Analysis of Oil and Gas Supply Chain Using Continuous-Time Discrete-Event Simulation

Zaid Kbah and Nadiye O. Erdil
Department of Mechanical and Industrial Engineering
University of New Haven
West Haven, CT 06516, USA

Faisal Aqlan
Department of Industrial Engineering
Pennsylvania State University, The Behrend College
Erie, PA 16563, USA

Abstract

Although every supply chain is unique and has challenges in achieving operational excellence, only a few are as complex as oil and gas supply chains. To stay competitive in the market, it is important for these supply chains to enhance their operational efficiency, responsiveness, resilience, and reliability. Different analysis techniques are used for this purpose, including analytical and simulation models. However, due to the high complexity and operational variability of oil and gas supply chains, it is difficult to develop accurate analytical models to study the behavior of the supply chain. In this case, simulation is the most appropriate method to use because of its ability to provide a detailed and dynamic view of the supply chain. In this study, a Continuous-Time Discrete-Event (CTDE) simulation model is used to study the behavior of oil and gas supply chains in order to improve their performance. A case study for an oil and gas supply chain in one of the world’s largest oil producing countries is considered. Different scenarios are analyzed and a statistical comparison is performed to validate the CTDE model. Results obtained from the simulation model are used to provide recommendations to improve the performance of the supply chain. The proposed improvements increase the average number of gasoline and LPG served customers by 23% and 78%, respectively.

Keywords: Oil and gas industry, supply chain management, Continuous-Time Discrete-Event simulation

1. Introduction

The recent turnover in the global market for oil and gas has led companies to question if they are capable of thriving in a business environment where the production exceeds the demand. The traditional systemic balance in the oil and gas market has been replaced by a vast increase in supply and recession in demand, which resulted in drastic shrinkage in profit margins. As companies strive to increase their profits in the current environment, they inevitably look at their supply chains. Understanding the behavior of their supply chains and planning accordingly would help companies improve the supply chains’ efficiency and provide a competitive edge to the company in preserving or even increasing profits.

Oil and gas supply chains are divided into three streams: upstream, midstream, and downstream. Multiple activities occur in every stream. There are reservoirs, transportation, and logistics activities that drive the flow of information and material through these streams. Figure 1 represents a general distribution scheme of oil and gas supply chain. Oil and gas supply chain management encompasses many aspects. These aspects vary from traditional planning, such as distribution and transportation, to more complicated tasks such as inventory management and supply chain network design and configuration [1]. Despite the complexity and interdependency of the oil and gas supply chain elements, most researchers study supply chain entities separately and independently without adequate use, development, or deployment of modern simulation approaches and software [2].

In the case when changes in the system status occur continuously over time, discrete event simulation (DES) might not be an appropriate tool to model the system since it only reflects the discrete-change-state, not the continuous behavior. A system with continuous-change-state and discrete-change-state variables can be better simulated by a
combined continuous-time discrete-event (CTDE) simulation model. While the DES captures the discrete change of the system variables, the continuous-time simulation can demonstrate the continuous change in the system status by incorporating mathematical equations through algorithms. For instance, in modeling oil and gas supply chain operations, the flow of the products through the supply chain can be represented in continuous-time simulation, while technical malfunctions would be handled in DES [3].

![Distribution scheme of oil and gas supply chain](image)

**Figure 1: Distribution scheme of oil and gas supply chain**

The literature on oil and gas supply chain simulation modeling is limited. DES and mathematical modeling have been the most commonly used methods to study these supply chains, especially on the operational and the tactical levels. However, oil and gas supply chains are neither thoroughly discrete nor continuous, so both the continuous-change-state and the discrete-change-state of the system need to be addressed when developing a simulation model [4]. An analytical framework of discrete-continuous combined simulation that includes equations to capture the continuous changes of the supply chain was developed in [4]. This research shows the advantages of combining these two simulation approaches. A continuous-time formulation that solved the complex issues of scheduling short-term crude oil operations in an oil refinery was presented in [5]. In [6], the authors developed a decision support system by using DES that aimed to optimize the total average profits of the oil terminal operations. The applications of the Pipe Transportation Simulator (PTS) to model an oil refinery supply chain was described in [7]. The current decision support system (DSS) models that use the combined continuous-discrete event simulation, some of which are listed in this paper, focus on the operational level supply chain but fail to use a computerized simulation model to model the dynamic interactions of the system elements and the stochastic properties.

Oil and gas supply chains contain thousands of complex and sequential processes that extend across the world, making them susceptible to uncertainty [8]. Although the oil and gas supply chains encompass many complicated processes, simulation approach has been shown to be an effective tool capable of modeling these supply chains to capture the inherent uncertainty and test the proposed improvements. Such improvements can result in reduced costs and improved performance [9]. Using Arena® simulation software, this research develops a computerized simulation model to study and analyze an oil and gas supply chain. The proposed CTDE simulation considers the continuous-change-state, the discrete-change-state, the stochastic properties, the control policies, and the dynamic interactions among the supply chain entities. The user interface allows monitoring of material flow through the supply chain. Results from the simulation model are used to provide recommendations for improving the supply chain performance and customer satisfaction.

2. Simulation Modeling of Oil and Gas Supply Chain

Continuously changing variables of networks can be addressed using continuous-time simulation approach to account for the continuous-change-state of the variables over time. The relationship of the rate of change of system’s state with respect to time is defined by a partial derivative equation. In this study, the state of the system variables, for instance, the current level of liquid/gas in the tank is defined by state equations calculated by differential
equations with function \( f \) as \( x = f(t, \lambda, x_0) \), where \( t \) represents the time, \( \lambda \) represents model parameters, and \( x_0 \) represents the initial state of the system. In many cases, developing system state equations in terms of time, parameters, and initial condition is difficult due to complex and continuous interactions among system components. In oil and gas supply system, when the flow rate of one of the regulators equals zero, the current level of gasoline in the storage can be written as: Current Level = \( x_0 - \frac{dx}{dt} \), where \( \frac{dx}{dt} \) represents the change in the initial level of the gasoline at time \( t \). This equation can be complex if an inward flow occurs concurrently with the outward flow. Simulation software can help model these complex, continuous-time, processes.

To develop a CTDE simulation model, the configuration settings used to calculate the continuous changes need to be defined and established. The changes in the simulation element levels and rates are associated with differential equations that are continuously updated. In Arena® software, the parameters that dictate the update of the differential equations need to be defined in order to obtain accurate results. To increase the accuracy of the results, the interval time between the continuous-statistical calculations needs to be shortened within a reasonable range.

Trucks arriving and queuing at the distribution centers are modeled by using DES; however, the filling process of these trucks is modeled by continuous-time simulation. Probability distributions can be used to represent the system variables, such as trucks’ arrival and the inward and outward flow rates, to increase the system robustness and incorporate uncertainty.

In oil and gas supply chains, many control policies are necessary for the operational purposes. For instance, the maximum level of material in the storage unit should not exceed the maximum threshold limit (e.g., 90% of the storage unit capacity) nor should it go below the minimum threshold limit (e.g., less than 10% of the storage unit capacity). These control policies explain the flow of material among supply chain elements as well. The level of the material in the storage unit influences inflow, outflow, and surplus flow rate. In return, the supply of the raw gas influences the customer satisfaction and price. Concepts from system dynamics modeling can also be utilized where the storage units are considered as stocks and the pipelines as flows that convey materials from one element of the supply chain to another.

Dynamic control algorithms such as Flow Rate Control (FRC) and Material Level-Based (MLB) was used to control and adjust the flow of materials through the pipelines. FRC controls and adjusts the flow when the flow rate is over the pipeline capacity or under the desired value, while MLB algorithm controls the flow of surplus and contaminant to the flare to be burned.

3. Case Study

The case study considered in this research is based on a natural gas supply chain that encompasses two refinery plants (South and North Plants), three distribution centers, five main storage units, and other elements. Each refinery plant has its own supply chain with some overlapping. The two plants share one fractionation unit and Broad Cut storage unit, and they both transfer dry gas to the same dry gas distribution company. There are a few differences between the two plants. For instance, the South Region refinery has a Natural Gas Liquids (NGLs) processing unit and a Gas Treatment Unit (GTU) at the same location, while the North Region refinery has NGLs and GTU units at different locations. The process starts when the crude gas is produced from oil or gas wells and it ends when the gas products are sent to the consumers via pipelines and trucks. Figure 2 shows the two refineries for the company under study. The problems, as addressed in this paper, concern the following model inputs:

1) The arrival rate of trucks at the LPG and gasoline distribution centers, and the outward flow rates from the distribution centers to power plants and industries;
2) The configuration details of the refinery (the number and capacity of the storage tanks, and the capacity of the production/treatment units);
3) The flow rates of material among the supply chain elements via the pipelines;

We used the model to determine:

1) The average total quantity of material added/removed from the distribution centers;
2) The average total number of trucks that have been served/balked at the distribution centers.

Most refineries use operational restrictions and rules. We made assumptions that closely reflect real operational conditions. These are:

1) The trucks balk when not enough gas derivatives are in the distribution centers;
2) The flow of gas to the flares to be burned proportionally changes depending on the materials level in the production units and storage tanks;
3) The minimum allowable level of material (LLL) in the storage tanks is 10% of the tank capacity, and the maximum allowable level of materials (HHL) in the storage tank is 90% of the tank capacity;
4) The maximum and desirable mass flow rate passes through the pipeline per unit of time;
5) The inward and outward flows of material among the supply chain elements happen at the same time.

![Natural Gas Plant](image)

Figure 2: An Illustration of the South and North Regions refineries

### 3.1 Data Analysis and Input Modeling
Input data were collected for a two-month period. Each observation represents the average of 24 recordings collected hourly. The first type of data is continuous representing the flow rate of materials through the supply chain elements. The second type is customer demand, which is partially discrete and partially continuous, depending on the type of the customer. Customer demand was represented by the daily number of trucks arriving to the distribution centers and the flow rates of material from the distribution centers to the customer locations, power plants, and manufacturing companies. Stochastic simulation was used to incorporate uncertainty, capture the behavior of the system, and represent the input data. The collected data was fitted into probability distributions. Some of the probability distributions are shown in Table 1. The flow rates of material were converted into one unit (m$^3$/d) for simplification and accuracy purposes.

<table>
<thead>
<tr>
<th>Demand Type</th>
<th>Mode of Transportation</th>
<th>Expression (m$^3$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous (Flow Rate)</td>
<td>Pipelines (Gas Wells to NGL, 4 pipelines)</td>
<td>TRIA(9.34e+005, 1.23e+006, 1.45e+006)</td>
</tr>
<tr>
<td></td>
<td>Pipelines (GTU to DC, 4 pipelines)</td>
<td>TRIA(7.84e+005, 1.04e+006, 1.25e+006)</td>
</tr>
<tr>
<td></td>
<td>Pipelines (NGL to Broad Cut, 1 pipeline)</td>
<td>NORM(2.24e+003, 295)</td>
</tr>
<tr>
<td>Discrete (Number of Trucks)</td>
<td>Gasoline Trucks</td>
<td>POIS(40.3)</td>
</tr>
<tr>
<td></td>
<td>LPG Trucks</td>
<td>POIS(22.5)</td>
</tr>
</tbody>
</table>
3.2 Model Verification and Validation
During the model verification stage, we ran the model for multiple replications to verify and examine the functionality of the simulation elements and to debug model development errors. We also examined if the model’s elements reflected the conceptual model and worked correctly, while following the input parameters and the input data accurately. The verification step was successfully completed.

The validation of the simulation model was completed in three stages. At the first stage, we reviewed the supply chain structure and control policies multiple times with the experts from the company in order to ensure the model’s validity and credibility. Testing of the application of the control policies and the control algorithm functionalities during the second stage was accomplished by comparing the simulation results with the company experts’ evaluation of the system behavior for a given scenario. During the third stage, we compared the model’s outcomes with the collected data.

During the validation process, we ensured obtaining an agreeable estimation of the real system values and acquiring the number of replications that yields simulation outcomes with low margin error (less than or equal to 5%). This level is considerable since a higher percentage is critical to the supply chain in this sector. For example, in the case when the material level in the storage unit exceeds 5% of the upper threshold, the result could be a catastrophic disaster, such as creation of a suffocating vapor cloud and financial loss. We ran the simulation model for 64 days and 30 replications. Tables 2 and 3 summarizes the results of the statistical tests performed for model validation. One-sample t-test was used to compare the average total number of customers and the average total quantity of material added/removed at the distribution centers with the actual data.

The results show that the values obtained from the simulation model and those obtained from the real system are not statistically different (p-value > 0.05). Based on the statistical test results and the review of the simulation model with the company’s experts, we consider the model valid, and that it is an accurate representation of the real system.

<table>
<thead>
<tr>
<th>Quantity Added/Removed</th>
<th>Simulation</th>
<th>Actual</th>
<th>Difference (%)</th>
<th>P-value</th>
<th>Std. (simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Gas</td>
<td>637182735</td>
<td>637671143</td>
<td>-0.08%</td>
<td>0.71</td>
<td>7336162</td>
</tr>
<tr>
<td>LPG</td>
<td>296582</td>
<td>296793</td>
<td>-0.07%</td>
<td>0.61</td>
<td>3925</td>
</tr>
<tr>
<td>Gasoline</td>
<td>82199</td>
<td>81847</td>
<td>0.43%</td>
<td>0.2</td>
<td>1679</td>
</tr>
</tbody>
</table>

Table 3: Validating simulation model based on discrete output

<table>
<thead>
<tr>
<th>Number of Served Customers</th>
<th>Simulation</th>
<th>Actual</th>
<th>Difference (%)</th>
<th>P-value</th>
<th>Std. (simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline Trucks</td>
<td>2573</td>
<td>2571</td>
<td>0.10%</td>
<td>0.78</td>
<td>52.7</td>
</tr>
<tr>
<td>LPG Trucks</td>
<td>1437</td>
<td>1440</td>
<td>-0.16%</td>
<td>0.80</td>
<td>52.4</td>
</tr>
</tbody>
</table>

3.3 What-if Analysis
The elements of oil and gas supply chains are interdependent, and applying physical improvements are associated with high capital investment and uncertainties. Building a simulation model helps the decision makers understand the system and evaluate improvements strategies. In this paper, we focused on improving the supply chain performance by increasing the production of gasoline and LPG. These products are critical to the customer and their production level is relatively low in comparison to the dry gas. Gasoline is transferred to the customer by trucks only, while LPG is transferred via trucks and pipelines. The priority of the LPG customers was given to the industrial manufacturing companies who need an uninterrupted supply of LPG by pipelines for operational purposes. Therefore, we aimed to find the optimal number of trucks that LPG distribution center daily serves while ensuring uninterrupted flow of LPG to the industrial manufacturing companies and the optimal number of the gasoline trucks per day.

We assessed the utilization of the supply chain elements and the average level of materials of the base model to identify the potential opportunities for improvements and increase the production of LPG and gasoline. Since the average level of materials at the Broad Cut storage tanks is considerably high (~ 40%), we increased the daily outflow rate from the Broad Cut storage units to the fractionation unit by 10% to observe its impact on the utilization of the fractionation unit and the average number of the served customers at the LPG and gasoline distribution centers.
“What if” analysis was applied to find the optimal number of the served customers (trucks) for gasoline and LPG products in the improved model when the number of unserved customers converges or equals zero. Table 4 shows different scenarios that were tested to find the optimal number of served customers of the two products (gasoline and LPG). In Scenario (5), the average number of the daily customers increased from (~40) and (~23) in the base model to (49) and (41) customers for gasoline and LPG respectively while the unserved customers remained less than (0.5%). However, the average level of material at the Broad Cut storage tanks decreased from (~40%) in the base model to (~24%) in the improved model. Although the material level at the Broad Cut storage tanks was decreased by (~40%), it still is (~14%) over the minimum allowable level (LLL).

Table 4: What-if analysis results

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Controlled Factors</th>
<th>Gasoline</th>
<th>LPG</th>
<th>Broad Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of Gasoline Trucks</td>
<td># of LPG Trucks</td>
<td>Served Customers</td>
<td>Dismissed Customers</td>
</tr>
<tr>
<td>Scenario (1)</td>
<td>45</td>
<td>37</td>
<td>2880</td>
<td>0</td>
</tr>
<tr>
<td>Scenario (2)</td>
<td>46</td>
<td>38</td>
<td>2944</td>
<td>0</td>
</tr>
<tr>
<td>Scenario (3)</td>
<td>47</td>
<td>39</td>
<td>3008</td>
<td>0</td>
</tr>
<tr>
<td>Scenario (4)</td>
<td>48</td>
<td>40</td>
<td>3072</td>
<td>0</td>
</tr>
<tr>
<td><strong>Scenario (5)</strong></td>
<td><strong>49</strong></td>
<td><strong>41</strong></td>
<td><strong>3122</strong></td>
<td><strong>14</strong></td>
</tr>
<tr>
<td>Scenario (6)</td>
<td>50</td>
<td>42</td>
<td>3133</td>
<td>67</td>
</tr>
<tr>
<td>Scenario (7)</td>
<td>51</td>
<td>43</td>
<td>3131</td>
<td>133</td>
</tr>
<tr>
<td>Scenario (8)</td>
<td>52</td>
<td>44</td>
<td>3137</td>
<td>191</td>
</tr>
<tr>
<td>Scenario (9)</td>
<td>53</td>
<td>45</td>
<td>3148</td>
<td>244</td>
</tr>
</tbody>
</table>

4. Conclusions and Future Work

CTDE simulation considers the dynamic interactions among the system entities, incorporates uncertainty by representing the inputs in the theoretical distributions, captures the continuous and discrete aspects of the systems, and applies control algorithms. In this paper, we developed a CTDE simulation model for a natural gas supply chain to understand the behavior of the system and provide recommendations to improve the system performance. The model validation results show that CTDE simulation is an appropriate approach to model oil and gas supply chains. “What-if” analysis was performed to evaluate different scenarios. Further research will involve representing the flow rates of pipelines in the differential equations. In addition, financial considerations of the improvements can be investigated.

References