Proceedings of the 2005 Winter Simulation Conference
M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, eds.

DYNAMIC SIMULATION OF A PUSH – PULL DISTRIBUTION SYSTEM

Payman Jula
Mark S. Zschocke

School of Business
3-23 Business Building
University of Alberta
Edmonton, Alberta T6G 2R6, CANADA

ABSTRACT

This paper presents the methodology of the development and the results of a simulation model used to capture the complexities of sulphur distribution system run by Sultran Ltd. in Western Canada. Sulphur is a valuable by-product of natural gas which should be continuously transported from the gas plants to avoid plant shutdowns. The sulphur is routed via rail to port terminals, where ships with variable demands arrive. The empty cars are then assigned back to gas plants for reloading. This closed-loop rail transportation system is challenging to simulate due to the push-pull nature of the system, the high degree of variability, as well as the interdependency of simulated elements. The problem becomes even more challenging when we consider many tactical and operational policies. The developed model is used to study the results of different operations management policies and help the mangers make appropriate decisions.

1 INTRODUCTION

Sultran Ltd is an export sulphur logistics company servicing oil and gas plants in Alberta and British Columbia. Sultran was founded in 1977 as a joint venture of 30 petroleum producers and is responsible for the domestic logistics, distribution, and the seaborne export of commercially formed elemental sulphur. The majority of Canadian sulphur production is derived as a by-product of producing sour natural gas which contains hydrogen sulphide (H_2S). Remaining production results from the refining of sour crude oil. Currently, there are thirteen gas plants serviced by Sultran in Western Canada. Each plant produces one of four types of sulphur and is serviced by either Canadian National Railway (CN) or Canadian Pacific Railway (CP). The sulphur is then transported first to a train hub at Kamploops, from where it is sent to one of two terminals (or ports) in the Vancouver area – either Pacific Coast Terminals (PCT) or Vancouver Wharves (VW).

This transportation system is comprised of rail car resources in a closed loop distribution system, where returning empty rail cars are directed to meet requested plant loading dates and maximize equipment utilization. This system is challenging to simulate and manage due to the high degree of variability, resource availability and the interdependency of all elements.

In particular, the system represents both a push and a pull system. The produced sulphur at the gas plants needs to be transported to the terminals promptly. Inventory space at the gas plants is limited and filling up inventories must be avoided at all times because this will result in the gas plant having to shut down. At the same time, because of high cost of vessel time, the demand of the ships arriving at the terminals must be met as soon as possible.

Due to the high proportion of freight costs to Sultran's total distribution cost, there are high cost-savings opportunities in this system. We use simulation to understand the system and to address many challenges of the strategic, tactical and operational level in this complex transportation system.

The simulation of railroad transportation systems is a growing field (Brunner et al. 1998, Dessouky et al. 2002) and with intermodal services being one of the fastest growing segments of the railroad industry (Sarosky and Wilcox 1994), the opportunities for expansion of this simulation model are substantial. While the challenges of developing railroad simulations have been explored by Krueger et al. (2000), our simulation model focuses specifically on the challenges of accommodating a complex distribution system with combined push and pull strategies.

The simulation software Extend OR was used to build a discrete event simulation model. The model can be used on the strategic, planning, as well as operational level to analyze the effects of changing practices in the rail system or terminal operations. The following questions are among many questions that can be addressed using our simulation model:

- What is the maximum annual capacity of Sultran's rail fleet?
- What would be the effect of adding or removing rail cars?
- What would be the effect of increasing or decreasing turnaround times?
- What is the optimum fleet size required for various annual production levels?
- What is the maximum realizable throughput capacity at PCT and VW?
- What is the average berth occupancy at each terminal at varying levels of throughput?
- What is the extent of queuing delays at terminals at varying levels of throughput?

2 METHODOLOGY

Our approach to this distribution problem had four major phases:

- Preliminaries: data collection and analysis
- Modeling process: business process understanding and model development
- Model verification and validation
- Results: reports and sensitivity analysis.

2.1 Data Collection and Analysis

Two years of historical data was available for analysis, including sulphur production rates, transit times from gas plants to terminals, ship arrivals, and product demand in terms of sulphur grade and quantity. @Risk, a Monte Carlo simulation add-in for Microsoft Excel, was used to fit distributions to sample data. Results were analyzed and appropriate distributions were assigned to model production rates, and transit times. Furthermore, a schedule for vessel arrivals, and suitable discrete probabilities for product demand and ship sizes were derived for the model.

Uniform production rates are used for Gas plants to account for very little volatility in the gas and sulphur production.

High autocorrelation associated with transit times made it difficult to find a distribution with an appropriate fit to the rail transit time data. After analysis, including the removal of autocorrelation, we opted to use a triangle distribution. A triangle distribution with a "most likely" value slightly greater than the "minimum" value is intuitively justified since there is little opportunity to significantly shorten train travel times; at the same time, due to uncontrollable elements such as rail maintenance or bad weather as well as congestion, longer travel times and delays are frequent. While the simulation model accounts for congestion at the gas plants and terminals, congestion within the rail system of CP and CN are out of control of Sultran and therefore not implicitly included in the simulation model. Nevertheless, these delays are significant and common and must be considered in the train travel times.

Vessel arrivals and their demand were modeled based on historical data in terms of product mix and vessel size. There are six possible sulphur type combinations that can be demanded by a ship and must be satisfied by one of the terminals. Depending on the vessel size, each combination requires one of three different amounts of sulphur. The total expected vessel arrivals for a year was analyzed and arrival rates for the ships were derived, which closely matched the historical data. Short-term variability was also considered to account for operational volatilities such as ships arriving ahead of schedule or being delayed for reasons such as bad weather or break down. The arrival rate for ships can be set by the user to match historical or forecasted values. The short-term variability is incorporated through an exponential arrival rate. The overall result is a ship arrival schedule that has a systematic component while reflecting normal operational volatility.

In addition, operational data was required for an accurate simulation model. At the gas plants, there are four different types of storages:

1. Dry: Silo storage which is the preferred storage from which sulphur can easily be loaded onto the trains.
2. Liquid: Liquid tank storage is reclaimed through other organizations and transported out by trucks and doesn't follow the regular distribution path of formed sulphur.
3. Emergency: Sulphur is dumped on a tarmac pad and reclaimed via front-end loaders. This is a slow and costly process.
4. Block: Liquid sulphur solidifies into a solid block. Can be reclaimed via re-melting process, at which point sulphur re-enters the forming system.

Data was collected regarding the storage types and their capacities at each gas plant. Forecasts were used to estimate the sulphur production rates at each gas plant. Furthermore, an initial priority index was defined for every plant to create a ranking system which is used for the allocation of train cars to gas plants. Storage types, production type and rate, initial priority, and many other inputs such as the number of train cars to batch to a train, the load rate, and the re-melt rate differ between the 13 gas plants and all are documented and included in the model.

At the terminal side, data regarding maximum inventory capacities, load rates, and contractual restrictions were incorporated for each of the two terminals in the model.

2.2 Modeling Process

In our model, blocks are used to represent the various operational and business actions that occur within the distribution system. These blocks are then used to direct, delay and assign attributes to our entities (sulphur, rail cars and vessels) and control the information flow associated with various business decisions.

2.2.1 Model

In terms of a dynamic simulation, Sultran's distribution system is summarized in Figure 1.

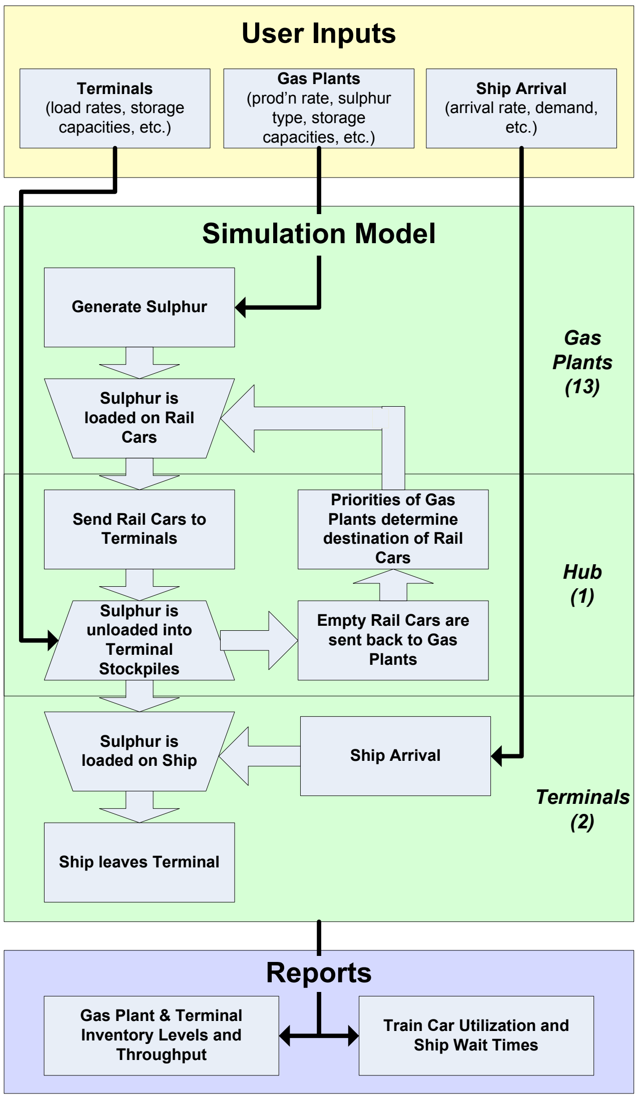

Figure 1: Overview of Sultran's Distribution Model

A sulphur type attribute is assigned to each sulphur entity (which represents one rail car's of sulphur) and a rail company attribute is assigned to each rail car. In turn, these attributes are used in directing rail cars to either PCT or VW terminals and then back to the gas plants. Attributes are also assigned to vessels to indicate the amount of product and the grade of sulphur to load.

Once the high level model was complete (including gas plants, storage capacities, two rail lines, and two terminals with varying stockpile types and capacities), we began to model the business and operational decisions, such as prioritizing the gas plants and routing trains and ships. Most of the decisions are made base on inventory levels at the gas plants and at the terminals. Sulphur that is en route to the terminals (providing additional inventory) and rail cars that are en route to gas plants (providing additional storage space) are both considered in the business decisions and need to be tracked in the model.

2.2.2 User Interface

To help the user navigate through the model, a simple graphical user-interface was developed by plotting the locations of gas plants, the rail hub, and terminals onto a map of Alberta and British Columbia . During the simulation runs, animation shows rail cars traveling from gas plants to hubs, to terminals, and returning.

User inputs were then categorized based on their relation to gas plants, rail, terminals or vessels. Users can easily change input data such as production rates at gas plants, storage capacities of gas plants and terminals, and rail transit times. The interface virtually eliminates any need for the user to navigate through the model's technical and visually daunting sub-models and blocks to change operations information. Figure 2 shows the user interface, where gas plants are depicted as heptagons, the hub as an ellipse, and the terminals as triangles.

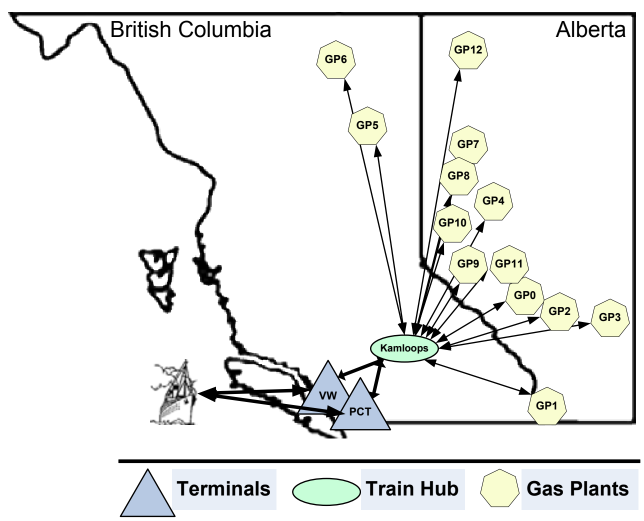

Figure 2: Simulation Model Graphical User Interface

2.3 Model Verification and Validation

After developing the model, we tested the model to be consistent with the specifications. Internal consistency checks ensured that the various algorithms within the model were operating as expected. The modular structure of the model facilitated this process by enabling the testing of smaller units, such as single gas plants, independently of the rest of the model.

Furthermore, we validate the model with the actual data. Towards this goal, we initialized the model to represent a certain time period in the past and then simulated the operations for a few weeks. Using the historical data, the accuracy of the model was tested and found to be within the acceptable range in terms of inventory moves and the final inventory levels at the gas plants and terminals.

2.4 Results and Reporting

The model's reports enable the user to monitor and analyze many important variables of the system, such as:

- Gas plant storage levels
- Gas plant throughput
- Train car utilization
- Terminal inventory levels
- Terminal throughput
- Wait times of ships

Model outputs can either be automatically transferred to a spreadsheet application for further analysis or monitored using dynamic plotters that show stockpile and plant storage inventory levels at each step of the system. These plots depict how inventory levels change over time and exhibit systematic patterns due to pick-up arrival times.

These statistics will help management make decision about their planning and operations at the gas plants, terminals, and rail fleet.

By tracking all gas plant and terminal throughputs, we can quantify the effects of any proposed changes in resources or business decisions. For example, by reporting gas plants inventories, we can identify any dangerously high inventory level situation at critical plants and indicate if a plant will shut down.

Another example is that with more frequent train arrivals at the gas plants, we would anticipate that less sulphur would be placed in storage and more would be transported to the terminals, ultimately to be loaded on the vessels. Figure 3 illustrates a scenario where the number of rail cars for the three CP served gas plants was increased by 30% from the current number. As a result, both the maximum inventory levels as well as the average amount of inventory were significantly reduced.

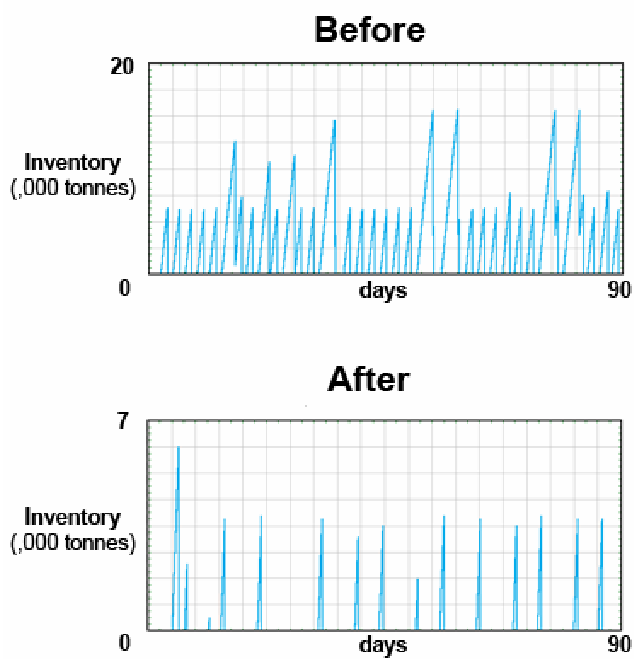

Figure 3: Changes of the Level of Inventories at the Gas Plants by Increasing Number of Rail Cars

3 DECISION MODELING

Sultran's tactical and operational decisions address the challenges of this complex push-pull system. These decisions include the allocation of loaded rail cars to meet the demand of the customers and to guarantee that an adequate number of empty rail cars are available at gas plants, preventing overstock and plant shutdown.

3.1 Decisions

The operational decisions listed below are currently made by Sultran's experienced staff using their personal judgment. We have created algorithms that mimic typical decisions made by these experts. These algorithms help us understand the decision making processes at different stages. By improving the performance of these algorithms and making them optimal, we believe that we can improve the efficiency of the system in the future. These algorithms will be explained in further detail in the algorithm section.

3.1.1 Gas Plant Decisions

- Gas plant priority: which plants most urgently need rail cars? The ultimate objective is to guarantee that sulphur storage at the gas plants does not exceed the capacity, which would force all production operations to be shut down. To avoid this situation, rail cars must be allocated appropriately based on gas plant production rates, available inventory levels, total available rail cars, and rail cars already en route to the particular gas plant.

3.1.2 Terminal Decisions

- Routing trains to terminals: which terminal is the best destination for a train? This decision considers sulphur type and quantity carried by the train, sulphur stockpile inventory type and levels at the terminal, demand type and quantity at the terminal, and any predetermined terminal preferences.
- Routing ships to terminals: at which terminal should ships berth? This decision considers the ship's size, demand type and quantity, vessel size restrictions at the terminal, stockpile inventory type and level at the terminal, and any predetermined terminal preferences.
- Product substitution at terminals: when a ship arrives, what type of sulphur should it load? This becomes a decision factor in the operations when there is a shortage of a certain type of sulphur; and higher quality products can be used to meet the demand (at the same price but higher cost).

3.1.3 Further decisions

Many other operational decisions made at the gas plants and terminals, are included in our model. At the gas plants, decisions must be made as to when a product should be reclaimed from block storage or from emergency storage. The emergency storage will only be reclaimed if a large number of trains is waiting to load sulphur and there is no sulphur stored in the dry storage silos. Block storage will slowly be reclaimed as the level of inventory of the dry storage drops below a certain threshold.

Operations at each plant vary significantly from one to the other in terms of sulphur type produced, production rate, storage capacity, and rail line service. Each gas plant sub-model includes sulphur storage logistics considerations (priority of sulphur reclaim from dry, emergency, and block storages, and circumstances of reclaiming more costly storage such as emergency and block) as well as a separate sub-model for liquid sulphur (collected via trucks instead of rail). Sulphur that is en route to the terminals (providing additional inventory) and rail cars that are en route to gas plants (providing additional storage space) need to be tracked in the model at gas plants, hub, and terminals. The rail car's terminal destination may be predetermined based on the rail line, the plant, or the type of sulphur that the plant produces.

At the terminals, an algorithm is used to set the priority of assigning the sulphur types to ships. When a ship arrives, the algorithm prioritizes sulphur types according to their surpluses against the demand and assigns them to the ship. The algorithm goes through the sulphur priority list to satisfy the demands for all types of sulphur. Once all the demands are fully satisfied, the algorithm terminates.

Sultran currently has limited control over vessel arrivals since that is an activity scheduled by marketers or customers. Sulphur type is segregated at the terminals according to its grade. Only one ship can load at a time and it can load only one type of sulphur at a time. However, if a car block or unit train is offloading a product that a berthed vessel is demanding, then the ship will simultaneously load from both the stockpile and the rail car. Mangers will always substitute products if inventory levels are insufficient; it will not wait for a train that is more than one day away.

All of these operations are represented in the simulation model to accurately reflect the system. The following is a discussion of the algorithms used specifically for the operational decisions.

3.2 Algorithms Used

Four major algorithms exist in our simulation model that reflect the four important decisions that need to be made:

1. Which gas plant should empty train cars be sent to?
2. Which terminal should loaded trains be sent to?
3. Which terminal should arriving ships be sent to?
4. What product substitution should be done at the terminals?

3.2.1 Gas Plant Priority

Sultran prioritizes its gas plants when routing empty rail cars back from the terminals. In the model, each plant is assigned a base priority score by the user by rating the gas plants from 0-12, with 0 representing the gas plant with the most critical operations.

Our model then incorporates a dynamic prioritization algorithm that considers the base priority score, current available storage at each plant, and rail cars that have already been allocated and are en route to the plant. For every gas plant, the priority P is calculated as:

$$P_i = \sum_{j=1}^{5} (I_{ij} / F_i) * W_{ij} + P_{i,inital}$$

where:

i = gas plants
j = storage types (including empty trains en route)
I_{ij} = inventory capacity for storage type j at gas plant i
F_i = daily form (production) rate at gas plant i
W_{ij} = defined weights for storage type j at gas plant i
P_i = priority index of gas plant i.

The priority score at each gas plant is calculated through a weighted total time of inventory space left. For each storage type, the currently free storage capacity is divided by the production rate (providing the "days of inventory left") and then multiplied by a weight. The highest weight was given to dry storage with decreasing weights to liquid, emergency and block storage. The loading capacities of trains en route to the gas plants was also treated as available inventory space and received the same weight as the liquid storage. The base priority of the plant is then added to this weighted days of free inventory space left which results in the final priority number. A lower number is treated as more urgent (less free inventory space left) and more trains are then routed to this plant. These weights can be optimized for optimal efficiency in future research.

We try to prevent the use of any storage types other than the dry storage, because other storage types (in particular, block and emergency) are costly to use. We also consider the loading capacities of the trains that are approaching to the gas plants to avoid big swings between having no trains followed by too many trains at the respective gas plants.

Every time an empty train reaches the point of last decision (two days after it left the terminal), the priority of each gas plant is updated and the train is then assigned to a certain gas plant.

3.2.2 Routing Trains to Terminals

Due to the type of sulphur that certain plants produce, some trains must be routed to a particular terminal. Other trains can be routed to either of the two terminals. In the simulation model, attributes are assigned to the trains when they depart the gas plants, to indicate whether their load needs to go to a particular terminal.

If a train has flexibility in terms of which terminal it can be routed to, an algorithm is used to assign the train to the terminal that is in the greatest need for the sulphur. PCT and VW both have minimum stockpile inventory level requirements but Sultran also has annual throughput contract obligations at VW. To avoid having to route all incoming trains to VW at the end of the year, the algorithm ensures that product arrives at VW on a continuous basis.

Figure 4 illustrates the six decisions of the algorithm, which are made in sequence 24 hours before the train's arrival at the terminal. In Figure 4, inventory levels include sulphur car loads that are en route to the terminal.

As soon as one of the conditions is satisfied, the algorithm is terminated and the train is sent to the respective terminal. As we progress from question one to six, issues of less and less urgency are addressed. If none of the above decisions have determined the terminal destination, the train will be sent to PCT.

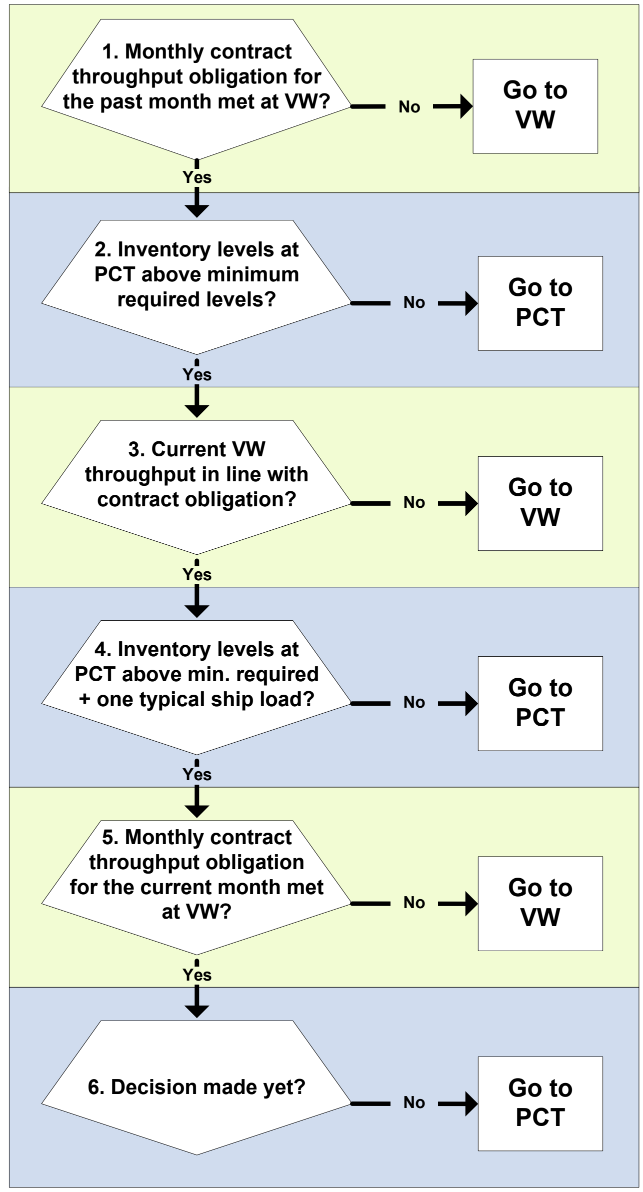

Figure 4: Routing Trains to Terminals Algorithm

3.2.3 Routing Ships to Terminals

Ships arrive at the ports on a predetermined schedule with a certain load size and demand for a combination of sulphur grades. Ships are directed to one of the two terminals based on their size, the type of sulphur demanded, the inventory levels at the terminals, the amount of sulphur en route to the terminals, as well as the ship queue lengths at the terminals. Figure 5 illustrates this algorithm. For the purpose of this figure, the inventory level at the terminal includes sulphur en route to that terminal. PCT is a lower cost option than VW and therefore it has higher priority when ships are being routed.

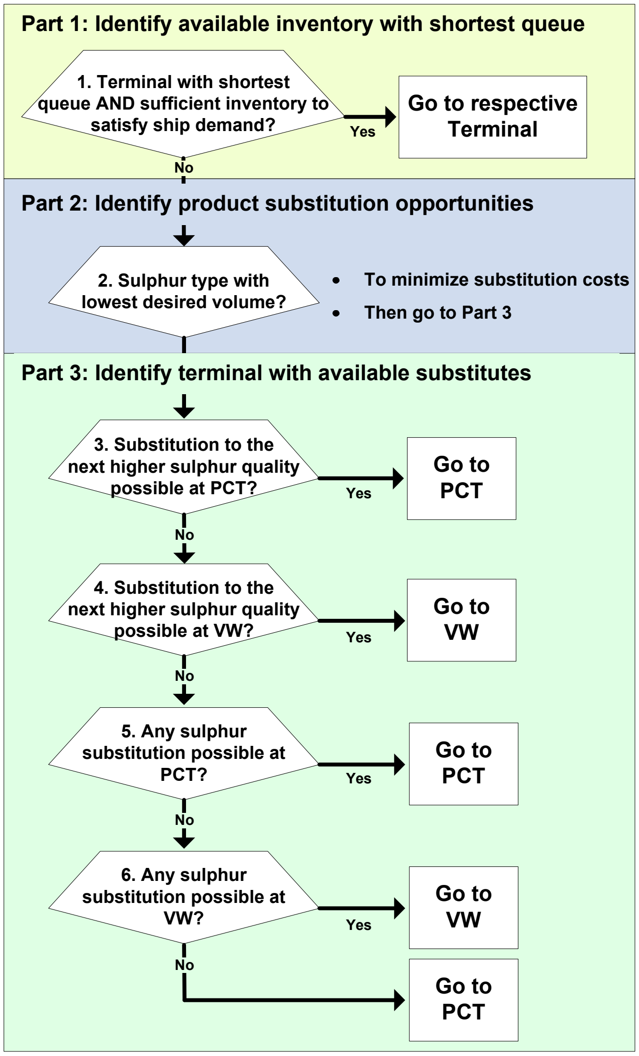

Figure 5: Routing Ships to Terminals Algorithm

3.2.4 Product Substitution at Terminals

Higher quality sulphur types can be used to meet the demand for lower quality sulphur (at the same price but higher cost). This becomes a decision factor in the operations when there is a shortage of a certain type of sulphur and there are inventories of higher grade products. The possible substitution options are depicted in Figure 6.

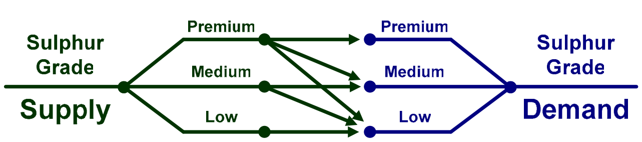

Figure 6: Product Substitution Process at Terminals

Once a ship has been routed to a particular terminal, it may wait in queue for a dock to become available. During this time, the available inventory mix at the terminal may have changed due to incoming trains and outgoing ships. The product substitution algorithm shown in Figure 7 is performed if the ship's demand cannot be satisfied when it is berthed.

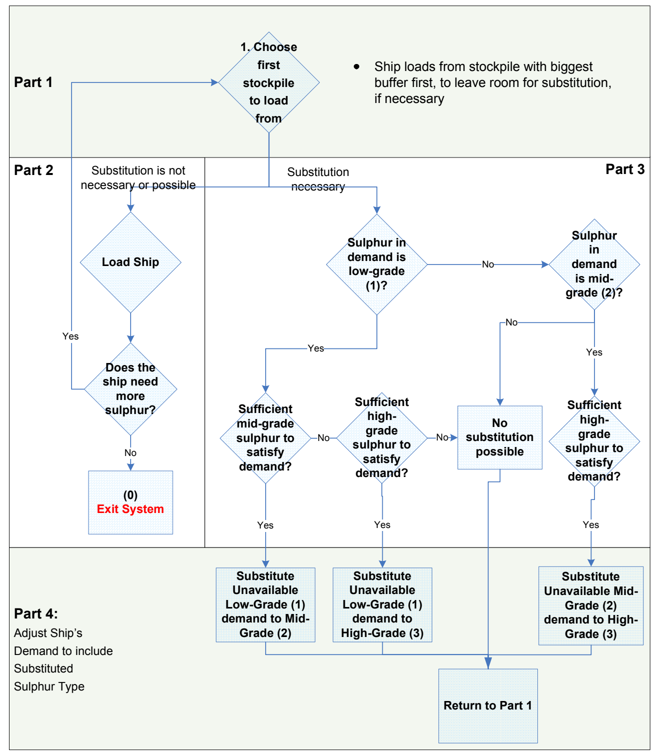

Figure 7: Product Substitution Algorithm

After the ship has satisfied its demand for sulphur it leaves the port, at which point the next ship can berth at the dock.

4 CONCLUSIONS & FUTURE STUDIES

The discussed dynamic simulation model has shown to be an effective tool for analyzing the managerial strategies in the complex sulphur distribution system. Decisions that were previously made based solely on the experience of the decision makers can now be analyzed using the developed simulation model. The simulation analysis plays an important role in evaluating the alternatives and help us develop algorithms to address the complexities that arise in this push-pull transportation system.

The simulation model further gives insight into how an expansion or contraction of the number of gas plants serviced could affect the overall operations. Developed natural gas reserves deplete over time while new discoveries in other areas go online. Using the simulation model, we can now analyze, for example, the effect of new gas plants coming online. We can now find the optimum number of rail cars that will not cause the system to exceed the desired inventory levels and ship wait times, while keeping the rail cost at a minimum.

The model will be expanded further and will be used for more detailed analysis. In particular, it will be used as a platform to test the efficiency and effectiveness of different algorithms that will be developed in planning and scheduling levels. A mathematical program is under development which addresses the complexity of the system and assigns the cars to gas plants and to terminals. Many local scheduling policies should be modified to generate optimal (or close to optimal) results. The research can further be expanded by jointly planning the fleet assignment and ship arrivals. Another future direction is to include workforce activities in the model.

ACKNOWLEDGMENTS

The authors would like to thank Lukas Deeg, Chelsea Baron and Jen Der, students at the University of Alberta, School of Business, who helped us with the creation of the model in the early stage of this project. The authors would also like to thank Leigh Scrivens from Sultran for her extensive efforts in providing us with the necessary data and understanding of the business processes of Sultran Ltd.

REFERENCES

Brunner, D., G. Cross, C. McGhee, J. Levis, D. Whitney. 1998. Towards Increased use of Simulation in Transportation. In *Proceedings of the 1998 Winter Simulation Conference*, ed. D. J. Medeiros, E. F. Watson, J. S. Carson and M. S. Manivannan, 1169-1175. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Dessouky, M. M., L. Quan, R. C. Leachman. 2002. Using Simulation Modeling to Asses Rail Track Infrastructure in densely trafficked Metropolitan Areas. In *Proceedings of the 2002 Winter Simulation Conference*, ed. E. Yucesan, C.-H. Chen, J. L. Snowdown, and J. M. Charnes , 725-731. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Krueger, H., E. Vaillancourt, A. M. Drummie, S. J. Vucko and J. Bekavac. 2000. Simulation Within the Railroad Environment. In *Proceedings of the 2000 Winter Simulation Conference*, ed. J. A. Joines, R. R. Barton, K. Kang, and P. A. Fishwick, 1191-1200. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Sarosky, T., T. Wilcox. 1994. Panel Discussion: Simulation of a Railroad Intermodal Terminal. In *Proceedings of the 1994 Winter Simulation Conference*, ed. J. D. Tew, S. Manivannan, D. A. Sadowski, and A. F. Seila, 1233-1238. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

AUTHOR BIOGRAPHIES

PAYMAN JULA is a Visiting Assistant Professor in the Department of Finance and Operations Management at the University of Alberta School of Business. He received the Ph.D. and M.S.E. degrees in Industrial Engineering and Operations Research from the University of California, Berkeley. His e-mail address is payman.jula@ualberta.ca.

MARK S. ZSCHOCKE is an undergraduate student at the School of Business, University of Alberta with a major in Management Science. He is actively involved in the university community and has placed first and second at the Student Conference on Operations (SCOPE), and the Intercollegiate Business Competition (ICBC), respectively. His e-mail address is markz@ualberta.ca.