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SIMULATION MODEL FOR REGIONAL OIL DERIVATIVES PIPELINE NETWORKS CONSIDERING BATCH SCHEDULING AND RESTRICTED STORAGE CAPACITY

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ABSTRACT

Oil refining companies and distributors often use pipelines to transport their products. In highly integrated, geographically challenging contexts, this may result in complex logistical systems. Pipelines which transport multiple products connect tanks, forming a particular, self-contained environment where distribution routes (called logistical channels), tactical inventory locations and operational criteria are defined to transfer, receive and deliver liquid oil derivatives. This paper describes a simulation model designed to represent such a regional pipeline network and includes a case study of a Brazilian region with refineries, a maritime terminal, a hub terminal and distribution bases.

1 INTRODUCTION

Oil refining companies and distributors often use pipelines to transfer their products. In highly integrated, geographically challenging contexts, this may result in complex logistical systems – especially if the pipelines carry multiple products.

Pipelines connect tanks, forming a particular, self-contained environment where distribution routes, tactical inventory locations and operational criteria are defined to transfer, receive and deliver liquid oil derivatives.

This paper describes a simulation model designed to represent a pipeline network. Cafaro et al. (2010) also applied simulation models to case studies about fuel supply chain. A case study of a Brazilian region with refineries, a maritime terminal, a hub terminal and distribution bases is also presented as a way to validate the model. Figure 1 displays this region.

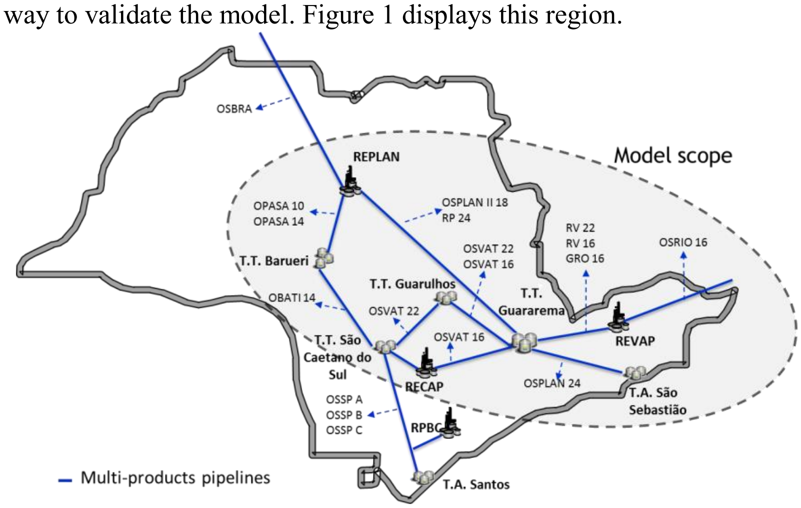

Figure 1: São Paulo region's fuel logistical system.

Four product lines are considered: Gasoline, Naphtha, two grades Diesel Fuel (DS10 and DS500) and Jet Fuel. Their demand within the considered region must be supplied either by local production or through imports (relative to the region; not necessarily international). Excess production is exported (also relative to the region).

It is very relevant that many of the pipelines transport multiple products and some even are reversible (two-way). These characteristics substantially increase the model's complexity and demand a scheduling solution.

The model's main objectives are to assess the actual logistical operation of the region's production and transfer network regarding demand fulfillment, bottlenecks, operational variations and evaluation of future modifications.

This paper is divided into the following sections: the conceptual model, model details, model implementation, verification and validation, simulation runs, output analysis, logistical channel analysis and conclusions.

2 CONCEPTUAL MODEL

According to Robinson (2013), the process of abstracting a model from part of the real world it represents ("the real system") is known as conceptual modeling. In other words, choosing what should be and what should not be included in the model. According to the same author, a conceptual model includes the objectives, inputs, outputs, content, assumptions and simplifications of the model. In this instance, the conceptual model was built using IDEF-SIM. According to Montevechi et al. (2010), the IDEF-SIM technique has been developed with focus on simulation and its main characteristic is the suitability of its application logic with the one used in discrete event simulation, which will make the stage of computational modeling easier. Figure 1 presents the São Paulo logistics network of clean products represented by the simulation model.

This logistical system supplies five points of sale in São Paulo State. It is also the main corridor to supply Brazil's West-Central region through the OSBRA pipeline. OSBRA's schedule is modelled as demand for batches of products which are input data.

Three refineries are considered in the system: REPLAN, REVAP and RECAP. Among them, they process over 700 kbpd of crude oil and their production is optimized to supply the national market. This means that surplus and insufficient products must be transported through the pipeline network. In general, there is surplus of high sulphur Diesel (DS500) and lack of low sulphur Diesel (DS10), Jet Fuel, Naphtha and Gasoline. To balance regional supply and demand, there is a maritime terminal in São Sebastião. This terminal is connected to the system through the "OSPLAN 24" pipeline. This pipeline transports multiple products both ways. Crude operations have a dedicated network. The only resources shared by crude and derivatives are one of the berths in São Sebastião and the port's access channel. To represent these interferences, dummy entities were created to make shared resources unavailable for certain periods of time. A similar trick was used to represent the use of pipelines to transport ethanol, a product that was not included in the model scope.

For simplification purposes, the model scope did not include production and logistics facilities at the Santos region. Santos's surplus destined to São Paulo's metropolitan area is sent through pipelines. These pipelines were modelled like an entry pipeline that delivers batches of products at São Caetano do Sul (as depicted in Figure 1), according to a delivery schedule. Likewise, the OSRIO pipeline, which connects São Paulo logistical network to Rio de Janeiro was represented like a pipeline that delivers or receives batches of products as scheduled.

The simulation conceptual model included all the elements (terminals and refineries) presented in the model scope area highlighted in Figure 1 in detail, which produced a very large diagram. As it is impractical to represent the entire IDEF-SIM diagram in this paper's format, Figure 2 presents the IDEF-SIM diagram for the Guararema Hub Terminal, which is a subset of the whole diagram and includes business rules, resources, entities and logistics flows represented by inbound pipelines from different origins and outbound pipelines to different destinations.

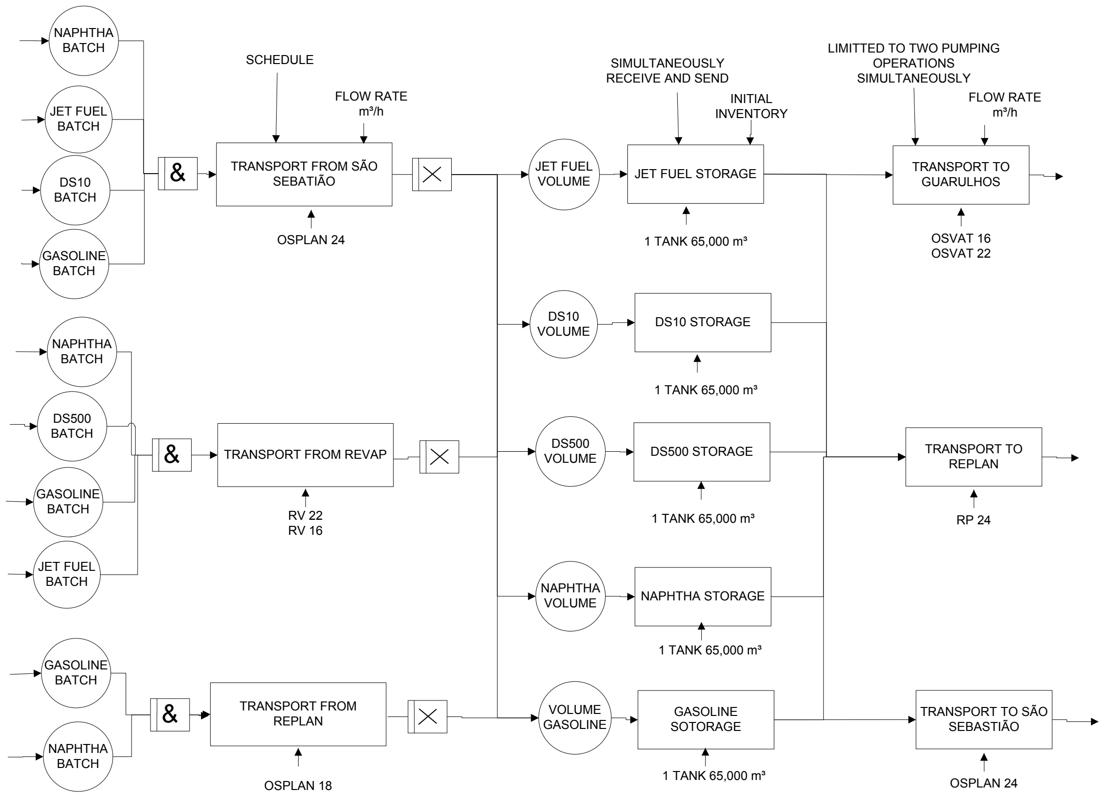

Figure 2: IDEF-SIM diagram for Guararema Hub Terminal.

In addition to the IDEF-SIM diagrams, the model uses operational information about tanks (location, product and capacity), pipelines (flow rate, orientation, availability and fail rate), products (pipeline compatibility, test and certification time and production flow rate), market demand and delivery rules and ship operation (rules and flow rates).

3 MODEL REQUIREMENTS

The model should try to completely fulfill the market demands, one of the most important company goals. In order to assure this, it must represent production and delivery at the refineries, transfers among producing and demanding points and imports and exports by ship.

3.1 Production and delivery

Refineries produce non-stop. This is represented by continuously adding product to the plants' storage tanks at every clock step. If a refinery runs out of storage capacity, its production is disrupted and this is registered on the simulation output. Production resumes as soon as possible.

Production rates are an input.

Refineries deliver the products locally or transfer it to terminals or other plants. Local deliveries are restricted by flow rate capacity and may follow other rules, such as work hours only, for instance.

3.2 Ship operations

Ship operations are simulated from the time a ship arrives near the maritime terminal until it leaves. Figure 3 presents the sequence performed by a ship in this timeframe. Each step requires a specific time and may depend on ship size, product or any other identifiable characteristic and are not necessarily deterministic.

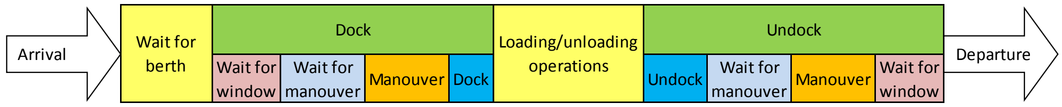

Figure 3: Synthetic representation of a ship's movement in the model scope.

3.3 Transfers

There are a large number of possible product transfers in the network. These transfers are subject to rules and the model should be able to accurately represent them. It must produce an output that allows these operations' efficacy to be evaluated considering the whole regional scope.

Transfers may be affected by many random events, such as equipment failure and ship delays.

The transfer of liquids also has a continuous characteristic which must be represented. As in previous works (Limoeiro et al, 2008 and Limoeiro et al, 2010), a technique called pseudo-continuous simulation was used. In this approach, a series of hourly discrete events associated with the flow rate emulate the continuous transfer of liquids.

These continuous transfers, however, are still associated with discrete events, such as tanks becoming empty or a ship arriving. It is necessary to let these different operations communicate.

Pipelines in the model transport multiple products and can even be reversed. These long pipelines hold multiple batches of products – possibly, different products. The batch sizes may be different depending on product, source, destination and demand. Each pipeline has its own length and diameter and, consequentially, internal volume.

If a batch is to enter a pipeline, it depends on many factors which can be classified as Capacity or Tactical factors.

Capacity factors regard volumes and spaces in the system. There must be enough, ready product at the source and enough space at the destination. The new product must also be compatible with the product previous pumped into the pipeline.

Tactical factors deal with the choice of the next batch to be pumped. In the model, this is based on a priority index, calculated from the ratio between the transferred volume of the product in the current simulation month and the expected monthly volume to be transferred, considering the surplus or deficit accumulated up to the previous month.

These factors interact with each other. A bad tactical choice may result in lack of space at the destination for the pipeline to discharge its batches or lack of product at the source to push the pipeline's contents. It must be remembered that batches cannot be modified once they are in the pipeline and neither can they change their sequence. Also, the pipelines are permanently full which means no product leaves the pipeline unless there is new product entering it and, conversely, no product may enter the pipeline unless some is leaving at the opposite end.

As products must traverse this logistical channel from their source to their destination, , there is a relevant lag between the production or arrival of some product and its delivery at the demand points. For example: when some product arrives at the maritime terminal, it is unloaded, transferred to at least one other terminal and then to the demand point. In this transit, it is stored in some of these sites and needs to be tested and certified, which consumes time. It will probably also need to wait for other products to move in their own channels, which share resources.

This whole collection of channels actually amounts to the simulation of a scheduling process. In order to match priority rules in an efficient way, the operations, which represent transfers, need to be grouped based on the resources necessary in the channel of which they are part. These groups have to be evaluated in a predefined sequence to prevent deadlocks in which some operations permanently blocked other operations.

4 MODEL IMPLEMENTATION

With the conceptual model ready and minding other requirements, volumetric balance diagrams, such as the one in Figure 4, can be designed for each product. These diagrams represent the flow operations implemented on the model and include refinery production, pipeline transfers, ship loading and unloading and market deliveries.

Each of these diagrams assures that the volumes that enter the system (production or imports) match those leaving the system (market delivery or exports). Without this constraint, the model would not represent reality; unduly creating or destroying products.

Figure 5 presents the basic simulation flowchart. It is actually comprised of two interacting parts: one dealing with the ships and another with product transfer.

Both parts are independently run at every hourly step of the simulation control clock. There is, however, one connection between them: when a ship is docked and ready to transfer product, a temporary tank is created and functions exactly as any other tank in the model. When the ship is ready to depart, the temporary tank is disabled.

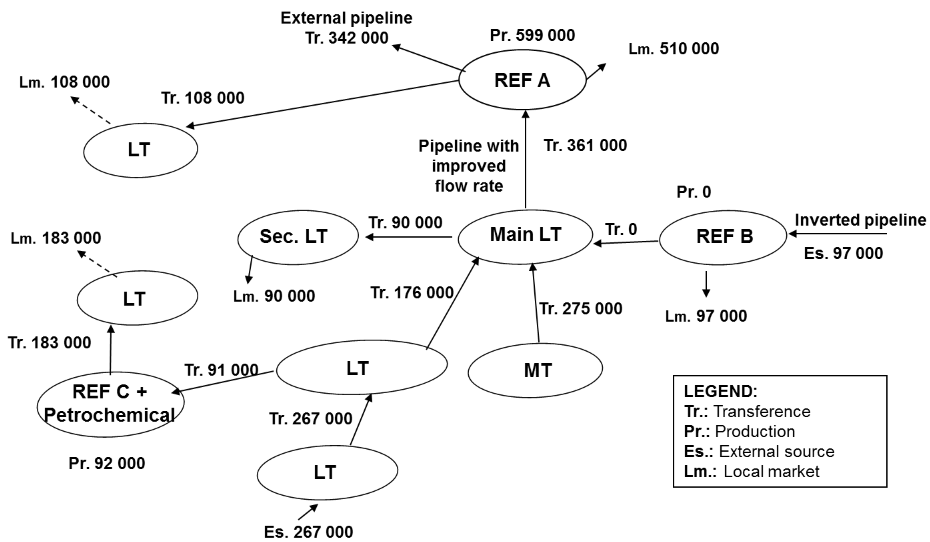

Figure 4: Volumetric balance diagram for one product.

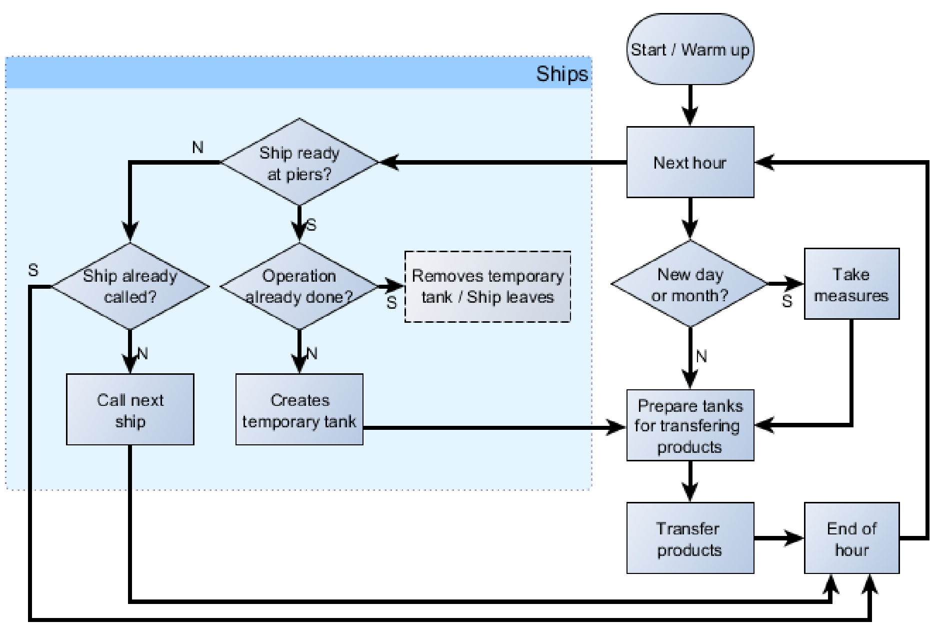

Figure 5: Simulation implementation flowchart.

The simulation model was implemented using the simulation software ProModel, with Microsoft Excel spreadsheets used for input and output.

5 VERIFICATION AND VALIDATION

According to Sargent (2013), the validation of a computational model is an important step in a simulation study. The author defines validation as proof that a computational model has accuracy consistent with the intended application. The model was verified and validated by different areas of the company involved in this project: the short-term planning area, terminal operation and, finally, commercial and logistics studies area.

Additionally, Sargent (2013) presents some procedures for validating a model. In this study, the conceptual model was validated with the experts and the computational model was validated by observing the system's behavior (through the model animation and variable values displayed during the simulation) and by comparing the model results against those from the real system.

The model with input data based on historical data generated outputs similar to the historical terminal performance. These results were approved by experts who work at the terminals. Therefore, the model was accepted and considered valid.

For some scenarios, which included new operations that are not currently performed, some sensitivity analysis was combined with face-to-face validation (Chwif and Medina, 2006). An experiment set was planned and the simulation runs gave incremental results which were easier to understand and analyze. This step-by-step approach with the experts' frequent participation since the conceptual model stage helped to build confidence in the model.

6 SIMULATION RUNS

The validated model was used in a case study whose objective was to analyze the possibility of using a pipeline which currently exports products to import them. Four scenarios were chosen:

- Scenario 1 considers the reversal of a pipeline's orientation (OSRIO 16 in Figure 1) and other changes expected to be necessary (such as a new Naphtha tank). These changes are mostly concerned with the flow of products affected by the pipeline's orientation reversal and its impact on the maritime terminal.
- Scenario 2 analyzes the consequences of not building the new Naphtha tank in the main hub terminal (Guararema in Figure 1).
- Scenario 3 is based on Scenario 2 and analyzes the real need of new Diesel Fuel tanks in the main hub terminal.
- Scenario 4 is also based on Scenario 2 and analyzes the impact of cutting back on investment on the pipeline which connects the main hub terminal to the region's largest refinery (REPLAN in Figure 1). This cut back means a 25% lower flow rate than on Scenario 2.

The study's goal was to determine minimal logistical investment scenarios which still enable full market demand supply.

The main output variables are:

- Market demand fulfillment level, which measures the total delivered volume against the total market demand.
- Refineries' production level, which measures the produced volume against the plant's nominal capacity.
- Berths' occupation level, which is the percentage of time with a docked ship.
- Pipeline occupation level, which is the percentage of time some product is being pumped.
- Monthly storage turnover, which is the ratio between the monthly volume that goes through a set of tanks and their total capacity.
- Annual quantity of ships of each product.
- External product pipeline arrival compared to the expected volume.

Each simulation run covers a one year cycle after a four month warm-up period. This warm-up period is necessary because the simulation starts with no inventory in the system, which is not a realistic situation. After some tests, four simulation months was the time it took for the inventory levels to reach regular levels.

30 replications of each scenario provided sufficient precision to distinguish them.

7 OUTPUT ANALYSIS

Table 1 shows the output for all the scenarios.

Table 1: Average simulation output for all scenarios in the case study. LT are land terminals.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Market demand fulfillment level	Refinery A - Gasoline (ext. pipeline)	100.1%	100.0%	100.0%	100.0%
	Refinery A - DS10 (external pipeline)	100.0%	100.0%	100.2%	100.0%
	Refinery A - Gasoline (local Market)	100.3%	99.7%	99.6%	91.6%
	Refinery A - Jet Fuel (local Market)	97.6%	97.0%	97.7%	96.8%
	Refinery A - DS10 (local Market)	99.6%	99.2%	92.6%	84.2%
	Refinery A - DS500 (local Market)	96.9%	96.7%	97.0%	92.4%
	Refinery B - DS10	100.6%	100.2%	100.5%	100.3%
	Refinery B - Gasoline	100.1%	100.1%	100.1%	100.1%
	Secondary LT - DS10	100.0%	100.0%	100.0%	100.0%
	Secondary LT - Gasoline	100.0%	99.9%	99.9%	100.1%
	Secondary LT - Jet Fuel	100.0%	100.0%	100.0%	100.1%
External product pipeline arrival	Reversed pipeline source - DS10	99.1%	99.5%	99.7%	99.6%
	Reversed pipeline source - DS500	99.6%	99.6%	99.7%	100.1%
	Reversed pipeline source - Naphtha	100.2%	100.3%	100.4%	100.3%
Production level	Refinery A	98.7%	98.9%	99.4%	99.9%
	Refinery B	97.6%	97.4%	96.9%	96.6%
	Refinery C	99.9%	99.8%	99.8%	95.5%
	Petrochemical plant	97.2%	97.0%	97.0%	96.6%
	WEIGHTED AVERAGE	98.8%	98.9%	99.1%	98.1%
Monthly storage turnover	Maritime Terminal - Gasoline	2.9	2.9	2.8	2.6
	Maritime Terminal - DS10	2.6	2.6	2.3	1.9
	Maritime Terminal - Jet Fuel	1.6	1.6	1.5	1.6
	Main Hub LT - Gasoline	6.8	6.6	6.5	6.1
	Main Hub LT - DS10	4.1	4.1	7.7	3.4
	Main Hub LT - DS500	7.2	7.3	7.3	6.9
	Main Hub LT - Jet Fuel	4.7	4.7	4.7	4.7
	Main Hub LT - Naphtha	2.4	3.9	3.8	3.9
	Secondary LT - Gasoline	3.1	3.2	3.1	3.1
	Secondary LT - DS10	5.0	5.0	5.0	5.0
	Secondary LT - Jet Fuel	8.9	8.9	8.9	9.0
Pipeline occupation level	Pipeline REF_B --> Main LT	24.7%	24.7%	24.7%	23.6%
	Refinery A --> Main LT pipeline	25.2%	25.4%	25.5%	25.8%
	Maritime Terminal --> Main Hub LT pipeline	37.3%	37.4%	34.8%	31.6%
	Main Hub LT --> Secondary LT pipeline	18.6%	18.7%	18.7%	18.7%
	Duct with improved flow rate	65.7%	65.2%	63.0%	77.0%
	Inverted duct	64.8%	65.0%	65.1%	65.1%
Berth occupation level	Berth A	89.8%	90.4%	88.4%	85.8%
	Berth B	84.8%	85.2%	81.4%	77.4%
	AVERAGE	87.3%	87.8%	84.9%	81.6%
Annual quantity of ships	Gasoline	102.7	101.8	100.4	92.2
	DS10	72.7	74.1	63.5	52.9
	Jet Fuel	44.1	43.9	44.0	44.6

Scenarios 1 and 2 fulfilled the market demand and kept the refinery production at adequate levels, but Scenario 2 is better because it requires a smaller investment, because existing tanks are repurposed instead of building new tanks.

Scenarios 3 and 4 failed to fulfill the market demand and were deemed bad options. Scenario 3 was unable to fulfill the demand for DS10 and Scenario 4 was even worse, failing to fulfill the demands for Gasoline, DS10 and DS500. Refineries B and C could not achieve an adequate production level.

It is relevant to notice that the berth occupation is always very high, which precludes the option of importing the necessary products by sea instead of reversing the pipeline. This is the reason why the focus is solely on the tanks and other pipelines.

8 LOGISTICAL CHANNEL ANALYSIS

Besides the output analysis, it was also possible to analyze the logistical channels and derive other important observations. The logistical channels are self-contained structures which, despite sharing resources, can be analyzed individually.

8.1 Delivery lag

When a ship starts unloading, the product takes a long time until it is available to be delivered. A typical flow of the time consuming events would be:

1. Unload the ship into the maritime terminal's tanks.
2. Test and certification of the product in the maritime terminal's tanks.
3. Product transfer to the main hub terminal through a long pipeline.
4. Movement along the pipeline.
5. Filling the hub terminal's tanks.
6. Test and certification of the product in the hub terminal's tanks.
7. Transfer to the destination sale point through another long pipeline.
8. Movement along the pipeline.
9. Filling the destination sale point's tanks.
10. Final test and certification of the product, which is now ready to be delivered.

Considering the flow rates, tank capacities, pipeline volume and test and certification times, the lag from arrival to availability may surpass 100 hours. The actual time is much higher because equipment failures, interference from other batches in the pipelines, lack of space in the destination tanks and other very common occurrences increase this time.

8.2 Batch frequency

When multiple batches of different products with different destinations share a pipeline, it is necessary to prioritize them.

This priority, as explained before, is based on the monthly demands. Therefore, it is expected that if, for instance, Diesel Fuel transfer demand is double the Gasoline transfer demand through a given pipeline, once a Gasoline batch enters the pipeline, another will have to wait until two Diesel Fuel batches of the same volume enter first. However, if other circumstances, such as lack of product at the source or space at the destination, prevent any of these batches from entering the pipeline at the right time, the sequence must be reviewed and a decision of wait or change the sequence must be made. In any case, delays in a part of the logistical channel mean that there will be no product ready at the right time downstream, which propagates the problems.

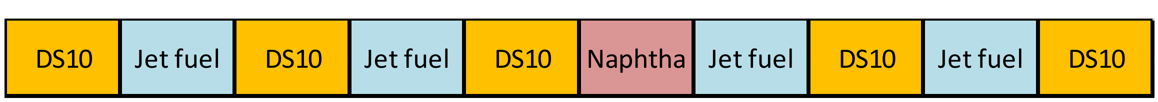

Figure 6: Batch sequence example.

In many cases, there are actually many products sharing a pipeline, which lead to a situation such as that of Figure 6, where three products alternate themselves in the pipeline and one problem can affect two other products.

8.3 Pusher batch availability

Another critical problem in the pipeline network is the need for available batches to push those in the pipeline to their destination. This means that once a batch enters the pipeline its flow does not depend only on the space available for itself at the destination. It also depends on the availability of other batches behind it and on space for batches ahead of it.

A long pipeline may hold a large volume of products and its entire volume plus the batch's volume must be pushed for a complete batch to reach its destination. This is time consuming and depends on multiple factors at both ends of the pipeline: at the source, there must be products to be pumped into the pipeline and, at the destination, there must be enough free space to receive the products.

8.4 Triple trouble

The pipeline that connects the maritime terminal to the main hub terminal carries many products and is reversible, which means it may transfer products either from the maritime terminal to the main hub terminal or from the main hub terminal to the maritime terminal. As the transferred volume increases, this structure may suffer from three possible reinforcing problems which compound with the previously mentioned problems:

The first possible problem is that the piers' berths may become too busy because ship unloading flow rates are smaller than the pipeline's effective flow rate. This effective flow rate is the average flow rate of the pipeline considering the time it remains stopped. The main factor which affects the effective flow rate is product and space availability in the terminal.

The second possible problem is insufficient storage capacity at the maritime terminal, which means ships must wait to unload and the main hub terminal may be unable to transfer products.

The last possible problem is that if the pipeline has to transfer too much of too many different products, the scheduling is not only difficult but also very susceptible to problems at the destinations.

Figure 7 shows an example of how these problems, which lower the system's efficiency, reinforce each other.

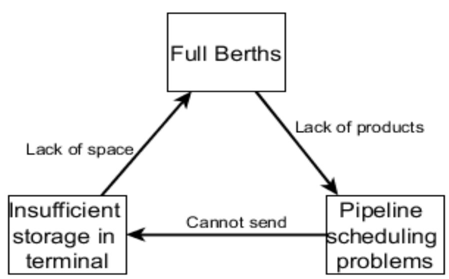

Figure 7: Reinforcing problems.

The effects of these problems may propagate to the rest of the system, which may mask the real causes of observed poor performance. In this situation, it may be tempting to add resources to other areas of the system, but, unless the reinforcing circle is broken, these improvements will be insufficient.

9 CONCLUSION

This paper has described a simulation model for regional oil derivatives pipeline networks considering batch scheduling and storage capacity, a case study of its application and a summary of the main sources of its complexity. The model was built in an oil company to solve a real problem.

A key element in the model's success was that it integrated people working for different areas of the company. This was achieved through the team's participation in the conceptual modelling and model validation phases of the simulation process.

As for the model approach, it is effective in analyzing the operational behavior of the transfer of products through a network of long pipelines with capacity restrictions. The scheduling of the batches is key to enabling the simulation and is based on a prioritizing heuristic which provides good, realistic scheduling solutions without incurring the computational cost of optimization or even meta-heuristics. Actually, the simulation applies many simple rules to represent a complex logistical system accurately.

The paths followed by the products from their source to their points of sale where identified as different, self-contained logistical channels which share resources along the way. Products take a long way to cover these channels and are frequently delayed by scheduling difficulties which must be avoided either by changing rules or providing resources.

For future work, this model and its ideas will be used for similar studies in the same region, and it can be adapted to other regions, as well as other companies or industries which use pipelines to transfer multiple products.

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