APPLICATION OF MULTI-NODAL NETWORK SIMULATION MODELS IN THE DEBOTTLENECKING OF A COMPLEX PIPELINE NETWORK

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ABSTRACT

The problem of identifying and removing bottlenecks in a multi-terminal oil & gas pipeline network while achieving quality and delivery targets is a very real and complex problem. The most effective way to meet the above business objective is to develop a terminal network simulation model.

This paper is a case study describing the approach in designing a complex multi-nodal pipeline network simulation model with the objective to resolve a critical inter-company storage problem for a major refiner.

Various complex system modeling techniques and approaches are elaborated with a focus on practical application. A case study is also presented to demonstrate the practical application of the modeling techniques for terminal network simulation model development.

INTRODUCTION

Lately, topics like system modeling, simulation, and production planning have become very popular research themes in the oil and gas industry. Information technology has progressed to the point that significant advancements in simulation accuracy and reliability are possible. Individual field components can now be modeled more easily and complex events like multiphase flow can be simulated with high accuracy. We can relatively easily optimize the performance of important equipment. The challenges arise when attempting to model an entire system of these components. Even when all components of a system are well known and their reaction to an input is clearly defined, we can only guess how the system as a whole will respond to a particular action [6].

Usually, there are two major factors that make the system's behavior difficult to predict and understand. One of them is the volume of information that needs to be accounted for. Mostly it is the result of a great number of components that have a series of properties or behavior patterns that need to be considered. Another one is the complexity of the system as a whole. A single change in one of the inputs might trigger a ripple effect of changes through the whole system. And sometimes the effect is completely opposite of what was originally expected.

The difficulty of predicting the reaction of a system to an action or change increases exponentially with the number of components or their complexity. This is where the simulation model of the system can help. In this case, a simulator calculates the dynamics of the systems by taking into account the system's current states, and predicts future states and their operational behavior. By running different scenarios, a systems' simulator can assist with operational analysis, bottlenecks identification, and in some cases in planning future operations.

LITERATURE REVIEW AND DEFINITIONS

Oil and gas transportation links the upstream and downstream functions and plays a crucial role in global supply chain operations in the oil industry. Pipeline network with a series of storage terminals as their nodes represent a complex system to model and simulate its operations. Lewandowski [7] was first to introduce an object-oriented methodology of modeling oil and gas transmission networks. He represented each element of the network (e.g., pipeline, node, tank, etc.) as an object, which can be later assembled into a network. The challenge at that time, as well as currently, resides with which simulation modeling method is to be used, and its implications on the designed system. As it is known, the simulation is only a representation of the real world system. As the result, the accuracy of the outcome always depends on the accuracy of representations. In other words, the behavior of the system will depend on the type of simulation method selected and its implementation. There are three simulation modeling methods that had an increased interest in industry: discreet-event, system dynamics, and agent-based. Each of these methods and its advantages and challenges are described below [5].

Discrete-Event Simulations

Discrete-event simulation (DES) is a modeling method where simulation state variables modeled as a discrete sequence of events in time. An event is when one or more state variables change at a particular instance in time. DES does not include continually in time changing variables. The advantages of the DES are that it is a highly flexible approach and models can be incredibly detailed if needed.

System Dynamics

System Dynamics (SD) is an approach where the structure of any real-world system is a causally closed structure that determines its behavior over time [4]. It suggests abstracting away from individual objects and thinking in terms of aggregates and the feedback loop. SD is more flexible in capturing an interaction between entities and their characteristics by describing graphically and mathematically the casual loop of influence and relationship between components.

Agent-Based Simulation

Agent-based simulation (ABS) modeling is a more recent modeling method used for complex systems composed of interacting, autonomous "agents" [1,3]. By representing agents with their individual characteristics and behaviors across an entire population, it can help explain how agent diversity affects emergent behaviors of the system as a whole. Currently, there is no standard or agreement on the definition of an agent; it all depends on the planned use of the model.

Each of the above methods has a better fit in relationship to model abstraction level. System dynamics has the best fit on higher and strategic abstraction level. Discrete event modeling is focused on a process that helps to clarify the complexity of the organizational behavior, and fits better for medium and medium-low abstraction. An agent-based model is the only one that can actually vary from detailed (modeling physical objects) to highly abstract (modeling competing entities for the same resource).

PROBLEM DEFINITION

The three modeling paradigms are basically the three different views a modeler can utilize when mapping the system's real world into the models. The selection of the modeling method depends on multiple factors: project goals, data availability, and the nature of the modeled system. Modelers based on their experience or personal observation might pick one or a combination of tools [5].

The cross-paradigm modeling concept is based on modelers developing a model within each paradigm and cycle between them carrying information from one model to the other. Thus, they avoid sacrificing aspects of each modeling method, but introduce a significant drawback due to not yet well-developed methodology to tackle all the issues of a dual-model approach. This is necessary because frequently the modelers cannot completely conform to one modeling paradigm by traditionally using a single method tool. They either use workarounds or leave parts of the problem outside the scope of the model. With time, this contributes to serious model limitations and usability concerns of cross-paradigm modeling concept.

The case study in this paper describes the successful application of the above methods and their combination in one model with the scope of simulating multi-nodal terminal pipeline network operations.

BACKGROUND

A large trans-national crude oil pipeline company was growing quickly and unable to resolve a chronic shortfall in its throughput and revenue performance. Specifically, one of the major regional terminals had unresolved apportionment problems that required dynamic modeling to understand the root causes of the problem and upstream and downstream effects [8].

Previously used traditional manual methods of analysis had limited capability of capturing the terminals interactions and was not suitable for the evaluation of large numbers of operating scenarios. The ability to run multiple operating scenarios was a key in identifying terminal network system bottlenecks and possible mitigation strategies to relieve the capacity constraints.

Objectives

The scope of the project was to develop a new terminal network simulation model and related data systems to increase the business ability to analyze apportionment problems in the affected region and evaluate multiple business scenarios on the one to two year planning horizon.

The model needed to have capability to assist businesses in discovering system bottlenecks, evaluating their mitigation options, and assessing the associated upstream and downstream effects. In addition, due to the significant projected infrastructure growth in the near future, the model needed capabilities to assess proposed capital project impact to bottlenecks and system throughput.

Network Model Benefits

The benefits of developing a functional terminal network simulation model are:

- Quantifiable data-driven decisions for new capital improvements.
- Improved understanding of cumulative effects of volume increases to local and network-wide operations.

- Increased confidence in representing system impacts, options, costs and benefits to senior management and external stakeholders for new capital additions.
- Reduced processing time for capital requests and better handling of document control.

The scope of this project was not only to develop a terminal network model, but also to use it in dealing with specific and tangible business problems (e.g., bottlenecks in existing system).

Project Approach

The modeling exercise was broken in five-step approach. The steps include:

Step 1: Data Collection, Review, and Analysis
Step 2: Develop a Base Case Operational Analysis and Scenario Definition
Step 3: Develop a Modified Base Case for Evaluating the Projects
Step 4: Model Development, Verification, and Validation
Step 5: Scenario Evaluation Phase

SYSTEM ARCHITECTURE

Terminal Network

Two approaches were considered for terminal network development: 'domino' and 'rule-based'.

In 'domino' terminal modeling approach each terminal model is built first on individual bases. The network is developed by connecting corresponding terminal's inputs and outputs. This approach envisions modeling of the network to be more of a cascade or "domino" type model, where the output of one model becomes the input for the downstream model. This approach has the benefit of maintaining continuity with what has already been developed and allows business to simulate the current operations. Another advantage of this approach is that it allows, for ease of manipulation/adjustments, to focus on a specific area of interest. Moreover, this approach usually takes less time to complete since it is based on previously completed work.

The key aspect of this approach is that the starting point is balanced around each of the terminals that represent a current operation for model calibration or validity and the batches or volumes the terminals were not able to run. In this manner, proper calibration of the network needs to be developed to match the volumetric limits based on the actual constraints.

In this case, the project evaluation analyses are done by making changes to the variables that relieves the identified constraint rerunning the original schedule and subsequent evaluation of the resulted volumetric changes. Then cascade this effect in reverse through the network. Clearly, this is more of a manual process from a networking standpoint.

However, the 'rule-based' model would be preferred when planning the evaluation of future volumetric projects. The 'rule-based' model allows the impact to propagate on all lines at the same time with the model running in a forward prediction mode, which may lack the granularity or ease of adjustment.

In this approach, each terminal output is based on the batch sequence rules defined by the business for each terminal. The timing of arrivals to the downstream terminal is factored in the model, along with the constraints. In this approach, the constraints and parameters, such as line volume rates for the basis, are fixed versus having a catch-up feature as in the previous model to handle the missed batches. The system either runs the volume and batches, or it doesn't. Then the user would debottleneck each constraint to analyze system-wide impact. The system-wide effects would be more readily apparent in this approach. However, emulation of the existing facilities would be less apparent with this approach because the model is predicting the sequencing as compared to trying to match actual data.

Modeling Methods

After engaging with the software vendor and completing preliminary analysis, it became clear that all three modeling methods have distinct advantages for modeling specific parts of the network system [8].

Discrete event – is excellent for pipelines where there is a queue waiting to be processed, yet inadequate for continuous processing over the course of time where time is critical. For example, it is useful at filling a tank at the start and stop, but unsuitable when it's dependent on rate. Flow between terminals is time dependent and needs to be reflected.

Agent basis – provides the most flexibility, allowing tanks to operate the way business wants with mixing, spill over, and so on. It does not handle time either. Moreover, it is computationally intensive and has stability issues.

System dynamics – allows for time factor that is not easily handled by the above two approaches. It authorizes a continuous process that is rate and time-dependent (e.g., equation base, stochastic, etc.).

Modeling Considerations

For the network model to assist in identifying the stress points and constraints that bottleneck the terminal, and analyze the debottlenecking solutions, it has to have the ability to change:

- Pooling

- Pipeline Rates
- Tank Allocation
- Connectivity Matrix
- Priority Mixing
- Commodities
- Injections rules (FIFO, most volume, etc.)
- Landing rules (Most Ullage followed by spillover)
- Investment flexibility to change tanks, lines, connectivity etc.
- Stochastic
- Batch movement on pipelines

The reporting requirements that have been identified as key model's output are:

- Throughput key metric (by line and commodity)
- Tank Utilization (by commodity and terminal)
- Line rate
- Time Floating
- Retention time
- Tank turns
- Output schedules

RESULTS / DISCUSSION

Case Study

A subset of the large multi-commodity crude oil and gas pipeline network located in the US was chosen as a candidate for modeling because of its strategic importance to the overall network performance. The selected subset of the network consisted of four large terminals and cumulatively over 160 medium and large diameter crude oil storage tanks with numerous interconnecting pipelines and associated meters and instrumentation. Scheduling of the terminal was done by a central planning group located some distance from the terminal. The terminal was operated remotely from a central operations control center.

After a series of workshops with the business community, it was determined that the model had to assist businesses in answering specific questions. Examples include:

- Are new tanks required to meet future requirements?
- What is the percent utilization of each tank?
- Is the current facility capable of meeting downstream shipper demands?
- If a tank is fully utilized, is it impacting the ability to deliver on time?
- If a tank is fully utilized and adversely impacting delivery, what buffers (in and out) are required to prevent outages?
- Are the system limits either terminal or pipeline related?

Results Discussion

After analysis of various modeling techniques and approaches, the project team successfully developed a terminal network model using modeling software AnyLogic 6.0. AnyLogic is the development platform that allows users to build complex simulation models, and is currently the only out-of-the-box simulation tool that supports all of the most common simulation methodologies. Other modeling platforms can be used to develop simulation models with similar characteristics, but the decision was made to use AnyLogic. The key characteristics and outcomes of this model are presented below.

Modeling Approach. The final model was developed using 'rule-based' approach, mostly due to the requirement to evaluate future capital projects from throughput planning purposes. The model allows the user to debottleneck each constraint, and see the system-wide impact.

Modeling Paradigm. After extensive analysis of the best practices, strengths, and weaknesses of each modeling method, the project team decided to take advantage of all of them, and as a result use a combination of discrete event, agent-based and system dynamic methods in the final network model. The network system components were attributed to the following modeling methods:

- **Agent-Based** - the major logical elements of the model are all decision-based, and this suggests agent-based modeling (ABM). ABM models behavior, and the choice of how to direct the oil through the network, particularly where it interacts with breakout terminals. This requires advanced behavior. ABM also lends itself best of all methods to OO simulation techniques, which are indicated to be required.
- **Discrete Event** - outside of a terminal, there is a simple process based on ordering on how to deal with the oil moving through the network. This suggests that process-centric or discrete-event modeling (DES) would be useful.
    - DES models processes, particularly constrained processes dealing with queues, throughput, and utilization. Since the model desires metrics like this, DES can easily provide them.
    - Also, the fact that in this specific case the oil in its network is tracked by discretizing the oil volumes into 'batches' suggested a discretized view of the network processes.
- **System Dynamics** - Continuous flow of oil, and the need to make decisions based on precise levels/control of this continuous flow suggested the need for system dynamics (SD). SD is excellent for continuous flow modeling, as well as abstract feedback-driven processes. While SD was chosen primarily for the former, the extensibility requirement also suggested that if SD elements were added later to more

accurately model other elements, SD would be useful, and so it was selected.

Model Logic. In addition to the model approach, required network-related operation's processes were determined. These included: Landing, Injection, Bypassing, and Routing.

- **Landing Logic.** The landing logic is handled inside the terminal class. It details the process by which a tank inside a terminal is chosen to hold a batch that arrives at the terminal from a pipeline. If no tank can be found in any case, the line the batch is landing from stops. Generally speaking, the objective was to minimize line stoppages since these represent a loss of revenue.
- **Injection Logic.** The injection logic is handled inside the terminal class as well, and it details the process by which a batch is chosen to inject into a specific line. If no batch can be found to inject, the line does not inject a batch. There is also logic in place that, when enabled, checks to see whether a line clearance is required and if so attempts first to clear that line by injecting an appropriate batch.
- **Bypass Logic.** The bypass logic is handled inside the pipeline class and deals with whether a batch is allowed to (and whether it needs to) move past a terminal without landing in that terminal. This is only allowed in certain locations, and so it is not always invoked.
- **Routing Logic.** The routing logic is handled inside the batch class and reflects the batch directing itself through the network. Every batch is assigned a route it wishes to take through the network at instantiation and follows that route. The routing logic is called whenever it lands and finds the next stop on its route through the network.

Inputs and configuration data. For the model to run successfully, the key input data are network configuration data (for more examples see above modeling considerations sections), and the model input schedule. The model input schedule is the sequence of the commodity batches and their volumes that are planned to land at models terminals. The schedule is required only for those pipelines that actually are inputs to the network subset. Other key elements of information that took considerable time for the project team to define and agree on were injection and commodities rules. Definition and agreement on business rules and their abstraction level in the model represent the most important, challenging and time-consuming part of the project.

Reporting. All business reporting requirements have been met in the new network model. The key reports that are generated after each simulation run are:

- Volume throughput
- Tank utilization
- Tank inventory by commodity over time
- Terminal inventory by commodity over time
- Schedules by terminal
- Retention time
- Transit Time
- Tank % floating time
- Convergence interval
- Operational constraint log
- Change orders/events log
- Pipeline events

Challenges and Design Considerations

Through model design and development, the project team had to deal with a series of challenges and design considerations. Some keys of the above are presented below.

Abstraction Level. Each model can vary from being very detailed (simulating pumps and batches molecules behavior) or very abstract (simulating terminal as just one big tank). The project team needs to reach a challenging balance between the model being good enough to answer business questions and level of model's complexity and cost.

Model goodness of fit. How good the model should be is also important and difficult to define. By agreeing in advance on the required model's level of accuracy and reliability, the development team will drive the required model complexity and time allocated for model verification and validation.

Scalability is another option that needs to be considered when developing the model. Can I easily extend this model by adding additional terminals, pipelines or tanks? This again will determine final model complexity.

'Reality check'. Variability needs to be introduced in order to increase the model's approximation of the real world situation. If the model follows defined rules and the provided schedule, the obtained results would be deterministic and predictive in nature. The reality of the real world is that there is always a chance of equipment malfunction, unscheduled power outage, unplanned injection or delivery batch delays. All these will ultimately impact the system's behavior in an unknown way. The challenge is to determine all statistically significant factors that would affect the system and, most importantly, predict their behavior and the impact to the network model. The development team should address this problem during model design and data analysis before commencing model development.

MODEL ASSUMPTIONS & RISKS

Model Intend

The primary assumption is that the model is to be used to assess the impact of infrastructure changes and their causes to the pipeline terminal network. If used in this context, the model should produce useful output.

Model Assumptions

The assumptions that are explicitly built in the model are:

- ***Component Assumptions*** - a general assumption of the model is that the input file is clean; it does not sanitize the input itself. This implies that if the input file is not clean, the model crashes on initialization.
- ***Batch Assumptions*** - a major assumption of the model is that batches cannot be created, split, combined, or destroyed, with the sole destruction exception being when the batch reaches its destination. Batches are also assumed to be one commodity only; while mixing does occur in the real system, the model does not track quality issues, and therefore the batches can be seen as administrative units rather than physical units.
- ***Terminal Assumptions*** - terminals are assumed to wish to avoid line shutdowns over incompatibility issues, except in very specific cases (e.g., NGL).
- ***Pipeline Assumptions*** - pipelines are assumed to run at only one of three rates. If more data on how pipeline rates are changeable, this assumption could be relaxed in the future. Side-streaming is explicitly not modeled, due to batch indivisibility.
- ***Landing Assumptions*** - The model assumes that landing is a rote process and that the rules are only flexible as far as the input file allows. This, along with the line rate assumption for pipelines, leads to more start/stop cases than what happens in the real network. The model assumes that spillover can occur over any number of tanks.
- ***Injection Assumptions*** - The model explicitly does not model deliberate destination change events on the part of a user as a tool to clear blocked lines.
- ***Bypassing Assumptions*** - The model assumes that there can be only one bypass line for each destination. This assumption will be violated in the future case of multiple bypass lines past terminal.

Risks

Simulation models should be strictly used as per intended design. For example, the users of the case study model need to keep in mind that:

- The developed model is not a scheduling tool – it can evaluate or validate how a given schedule might impact an infrastructure's performance, but it should not be used to create a better schedule.
- The model is not a solution tool – hence it will not provide the solution; instead it will validate solutions provided by the user.
- The model is an approximation of the real world – the level of abstraction, modeling complexity, and designed parameters are dependent of the modeler's experience and knowledge. And the level of details will always be different from the real world.

The biggest risk of any simulation model is when the user uses the model to answer questions that it was never designed to answer. Models are built for a specific purpose and were validated for that purpose, hence they should only be used for that purpose. To mitigate this risk, the project team used model accreditation to certify model's specific purpose.

FUTURE WORK

For this exercise, the model was designed and developed to simulate terminal network from throughput perspective only. But the reality is that operational and infrastructure planning decisions are never made solely on terminal network throughput view. The concepts of pooling quality, reliability, power consumptions, or integrity risk are types of other variables taken into considerations when strategic decisions were made.

The opportunity to evolve this model to represent the holistic view of the network and represent other dimensions like quality, operating costs and risk needs to be considered.

Simulation models are foundations for the development of complex optimization engines. That can be used for capital and operational optimization.

CONCLUSION

This paper described the typical terminal pipeline network modeling challenges, and demonstrated how simulation models can be developed to meet business objectives.

Various modeling techniques and approaches were discussed with a focus on practical application. A case study is also presented to demonstrate the practical application of the modeling techniques for terminal network simulation model development.

DISCLAIMERS

The opinions expressed are those of the authors only.

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