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PLANNING OF TRANSPORTATION OF RHEOLOGICAL COMPLEX OILS FROM VARIOUS FIELDS THROUGH AN EXTENSIVE PIPELINE SYSTEM, TAKING INTO ACCOUNT ENSURING THE SPECIFIED QUALITY OF THE DELIVERED OIL

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The article discusses the problem of operating an oil pipeline system in the presence of a significant number of suppliers of rheologically complex oils with different sulfur content and a large number of oil consumers with different requirements for oil quality in terms of sulfur and other parameters. The problem of determining optimal cargo flows in such a system is discussed. A method is proposed for determining optimal cargo flows in a branched oil pipeline system, providing a global optimum in terms of minimizing energy costs for pumping. The article provides an algorithm for implementing the method using a conditional example.

Keywords: oil, oil pipeline system, rheologically complex oil, oil quality by sulfur, viscosity, dynamic programming, algorithmic complexity, optimization of cargo flows

1 INTRODUCTION

Modern oil transportation systems in many countries, including the USA, Russia, China, are complex, branched networks of trunk pipelines. Oil enters the pipeline system from various fields and can differ significantly in properties. On the part of consignees, the requirements for the quality characteristics of the supplied products may also differ, including in terms of the content of sulfur impurities [1].

At the same time, both in Russia and throughout the world, there is a steady tendency to increase the production of high-viscosity oil [2], oil with a high sulfur content [3], and, in general, rheologically complex oils [4]. Thus, the variety of oils produced in one region can be great [5]. Even within the same field, the chemical composition of oil can vary from well to well.

As oil enters a single pipeline system from various senders, its mixing inevitably occurs. The technology of controlled mixing (compounding) in order to obtain a product of a given quality is widely used both for the production of commercial oil and in the preparation of oil for processing at refineries [6].

The described situation is also typical for the trunk pipeline system of Russia, through which low-sulfur oil is currently transported eastward, sour oil to refineries in the central part of Russia and the Ural-Volga region, for export through the Novorossiysk seaport, the ports of Primorsk and Ust-Luga, via the Druzhba oil pipeline system [7], high-sulfur oil – at the Bashkortostan oil refinery [7]. Moreover, since 2010, there has been an increase in the production of high-sulfur oil in Tatarstan, Bashkortostan, Udmurtia, Orenburg and Samara regions [7]. The quality indicators of transported oil are affected by the development of new fields and transport infrastructure. In general, the optimal distribution of cargo flows along an extensive oil pipeline system is an urgent and complex problem, which is still solved with a high proportion of manual labor [9, 10].

At the same time, for various reasons, there is a need to redistribute the flow of transported oil. One of these reasons may be the use of additives that affect the throughput and efficiency of the pipeline in various sections [11].

In this case, the task of the transport company is to ensure the transportation of products with minimal economic costs, which in the case under consideration can be conditionally considered equivalent to minimal energy costs [12]. In Russia, the basic principles of distribution of cargo flows in the oil trunk pipeline system are based on providing design volumes of oil pumping, generated at the request of shippers, with specified quality indicators in accordance with standardized values and the scheme of normal cargo flows.

If the issues of regulating the operating modes of a main oil pipeline can currently be considered well-developed [13], then regulating the operation of an extensive system of oil pipelines that ensures the transportation of rheologically complex oils, subject to compliance with specified parameters (for example, restrictions on sulfur content), is a much more complex task [14].

There are traditional methods for solving transport problems [15]. However, the algorithms [15, 16, 17] are not applicable when several parameters are taken into account: mass flow, sulfur content, viscosity and specific energy consumption [18]. The purpose of this research is to develop a methodology and algorithm for planning cargo flows of rheologically complex oil in a branched system of main pipelines, taking into account ensuring the specified quality of delivered oil in terms of sulfur content and minimum energy consumption.

It is worth noting that the viscosity values of different oils can differ greatly from each other. For example, the difference in viscosity of low-viscosity and high-viscosity oils supplied to the Russian main pipeline system can be up to 100 times, therefore, the costs of pumping such oils under the same conditions can differ significantly. Also, viscosity in the general case of additivity is not applied, and, in fact, determining the viscosity of a mixture of oils is a separate problem. In the ideal case, the logarithm of the viscosity of the mixture is equal to a linear combination of the logarithms of the viscosity of the mixed oils (which is described by the Arrhenius equation [19]. However, there are cases when the logarithm of the viscosity of the mixture is less than the mentioned linear combination and the properties of “minimum viscosity” appear (rational mixing, singular mixing), so more, and «maximum viscosity» appears (irrational mixing). Here, in other words, the properties manifest themselves rheologically. complex oils Therefore, predicting the viscosity of mixtures of oils from various fields formed during technological operations is an important task when designing new pipelines and calculating technological pumping modes.

In the condition of pumping oils from different fields with different properties, technological mixtures with different contents of the initial mixed oils and, accordingly, with different viscosities are pumped in separate parts of the pipeline system. Taking into account regular changes in pumping modes in individual sections of oil pipelines, oil is mixed in different ratios. Thus, at each section of the oil pipeline system, not only the technological parameters of pumping, but also the properties of the oil can change.

Thus, optimal planning of cargo flows along an extensive system of oil pipelines, taking into account the properties of rheologically complex oils and various requirements for product quality upon delivery, is an urgent scientific and practical problem.

2 FORMULATION OF THE PROBLEM

Let us formulate the transport problem as follows.

Let there be y suppliers of oil to the pipeline system. Each i -th supplier supplies oil with a given properties and component composition, namely, density ρ_i at a given temperature, sulfur content S_i , paraffins P_i , resins R_i , asphaltenes A_i . Each supplier has the ability to supply oil in a certain interval ($G_{i\,\min} \ldots G_{i\,\max}$). Within the framework of the current problem, we conditionally assume that the oil flow is isothermal, the oil temperature is 10 ºC. We also take into account that the viscosity of the mixture does not lend itself to additivity when mixing individual oils.

There are also m consumers, each of whom needs to supply oil at a given flow rate G_I with sulfur content in the range ($S_{i\,\min} \ldots S_{i\,\max}$), paraffins in the range ($P_{i\,\min} \ldots P_{i\,\max}$), resins in the range ($C_{i\,\min} \ldots C_{i\,\max}$), asphaltenes in the range ($A_{i\,\min} \ldots A_{i\,\max}$) and density in the interval ($\rho_{i\,\min} \ldots \rho_{i\,\max}$).

Oil flows from suppliers to consumers through a pipeline system, which includes oil pipeline sections and oil pumping stations. Each section of the oil pipeline can be operated in certain previously known operating modes. Taking into account the fact that it is possible to use cyclic pumping, as well as the use of various additives, we assume that each section is characterized by a continuous dependence of specific energy consumption E from mass flow G.

The result of solving the transport problem will be the determination of the optimal volumes of oil supplies to the pipeline system from each supplier (optimal cargo flows), taking into account the global minimum energy costs, as well as the determination of the flow rate and oil content in each element of the system.

A diagram of a conventional pipeline network is presented in Figure 1.

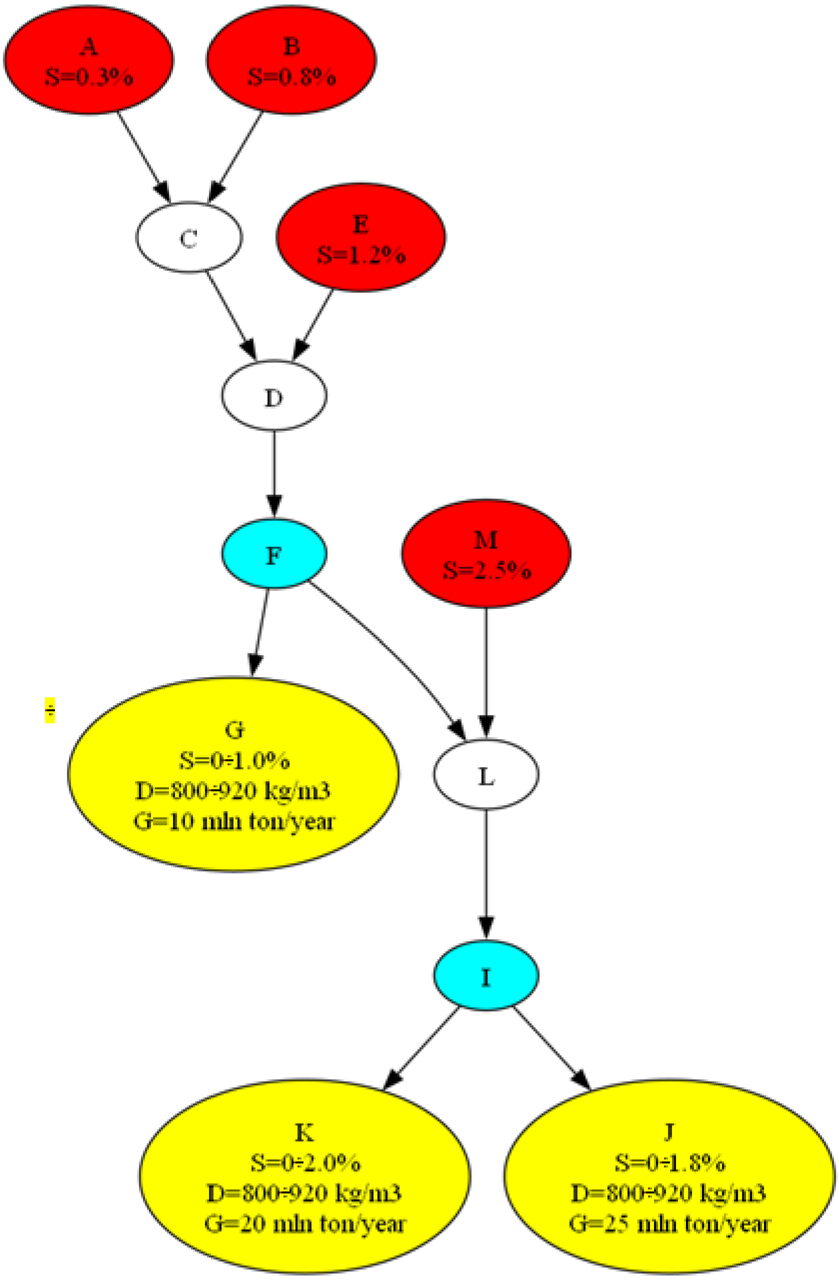

Fig. 1. Diagram of the analyzed oil pipeline system

Below are the properties of oil supplied from fields (Table 1), requirements for oil supplied to consumers (Table 2) and parameters of sections of the oil pipeline network (Table 3).

Table 1. Properties of oil suppliers

Scheme point	Maximum possible consumption Gmax, million tons /year	Sulfur content S, %	Oil density ρ, kg/m3	Paraffin content P, %	Resin content R, %	Asphaltenes content A, %	Analogue of oil among produced
A	70	0.3	816	16.2	17.9	1.1	Tengutinskaya
B	50	0.8	889	5.08	70.54	4.96	Sultangulovskaya
E	45	1.2	904	6	78	4.47	Radaevskaya
M	60	2.5	930	4.4	62.72	6.16	Krasnoyarsk Artinsky

Table 2. Requirements for oil supplied to consumers

Scheme point	Oil consumption G, million tons /year	Sulfur content S, %	Oil density ρ, kg/m^3	Paraffin content P, %	Resin content R, %	Asphaltenes content A, %
G	10	0…1	800…920	0…12	0…80	0…10
K	20	0…2	800…920	0…6	0…80	0…10
J	25	0…1.8	800…920	0…6	0…80	0…10

Table 3. Parameters of sections of the oil pipeline network

Pipeline section	Allowable pressure P_{max}, MPa	Pipe outer diameter, mm	Pipe thickness, mm	Equivalent roughness, mm	Elevation difference Z, m	Length of pipeline section L, m
A C	6.4	720	10	0.2	0	100
B C	6.4	720	10	0.2	0	100
C D	6	720	10	0.2	-10	100
E D	6.4	720	10	0.2	-10	100
D F	6.4	820	10	0.2	-5	100
F G	5.5	820	10	0.2	-20	100
F L	6.4	1020	10	0.2	-20	100
M L	6.4	1020	10	0.2	-40	100
L I	6.4	1220	10	0.2	-20	100
I K	6.4	1220	10	0.2	-20	100
I J	6.4	1220	10	0.2	-10	100

The viscosity of a mixture generally does not lend itself to additivity, but other parameters, such as density and the content of individual components, correspond to additivity. To be able to predict the oil mixture depending on the properties of individual oils, we will use the results of studies conducted by the authors earlier [20]. According to them, viscosity can be estimated with sufficient accuracy based on the mentioned oil parameters. In particular, it has been established that the viscosity of oil at 10 ºC in the general case can be estimated using the following formula:

$$\nu_{10} = \exp(-13.4+172P-6.46S-227A+5.51\rho_{20}-180P^2+375PA-179P\rho_{20}-11.1SP-0.835S^2-6.84SA+9.24S\rho_{20}-25.9A^2+245\rho_{20}A+15.2\rho_{20}^2) \quad (1)$$

where viscosity ν_{10} is presented in the dimension mm^2/s, the content of paraffins P, resins C, asphaltenes A – in fractions, density ρ_{20} – in t/m^3.

3 PROPOSED SOLUTION METHODOLOGY

The main problem of finding optimal cargo flows in a complex network is determining the global optimum of solutions. Fast solution search methods such as gradient boosting, unfortunately, only leads to a local optimum. Therefore, to solve the current problem, an approach that is ideologically close to dynamic programming will be used. For each element of the circuit, all possible states and corresponding energy consumption will be sequentially determined. When analyzing subsequent elements of the circuit, if there are several ways to obtain the same state, then those that have the least energy consumption are selected.

To be able to obtain a finite amount of state, it is necessary to have discrete values of the input quantities, thus, the step (error) of the variables used should be determined. In this calculation, it is adopted as follows: sulfur content – 0.1%, density – 10 kg/m^3, paraffin, resin and asphaltenes content – 1% each.

The example under consideration takes into account all the main cases that may occur in practice. Note that parallel or series pipelines (if any) are replaced by one with a common hydraulic characteristic. When implementing the method, all elements of the system are analyzed (pipelines, pumping stations, consumers, suppliers) according to the calculation scheme in Figure 1. For each element, the following sequence of actions is performed.

The implementation of the algorithm was carried out using the Python programming language; the calculation is fully automated if complete initial data and a calculation scheme are available.

4 ANALYSIS OF THE CIRCUIT ALONG THE FLOW PATH

When analyzing diagrams along the flow path, for example, starting from suppliers A and B, the mass flow rate is unknown, and all flow parameters depend on it. Let, taking into account the step, the range of values of each variable contain *n* points.

Thus, each of these suppliers can supply oil with *n* different costs, in other words, have *n* different states. We note that subsequent sections (in this case, AB and AC) will also have *n* state, provided there are no capacity restrictions.

When analyzing a node where oil flows are mixed, for example pumping station C, it is necessary to take into account the states of previous elements, in this case pipelines AB and AC. After mixing at the site, the density and content of sulfur, paraffins, resins and asphaltenes, generally denoted as *x*, are determined by the following formula

$$x = \frac{x_1 \cdot G_1 + x_2 \cdot G_2}{G_1 + G_2} \tag{2}$$

where indices 1 and 2 correspond to the previous elements of the circuit (in this case, pipelines AB and AC); *G* – oil mass flow.

Energy consumption for each state is determined. The number of states saved is estimated to be *O(2n)*, the same will be the algorithmic complexity in terms of calculation time. Next, the obtained values are rounded according to the accepted discreteness in steps.

If several identical states are obtained, but with different energy consumption, then only the one with the lowest energy consumption is retained.

Taking into account the fact that the state of the nodes is initially described only by flow rate, the algorithmic complexity both in memory and time for each node will be *O(k·n)*, where *k* is the number of suppliers and oil mixing points to a given node.

5 UPSTREAM ANALYSIS

In general, the analysis algorithm is similar, however, at this stage the flow rate at each analyzed point is known, but the oil parameters are not. Based on this, the number of saved states is much greater. The algorithmic complexity in this case can be estimated as $O(n^p)$, where *p* is the number of oil parameters (in this example – 5).

6 ANALYSIS OF NODES WHERE INPUT AND OUTPUT PARAMETERS ARE KNOWN

When analyzing the scheme for the movement of oil, and then against it, we ultimately converge at some points. In cases where the parameters of the input stream are known, but there is one known outgoing stream and one unknown, then you can use the technique of replacing the outgoing stream with an incoming one with negative parameters.

Ultimately, all nodes will be analyzed, and all possible state options with corresponding energy costs will be stored in the last node. Obviously, it will be necessary to choose the state where energy consumption smallest.

The result of analyzing the circuit using this algorithm is presented in Figure 2.

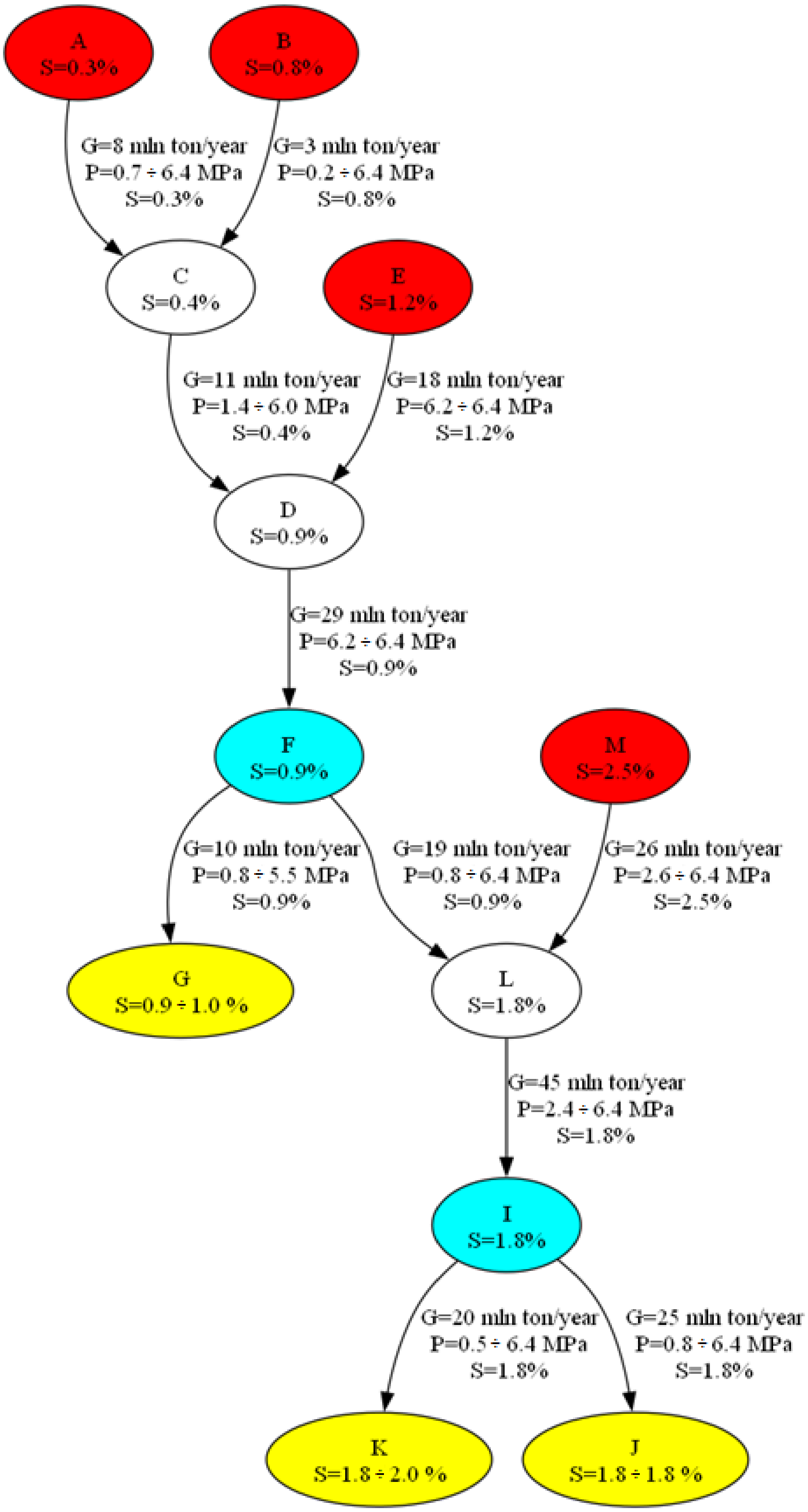

Fig. 2. Results of calculation of optimal cargo flows of the pipeline system

7 THE DISCUSSION OF THE RESULTS

Let's estimate the costs from memory. The largest number of states for one node was for point G – 144000. Pandas type tables were used to store information about the state in the nodes DataFrame. All information about all nodes took up 50.8 MB of memory space, which is not much in modern realities. Executing the algorithm on a personal computer took about 2 seconds.

In general, the algorithmic complexity of the presented method is $O(k \cdot n^p)$, while a complete search over the flow rates of suppliers and flow divisions will be $O(k \cdot n^k)$. Note that k can be estimated as the number of suppliers plus the number of consumers minus one ($k = y + m - 1$).

Thus, for complex oil pipeline systems in which the value of k is significantly greater than the number of controlled oil parameters (in this case 5), it is advantageous to use the presented algorithm. Otherwise, it is more profitable to use a complete search for flow rates.

Analyzing the considered solution scheme, the following conclusions can be drawn.

1. If there is a consumer in the system with a requirement for low sulfur content in oil, then, most likely, oil with a threshold quality value will be delivered to him; Accordingly, optimization of cargo flows will be limited to this particular consumer. In the example considered, consumer J (refinery 2) has the highest requirements for oil quality, and the oil supplied to him is characterized by a sulfur content of S = 0.8 %, equal to the maximum.
2. Pumping from suppliers located closer to consumers is more profitable (which, however, is quite obvious). Thus, in the considered example, more oil is accepted from supplier E than on average from suppliers A and B. However, this rule is violated if high-sulfur oil enters the system. So, up to consumers J and K it is cheaper to pump oil from the nearest supplier M, but the oil supplied from it has a high sulfur content. The greatest restrictions on the sulfur content of the consumer J limit the supply of oil from the supplier M , and it is necessary to accept much more oil from the direction F – L , along which oil is transported with much less sulfur content .
3. If the system has a supplier of oil characterized by significantly lower sulfur content than other suppliers, then it would be optimal to receive as much product as possible from him, even if pumping costs are high. Increasing the volume of low-sulfur crude oil will allow us to accept a larger volume of high-sulfur crude oil from suppliers closest to the mixing/separation unit. The considered example shows that supplier A, which sells the least sulfur oil, has the highest consumption compared to others, despite the fact that it is the most distant.

8 CONCLUSIONS

A method is proposed for determining optimal cargo flows in a branched oil pipeline system, taking into account ensuring a given oil quality in terms of sulfur content. The execution time of the algorithm, depending on the input parameters, is $O(k \cdot n^p)$, which is much faster compared to the brute-force method – $O(k \cdot n^k)$. Thus, the developed method for solving the transport problem is relevant for complex pipeline systems containing a large number of oil suppliers and consumers.

We note that the proposed method allows us to take into account the features of non-Newtonian oils, in particular, that the viscosity of a mixture of oils may not be subject to non-additivity.

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