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A mathematical approach to optimization of oil flow scheduling in pipeline systems

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ABSTRACT

One of the urgent and time-consuming problems in the area of oil and oil products transportation is the problem of oil cargo flows scheduling in trunk pipeline systems. The problem is complicated by the necessity to take into account both the characteristics of the oil pipelines themselves, the properties of oil and capacity of tank terminals.

The relevance of this topic is due to the deterioration in the composition and properties of incoming oil to the pipeline systems from suppliers, the increase in the share of high-sulfur oils and the need to supply low-sulfur oil to consumers.

The article considers a new approach to oil transportation scheduling in branched oil pipeline systems. A new approach based on mathematical model that solves the optimization transport problem. The transport problem is formalized as a system of objective function and constraints then this system is solved using linear and sequential quadratic programming methods. The system can be varied depending on the needs of a given pipeline system.

The approach allows to compute oil flow distribution during the certain time period (day, week, month, etc.) with given time sampling (hour, day, week, etc.) considering pipeline characteristics (flow capacity, technological regimes, etc.), oil properties (mass sulfur fraction, density, etc.) and capacity of tank terminals. Also, the approach allows to optimize oil transportation by energy consumption.

The possibilities of the proposed approach are shown using a system of 10 oil pipelines, 4 transitional tank terminals, 3 oil suppliers and 6 oil consumers. The result of flow distribution calculation in a branched system is the schedule of cargo flows for each pipeline in a whole pipeline system with all constraints satisfied and optimized objective function.

INTRODUCTION

Oil pipeline system in many countries (like USA, Russia, Canada etc.) is a large number of branched pipelines with many consumers and suppliers. The problem of optimizing oil transfer from suppliers to consumers under necessary limitations is a difficult mathematical, engineering and technical problem for transportation companies.

One of the urgent and time-consuming problems in the area of transportation of oil and oil products is the problem of oil cargo flows scheduling through trunk pipeline systems. The problem is complicated by the necessity of taking into account both the characteristics of the oil pipelines themselves, the properties of oil and the capacity of tank terminals. In addition, it is necessary to optimize electricity costs for oil pumping and to take schedule of maintenance work into consideration.

Many scientific and engineering works are devoted to the optimization of energy consumption costs when planning cargo flows for a single main oil pipeline [Sergienko 2012; Economides and Kappos 2009; Zhang and Liang 2016; Wu et al. 2017]. In these works, special attention is paid to the selection of pumping equipment at pumping stations, as well as the selection of technological regimes for oil pumping.

For a system consisting of several pipelines, problem statement is more general, and the choice of technological regimes for pumping in oil pipelines is characterized not only by optimizing the energy costs, but also by the necessity of fulfilling a number of other limitations. For example, it is necessary to coordinate oil cargo flows per time step in tied pipelines, take into account the capacity of the tank terminals, as well as the properties of pumped oil and the oil mixing (compounding). More details and problems about oil flow scheduling in a branched pipeline system are described in [Milidiu 2003, Grishanin et al. 2016].

Nowadays, the problem of oil flow scheduling optimization in pipeline systems is very relevant due to the following reasons:

- the deterioration of incoming oil quality from suppliers;
- the increase in the share of high-sulfur oil from suppliers;

- the need to supply low-sulfur oil to consumers.

In this regard, it is necessary to schedule pipeline cargo flows to provide required properties of oil supplied to consumers. [Grishanin et al. 2016].

There are many articles featuring different approaches to oil transportation scheduling in pipeline systems. In some articles [Arya and Honwad 2015; De la Cruz et al. 2003; Narvaez and Galeano 2004; Narvaez and Galeano 2004] genetic algorithm is proposed to solve the problem of oil flow scheduling optimization, in others [Vlot 2017; Oosterhuis 2015; Wang and Lu 2015; Jamshidifar 2009; Grelli 1985; Osiadacz 1994] dynamic programming is used to optimization pipeline networks. Nowadays gradient search techniques [Mercado et al. 2002; Rozer 2003; Tabkhi 2007] and heuristic methods [Ferber 1999; Conrado and Rozer 2005] are quite widespread in transport of oil and gas pipeline systems optimization. However, the methods used in these techniques have a drawback of getting trapped in local optima. The solution depends on the initial chosen solution, and these methods are not efficient in handling discrete variables.

In addition, there is no consensus among researchers, which method of cargo flows optimization in oil pipeline systems is the best. Since this problem is highly relevant in modern oil and gas field, we developed a new approach to solve the problem. The designed approach allows to compute oil flow schedule for a certain time period (day, week, month, etc.) with given time sampling (hour, day, week, etc.) for all pipelines of a pipeline system.

PROPOSED APPROACH

For detailed scheduling of oil cargo flows through a branched pipeline system, it is necessary to calculate pumping for each pipeline for a given period with a certain sampling of the time steps in such a way that the following conditions are met:

• the capacity and availability of only fixed regime flows for a pipeline were taken into account (if a pipeline flow is not specified due to the planned operations or there is no fixed set of technological regimes on this pipeline);

• The capacity of tank terminals was taken into account (at each step there was no exceeding of the maximum allowable amount of oil in tank terminals or the achievement of the tank oil level below the minimum allowable value);

• The total amount of oil taken from the suppliers and transferred to consumers was in accordance with the general transportation schedule;

• limitations on the oil properties (density, mass fraction of sulfur, etc.) at specified control points (consumers, tank terminals) were taken into account;

• at the juncture of several pipelines (the point where flows mix) and in tank terminals, oil was mixed using the weight additivity rule;

• scheduled operations (planned stops of pumping, extra regimes, that are not included in a fixed set of regimes, etc.) were taken into account for all pipelines;

• when calculating the oil properties at control points, the transportation of oil was taken into account, that is, the movement of oil with different properties at the flow rate.

For the following formulation of the problem these conditions can be formalized as a system containing an optimized objective function *φ(x)* and constraints *b(x), c(x)* that are equalities/inequalities.

The objective function has the following general form:

$$\varphi(x) = N_1 f\left(q_k^\theta, t_{ij}^\theta\right) + N_2\gamma\left(q_{km}, t_{ij}^\theta\right) + N_3\vartheta\left(t_{ij}^\theta, T_{step}\right), \; x = \left\{t_{ij}^\theta, q_k^\theta\right\} \quad (1)$$

where $f(q_k^\theta, t_{ij}^\theta)$ – function of energy costs for oil pumping through the pipeline system; $\gamma\left(q_k^\theta, t_{ij}^\theta\right)$ – function of discrepancy of the total amount of oil actually delivered by suppliers and received by consumers from the amount specified by schedule; $\vartheta(t_{ij}^\theta, T_{step})$ – function that describes the amount of transitions between regimes in a pipeline system; *I* –index of a pipeline in studied pipeline system with fixed map of technological regimes; *j* – index of a technological regime (only for pipelines with fixed set of technological regimes); θ –index of the time step; *k* – index of a pipeline without fixed set of regimes; *Tstep* –duration of the time step; t^θ_{ij} –pumping time on the *i*-th pipeline for *j*-th technological regime at θ-th time step; ρ_n^θ, S_n^θ – density/ mass fraction of sulfur (%) at control point at θ-th time step; N_1, N_2, N_3, N_4, N_5 – weighting numbers.

It is necessary to note that function $\gamma\left(q_k^\theta, t_{ij}^\theta\right)$ was added to the objective function to provide a solution after solving the optimization problem using the proposed approach even in case when there is not possible to transport all planned oil volumes from suppliers to consumers.

In that case, the approach tends to minimize the discrepancy between actual and planned transported oil volumes.

The approach suggests arranging weight numbers in the following order:

$$0.01N_2 > N_1 > N_3 \quad (2)$$

In this form when solving the problem firstly

According to specific demands of a certain pipeline system new terms can be added to the optimized function.

General constraints *b(x), c(x)* are written as follows:

$0 \le t_{ij}^\theta \le T_{step}$– the operating time of pipeline for a technological regime must not exceed the duration of a time step *Tstep* and cannot be negative;

$0 \le q_k^\theta \le Q_i$ – the pumping rate can not exceed the pipeline capacity Q_i and cannot be negative. It is set for pipelines, which do not have a fixed set of technological regimes.

$s_n^{min} \le s_n^\theta \le s_n^{max}, \rho_n^{min} \le \rho_n^\theta \le \rho_n^{max}$ - values of oil properties at control points must be in the range of constraints

As constraints at junctures of a pipeline system and in tank terminals, the law of conservation of mass is used:

$\left(\sum_{i=1}^{I}\sum_{j=1}^{J} q_{ij}t_{ij}^{\theta}\right)^{in} = \left(\sum_{i=1}^{I}\sum_{j=1}^{J} q_{ij}t_{ij}^{\theta}\right)^{out}$ – at junctions incoming and outcoming oil volumes are equal;

$V_{min} \leq \left(V_{RP}^{\theta-1} + \left(\sum_{i=1}^{I}\sum_{j=1}^{J} q_{ij}t_{ij}^{\theta}\right)^{in}\right) - \left(V_{RP}^{\theta} + \left(\sum_{i=1}^{I}\sum_{j=1}^{J} q_{ij}t_{ij}^{\theta}\right)^{out}\right) \leq V_{max}$– oil volume in a tank terminal V_{RP} must be no less than minimal given value V_{min} and must be no more than maximal given value V_{max} at each time step.

$t_{ij}^{\theta} = T_{plan}$ - in case of scheduled pipeline works pumping time of a regime required for works is fixed.

In addition to the above limitations, additional equations can be added to the system of equations in the formulation of special problems for a particular pipeline system.

The objective function and constraints described above are general and serve as the basis for the described approach for scheduling of oil flow in branched pipelines using algorithms to solve the optimization transport problem. General information on the formulation and solution of transport problems can be found in [6, Chapter 5], [7, Chapter 2]. The values of the coefficients in the objective function, as well as the complete set of constraints, will depend on the specific tasks assigned when scheduling oil cargo flows.

The optimization transport problem can be solved both by the methods of sequential quadratic programming [8, Chapter 9], [9, Chapter 7] and by linear programming methods [10, Chapter 1], [11, Chapter 4] depending on the complexity of a branched transport network and given tasks when scheduling oil flows.

For the above-mentioned *φ(x)* and *b(x), c(x)* the optimization problem is solved using linear programming algorithms (for example, simplex method or potential method.) The calculation step is equal to the sampling step (for example, 1 hour). The calculation period is, for example, 1 month (744 hours).

The result of the calculation is the determination of the technological pumping regimes for all pipelines with a fixed set of regimes at each calculation step, as well as the mass pumping flow rates at each step for pipelines that do not have a fixed set of technological regimes.

If it is not possible to find a solution to the problem in the above formulation, it is concluded that the pipeline system cannot pump required volumes of oil under given constraints on the oil properties at control points.

In this case, we must remove the restrictions on $s_n^{\theta}, \rho_n^{\theta}$ from *b(x), c(x)* and add two additional functions α, β to the objective function *φ(x):*

$$\alpha\left(S_n^{\theta}, S_n^{max}, S_n^{min}\right) = \sum_{i=1}^{m} e^{N_4(S_i - S_n^{\max})} + e^{N_4(S_n^{\min} - S_i)} \quad (3)$$

$$\beta\left(\rho_n^{\theta}, \rho_n^{max}, \rho_n^{min}\right) = \sum_{i=1}^{m} e^{N_5(\rho_i - \rho_n^{\max})} + e^{N_5(\rho_n^{\min} - \rho_i)} \quad (4)$$

Hence, the objective function takes the following form:

$$\varphi(x) = N_1 f\left(q_k^{\theta}, t_{ij}^{\theta}\right) + N_2\gamma\left(q_{km}, t_{ij}^{\theta}\right) + N_3\vartheta\left(t_{ij}^{\theta}, T_{step}\right) + \alpha\left(N_4, S_n^{\theta}(t_{ij}^{\theta}, q_k^{\theta}), S_n^{max}, S_n^{min}\right) + \beta\left(N_5, \rho_n^{\theta}(t_{ij}^{\theta}, q_k^{\theta}), \rho_n^{max}, \rho_n^{min}\right), x = \left\{t_{ij}^{\theta}, q_k^{\theta}\right\} \quad (5)$$

where *N4*, *N5* ≈ 10-100. In this form, even a slight deviation of oil properties from restrictions will lead to a significant increase in the value of the objective function.

It should be noted that the linearity/ non-linearity of the objective function and constraints depends on the complexity of a pipeline system under consideration.

In case of a branched pipeline system with a large number of tank terminals and flow mixing points, the objective function (5) will be nonlinear due to the functions α and β. Since the use of quadratic programming methods significantly increases the calculation time of the optimization problem, and the calculation time has an exponential dependence on the number of variables x, then with the number of variables exceeding $\approx 10^5$ and the necessity of using the functions α and β in the objective function, it is proposed to solve the problem in two stages as follows:

1. In the first stage the objective function *φ(x)* is similar to (5). The optimization problem is solved by quadratic programming methods [8, Chapter 9], [9, Chapter 7], since the functions $\alpha(S_n^{\theta}, S_n^{max}, S_n^{min})$ and $\beta(\rho_n^{\theta}, \rho_n^{max}, \rho_n^{min})$ are nonlinear. The time step is equal to the calculation period (for example, 1 month, 744 hours). The result of the first stage is the calculated values of the properties at the control points, which become new constraints for the second stage.

2. In the second stage of the calculation, the objective function *φ(x)* is similar to (1). And the optimization problem is solved using linear programming algorithms (for example, the simplex method or the method of potentials).

In the second stage, the calculation step is equal to the sampling step (for example, 1 hour). The calculation period is, for example, 1 month (744 hours). The result of the calculation in the second stage is the determination of the technological pumping regimes on all pipelines that have a fixed set of regimes at each calculation step, as well as the mass flow rates at each step for pipelines that do not have a fixed set of technological regimes.

When creating the approach, the authors made the following assumptions:

• transient processes (including those caused by cavitation) within the technological section of a pipeline are not taken into account, that is transition from one steady-state regime to another is momentary;

• transient processes and the changes of the regime mass flow associated with discrete mixing and changes of oil properties, as well as the presence of mixing zones along the entire pipeline are not taken into account. It is assumed that the regime mass flow rate is constant and does not depend on the oil properties in the pipe at any time. The assumed assumption that the regime mass flow rate in the pipe is constant leads to an error in calculating the cargo flow in the pipe associated with the change in density in the pipeline. The magnitude of error depends on the range of density variation in the pipeline system;

• The movement of oil is considered one-dimensional and piston, that is, oil with different properties in a pipe is not mixed while pumping through a pipeline;

• the temperature of oil and the ambient temperature are not taken into account;

• mixing of oil at the mixing point of flows is considered instantaneous and complete;

• the passage of pigs is not taken into account;

•a tank terminal is not divided into separate tanks and is considered as a single container with oil, in which complete uniform mixing of oil occurs when oil enters. One tank terminal can be divided into several groups of tanks. A group can consist of either one or several tanks.

The result of solving the optimization problem of scheduling of oil cargo flows are the values of all the variables included in the objective function, i.e. data on pumping time in various technological regimes (t^{θ}_{ij}) for pipelines, which have a fixed set of technological regimes; mass flow rate (q_{ij}) at each step for pipelines, which do not have a fixed set of technological regimes, as well as volumes of oil that were not transported from suppliers and not delivered to consumers. The determination of these variables will allow to calculate the volume of oil in all tank terminals, the oil properties at control points and the operating regimes of all pipelines at each time step.

The use of this approach makes it possible to solve the problem with given input data, and if there is no solution with the initial data, it shows how much it is necessary to reduce the traffic flow or change the limitations on the oil properties so that the solution becomes possible. At the same time, the solution is optimized for energy costs.

EXAMPLE OF COMPUTATION OF OIL FLOW SCHEDULE IN A BRANCHED PIPELINE SYSTEM

To test the approach described above, a branched oil pipeline system consisting of 10 separate pipelines, 4 tank terminals, 3 suppliers and 6 consumers was chosen. Wherein, technological regimes of pipeline 2 and pipeline №3 are tied. The scheme of the oil pipeline system is shown in Figure 1.

The pipeline №5 can be supplied from the tank terminal № 1 and the tank terminal № 2, oil completely mixes at the inlet to the pipeline №5. Oil properties after mixing are calculated by the mass additivity rule. At the same time, pipes running from tank terminal №1 and tank terminal №2 to pipeline №5, do not have fixed technological regimes, so the flow rate during pumping can take any values, from zero to the capacity of the pipe. Similarly, for pipes from pipeline №1 to consumer № 1, from tank terminal №3 to consumer №4, from pipeline №8 and pipeline №9 to consumer №5 and in tank terminal № 4.

When calculating the test case, a transfer period of one month (31 days, 744 hours) was chosen with a step increment of one hour. In the general transportation schedule, the gross pumping volumes for the month received from suppliers and supplied to consumers are set. Limitations on the mass fraction of sulfur and the oil density among consumers are as follows: the mass fraction of sulfur for all consumers should not exceed 1.9%, and density 880 kg/m^3 (54.94 lb/ft^3). Gross volumes of pumping (transportation schedule), the value of the properties of oil from suppliers, as well as restrictions on the properties of oil are presented in Tables 1 and 2.

As initial data, one can specify both the total gross volume of supply and consumption, and the distribution of the supply by days or steps, for example, uniform distribution or accurate values (if an accurate schedule of supply and consumption is known), i.e. on what day, how much oil should be taken from suppliers and delivered to consumers. Also, the initial data set oil properties in pipes, the amount of oil in tank terminals and the properties of this oil at the beginning of the calculation period and the maximum / minimum capacity of tank terminals (Table 3). Moreover, the maximum and minimum capacity of a tank terminal can vary during the calculation period, for example, due to the withdrawal of some tanks for repairs, etc.

In addition, the capacity was set for the pipelines without fixed technological regimes and technological regimes for all other pipelines, as well as the schedule of maintenance works. The technological regimes and the capacity of the pipelines are indicated on the graphs of the solution (Figures 2-4).

Schedule of maintenance works is shown in Table 4. It should be noted that the assumption that the mass flow rate is constant at the indicated range of density changes (see Table 1) in the pipeline system will lead to a maximum error in the calculation of cargo flows of about 7-8% (for the given example, if the mass flow rate was estimated for a density of 890 kg/m^3 (55.56 lb./ft^3), and the actual density of oil was 845 kg/m^3 (52.75 lb./ft^3)).

Thus, using the proposed approach, the task of calculating the schedule of oil cargo flows in a branched pipeline system was solved for the input data described above. The results of the solution are most visibly displayed as graphs showing the change in the mass flow rate of oil pumping through a pipeline over time (Figures 2-4), as well as the change in the amount of oil in tank terminals (Figure 5) and oil properties at control points (Figure 6).

Figure 2 shows the mass flow rates from time in pipelines coming from suppliers (Pipeline №1, Pipeline № 2, Pipeline №4). The mass flow rate in pipeline 3 is unambiguously tied with the mass flow rate in pipeline №2. The mass flow rate in Pipeline №2 is shown before the withdrawal at Pipeline №3.

Flow rates that are not from the set of fixed technological regimes and stopped state in Pipelines№1, №2 and №4 are due to the schedule of maintenance works (see Table 4).

Figure 3 shows the graphs of mass flow rates from time in intermediate pipelines, which connect tank terminals to each other: Pipeline 6, Pipeline 8, Pipeline 9. For pipes without fixed technological regimes (see Figure 1), the limitation on mass flow rate is only their capacity.

Mass flow rates diagrams in Pipeline 5, 7 and 10 for which oil is supplied to consumers are shown in Figure 4. Based on the calculation results, all suppliers pumped the amount of oil specified in the transportation schedule (Table 1), and all consumers received the amounts of oil shown in Table 2. The difference between the total mass of oil supplied to the pipeline system and the amount of oil delivered to consumers is 10,000 tons (22 046.226 ths.lb). According to the solution, this difference remained in the tank terminals.

In addition to graphs of mass flow rates in pipelines, the solution result is shown in form of graphs of the amount of oil in all tank terminals from time (Figure 5). During the whole period of the calculation, none of the tanks was re-emptied or overflowed, i.e. $V_{min} \leq V\_RP^{\theta} \leq V_{max}$ for each time step.

Oil properties at the consumers # 3, # 4, # 5 and # 6 will actually be determined by the value of properties in the tank terminal # 3. Properties at the consumer №1 will be equal to the properties at the supplier №1. Therefore, two graphs are presented in Figure 6: the mass fraction of sulfur from time for consumer No. 2 and tank terminal No. 3. Graphs of oil density will look similarly. The density for all consumers did not exceed 880 kg/m^3 (54.94 lb./ft^3) during the entire pumping period.

Using the graphs shown in Figures 2-6, it is possible to make a daily oil transportation schedule for a month, to determine the transition map for the technological regimes of the pipelines in the whole pipeline system, to determine the mixing of oil at the outlet from the tank terminals to the pipelines and in the tank terminals themselves, and also to control the technological pumping process.

CONCLUSIONS

The article describes a new approach to scheduling of the oil flows for a certain period with a given sampling step in a branched pipeline system, taking into account the fulfillment of the requirements for the quality of oil received by consumers, planned operations, pipeline technological regimes and the amount of oil in tank terminals.

With the help of this approach, oil cargo flows were calculated in a branched pipeline system taking into account all the conditions and limitations set by the user for the maximum value of the oil volume in tank terminals, pipeline capacity, properties of oil received by consumers, etc. Calculation results for the described pipeline system per month with time sampling 1 hour are given in the article. Values were obtained for oil pumping through the pipeline system (oil volume in tank terminals, technological conditions in pipelines, oil properties at controlled points, etc.) at each time step. The approach is quite universal and can be modified to take into account various conditions when scheduling oil flows in a particular branched pipeline system.

REFERENCES

1. Arya, A.K., and Honwad, S. (2015). “Modeling, simulation and optimization of a high-pressure cross- country natural gas pipeline: application of ant colony optimization technique.” J Pipeline Syst Eng Pract, 10.1061/(ASCE)PS.1949-1204.0000206.
2. Bienstock, D. (2001). Potential Function Methods for Approximately Solving Linear Programming Problems: Theory and Practice, Springer, New York.
3. Bonnans, J. F., Gilbert, J. C., Lemaréchal, C., and Sagastizábal, C. A. (2006). Numerical optimization: Theoretical and practical aspects, Springer-Verlag, Berlin, Germany.
4. Conrado, B. S., and Rozer, M. (2005). A hybrid meta-heuristic approach for natural gas pipeline network optimization, Springer, Berlin.
5. Cornuéjols, G. (2008). “Valid Inequalities for Mixed Integer Linear Programs.” Mathematical Programming Ser. B, V.112 (Issue 1), 3–44.
6. De la Cruz, J.M., de Andres-Toro, B., Herran, A. Besada porta, E., and Blanco, P.F. (2003). “Multiobjective optimization of the transport in oil pipelines networks.” IEEE Conference on Emerging Technologies and Factory Automation. V.1 Proceedings, 566-573.
7. Eaton, J.W., Bateman, D., Hauberg, S., and Wehbring, R. (2016). “GNU Octave: Free You Numbers.” 〈https://octave.org/doc/octave-4.0.3.pdf〉 (July 2016)
8. Economides, M., and Kappos, L. (2009). Petroleum Pipeline Network Optimization, EOLSS Publishers, Oxford, U.K.
9. Ferber, E., Philip, P., Ujjal, V., and William, B. (1999). “CNGT installs fuel minimization system to reduce operating cost.” Pipeline and Gas Industry, 97–102.
10. Foster, C.D. (1975). The Transport Problem, Croom Helm, London.
11. Gomes, F.A.M. (2007). “A Sequential Quadratic Programming Algorithm That Combines Merit function and Filter Ideas.” Computational & Applied Mathematics, V. 26 (3), 337-379.
12. Grelli, G. J. (1985). Implementing an optimization program for a natural gas transmission pipeline, Pipeline Simulation Interest Group, Albuquerque, New Mexico.
13. Grishanin, M.S., Andronov, S.A., Kacal, I.N. and Kozobkova, N.A. (2016). “Управление качеством нефти: Информационное обеспечение [Oil quality management: information support].” Oil pipeline transportation, 4, 4-11 (In Russian).
14. Jamshidifar, A., Torbati, H. M., and Kazemian, M. (2009). “GTNOpS, an agent-based optimization software for gas transmission network.”24th World Gas Conf., Argentina.
15. Land, A. H., and Doig, A. G. (1960). "An automatic method of solving discrete programming problems." Econometrica, 28 (3), 497–520.
16. Luenberger, D.G., and Yinyu, Y. (2008). Linear and Nonlinear Programming, Springer Science & Business Media, New York.
17. Mercado, R.Z., Wu, S., Scott, L.R., and Boyd, E.A. (2002). “A reduction technique for natural gas transmission network

optimization problems." Ann. Oper. Res., 117(1), 217–234.
18. Milidiu, R.L., and dos Santos Liporace F. (2003). Planning of Pipeline Oil Transportation with Interface Restriction is a Difficult Problem, PUC, USA.
19. Mitradjieva-Daneva, M. (2007). Feasible Direction Methods for Constrained Nonlinear Optimization. Suggestions for Improvements, Linkoping, Sweden.
20. Morgan, S. S. (1997). A Comparison of Simplex Method Algorithms, Master of Science thesis, University of Florida, USA.
21. Murty, K. G. (2000). Linear programming, John Wiley & Sons Inc.1, Chichester, U.K.
22. Narvaez, P.-C., and Galeano, H. (2004). "Genetic Algorithm for the Optimization of pipeline Systems for Liquid Distribution (1)." CT&F – Ciencia, Technologia y Futuro, V.2 (4), 55-64.
23. Narvaez, P.-C., and Galeano, H. (2004) "Genetic Algorithm for the Optimization of pipeline Systems for Liquid Distribution (2)." CT&F – Ciencia, Technologia y Futuro, V.2 (5), 117-130.
24. Nocedal, J., and Wright, S. J. (2006). Numerical Optimization, Springer, New York.
25. Oki, E. (2012). Linear Programming and Algorithms for Communication Networks: A Practical Guide to Network Design, Control, and Management, CRC Press, USA.
26. Oosterhuis, S.B.J. (2015). Robust pipeline flow scheduling at an oil company, Master of Science Thesis, University of Twente, Netherlands.
27. Osiadacz, A. J. (1994). "Dynamic optimization of high pressure gas networks using hierarchical systems theory." 26th annual meeting of Pipeline Simulation Interest Group, San Diego.
28. Rachev, S.T., and Ruschendorf, L. (1998). Mass Transportation Problems, Springer Science & Business Media, New York.
29. Rozer, M. (2003). "Efficient operation of natural gas pipeline networks." Computational Finding of High-Quality Solutions, Int. Applied Business Research Conf., AccessEcon.
30. Reeb, J., and Leavengood, S. (2002). Transportation Problem: A Special Case for Linear Programming Problems, Oregon State University, USA.
31. Sergienko, I.V. (2012). Methods of Optimization and Systems Analysis for Problems of Transcomputational Complexity, Springer Science & Business Media, New York.
32. Stoer, J., and Bulirsch, R. (1993). Introduction to Numerical Analysis. 2nd Edition, Springer -Verlag, Berlin, Germany.
33. Tabkhi, F. (2007). Optimization of gas transmission networks, Ph.D. thesis, Grenoble Institute of Technology (INP), Grenoble, France.
34. Vlot, S.J. (2017). Batch Scheduling of Multi-Product Pipeline Networks, Master of Science Thesis, Delft University of Technology, Netherlands.
35. Wang, Y., and Lu, J. (2015). "Optimization of China Crude Oil Transportation Network with Genetic Ant Colony Algorithm." Information, 6, 467-480.
36. Wu, T., Zhiwu, L., and Qu, T. (2017). "Energy Efficiency Optimization in Scheduling Crude Oil Operations of Refinery Based on Linear Programming." Journal of Cleaner Production, V.166, 49-57.
37. Zhang, H.-R., and Liang, Y.-T. (2016). "Supply-based optimal scheduling of oil product pipelines." Petroleum Science, V.13 (Issue 2), 355-367.

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FIGURES

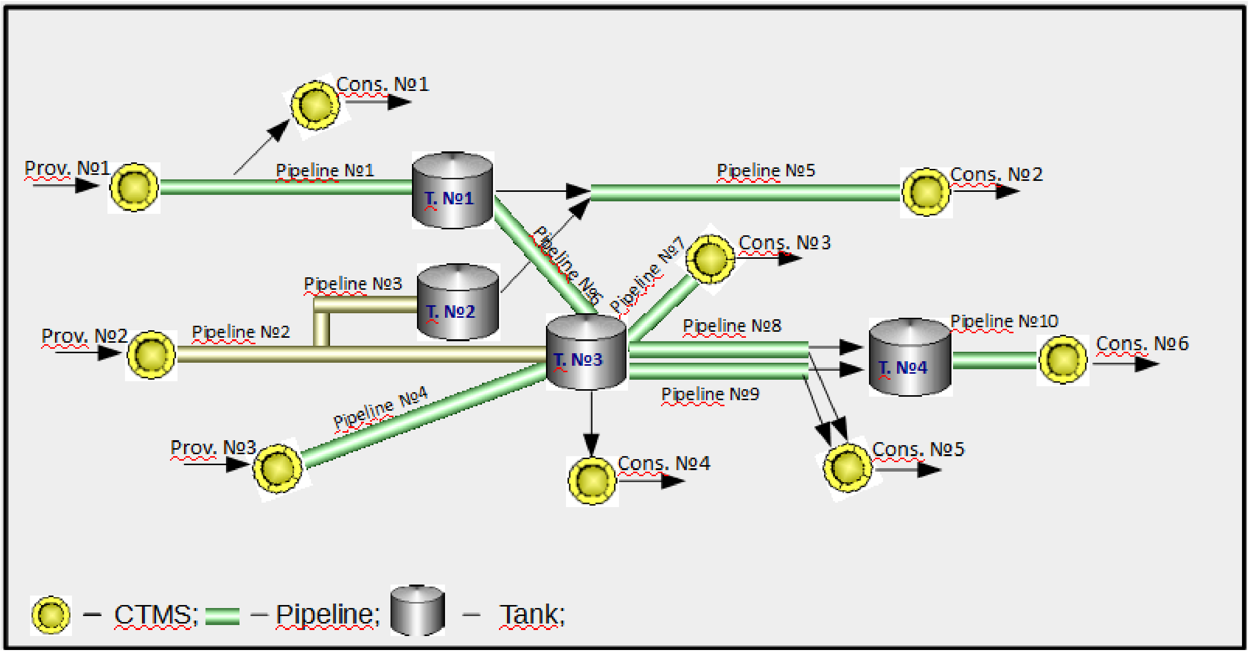


Figure 1 – Scheme of the branched oil pipeline system. «Cons. №__» - Consumer №__; «Sup. №__» - Supplier №__.

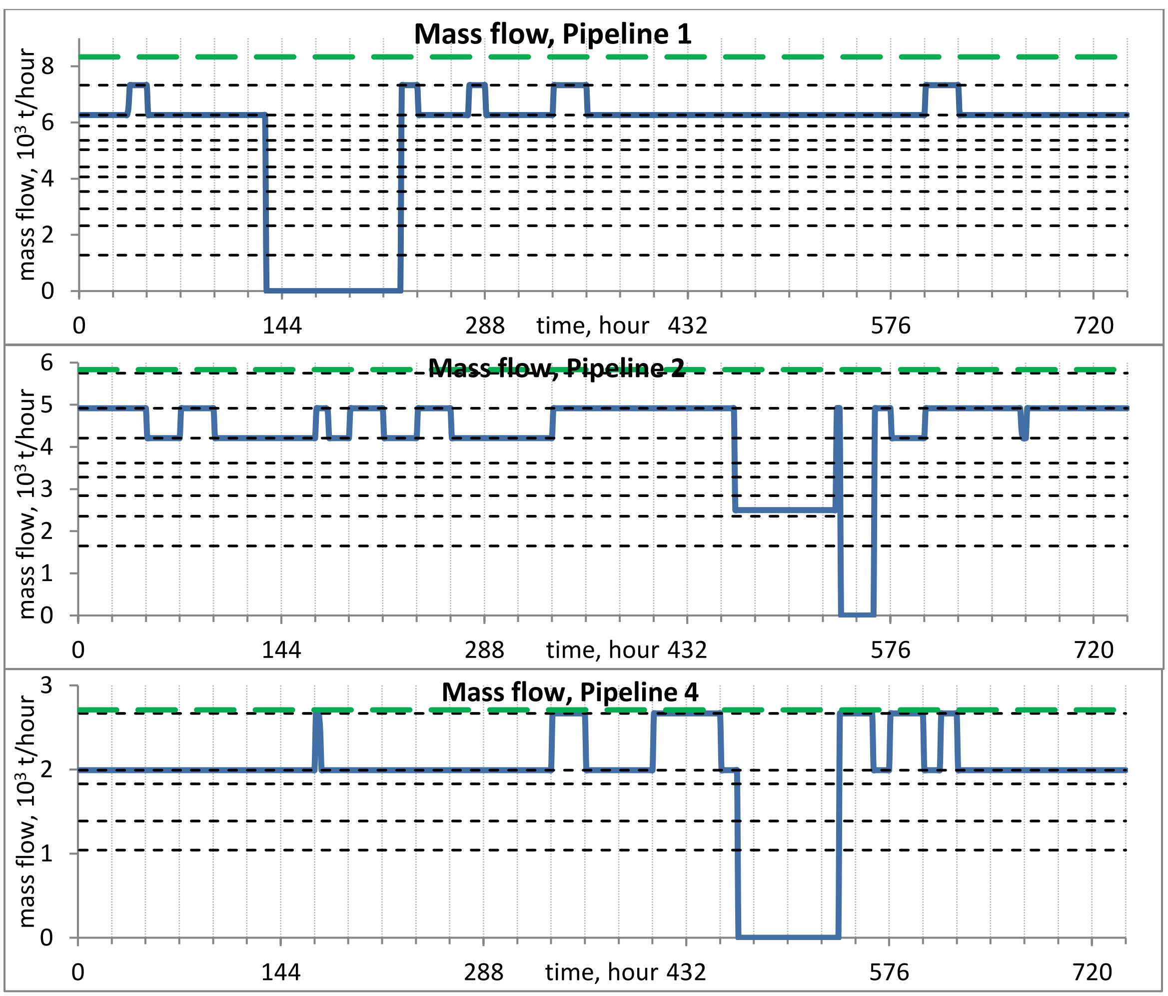


Figure 2. Oil mass flow rates in pipelines, coming from suppliers. Blue line - mass flow rate in a pipeline, green intermittent line – pipeline capacity, black dot-dash line - mass flow rate of pipeline technological regimes.

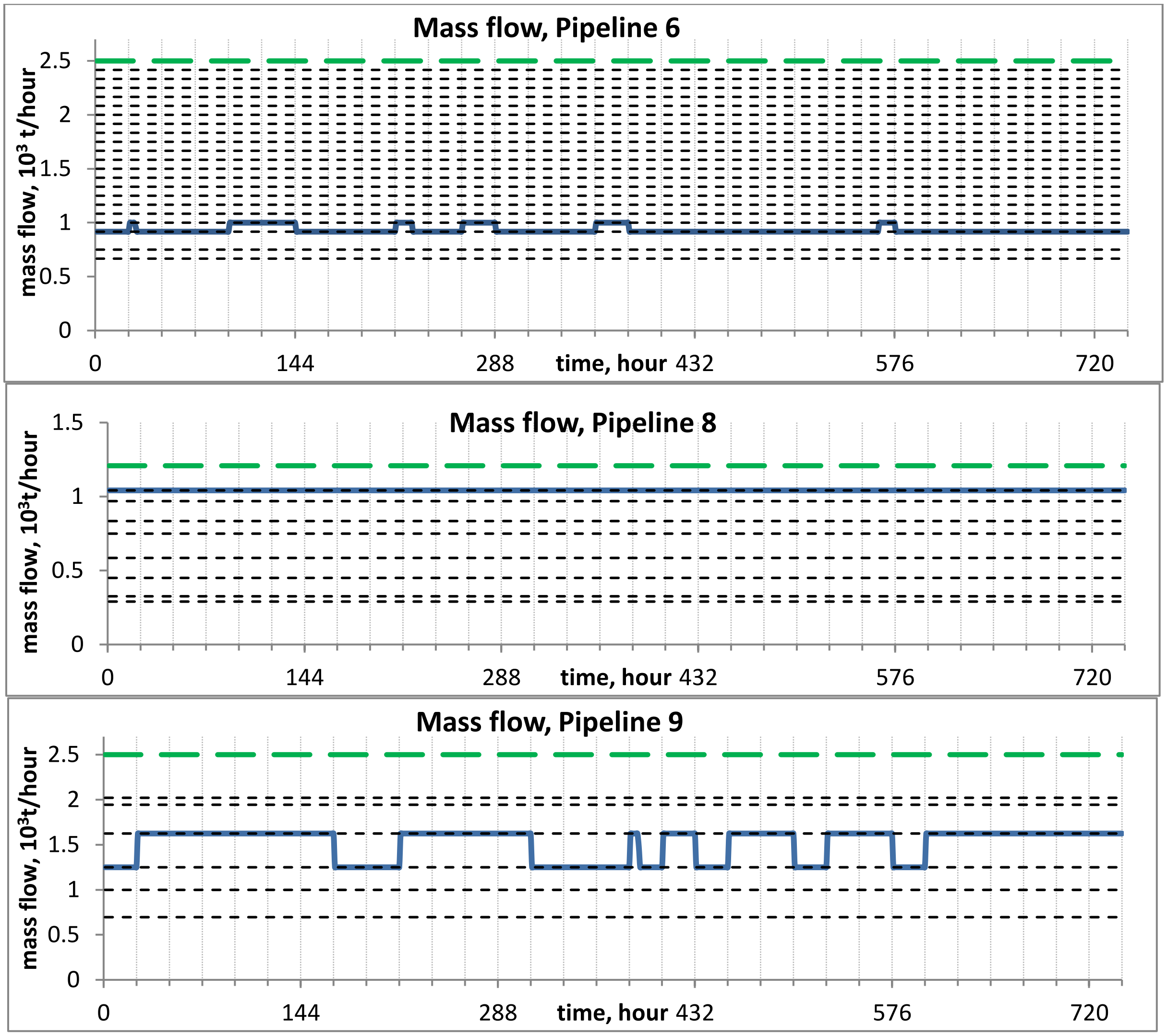
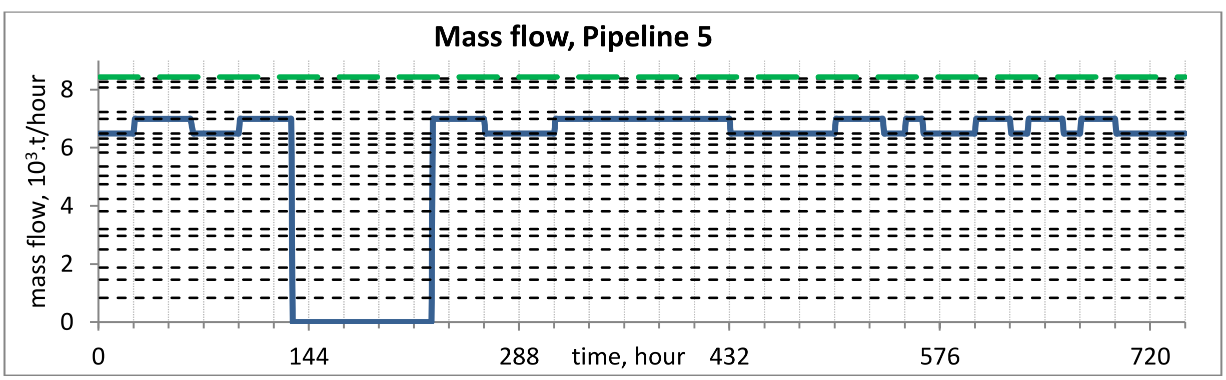


Figure 3. Oil mass flow rates in pipelines, located between tank terminals. Blue line - mass flow rate in pipeline, green intermittent line – pipeline capacity, black dot-dash line - mass flow rate of pipeline technological regimes.



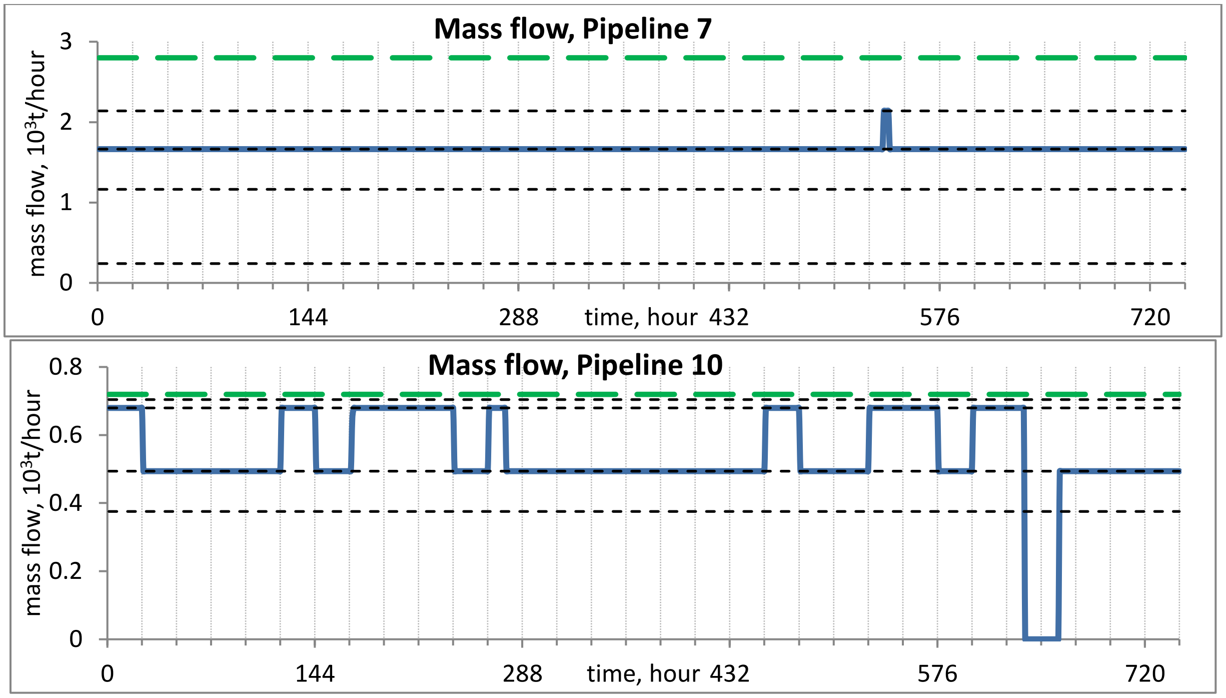
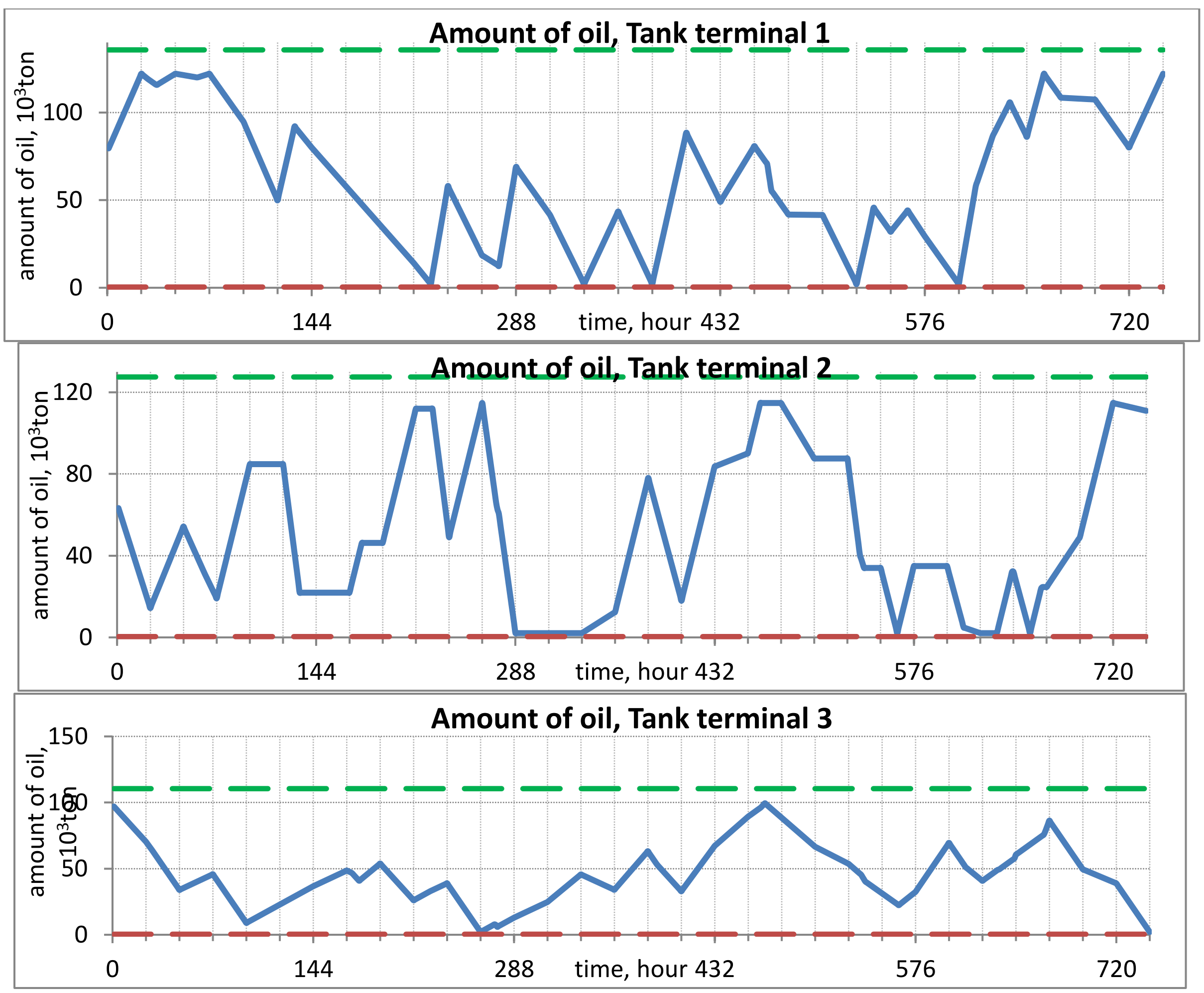


Figure 4. Mass oil flow rates in pipelines, going to consumers. Blue line - mass flow rate in pipelines, green intermittent line – pipeline capacity, black dot-dash line - mass flow rate of pipeline technological regimes



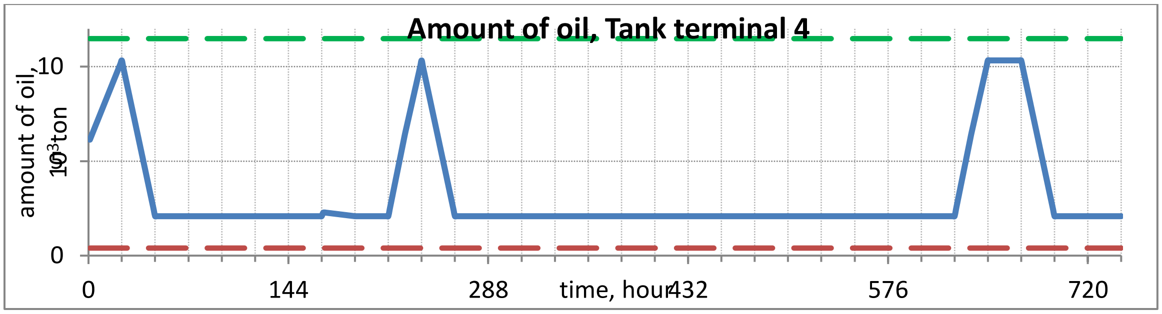


Figure 5. The amount of oil in the tank terminals. The blue line is the amount of oil in the tank terminals, the green intermittent line is the maximum allowable amount of oil in the tank terminals, the orange intermittent line is the minimum allowable amount of oil in the tank terminals

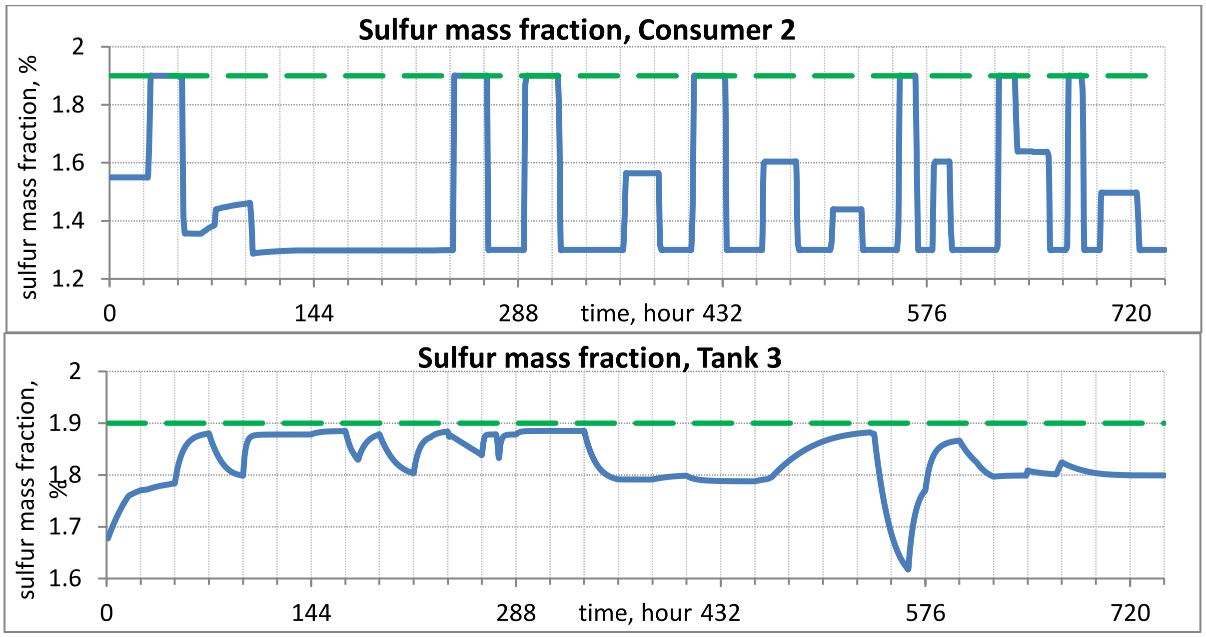


Figure 6. Mass fraction of sulfur in oil. The blue line is the mass fraction of sulfur in oil, the green intermittent line is the maximum allowable value of the mass fraction of sulfur in oil.

TABLES

Table 1. Scheduled gross oil supplies from suppliers and oil properties

Supplier	№1	№2	№3
Scheduled mass of oil supply, ths. tons (mln. lb)	4150 (9149.184)	3200 (7054.792)	1430 (315.261)
Mass fraction of sulfur, %	1.3	2.1	1.7
Density, kg/m^3 (lb./ft^3)	845 (52.75)	890 (55.56)	850 (53.06)

Table №2. Scheduled gross oil supplies to consumers and limitations on oil properties

Consumer	№1	№2	№3	№4	№5	№6
Scheduled mass of oil consumption, ths. tons (mln. lb.)	120 (264.555)	4380 (9656.247)	1150 (2535.316)	1240 (2733.732)	400 (881.849)	1500 (3306.934)
Limitations on oil properties at consumers						
Mass fraction of sulfur, %	1.9	1.9	1.9	1.9	1.9	1.9
Density, kg/m^3 (lb./ft^3)	880 (54.94)	880 (54.94)	880 (54.94)	880 (54.94)	880 (54.94)	880 (54.94)

Table 3. Initial mass of oil and oil properties in tank terminals and maximum/minimum allowable mass of oil in tank terminals.

Tank terminal	№1	№2	№3	№4
Initial mass of oil, ths. tons (ths. lb)	77.69 (169.756)	65.45 (143.3)	98.175 (216.053)	5.95 (11.023)
Mass fraction of sulfur, %	1.22	2.15	1.67	1.7
Density, kg/m^3 (lb/ft^3)	850 (53.06)	850 (53.06)	850 (53.06)	850 (53.06)
Maximum allowable mass, ths. tons (mln. lb)	135.75 (297.624)	127.5 (279.987)	110.5 (242.508)	11.48 (24.251)
Minimum allowable mass, ths. tons (mln. lb.)	0.4 (881.8)	0.4 (881.8)	0.4 (881.8)	0.4 (881.8)

Table 4. Schedule of maintenance works for the pipeline system.

Pipeline	Start hour, hours	Duration, hours	Pipeline capacity, ths. tons (mln.lb) per day
Pipeline №1	156	96	0
Pipeline №2,3	489	72	60 (132.277)
Pipeline №2,3	564	24	0
Pipeline №4	492	72	0
Pipeline №5	156	96	0
Pipeline №10	660	24	0