Simple Analysis of Gas Transportation Flows and Gas Pipeline Networks Utility In Central Asia

V. V. Savin, T. A. Mitrova, V. N. Sidorenko

Abstract - **Pipeline gas flows from post-Soviet Central Asia plays an important role in the world gas trade. The access to gas reserves of the region plays an important role in geoeconomic considerations of all global players involved in the region: USA, China, Europe, and Russia.**

In this paper we use mainly the "ecological" goal function to understand patterns of gas flows for natural gas pipelines (existing and under construction) in Central Asia and try to develop suggestions for pipeline structures optimizing the overall system's efficiency in terms of direct network utility.

JEL D74, D85

Index Terms – **"ecological" goal function, gas pipeline networks in Central Asia**

INTRODUCTION

Central Asia is one of the new frontiers in the global "battle" for natural gas. Post-Soviet Kazakhstan, Turkmenistan and Uzbekistan are trying to come out from "isolation" and to diversify their export routes. Russia and China want to "lock in" as much energy resources from Central Asia as required and to direct their flows through pipelines they own partly or in whole. At the other end, the US and the EU, try to push for diversion of resource flows away from traditional Russian pipeline network.

The aim of our undertaking presented here is to explore the natural gas transportation options from Central-Asia using two simple approaches: the well-known transportation problem approach [Hiller, Liebermann 2005] and the network direct and indirect utility analysis approach [Patten, Fath 1998]. Both approaches identify and trace important chains of causation which give rise to a particular configuration of the gas pipelines in Central Asia, and show numerically why this or that particular pipeline network configuration optimizes interests of the key players.

GAS PRODUCTION AND CONSUMPTION IN CENTRAL ASIA

First, we look at the statistical data describing the situation with gas production, consumption and import/export in Central Asia (Kazakhstan, Turkmenistan and Uzbekistan), Russia, China, Europe and USA. For that reason we used time series data from BP Statistical Yearbook of World Energy 2009 (see Tab. 1, 2, 3, 4, 5).

TABLE I

CENTRAL ASIA'S GAS PRODUCTION AND CONSUMPTION (BCM)

	1985	1990	2000	2005	2008
Central Asia's Gas Production	124.26	131.76	109.15	138.82	173.19
Central Asia's Gas Consumption	61.86	72.72	72.58	86.25	97.59

TABLE II

RUSSIA'S GAS PRODUCTION AND CONSUMPTION (BCM)

	1985	1990	2000	2005	2008
Russia's Gas Production	418.12	580.09	528.69	580.1	601.68
Russia's Gas Consumption	350.42	407.6	365.97	393.03	420.23

TABLE III

EUROPE'S GAS PRODUCTION AND CONSUMPTION (BCM)

	1985	1990	2000	2005	2008
Europe's Gas Production	205.09	197.62	273.91	289.71	283.43
Europe's Gas Consumption	296.12	326.77	443.82	499.44	494.07

Using these data we could see that Central Asia's natural gas production fluctuated during last 20 years: it diminished in 1990s and recovered in 2000s reaching more than 170 bcm in 2008; simultaneously the Central Asia's

natural gas consumption rose steadily during the whole period 1985-2008 and reached the level of about 100 bcm in 2008. Not surprisingly the natural gas exports from the region stopped in 1995-1996, but in 2008 rose to more than 75 bcm (compare Tab. 1).

TABLE IV

EUROPE'S GAS PRODUCTION AND CONSUMPTION (BCM)

	1985	1990	2000	2005	2008
China's Gas Production	12.93	15.3	27.2	49.32	76.08
China's Gas Consumption	12.93	15.25	27.5	49.44	83.3

TABLE V

USA'S GAS PRODUCTION AND CONSUMPTION (BCM)

	1985	1990	2000	2005	2008
USA's Gas Production	465.9	504.3	543.2	511.1	582.2
USA's Gas Consumption	489.3	542.9	660.7	623.3	657.2

Russia's natural gas production rose since 1985 till 2008 from 420 to quite 600 bcm a year, Russia's natural gas consumption stayed about constant on the level of 400 bcm a year during the same period, so Russia could export about 200 bcm a year. However, it is also worth mentioning that this growth was not monotonous: after Soviet Union collapse Russia diminished both - production and consumption of natural gas - and only after slow economic recovery since 2000 the new growth in production and consumption took place (compare Tab. 2).

USA, Europe, and China were 2008 gas importers. However, gas import patterns developed by each of them were not similar. USA imported only small amounts of gas in 1985, rose its imports to more than 100 bcm in 90s, but diminished them to less than 80bcm in 2000s. Europe was a major gas importer during the whole period under consideration: it imported about 100 bcm in 1985, and more than 200 bcm in 2008. China balanced its gas production and consumption during all last 20 years, but began to rely on gas imports at the end of 2000s (compare Tab. 3, 4, 5).

ARTIFICIAL GAS TRANSPORTATION PROBLEM

After having the description of the gas production and consumption in Post-Soviet Central Asia, Russia, China, and Europe we begin our analysis with developing numerical feeling for the problems of the Central Asia's gas exports to Europe and China using the very simple and very well-known standard approach of solving transportation problems.
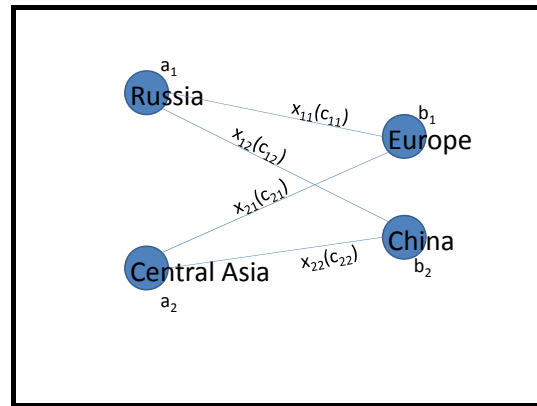

Fig. 1. Nodes and links in the artificial gas transportation problem solved

In the framework of this approach we represent the gas export from Central Asia and Russia as a simple case with two exporters (Russia and Central Asia) and two importers (China and Europe) (compare Fig. 1), and asked which transportation pattern would minimize the cumulated costs of exporting gas.
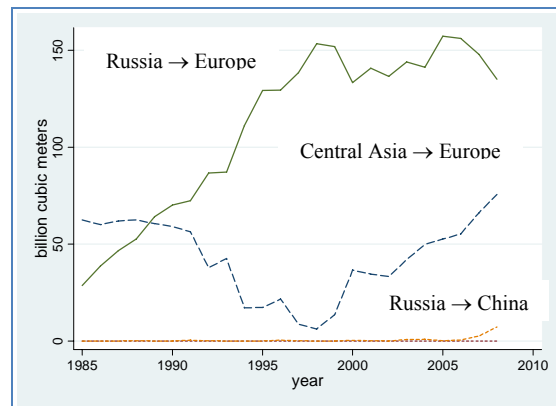

Fig. 2. Optimal transport plans for natural gas according to standard transportation problem solutions

For solving the problem we used the distances between the geographical centers of Russia,

Central Asia, Europe, and China derived from Google Earth 5, and average costs for transporting one bcm of natural gas for 100 km between different locations derived from ERIRAS world gas model. The solution for this very artificial problem is presented in Fig. 2, 3 and Tab. 6.

TABLE VI

OPTIMAL TRANSPORT PLANS FOR NATURAL GAS ACCORDING TO STANDARD TRANSPORTATION PROBLEM SOLUTION (BCM)

	1985	1990	2000	2005	2008
Russia's export to Europe	28.63	70.11	133.34	157.16	135.04
Russia's export to China	0	0	0.30	0.12	7.22
Central Asia's export to Europe	62.40	59.04	36.57	52.57	75.60
Central Asia's export to China	0	0	0	0	0

As could be seen from the Tab. 6, in this artificial problem exports from Russia to Europe should fluctuate at high level, exports from Central Asia to Europe should increase, there should be quite no natural gas export from Central Asia to China, and Russia should slowly begin to deliver pipeline gas not only to Europe, but also to China.
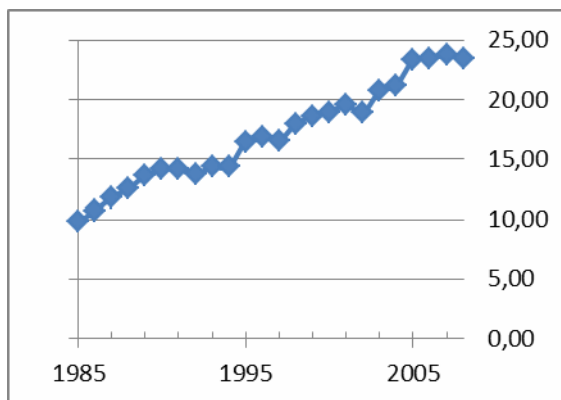

Fig. 3. Total optimal costs (for gas pipeline transport between four nodes) according to standard transportation problem solutions (in bln USD / year)

Also mentionable is the fact that the total volume of transported gas and total transportation costs are increasing (see Fig. 3).

At the same time, sum of net exports of natural gas was always (for all time periods in 1985-2008) bigger than sum of net imports.

We see that our artificial example of gas flows between four nodes contradicts to reality: for example, according to our solution gas from Central Asia "should" go not to China, which contradicts to the observable reality (in 2010 China received first gas from Central Asia). Certainly this approach could not be viewed as the "best" mean of analyzing complex issues in pipeline networks. So, having played with transportation problem we could move to studying pipeline networks with more elaborated methods.

INTEGRATED UTILITY APPROACH

Using the seminal work of Patten and Fath (Patten & Fath, 1998) and following the work of Lobanova et al. (Lobanova, Fath, & Rovenskaya, 2009), we constructed the network model of gas production, gas consumption, and gas transportation (for which we used data from Energy Research Institute of Russian Academy of Sciences) that helped us to "feel" better issues of gas exports from Central Asia. The network model has 31 nodes (see Fig. 4):

- 13 nodes for Russia – 1) Russia's Yamal, 2) Russia's Nadym, 3) Russia's Sakha-Yakutia, 4) Russia's Sakhalin, 5) Russia's Stockman, 6) Russia's Far East, 7) Russia's Siberia South-East, 8) Russia's Siberia South-West, 9) Russia's Ural area, 10) Russia's Volga area, 11) Russia's Moscow area, 12) Russia's North Caucasus, 13) Russia's North-West.

- 5 nodes for North-East-Asia – 14) China's Xinjiang, 15) China's North-East, 16) China's Coastal South East, 17) South Korea, 18) Japan.

- 8 nodes for Central Asia – 19) Kazakhstan's West, 20) Kazakhstan's East, 21) Uzbekistan, 22) Turkmenistan's West, 23) Turkmenistan's East, 24) Azerbaijan (through it is actually the part of South-Caucasus), 25) Iran's North, 26) Iran's South (through Iran should actually be modeled as a part of Persian Gulf countries).
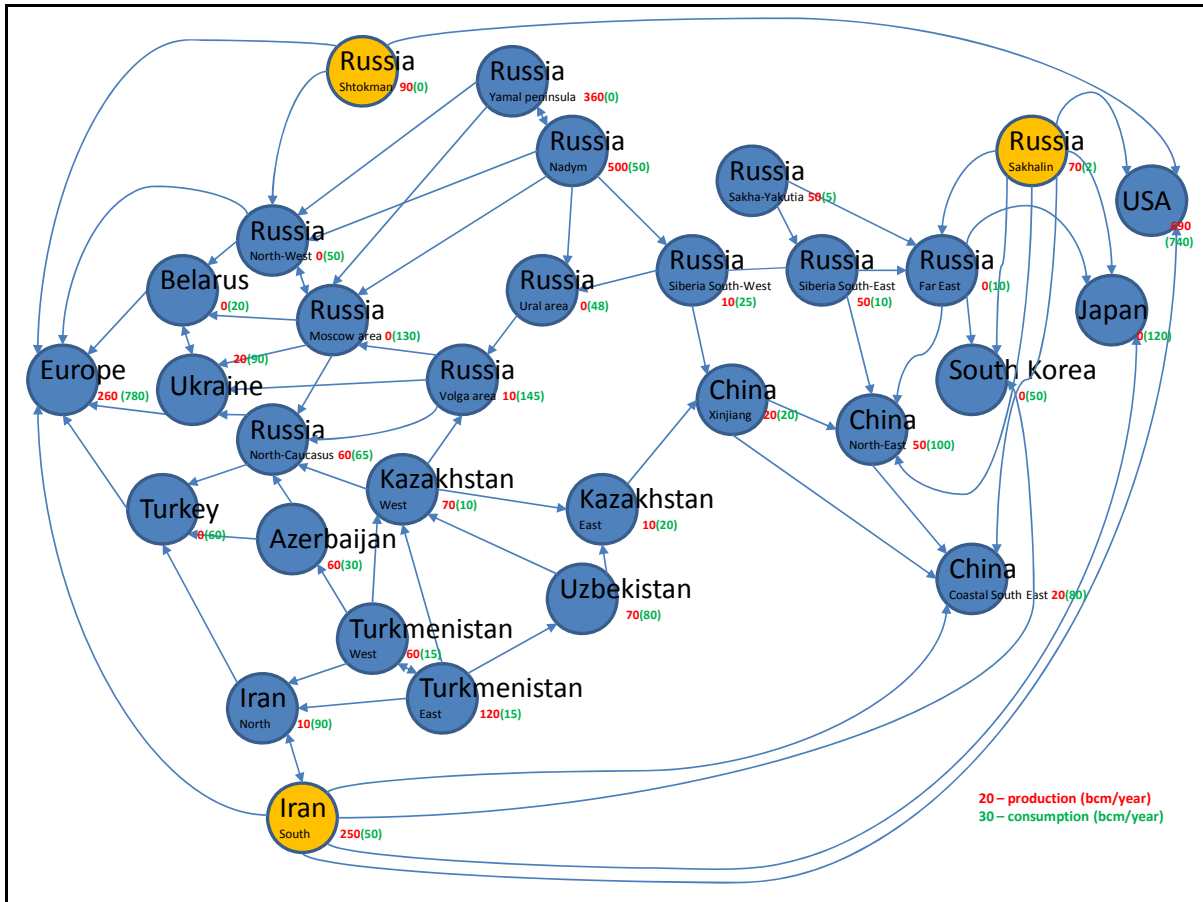
Fig. 4. Total optimal costs (for gas pipeline transport between four nodes) according to standard transportation problem solutions (in bln USD / year)

- 3 nodes for transit countries between Russia and Europe – 27) Belarus, 28) Ukraine, 29) Turkey.

- 2 nodes for major consumers – 30) Europe, 31) USA.

In this framework we were interested in identifying such gas flow configurations that satisfy the demand and supply constraints for network nodes and maximize the overall network utility.

For doing so, first we defined the in-, out- and between-flows for every node in our network and constructed the corresponding direct flow matrix $F=(f_{ij})$. Using this matrix F, we have built two matrices: the direct non-dimensional utility matrix, or direct normalized flow matrix, $D=(d_{ij})$, where $d_{ij} =((f_{ij} - f_{ji}))/T_i$, T_i is the total flow through the node i, and the non-dimensional integral utility matrix $U=(u_{ij})$,

where $U=D^0+D^1+D^2+D^3+\cdots$, D^0 is the identity matrix I, $D^2=D \cdot D$, $D^3=D \cdot D \cdot D$, etc.).

The elements d_{ij} of matrix D lie in interval (-1, +1) and define direct non-dimensionalized utilities experienced by node i through its direct relationships with node j in the network. The elements u_{ij} of matrix U could potentially have range $-\infty < u_{ij} < +\infty$, and define integral non-dimensionalized utilities (benefits or costs) experienced by node i through its direct and all indirect relationships with node j in the system network. U thus provides an intensive measure of direct plus indirect utility, or ultimate value of the network (Patten B. C., 1992, p. 53).

The sum of d_{ij} in the network was negative ($Dsum = \sum_{i=1}^{31} \sum_{j=1}^{31} d_{ij} = -0.523$) indicating very competitive nature of the pipeline

network. The sum of u_{ij} was positive ($Usum = \sum_{i=1}^{31} \sum_{j=1}^{31} u_{ij} = +22.844$) indicating the existence of mutualism in the network if the indirect relations were co-reflected. These two measures (Dsum, the aggregated direct non-dimensionalized utility of the network as a whole, and Usum, the aggregated integral non-dimensionalized utility of the network as a whole) could be considered as the main indicators of the pipeline network "qualities".

We could also look at the network more specifically, summing up direct (d1) and integral (u) utilities that each of the 31 nodes enjoys from being a part of the network, and also the direct (d2) and indirect (u2) utility that the network as a whole enjoys from the corresponding node.

- 13 nodes for Russia – 1) Russia's Yamal (d1=–0.97, u1=0.24, d2=1.09, u2=1.24), 2) Russia's Nadym (d1=–0.88, u1=0.34, d2=2.41, u2=2.30), 3) Russia's Sakha-Yakutia (d1=–0.90, u1=0.42, d2=0.43, u2=1.21), 4) Russia's Sakhalin (d1=–0.97, u1=0.01, d2=0.69, u2=1.34), 5) Russia's Stockman (d1=–1.00, u1=–0.26, d2=0.14, u2=0.95), 6) Russia's Far East (d1=0.11, u1=0.52, d2=–0.15, u2=0.50), 7) Russia's Siberia South-East (d1=–0.36, u1=0.71, d2=0.03, u2=0.47), 8) Russia's Siberia South-West (d1=0.15, u1=0.78, d2=0.59, u2=0.97), 9) Russia's Ural area (d1=0.33, u1=0.65, d2=–0.08, u2=0.35), 10) Russia's Volga area (d1=0.68, u1=1.19, d2=–1.15, u2=0.38), 11) Russia's Moscow area (d1=0.34, u1=0.81, d2=0.05, u2=0.14), 12) Russia's North Caucasus (d1=0.04, u1=0.87, d2=–0.13, u2=0.77), 13) Russia's North-West (d1=0.18, u1=0.75, d2=0.06, u2=0.30).

- 5 nodes for North-East-Asia – 14) China's Xinjiang (d1=0.00, u1=0.85, d2=–0.24, u2=0.67), 15) China's North-East (d1=0.36, u1=0.93, d2=–0.58, u2=0.55), 16) China's Coastal South East (d1=0.75, u1=1.57, d2=–0.68, u2=0.48), 17) South Korea (d1=1.00, u1=1.30, d2=–0.47, u2=0.59), 18) Japan (d1=1.00, u1=1.20, d2=–0.77, u2=0.21).

- 8 nodes for Central Asia – 19) Kazakhstan's West (d1=–0.49, u1=0.24, d2=0.19, u2=0.71), 20) Kazakhstan's East (d1=0.33, u1=1.12, d2=0.07, u2=1.01), 21) Uzbekistan (d1=0.10, u1=0.96, d2=0.16, u2=1.00), 22) Turkmenistan's West (d1=–0.75, u1=0.71, d2=0.41, u2=1.29), 23) Turkmenistan's East (d1=–0.88, u1=0.30, d2=0.88, u2=1.45), 24) Azerbaijan (d1=–0.45, u1=0.43, d2=0.29, u2=1.12), 25) Iran's North (d1=0.63, u1=0.79, d2=–0.32, u2=0.11), 26) Iran's South (d1=–0.80, u1=0.12, d2=1.43, u2=1.36).

- 3 nodes for transit countries between Russia and Europe – 27) Belarus (d1=0.08, u1=0.52, d2=–0.53, u2=0.55), 28) Ukraine (d1=0.27, u1=0.90, d2=–0.65, u2=0.50), 29) Turkey (d1=0.86, u1=1.52, d2=–0.66, u2=0.58).

- 2 nodes for major consumers – 30) Europe (d1=0.67, u1=1.36, d2=–2.66, u2=–0.79), 31) USA (d1=0.07, u1=1.00, d2=–0.37, u2=0.54).

FINDING THE OPTIMAL PIPELINE STRUCTURES IN THE 31 NODE PIPELINE NETWORK

Then we tried to find the optimal pipeline structures in our 31 node pipeline network, optimal in the sense of maximizing DSum measure of the pipeline network (and check where Nabucco should be constructed). For doing this we solved the following constrained nonlinear optimization problem:

$$\text{Maximize } Dsum = \sum_{i=1}^{31} \sum_{j=1}^{31} d_{ij} \quad (1)$$

$$\begin{cases} Production_t + Inflows_{j \to t} = Consumption_t + Outflows_{t \to j}, \forall t \in \overline{1,31}, \\ Lower\ bound\ constraints, Upper\ bound\ constraints. \end{cases}$$

The model was formulated in terms of elements f_{ij} from the direct flow matrix $F=(f_{ij})$, so the goal of our program was to find such a structure of gas flows that would maximize the cooperation in the pipeline network. The objective function was obviously non-linear. The constraints however were linear; more than that: the through flow equations are balance equations, and in this sense self-explainable (gas production and all gas inflows are set to be equal to gas consumption and all gas outflows

for all 31 nodes). All lower bound constraints were set to be zero, all upper bound constraints were set to be two times the flows between nodes on the Fig. 4.

The solution was gained using the Sequential Quadratic Programming (SQP) method realized in Matlab (and Maple) software (fmincon-solver in Matlab Optimization toolbox).

The sum of d_{ij} in the network with maximized Dsum measure was positive ($Dsum = \sum_{i=1}^{31} \sum_{j=1}^{31} d_{ij} = 2.9138$) indicating cooperative nature of the pipeline network. The sum of u_{ij} in the network with maximized Dsum measure was positive too ($Usum = \sum_{i=1}^{31} \sum_{j=1}^{31} u_{ij} = +25.0455$).

The new flows (matrix F with maximized Dsum measure) when compared to initial flows are following:

1. Russia's Yamal delivers more gas to Russia's Nadym and quite the same volumes of gas to Russia's Moscow area and Russia's North-West,

2. Russia's Nadym delivers more gas to Russia's Yamal, Russia's Moscow area and Russia's North-West, but less to Russia's Siberia South-West and Russia's Ural area,

3. Russia's Sakha-Yakutia delivers more to Russia's Siberia South-East and quite stops deliveries to Russia's Far East,

4. Russia's Sakhalin quite stops deliveries to Russia's Far East and China's North-East, but delivers more to China's Coastal South East, to South Korea, to Japan, and to USA,

5. Russia's Stockman quite stops deliveries to Russia's North-West, delivers less to USA, but more to Europe,

6. Russia's Far East quite stops delivering to China's North-West, and delivers quite the same volumes to South Korea and Japan ,

7. Russia's Siberia South-East delivers quite the same to Russia's Far East, but significantly more to China's North-West,

8. Russia's Siberia South-West delivers more to Russia's Siberia South-East and to

China's Xinjiang, but quite stopps deliveries to Russia's Ural area,

9. Russia's Ural area stops all deliveries (no more deliveries to Russia's Volga area),

10. Russia's Volga area also stops all deliveries (quite no more deliveries to Russia's Moscow area, to North Caucasus, and to Ukraine),

11. Russia's Moscow area delivers quite the same volumes to Ukraine and Belarus, more to North Caucasus, and quite nothing to Russia's North-West,

12. Russia's North Caucasus delivers more to Turkey and quite stops deliveries to Ukraine,

13. Russia's North-West delivers less to Russia's Moscow area, quite the same volume to Belarus and more to Europe

14. China's Xinjiang delivers more to China's Coastal South East, and quite stops deliveries to China's North-East,

15. China's North-East delivers less to China's Coastal South East,

16. China's Coastal South East does not deliver anything (as in the previous case),

17. South Korea does not deliver anything (as in the previous case),

18. Japan does not deliver anything (as in the previous case),

19. Kazakhstan's West delivers more to Russia's Volga area and quite nothing to Russia's North Caucasus and to Kazakhstans' East,

20. Kazakhstan's East delivers quite nothing to China's Xinjiang,

21. Uzbekistan delivers more to Kazakhstan's West and less to Kazakhstan's East,

22. Turkmenistan's West delivers more to Kazakhstan's West and to Azerbaijan (*so, our hypothesis about the "deleting" the route from Turkmenistan's West to Azerbaijan was not correct*), and quite nothing to Iran's North,

23. Turkmenistan's East delivers more to Kazakhstan's West and to Uzbekistan, but less to Iran's North,

24. Azerbaijan delivers more to Turkey, and less to Russia's North Caucasus,

25. Iran's North quite stops deliveries to Turkey (*so, our hypothesis about "deleting" the route from Iran's North to Turkey was correct*),

26. Iran's South delivers quite the same volumes of gas to South Korea, Japan, and USA, less to Iran's North and more to Europe (*so, our hypothesis about the "deleting" the route from Iran's South to Europe was not correct*),

27. Belarus reduces its deliveries to Ukraine and correspondingly increases its deliveries to Europe,

28. Ukraine reduces its deliveries to Belarus and to Europe (and so, reduces its significance as the transit country),

29. Turkey quite stops all deliveries to Europe,

30. Europe does not deliver anything (as in the previous case),

31. USA does not deliver anything (as in the previous case).

We show that in the pipeline structure with maximized DSum measure the Nabucco pipeline does not exist: there are mayor interruptions between Turkey and Europe, and also between Iran's North and Turkey. Also, the presented results show that through the direct utility of the whole pipeline network was maximized some of the nodes experience decline in direct and/or integral utility (for example, Uzbekistan's direct and integral utility is declining).

DISCUSSION

Question could arise about the transportation problem exercise in the beginning of this article. Why have we used the original transportation problem approach and didn't switch to more elaborated transshipment problem approach, where not only pure demanding and pure supplying nodes, but also nodes both demanding and supplying are possible? This question - through necessary - remains rhetoric since transportation and transshipment problems approaches deliver modest results for network problems. It also was mentioned in the text above that the transportation problem was used just for showing that not the considerations of minimizing the transportations costs but other (geopolitic / geoeconomic) considerations could be regarded as a cornerstone for the problem.

The next question is, why could we be sure that simple input-output analysis (and direct / integral utility approach) delivers good approximation for geopolitic / geoeconomic considerations of gas pipeline networks? This sureness exists because of systemic approach of network analysis techniques.

Nevertheless, the pipeline network models presented in this article are a great deal simplification of the real world and have some shortcomings (e.g. since we didn't analyze specifically MENA- (Middle East and North Africa), South America's and South Asia's countries we had to assume that all Europe's, USA's and China's gas imports were covered through nodes presented in the model, that is, through Russia's, Iran's, Azerbaijan's, Kazakhstan's, and Turkmenistan's nodes). So, we will continue our study with a more elaborated model of 70-80 nodes.

The next issue could be the dynamic case with production and consumption deterministically of stochastically changing over time. As an interesting question remains also problem of influence of sudden network structure changes on the overall network performance.

CONCLUSIONS

According to standard transportation problem approach we obtained results for the optimal (optimal in the sense of minimal transportation costs) transportation of natural gas from Russia and Central Asia to China and Europe (see Fig. 3): the exports from Russia to Europe are stagnating at high level, the exports from

Central Asia to Europe are increasing, there is no natural gas export from Central Asia to China, and Russia begins slowly to deliver natural gas not only to Europe, but also to China. Another result, due to the network utility approach, is the fact we could prove that Nabucco-pipeline (in its proposed form) diminish degree of synergism exhibited in Eurasian gas pipeline network (compare DSum measures for different pipeline structures).

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BIOGRAPHIES

V.V. Savin (PhD), studied Economics and Econometrics at Moscow State University (B.Sc., M.Sc.), got M.Sc. in Sinology and PhD degree in Organizational Psychology at Munich University, and PhD degree in International Energy Political Economy at Higher School of Economics & Russian Council of Productive Forces. Now he is a leading scientific employee at ERIRAS (Energy Research Institute of the Russian academy of Sciences). He is also the corresponding author for this paper (e-mails: w11bsavi@mail.ru, vsavin@hse.ru).

T.A. Mitrova (PhD), studied Economy at Moscow State University (B.Sc., M.Sc.), and got there also PhD degree. Now she is the head of the center at ERIRAS (Energy Research Institute of the Russian academy of Sciences).
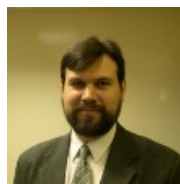
V.N. Sidorenko (PhD), studied Physics (Diplom), Economics (Diplom), and Law (Diplom) at Moscow State University, got there also three PhD degrees (in Physics, Economics, and Law). Now he is a docent at Economic Department of Moscow State University.