model, which in effect overrules most of the important variables that RTO may wish to set. Another problem for a small scope RTO is that providing marginal stream prices that correctly reflect overall refinery economics is a very difficult task. Calculating marginal intermediate stream values using raw product prices and unit operating costs using LP models is both difficult and inaccurate. Incremental product property values are also very difficult to calculate from LP models. Results from RTO and the LP model differ due to these erroneous intermediate stream prices, and lead to confusion. Larger scope problems offer significantly higher potential benefits by incorporating more difficult optimization decisions that are not usually possible to solve with MPC. An additional benefit of large optimization scopes is reduced dependence on intermediate stream prices for the RTO objective function.

4.4.2 Building high-fidelity, accurate models

It is truly a challenge to build a high-fidelity model using commercially available simulators. Model accuracy is limited by fixed model forms and parameters that represent the equipment behavior and equipment health. Some of the challenges faced to build accurate RTO models are:

- Limitations in kinetic models – High fidelity kinetic models require extensive deactivation data, accurate feed characterization, accurate product characterization, and process yield data. In practice, it is either expensive or infeasible to gather this data. Lack of this data results in poor understanding of the kinetics and results in development of kinetic models with low fidelity
- Limitation in modeling – Column pressure profiles, tower flooding, tower tray drying and valve characteristics are difficult to model using current simulators. Non-ideal process behavior such as vapor bypassing is difficult to capture using existing model tuning parameters. Choosing the number of pseudo components and lumps correctly and choosing the thermodynamic methods correctly remains an art
- Lack of data for tuning - Special plant tests and laboratory analysis of feed and products are necessary to generate data for model tuning. A limited window of opportunity is usually provided to generate such data. The data gathered does not usually span a wide operating region. There is a lack of a systematic approach to generate good data for model tuning and perform the model parameter tuning and validation
- Lack of online instrumentation and faulty instruments – Online measurement of stream properties is expensive and difficult to maintain. Online instrumentation, such as flow meters and thermocouples to capture important process behavior, are often inaccurate or unavailable. Due to this lack of reliable measurements the weighting placed on the data to fit model parameters can become arbitrary. In addition, the lack of online data makes it difficult to represent RTO constraints accurately
- There is very limited availability of competent, trained personnel for RTO implementation and maintenance

Adaptive MPC and non-linear controller technologies assume that their models capture non-linear behavior but due to the many reasons listed above these models are not accurate. The authors’ experience is that the gains from RTO models and those from plant step-test data seldom match. Setting the MPC gain from a non-linear model that is inaccurate will not yield benefits over linear MPC, but rather may seriously compromise the controller performance. Non-linear process relationships can often be adequately modeled in linear MPC controllers, anyway, using transformations. Transformations are developed using process data that characterizes the non-linearity.

4.4.3 Transparency and usability of the models

A model is transparent if the inner workings of the model are available for users to explore, understand, and explain model behavior easily and quickly. A model tuning constant and its impact on model results should be clear. An RTO model, being complex, is not transparent and requires capable tools to aid the user in interpreting the results. A model is usable if tools are provided to make its use and interpretation easy and quick. Excel front-ends have been commonly used to make more user-friendly interfaces from which a user can easily run "if-then" studies. The more difficult problem is interpreting and explaining the optimizer solution, which will only be implemented if refinery management has confidence in it. Simply reporting that "the model says …." is not, and should not be, enough to convince management to alter refinery operating strategy.

Tools to monitor, interpret and validate model results are necessary to achieve confidence in the model throughout the refinery decision-making community.

4.4.4 Difficult to Maintain

A common problem is that engineers intimately involved in building an application are not assigned to its maintenance. The nuances of the system are rarely documented and the engineer inheriting the application may get little training. This often makes RTO application maintenance insufficient to sustain any benefits that have been captured initially.

4.5 Cost versus Risks of RTO Projects

RTO project cost for a major refining unit can easily run into several million dollars. The software license fees and project execution costs are high, and the applications require high maintenance. The benefits available beyond a good MPC controller with a well-tuned LP may be small. A typical RTO project takes 1-2 years to execute with no return on investment until the system is on-line, closed-loop. This compares unfavorably to an MPC project with one quarter the cost, proven benefits over regulatory control and a schedule of 4-6 months.

Cutler and Perry state that RTO success depends on:

- Model parameter accuracy
- Accuracy of process constraints
- Accuracy of process model
- Accuracy of pricing
- Accuracy of MPC

An additional factor for RTO success is the capability of support staff.

The probability of success is a multiplication of the above six factors:

$$\text{Probability of sucess of optimization} = \begin{bmatrix}\text{Relative accuracy of} \\ \text{model parameters}\end{bmatrix} \times \begin{bmatrix}\text{Relative accuracy of} \\ \text{process constraints}\end{bmatrix} \times \begin{bmatrix}\text{Relative accuracy of} \\ \text{process model}\end{bmatrix} \times \begin{bmatrix}\text{Relative accuracy of} \\ \text{unit values}\end{bmatrix} \times \begin{bmatrix}\text{Relative accuracy of} \\ \text{process control system}\end{bmatrix} \times \begin{bmatrix}\text{Capability of} \\ \text{support staff}\end{bmatrix}$$

Clearly the risk of failure with RTO is very high!

4.5.1 How should one approach RTO?

In spite of the high risks of failure with RTO, controlling these risks and selecting a scope covering multiple-units can lead to benefits that are attractive.

A few recommendations to consider before embarking on an RTO project are:

- Define the RTO scope to maximize benefits
- Identify potential benefits from RTO over MPC using off-line simulation
- Develop an execution plan to do the project in phases. For instance, use the model off-line first and capture benefits from data reconciliation and monitoring of model parameters. Validate model accuracy with open-loop predictions and work to verify the validity of the open-loop optimization solution
- Use off-line kinetic models to identify limitations and data requirements to keep the model tuned
- Build in-house simulation and modeling experience and expertise
- Improve quality of online process data
- Select competent engineers to execute and maintain RTO applications

5. CONCLUSIONS

There remain significant linear MPC benefits that are not being captured by existing controllers; the actual success rate of these controllers has been overstated. These benefits can be captured by building better controllers and by improving controller maintenance. Tools that simplify troubleshooting and maintenance of MPC controllers and add to project execution efficiency will increase realized benefits.

Non-linear models, either empirical or first-principles, are not accurate enough for dynamic control. Adaptive MPC controllers receiving gain updates from inaccurate non-linear models will, at best, not deliver additional benefits. The non-linear behavior of most refinery processes can be adequately addressed in linear MPC using variable transformations. These non-linear transformations capture most of the benefits expected from non-linear dynamic control. Therefore, the justification of non-linear dynamic control in refining applications is questionable given the cost, complexity and model inaccuracy concerns.

RTO in its current form tends to take the same process scope as MPC controllers. This limits the benefits by excluding many “big” and “difficult” decisions that are left by default to the approximate linear models in the Refinery LP. Many units have only small incremental benefits for RTO over MPC on the same scope.

RTO models tend to be opaque; known only by very few specialist engineers who were involved in building and tuning them. They live in “back room” computers and are not visible to the engineer and manager community in the plant. The models’ credibility is limited by this “black box” perception, and whatever power and multi-use capability they have is unavailable to those that have a need for it.

However, Real-time optimization has the potential to deliver benefits. Selecting a scope with a high potential benefit is necessary to justify the high cost. Commitment from management and a strong execution plan is needed to capture the benefits. To increase the number of successful projects will require competent engineers to execute and maintain RTO applications, improved RTO model accuracy through technology and improved quality of online data. Tools for using RTO models for “off-line” applications and to interpret RTO results will increase its use and help build model credibility. Improving MPC performance will also increase the likelihood of successful RTO projects.

The refinery optimization business problem offers many benefits that have not yet been captured by the current typical hierarchy of applications. These benefits, however, lie in the most difficult and complex decisions in refinery strategy, mostly involving large problem scopes. These potential benefits may be very large, but the challenges facing those who seek to capture them are many. Unsentimental assessment of the pros and cons of current practice is a good place to start in addressing those challenges.

REFERENCES

NPRA Question and Answer Sessions, Computer/Process Control, 1995-2000.

David Holden (Moderator), NPRA Question and Answer Session on Modeling, Simulation, and Optimization, November 16-18, 1998.

Cutler, C. R., and Perry, R. T., “Real Time Optimization with Multivariable Control is Required to Maximize Profits”, *Computers and Chemical Engineering*, **Vol. 7**, No 5, pp. 663-667, 1983