Interactive Simulation Software for Multi-Regional Model of Freight Transportation

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Abstract. The paper develops a know mathematical model of multiregional flows of goods. We determine the most probable spatial distribution of flows. Transportation costs depend on the distance between the regions within the "gravity model" approach. We use the shortest way length in a transportation network as a measure of these distances. The underlying mathematics of the model is a convex mathematical programming. The problem is represented as nonlinear minimization of a function with linear constraints which is solved numerically. Developed software is implemented for interactive modeling and visualization of the problem solution. The code is implemented on a high-performance cloud-server platform and consist of modules for simulation, visualization and control. Asynchronous http-queries are used for interaction between the platforms. For the data exchange between these modules a declarative model in the JSON format is implemented. The paper demonstrates a practical problem solution for the gasoline freight transportation for Pacific Russia region and the simulation software usage.

Keywords: Spatial · Multi-regional · Transportation · Gravity · Entropy · Network · Pacific Russia

1 Introduction

Modeling multi-regional freight transportation flows for a national economy is the important problem for studying a level of economic integration among regions of the country. In a market economy such flows are formed in accordance with the economic agents own free interests. We assume that such flows are self-organized in a transportation network. In a case of incomplete statistics about all the bilateral flows among regions it is possible to use the equilibrium network approach which allows to get the most probable spatial distribution of flows. The power of such equilibrium models is that they can be used for simulation

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the flows distribution among regions in a ‘comparative statics’ approach when technical and economic parameters of the model are changed.

It seems that the issue of multi-regional flows simulation was pioneered by Leont’ev [9]. Anderson and Wincoop [2] demonstrated how the multi-regional general multi-product equilibrium model from microeconomics theory can explain the outflows and inflows of goods. They show that the fundamental of trade flows volume that emerge among territories are very similar to the “gravity” rule in physics and this fact and was widely applied for international trade and the theory and practice of regional economics. Wilson and others [10] has developed the entropy modeling approach to take into account the incompleteness of information in the application to an equilibrium modeling for complex communication systems which can be applied to simulate multi-regional multi-product flows. The gravity modeling approach and the principle of entropy maximization [3] are interrelated in many ways. Further development of Wilson’s approach was conducted by Boyce and others [3]-[7]. The researchers use the mathematical models for practical application of multi-regional trade flows analysis regarding the configuration of the transportation network of USA with multi-modality of flows concerning various modes of transport.

The paper is organized as follows. First we describe a mathematical model for solving the problem mentioned above. Then a web-based computer service for more convenient analysis and interactive simulation of the problem is presented. And afterwards we provide an example of the proposed mathematical model and software for the multi-regional flows modeling for Pacific Russia.

2 “Gravity” Principle in the Model of Freight Transportation

This section sketches the model, solution for the correspondent mathematical problem and gives its visualization for gasoline freight transportation for Pacific Russia region.

2.1 Mathematics of Freight Transportation Model

The model consider the economy of k regions producing and consuming a product. Let z_{ij} is an unknown volume of a product delivered from region i to the region j, $i, j = 1, \ldots, k$. The flow z_{ii} is not necessarily assumed to be zero. Strictly positive values of z_{ii} corresponds the part of the production of a region that is consumed in this region.

The total flow from region i to j can be interpreted as the total consumption of the product in the region j which equals $\sum\limits_{i=1}^{k} z_{ij}$. We define V_j as a known inflow (import) of a product to the region j given by official statistics. Obviously $V_j = \sum\limits_{i=1}^{k} z_{ij}$. Total outflow (export) of a product from the region i to other regions is the total production of a product in the region i. The value $\sum\limits_{j=1}^{k} z_{ij}$ is assumed to be known from official statistics, and let it be defined as W_i.

The production and consumption of a product defined above is subject to evident balance equations

$$\sum_j V_j = \sum_i W_i = \sum_{i=1}^{k} \sum_{j=1}^{k} z_{ij}. \tag{1}$$

Equations (1) put an additional restriction on the given values of W_i and V_j so the total flows should be balanced in the considered system of regions.

However since the system of regions cannot be closed and we can observe flows of the assumed regions with others, the aforementioned balance (1) based on statistics would not be observed. This means that for the system of regions $j = 1, \ldots, k$ there are flows of a product between these regions and other undefined "external" regions. The problem is complicated by the fact that neither the total inflow or outflow of such "external" regions are known. Obviously in this case the model requires modification.

To solve this problem let's aggregate the "external" regions to $(k+1)$-th region and let's consider additional flows $z_{i\ k+1}$ and $z_{k+1\ j}$ which are unknown but moreover can be identified.

Freight transportation is carried out by economic agents under the influence of the transportation costs which depend on the distances between regions. These distances are estimated as the shortest way length in a transportation network by available modes of transport. Consider the gravity model for transportation costs which can be represented by $v_{ij} = \exp(-dT_{ij})$, where v_{ij} is '*a priori*' defined the flow of products from region i to j, T_{ij} is an assessment of the distance between regions i and j, and d is the parameter that are responsible for the flow sensitivity to distance transportation for a product. Parameter d is non-negative which means that the higher the value of the distance, the smaller an amount of flow between the regions i and j is. It is additionally assumed that $v_{ii} = 0$ for $T_{ii} = 0$ and $v_{ij} = v_{ji}$ because we assume that $T_{ij} = T_{ji}$.

Calibration of such non-negative parameter d with actual official statistics is a separate problem of applied statistics. This assessment is carried out by methods such as least squares applied to the linear regression model $\ln v_{ij} = \alpha - dT_{ij} + \varepsilon_{ij}$ for all l$i, j = 1, \ldots, k$ and $i > j$ where ε_{ij} is a normally distributed residuals of the regression for all i and j.

Paper [10] it is considered an approach of modeling flows in a communication networks corresponding to the principle of the most probable values of the spatial distribution of flows. This approach assumes the conditions of incomplete information when only some balance equations for these flows are given. Adaptation of this approach for the model of multi-regional freight transportation makes it necessary to minimize the nonlinear functions of the form $\sum\limits_{i,j=1, i \neq j}^{k+1} z_{ij} \ln(z_{ij}/v_{ij})$ on the set of unknown flows z_{ij}.

The presence of such features makes it necessary to specify strictly positive freight transportation z_{ij} which is modeled by specifying lower restrictions on flows by preassigned small parameter $\varepsilon > 0$.

Then we solve a nonlinear optimization problem with already considered balance equations as linear constraints and the objective function that is motivated by the most probable flows approach in a case of incomplete information about the communication system [10]:

$$\sum_{i,j=1, i\neq j}^{k+1} z_{ij} \ln(z_{ij}/\hat{v}_{ij}) \to \min_{\{z_{ij}\}}, \tag{2}$$

where $\hat{v}_{ij} = \exp(-\hat{d}T_{ij}), \hat{d}$ is known estimates of the parameter. Constraints of the problem are given further:

$$\sum_{i=1}^{k+1} z_{ij} = V_j, j = 1, 2, \ldots, k, \tag{3}$$

$$\sum_{j=1}^{k+1} z_{ij} = W_i, i = 1, 2, \ldots, k, \tag{4}$$

$$z_{ij} \geq \varepsilon > 0, i, j = 1, 2, \ldots, k+1. \tag{5}$$

2.2 The Solution and Visualization

Implemented computer software for multi-regional freight transportation simulation is used to determine the equilibrium multi-regional freight traffic in the transportation network of railway, road and marine transport of the Pacific Russia regions. The data is used as input data of Rosstat official statistical handbooks of different years "The regions of Russia. Socio-economic indicators of the multi-regional trade". The main products (commodities) are foodstuff, fuel, goods for technical purposes.

Table 1. Flows of gasoline from the Russian Pacific regions

Regions	Outflow (production), thous. tons	Inflow (consumpition), thous. tons
1	11.2	459
2	507	63.5
3	0.01	138
4	0.01	45.2
5	0.01	42.4
6	0.2	0.8
7	0.01	21.6
8	0.01	37.2
9	0.01	0.2

Primorskiy kray - 1, Khabarovskiy kray - 2, Amurskaya oblast' - 3, Evreyskaya avtonomnaya oblast' - 4, Respublika Sakha (Yakutiya) - 5, Magadanskaya oblast' - 6, Sakhalinskaya oblast' - 7, Kamchatskiy kray - 8, Chukotskiy avtonomnyy okrug - 9.

As the centers of production and consumption corresponding administrative centers of 9 Pacific Russia regions are considered: Primorskiy krai (Vladivostok), Khabarovskiy krai (Khabarovsk), Amurskaya oblast' (Blagoveshchensk), Evreyskaya avtonomnaya oblast' (Birobidzhan), Respublika Sakha (Yakutsk), Magadanskaya oblast' (Magadan), Sakhalin region (Yuzhno-Sakhalinsk), Kamchatskiy krai (Petropavlovsk-Kamchatsky), Chukotskiy avtonomnyi okrug (Anadyr).

Estimates of the distances between regions are shown in Table 2 which correspond to the shortest paths between the administrative centers of the regions in aggregated transportation network of railway, road and marine transport of Pacific Russia.

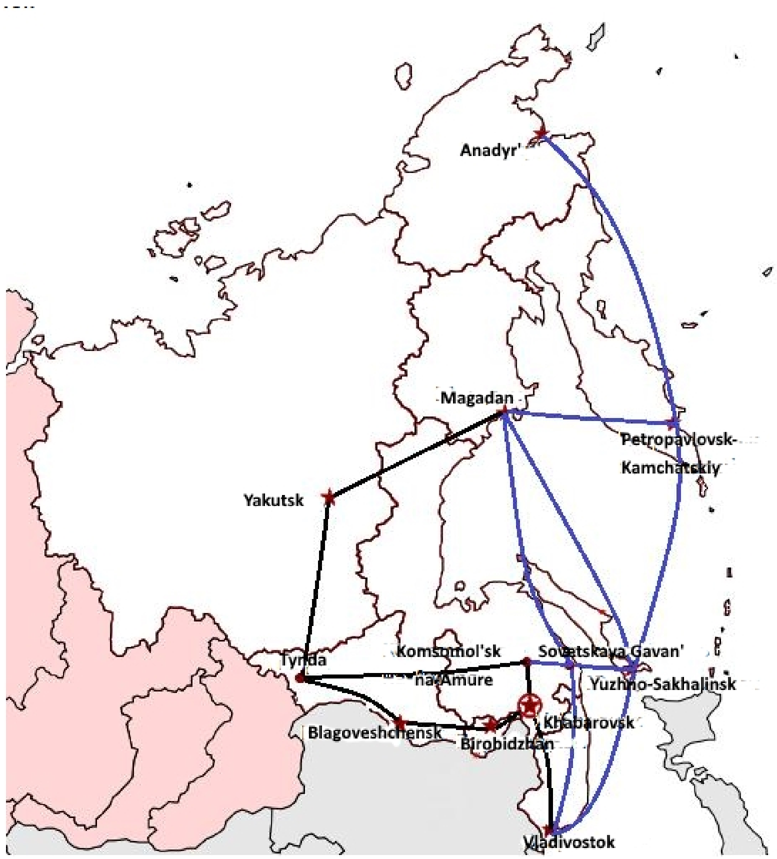


Fig. 1. Aggregated transportation network of Pacific Russia

Table 2. Estimates of the distances between the regions of Pacific Russia, thous. km

Regions	1	2	3	4	5	6	7	8	9
1	0	0.76	1.41	0.94	3.31	2.49	0.99	2.49	4.49
2	0.76	0	0.78	0.18	2.55	2.53	1.03	2.53	4.53
3	1.41	.0.78	0	0.60	2.04	3.18	1.81	3.18	5.18
4	0.94	0.18	0.60	0	2.38	2.71	1.21	2.71	4.71
5	3.31	2.55	2.04	2.38	0	1.74	3.59	2.74	4.74
6	2.49	2.53	3.18	2.71	1.73	0	1.5	1.0	3.0
7	0.99	1.03	1.81	1.21	3.59	1.5	0	1.5	3.5
8	2.49	2.53	3.18	2.71	2.74	1.0	1.5	0	2.0
9	4.49	4.53	5.18	4.71	4.74	3.0	3.5	2.0	0

Primorskiy krai - 1, Khabarovskiy krai - 2, Amurskaya oblast' - 3, Evreyskaya avtonomnaya oblast' - 4, Respublika Sakha (Yakutiya) - 5, Magadanskaya oblast' - 6, Sakhalinskaya oblast' - 7, Kamchatskiy krai - 8, Chukotskiy avtonomnyi okrug - 9.

Table 3. Simulation result for gasoline transportation, thous. tons

Regions	1	2	3	4	5	6	7	8	9	10
1	0	3.13	3.98	1.84	1.12	0.02	0	0.36	0.75	0
2	314.8	0	92.55	14.53	36.31	0.69	15.88	32.04	0.18	0.01
3	0.01	0	0	0	0	0	0	0	0	0
4	0.01	0	0	0	0	0	0	0	0	0
5	0.01	0	0	0	0	0	0	0	0	0
6	0.1	0.04	0.04	0.02	0	0	0	0	0	0
7	0.01	0	0	0	0	0	0	0	0	0
8	0.01	0	0	0	0	0	0	0	0	0
9	0.01	0	0	0	0	0	0	0	0	0
10	144.07	60.32	41.43	28.8	4.96	0.09	5.36	4.41	0.01	0

Primorskiy kray - 1, Khabarovskiy kray - 2, Amurskaya oblast' - 3, Evreyskaya avtonomnaya oblast' - 4, Respublika Sakha (Yakutiya) - 5, Magadanskaya oblast' - 6, Sakhalinskaya oblast' - 7, Kamchatskiy kray - 8, Chukotskiy avtonomnyy okrug - 9, Other regions - 10.

Table 3 shows the result for the gasoline freight transportation simulation as solution of the problem described above as the spatial distribution of the most probable flows in the system of the Pacific Russia regions and other "external" regions. These "external" regions are aggregated in one additional region that is added in Tab.3 in the last row under the number "10".

Consider the transportation of motor gasoline between the regions of Pacific Russia (Figure 2, Table 4). From the simulation result shown in Tab.3 it is possible we can conclude that rather large quantities of gasoline is transported from Khabarovskiy krai to Primorsky krai, smaller quantities are transported to Amurskaya oblast', and a very little amounts are transported to Respublika Sakha (Yakutiya) and Kamchatskiy krai, as well as to Evreyskaya avtonomnaya oblast' and Sakhalinskaya oblast'. Second conclusion is that there is a huge amount of gasoline that is needed to be transported from other "external" regions that are not regions of the Pacific Russia. Gasoline was transported mainly to Primorsky Kray, at less extent to Khabarovskiy krai, Amurskaya oblast' and Evreyskaya avtonomnaya oblast'.

The visual presentation of the data from Tab. 3 is shown in Fig. 2.

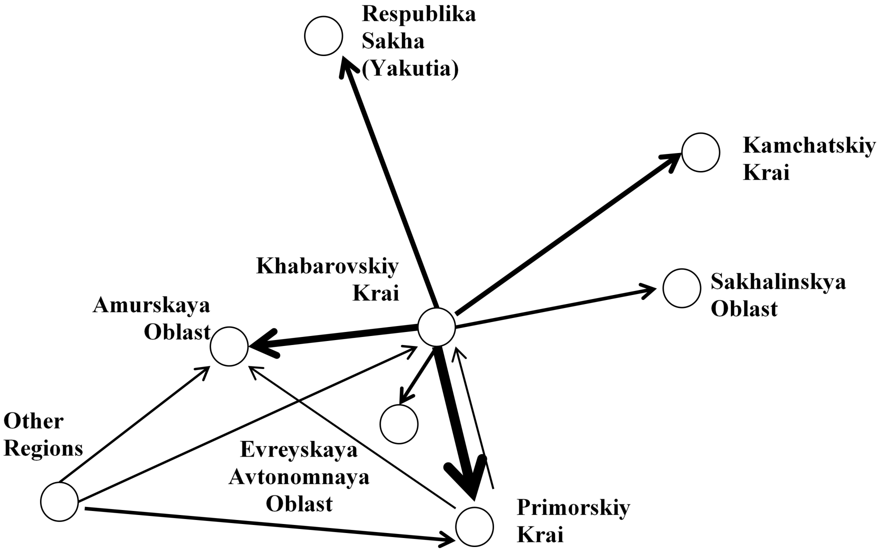


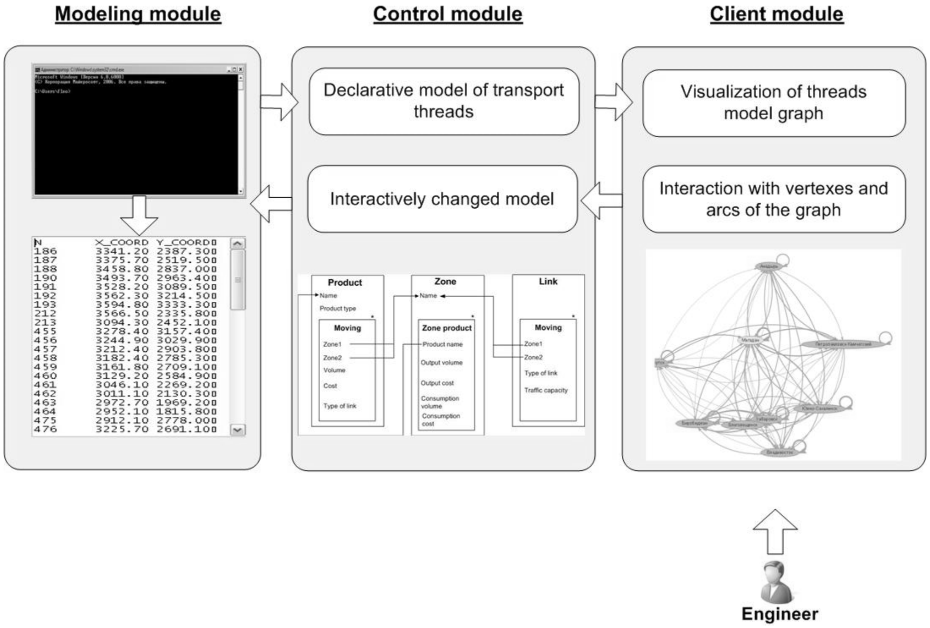
Fig. 2. Simulation result for gasoline transportation

3 Software Implementation

Software that implements the described above mathematical model is realized. It is used to find the equilibrium multi-regional freight traffic in the transportation network system of regions. An indicator of "connectedness" of the regions for a specific industry or aggregated for all products is defined as $L_{ij} = \frac{2(z_{ij}+z_{ji})}{E_i+E_j+I_i+I_j}$ where z_{ij} is an outflow from the region of i to the region j and E_m is a total export of a product from the region m to all other regions, and I_m is total imports to the region m from all other regions.

Output results of the program are calculated equilibrium values of the freight traffic between transportation network nodes, the matrix of multi-regional flows and "connectedness' matrix of regions.

Model implementation is carried out in the MPL language [1] and Octave [5] on the SuperServer 6037R-72RFT+ server platform by SuperMicro company. A generalized architecture of the cloud service is presented in the Fig. 3. The software consists of three modules: a module of freight transportation simulation, a control module and a visualization module.



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N               X_COORD Y_COORD▯
186             3341.20 2387.30▯
187             3375.70 2519.50▯
188             3458.80 2837.00▯
190             3493.70 2963.40▯
191             3528.20 3089.50▯
192             3562.30 3214.50▯
193             3594.80 3333.30▯
212             3566.50 2335.80▯
213             3094.30 2452.10▯
455             3278.40 3157.40▯
456             3244.90 3029.90▯
457             3212.40 2903.80▯
458             3182.40 2785.30▯
459             3161.80 2709.10▯
460             3129.20 2584.90▯
461             3046.10 2269.20▯
462             3011.10 2130.30▯
463             2972.70 1969.20▯
464             2952.10 1815.80▯
475             2912.10 2778.00▯
476             3225.70 2691.10▯
```

Fig. 3. Architecture of software modules

3.1 Control Module

The freight transportation simulation module and the visualization module are the independent sybsystems located on different servers. To provide interaction between them an additional module of control is required. . The main task of the control module is to get and transfer information from the simulation module and the visualization module in a previously defined format that is understandable for them. A convenient data format for the simulation module is a matrix representation; a convenient data format for visualization is a graph. Both formats are specialized and useful for specific tasks. Therefore, we need an intermediate format for exchanging information between them. For this aim, we have developed a declarative format for freight transportation 14. That format consists of three base types of objects: products, zones and communications. A declarative representation of the objects is realized with JSON format. A structure of each type and links between them are provided in the Fig. 4.

The control module uses the http-protocol and asynchronous requests. The visualization module sends an asynchronous http-request to the control module

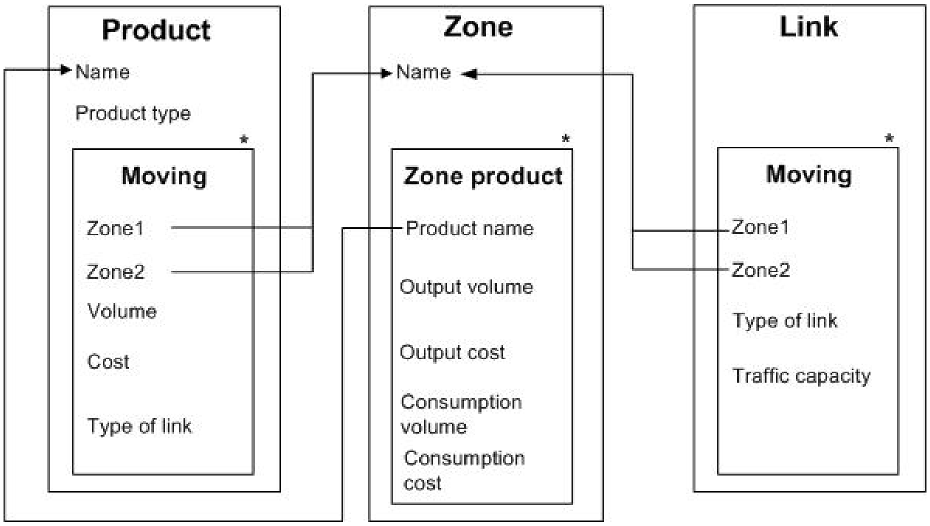


Fig. 4. The declarative model of freight transportation

for getting input data from the simulation module. The control module initiates an http-request for getting or calculating data about a state of freight transportation. The simulation module forms data in the declarative representation and then sends an answer to the visualization module using the control module. Then the visualization module builds a graph of freight transportation by obtained data. The control module is different from existing methods for multi-regional flows because it provides interaction between two environments (environment of calculations and environment of visualization) which are on the different platforms.

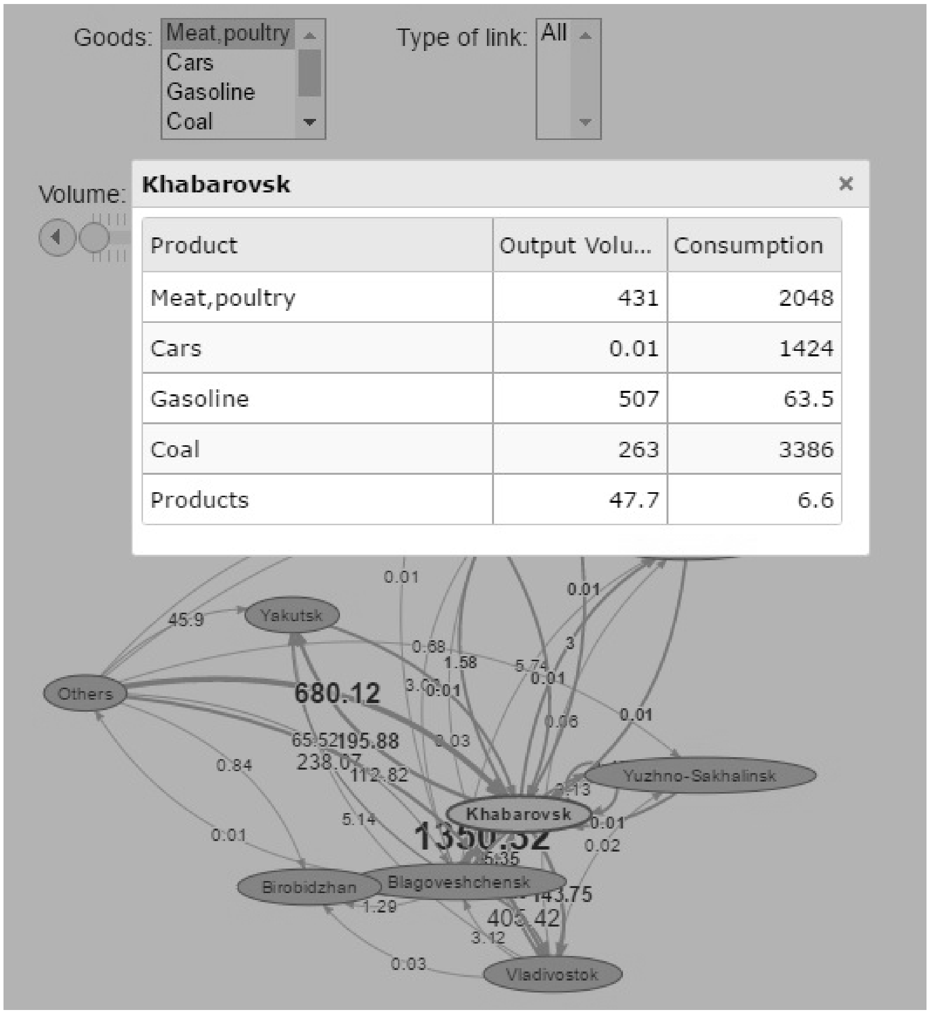
3.2 Visualization Module

The visualization module gives a possibility to represent complicated matrix data about freight flows visually (graphically) in form of oriented graph. Arcs of that graph are freight flows and vertexes are points of destination of these flows.

The visualized transport net allows users to see results of the modeling and to change them interactively, by editing parameters of vertexes and arcs by a program interface.

The visualization module displays different variants of the oriented graph in depend of needed parameters. For this on base of the declarative model there are formed automatically control elements for the graph of freight transportation [6]. By these control elements a user can select type of communication it is needed to display in sampling. The visualization module have some advantages, main of them are: implementation of the module is done on the cloud platform and software is accessible for users via the Internet; the visualization module allows users to change interactively parameters of the model and to see results in the real-time mode.

Interactive editing of the graph supposes a change of the parameters vertexes and arcs of the graph. (Fig. 5). In accordance with user modification the dynamic asynchronous request is sent to the simulation module server via the control module and as a results a new declarative model of trade flows will be received and graph visualization will be changed.



Khabarovsk

Product	Output Volu...	Consumption
Meat,poultry	431	2048
Cars	0.01	1424
Gasoline	507	63.5
Coal	263	3386
Products	47.7	6.6

Fig. 5. Interactive simulation service

The parametric sampling and the visualization of only part of information matters a lot for clarity of the received results especially if parts of these results are entirely (or partially) are independent from each other. Addition graphical parameters are used for the visualization of the transport flows graph: a color and thickness of arcs. The color characterizes a type of communication of flows. The thickness characterizes a volume of flows' loads.

Implementation of the visualization module as a cloud service gives a convenient way to use and display the results of mathematical modeling for many users via the Internet.

4 Conclusion

The paper sketches the "gravitation" model for multi-regional trade. The underlying mathematical problem of the model is based on the approach of finding the most probable spatial distribution of flows in a case of incomplete information about the communication system. The nonlinear convex optimization problem with linear constraints is needed to be solved. The paper demonstrates the simulation of multi-regional freight transportation of gasoline for the Pacific Russia.

The software package is a cloud service, and it consists of three main modules. First, simulation module of trade flows based on the mathematics of the model. Second, the control module, and the third, module for visualization. Modules for control and visualization are implemented on the cloud platform using a multi-agent approach. The interaction between the cloud platform and the high-performance computing platform is organized with dynamic asynchronous requests using a http-protocol.

The software is designed for professionals dealing with the problem of analyzing multi-regional flows of products and planning the strategical plans of regional economic development. Overall methodology and conclusions can be used for multi-regional trade simulation for other regions and municipalities.

Due to a huge dimension of a problem and high practical computational complexity further research could be managed in a way of special numerical algorithms design including parallel ones. The use of a high-performance computing platform could be efficient in a case of a huge number of constraints in the considered mathematical problems.

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