DOCTORAL (PHD) DISSERTATION THESES

Development of event-driven simulation methods for transporting products in pipeline networks

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1. Introduction

At the beginning of the 21st century, the oil industry continues to play a decisive role in the global economy. The processes and systems related to oil extraction and distribution are extremely complex, capital-intensive, and therefore require the use of the most modern technologies. The oil industry is generally divided into three main parts: upstream, midstream and downstream. Upstream includes the exploration and extraction of crude oil, midstream includes the transportation and storage of crude oil, and downstream includes the refining of crude oil into various final products and the distribution of these products. Refining is a complex task in which the goal is to convert crude oil into final products. Such final products include gasoline, kerosene, jet fuel, diesel, heating oils, lubricants, waxes, asphalt, natural gas, automotive gas, and hundreds of other petrochemical products.

Every year, oil companies pay more and more attention to solving scheduling problems in order to reduce costs. Companies need to transport various fuels and semi-finished products from refineries to distribution sites for sale. In pipeline transport, when a new product enters the pipe, it pushes the products already in the pipe. It follows that the delivery of a product depends on the pumping operations of the following products. In the case of pipe branches, it is necessary to determine exactly when a valve should be adjusted. There is no physical separation between the products in the pipes, so the products mix at the interface. Since the diameter of the pipes is very small compared to their length, the amount mixed is also small. Therefore, product mixing is not dealt with at the scheduling level. The resulting mixture, or slop, is transported back to the refinery.

Depending on the type of scheduling problem either optimization or simulation is used in the oil industry. Optimization is typically employed to solve operational issues when the problem is not overly complex. For instance, it might be used to minimize the shutdowns of pumping stations or reduce electricity cost. In such cases, the goal is to select the best solution from several possible options. Conversely, simulation is used to analyze a specific solution and demonstrate how it unfolds over time. For example, it can be used to check the feasibility of a scheduling plan or to evaluate the impact of certain valve operations.

The research findings presented in the dissertation are based on a discrete-event simulation system capable of verifying the feasibility of scheduling plans on multi-source, mesh-like pipeline networks in a short CPU time. If a scheduling plan is not feasible, the method indicates the exact cause and timing of the issue to the scheduler. An enhanced version of the model enables schedulers to reroute or split a product within a pipe, reverse the flow direction, and execute various tank operations, such as blending, truck loading, and tank transfer. Besides the default strict simulation mode, the dissertation also introduces a new time-shifted simulation mode, which automatically adjusts the start times of pumping operations in the event of resource constraints.

2. Problem definition

2.1 An illustrative example of the operation of a pipeline network

Product pipeline networks consist of three main components: sites, tanks, and pipelines. The sites are geographically dispersed and can be refineries and/or distribution points. Each site has several tanks that store different products. These sites are connected by pipelines that transport liquid products. Figure 1 illustrates a simple pipeline system containing E5 gasoline (up to 5% ethanol), E10 gasoline (up to 10% ethanol), and B7 diesel (up to 7% biocomponent). The figure shows 6 sites (A, B, C, D, E, F) connected by pipelines (pipes AB, AD, BC, BE, DE, EF). Pumping operations are conducted at the sites marked with an asterisk. The color of a product within a pipe indicates its target site, and the arrow shows the direction of product flow when the pipe is in use. Pipeline transportation can only begin if there is a sufficient quantity of the product available at the source site. A product can be received from the pipeline either at a site or transferred to another pipeline. The route of a product is the sequence of pipelines it must follow. For example, E5 gasoline in pipe AB must travel through pipes AB and BC to reach site C.

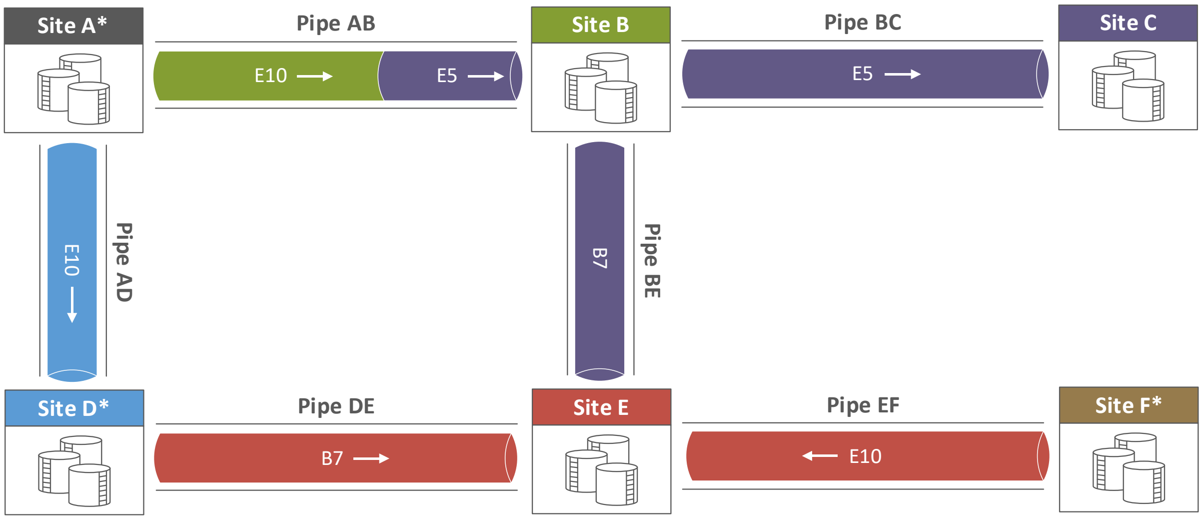

Figure 1. Illustrative example of a simple pipeline network.

2.2 Description of a real pipe network

In real life, schedulers must create scheduling plans for a much more complex pipeline system, taking into account numerous secondary factors. A good example of this is the 1,250 km long Hungarian product pipeline network operated by the Central European oil company MOL (see Figure 2). In the figure, each green line represents a pipeline, the blue dots indicate refineries, and the red dots indicate distribution sites. The product pipeline network connects a total of 13 sites, two of which serve as both refining and distribution locations. The pipe diameters range from 6” to 12”, the permissible pressure throughout the entire system is 63 bar, and two-way transportation is also allowed. The length of individual lines ranges from 1.6 km to 130 km. These pipelines transport various fuels and specialty products, such as mineral oil, aromatics, and fatty acid methyl esters.

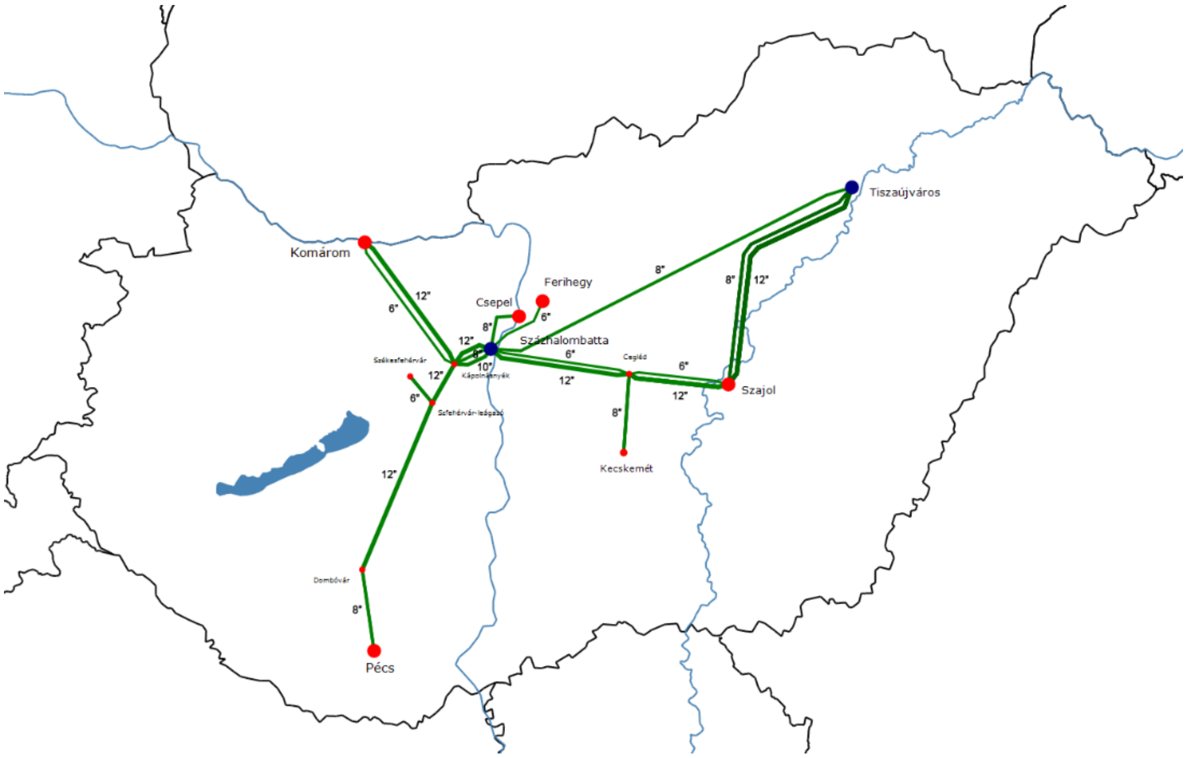

Figure 2. The product pipeline network of MOL in Hungary.

Initially, the schedulers of the MOL's logistics group could only prepare a rolling schedule of 3-4 days. This is due to the complexity of the system. The goal of the company is to quickly satisfy the demands of the sites without a significant stock level. Production in refineries is intermittent and must be in sync with the demand. Refined products are stored in tanks with specific lower and upper limits. The pipe system is mesh-like, containing loops. Various products flow in the pipes, which may have different destination sites. In order to direct the products, the valves at the branches must be properly adjusted. A product in a pipe can move if a product is pumped into the pipe. It may happen that such a product is pumped into the pipe which does not satisfy a demand of a site but enables the download of a product already in the pipe. In some cases, the destination site of the products in the pipes can be modified even if it requires the reversing of the initial flow direction of the pipe. If the scheduler schedules a pumping operation too early or too late, it can generate various problems, for example, a pipe to be used is occupied by another pumping operation, or there is not enough free tank capacity at the destination site.

2.3 Description of the pipe network operation

The following assumptions and constraints must be considered in the simulation model:

- The pipeline network is represented as an arbitrary graph, which may include loops.
- Products can be produced at multiple sites, and demand can be met from any site.
- The simulator divides the time horizon into one-minute intervals. Since the execution time of the physical operations at the sites (e.g., adjusting the appropriate valves) is on the same scale, shorter intervals are not necessary.
- For each time interval, the complete state of the system must be determined, including all tank levels, the locations of products in the pipelines, and the states of the valves at the pipe branches.

- In the initial version of the simulation model, products in the pipelines had to be delivered to a predefined destination site. However, unexpected events (e.g., a pipeline break) may necessitate changing the destination of a product in a pipeline. In the final simulation model, the scheduler can split a product already in the pipeline. This operation requires the split time, pipe ID, product ID, and quantity. In addition to splitting, route changes are also possible. This operation allows the scheduler to modify the route and/or flow direction of the product in the pipeline at a specific time.
- A product in a pipeline can be directed to a tank or another pipeline. The model does not currently support partial deliveries (where part of a product is directed to a tank and another part to a pipeline).
- Multiple pipeline operations can occur at a site simultaneously, provided local resources (e.g., available pump capacity) permit.
- Scheduling plans are prepared by the pipeline operators, and the simulation model verifies these plans.
- When creating a scheduling plan, schedulers take into account inventory levels at the sites as well as future production.
- Schedulers typically transport products along preferred routes (predetermined pipeline order and flow direction) but may deviate from these.
- Schedulers aim to execute the scheduling plan such that successive products in the pipeline are compatible with each other. For example, if possible, one type of gasoline should follow another type of gasoline.
- Schedulers do not consider the costs of pumping.
- Schedulers do not take into account topographical features, as these only result in minimal additional mixing relative to the pipeline lengths.
- Delivery tasks must be completed within a predefined time horizon.
- Products in pipelines can stop. Certain sections of the pipeline network can also be used for storage.
- In the simulation, production (blending) is carried out in batches. During a blending operation, the tank is locked and cannot be used for loading or unloading operations. When a blending operation is created, the scheduler specifies the start time, tank ID, site ID, product ID, quantity, and mixing speed. After the blending operation is completed, the tank becomes available with the amount of blended product.
- From distribution sites connected by pipelines, products are transported to customers using suitable transport vehicles. Delivery by road tanker can only take place during the site's operating hours.
- On-site tank transfer can only occur between products of the same type.

2.4 Defining the goal

The management of MOL set the goal of a reliable 30-day long schedule, so the logistics department of the company tried to find a commercially available simulation software capable of validating the schedule plans. During the preliminary testing, however, it was revealed that no simulation software is able to fully take into account the operating characteristics of MOL. After that, the company came to the conclusion that a custom simulation software was needed. At the request of MOL, we started working on a simulation method that validates the feasibility of a scheduling plan.

3. New scientific results

1. **I developed an event-driven simulation method to verify the product delivery schedules in multi-product mesh-like pipeline networks. [1], [2], [4], [5], [6]**
    a. I created the foundation of the simulation for the pipeline product delivery scheduling. I specified the events that operate the system and their behavior.
    b. I created a simulation software to test the operation of the simulation procedure.
    c. I presented the operation of the event-driven simulation through a real example.
2. **I developed a time-shifted event-driven method for the automated correction of faulty product delivery schedules in multi-product mesh-like pipeline network. [3], [7]**
    a. I created an error correction procedure for infeasible scheduling plans.
    b. I improved the simulation software to test the operation of the time-shift simulation procedure.
    c. I defined three operating cases to demonstrate the time-shifted simulation method: if the source tank is busy or empty, if the pipe is busy, if the destination tank is busy or full.
    d. I pointed out the problem of product fragmentation occurring during the intermittent execution.
3. **I improved the event-driven simulation method for rerouting products in pipelines and determining valve operations. [3], [7]**
    a. I developed a simulation method that can be used to change the route and flow direction of the products in the pipe.
    b. I implemented a simulation procedure that can be used to split a product in a pipe. This allows individual parts to be received at different destination sites.
    c. I developed two return strategies for automated rerouting of products in pipes.
    d. I implemented a method that defines the valve actions.

4. Application of the scientific results

The presented discrete event simulation system in the thesis provides significant help to product schedulers of MOL. The simulator can verify the feasibility of the scheduling plan on multi-source mesh-like pipeline networks in a short CPU time. If the scheduling plan is not feasible, the method indicates the exact cause and time of the problem to the scheduler. The improved version of the model allows schedulers to reroute, split a product in a pipe, reverse the flow direction of the pipe, and perform various tank operations (mixing, truck loading, tank transfer). The implemented simulation method can be used for any oil industry pipeline network. In the case of MOL, this is particularly important, since the goal is to connect the pipe networks of foreign subsidiaries with the Hungarian pipe network.

5. List of publications

The MTM profile of the author can be accessed via the following link: https://m2.mtmt.hu/gui2/?type=authors&mode=browse&sel=10064020

5.1 Related publications

Articles in international journals

[1] **B. Csontos**, L. Halász, I. Heckl, “Event-driven simulation of liquid transportation through pipeline networks for oil companies”, Chemical Engineering Transactions, vol. 70, pp. 1741-1746, 2018.

[2] **B. Csontos**, L. Halász, I. Heckl, “Event-driven simulation method for fuel transport in a mesh-like pipeline network”, Computer & Chemical Engineering, vol. 157, 107611, 2022, **IF: 4.3**.

[3] **B. Csontos**, L. Halász, I. Heckl, “Improved event-driven simulation method for fuel transport in a mesh-like pipeline network”, Computer & Chemical Engineering, vol. 168, 108066, 2022, **IF: 4.3**.

Articles in conference proceedings

[4] **B. Csontos**, I. Heckl, “Simulation models for transporting oil materials in pipelines”, Proceedings of the Pannonian Conference on Advances in Information Technology (PCIT'2019), vol. 1, pp. 139-144, 2019.

International conference presentations

[5] **B. Csontos**, I. Heckl, “Simulation models for transporting oil materials in pipelines”, PRES 2018 (21st Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction), Prague, Czech Republic, 2018.

[6] **B. Csontos**, I. Heckl, “Simulation models for transporting oil materials in pipelines”, Pannonian Conference on Advances in Information Technology (PCIT'2019), Veszprém, Hungary, 2019.

[7] **B. Csontos**, I. Heckl, “Custom simulator for validating pipeline schedule in the oil industry”, EDSI 2022 - EDSI 12th Annual Meeting, Dublin, Ireland, 2022.

5.2 Other publications

International journal articles

[8] **B. Csontos**, I. Heckl, “Accessibility, usability, and security evaluation of Hungarian government websites”, Universal Access in the Information Society, vol. 20, pp. 139-156, 2021, **IF: 2.8**.

[9] **B. Csontos**, I. Heckl, “Improving accessibility of CMS-based websites using automated methods”, Universal Access in the Information Society, vol. 21, pp. 491-505, 2022, **IF: 2.8**.

Articles in domestic conference proceedings

[10] **B. Csontos**, I. Heckl, "A magyar közszférabeli weboldalak használhatóságának, akadálymentesítésének és biztonságának vizsgálata", Orvosi Informatika 2018. A XXXI. Neumann Kollokvium konferencia-kiadványa, Szeged, Hungary, vol. 31, pp. 74-79, 2018.

[11] **B. Csontos**, I. Heckl, "Akadálymentesítő módszerek a tartalomkezelő rendszerekhez", Orvosi informatika 2019. A XXXII. Neumann Kollokvium konferencia-kiadványa, Veszprém, Hungary, vol. 32, pp. 30-35, 2019.

[12] **B. Csontos**, I. Heckl, "Akadálymentesítő módszer megvalósítása a WordPress Gutenberg blokkszerkesztőhöz", Orvosi informatika 2020. A XXXIII. Neumann Kollokvium konferencia-kiadványa, Szeged, Hungary, vol. 33, pp. 62-67, 2020.