Software System for Interactive Simulation of Interregional Trade

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Abstract. The paper describes a mathematical model of trade flows in a transport network. Based on the model the software package is implemented as a cloud service on heterogeneous computing architectures: simulation module is realized on a high-performance server platform, control and visualization modules are produced with the IACPaaS cloud platform. Communication between the platforms is established via asynchronous http-requests. For information exchange between the modules the declarative model with JSON format is developed and implemented for the objects considered in the mathematical model which are products, areas and communications. The visualization module allows us to present graphically the original and the resulting matrix data and to modify the input parameters of the model interactively. The paper demonstrates the use of software for the simulation of interregional freight traffic of the Russian Far East region based on input data provided by open statistics sources.

Keywords: spatial, transportation, model, visualization, cloud service, software, heterogeneous, computing, architecture

1 Introduction

Operation of a transport system that connects the regions of the country is essential for the safe and stable functioning regions as an economic system that ensures the processes of production and consumption. Since the creation of such a system is a time-consuming task, a necessary condition is a preliminary analysis and assessment of the design and management solutions to their application in the real world. Such decisions can be directed to the modernization and construction of the individual sections of the region's transport network, especially in approaches to ports, large industrial areas, large urban agglomerations and new fields.

Transport systems in modern conditions characterized by an independent non-cooperative behavior of a large number of heterogeneous economic agents realizing their individual interests, sharing of road network, air, pipeline, sea and railway transport for both freight and passenger traffic.

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Simulation of interregional flows in the interdisciplinary setting was proposed by Wassily Leontief [1]. In terms of general economic equilibrium and "gravity" approach the model is discussed in paper [2]. In papers [3], [4] more general approach of communication systems simulation under incomplete information was developed. At present these approaches are now widely used for passenger and freight traffic modeling in the transportation systems in Russia and abroad [5]–[10].

However, approaches to constructing a mathematical model of trade flows have the following disadvantages. They do not include export and import flows outside the system of considered regions. Second, these models do not consider that transportation can be both multi-product and multimodal, i.e. transportation can be implemented in different ways and/or various types of transport, by road, rail, sea and air transport modes. Third, import and export of goods corresponding the processes of supply and demand of goods by a region can be attributed to the same regions, and not only the different regions. Input data can be defined inaccurately, in this case it is possible to modify the model assuming interval input data as discussed in [11]. No less important for the use of models in practice is the creation of interactive simulation systems with visualization of the results in a user-friendly form primarily in the form of graphs and networks.

The purpose of the paper is a description of the mathematical model and the software package implemented on heterogeneous computing architectures for interactive simulation of interregional trade.

2 Gravity model of trade flows

In this section the mathematical model, program implementation and visualization of trade flows for the Far East of Russia Macro-region is given.

2.1 Mathematics of trade flows model

Consider the model of the economy of m regions in each of which there is an n products. Let x_{ij}^r is an unknown number of a product of r-th type, $r = 1, \ldots, n$ delivered from the i-th region in the j-th, $i, j = 1, \ldots, m$. Here and below the superscripts correspond to the product type, subscripts correspond regions. Note that the flow x_{ii}^r is not necessarily assumed to be zero, this flow corresponds to the regions where the product is consumed and also produced and therefore its transportation is not carried out.

The total product flow from region r to the j-th region ("total consumption" of the product r to the region j) is an unknown variable and it equals $\sum\limits_{i=1}^{m} x_{ij}^r$. The last sum also equals to V_j^r that is a known cumulative import of product r to the region j given by official statistics. Total export of product r from the region i in other regions ("total production" of product r to the region i) is $\sum\limits_{j=1}^{m} x_{ij}^r$ which in turn is known from official statistics and is defined as W_i^r.

The production and consumption of each product $r = 1, \ldots, n$ defined in the above way is subject to obvious for a closed system of balance equation

$$\sum_{i=1}^{m} \sum_{j=1}^{m} x_{ij}^r = \sum_j V_j^r = \sum_i W_i^r, \tag{1}$$

which imposes an additional restriction on the values of V_j^r and W_i^r.

However, since the real system of regions may be not closed, the aforementioned balance (1) formed on the statistical data is not be observed. This means that there is a flow of products between these k regions and other unknown "external" regions in relation to the considered system of regions. The problem is complicated by the fact that neither the total import or export 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 $(m + 1)$-th region and let's consider additional flows $x_{i\ m+1}^r$ and $x_{m+1\ j}^r$ which are unknown and moreover are unidentified.

Trade flows are carried out by economic agents under the influence of the transportation costs which principally depends on the geographical distance between regions. Consider the gravity model for transportation costs which can be represented by $v_{ij}^r = \exp(-d^r T_{ij})$, where v_{ij}^r is a priori defined the flow of products from the i-th region in the j-th, T_{ij} is an assessment of the geographical distance between regions i and j, and d^r are the parameters that are responsible for the flow sensitivity to distance for the product r. Parameters d^r are non-negative which means that the higher the value of the distance between, the smaller an amount of flow between the regions i and j is. It is additionally assumed that $v_{ii}^r = 0$ for $T_{ii} = 0$ and $v_{ij}^r = v_{ji}^r$ because of $T_{ij} = T_{ji}$.

Calibration of non-negative parameters d^r with actual official statistics is a separate problem of applied statistics. This assessment is carried out by methods such as least squares (LS) applied to the regression model which is represented by a linear by parameters model $\ln v_{ij}^r = \alpha - d^r T_{ij} + \delta^r$ for all l$i, j = 1, \ldots, m$ and $i > j$ where δ^r is a normally distributed residuals of the regression for all r.

In papers [3], [4], [10] it is considered an approach of modeling flows in a communication networks corresponding to the principle of the most likely values of the distribution of flows in conditions of incomplete information when only some balance equations for these flows are given. Adaptation of this approach for the model of interregional trade flows makes it necessary to minimize the non-linear functions of the form $\sum\limits_{r=1}^{n} \sum\limits_{i,j=1, i \neq j}^{m+1} x_{ij}^r \ln(x_{ij}^r / \nu_{ij}^r)$ on the set of unknown flows x_{ij}^r.

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

Thus for modeling of trade flows it is necessary to solve a nonlinear optimization problem with the objective function and linear constraints:

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

where $\hat{v}^r_{ij} = \exp(-\hat{d}^r T_{ij}), \hat{d}^r$ are known estimates of the parameters and constraints of the problem are given further:

$$\sum_{i=1}^{m+1} x^r_{ij} = V^r_j, \tag{3}$$

for all $j = 1, 2, \ldots, m$ and $r = 1, 2, \ldots, n$,

$$\sum_{j=1}^{m+1} x^r_{ij} = W^r_i \tag{4}$$

for all $i = 1, 2, \ldots, m$ and $r = 1, 2, \ldots, n$,

$$x^r_{ij} \geq \varepsilon > 0 \tag{5}$$

for all $i, j = 1, 2, \ldots, m + 1, r = 1, 2, \ldots, n$.

3 Software system requirements and basic principles of its implementation

Modeling of economic relations of territories is used for decision-making on regional social and economic policy. It aims at reducing the negative effect of interregional heterogeneity in economic development in order to prevent depression, uncompetitive, distressed areas, lagging behind the leading regions, and in general, in order to integrate economically regions of the country.

The software interregional trade simulation is intended for specialists from various ministries and departments dealing with the problem of optimizing and planning of the interregional flows of industries products based on multi-product approach and multimodal transport networks.

Base requirements for the software are the following.

1. Software implementation is a cloud service for supplying wide availability of the developed applications. Use of application as a cloud service doesn't do extra limitations to a platform installed on a client's computer, random-access memory and other characteristics of a computer and also it doesn't requires special skills to install the application [12], [13].
2. A possibility of a trade flow modeling in real time. Trade flow modeling requires a lot of computational resources, so a modeling block must be realized with high-performing computational platforms to provide an effect of the "real time" during the modeling process.
3. A system must have tools for input data and visualization of modeling results in a convenient form for a user.

The cloud platform IACPaaS [14] was selected as a tool for realization of modules for visualization and interactive modeling to fit key requirements for the software. The IACPaaS platform is a software-informational Internet-complex for maintenance of development, control and remote use of application and instrumental multi-agent cloud services and their components. To realize a modeling block there a high-performance computational cluster is used for implementation the simulation module. A link between the platform IACPaaS and the computational cluster is done through asynchronous http-requests.

A generalized architecture of the cloud service is presented in the Fig. 1. The software consists of three modules: a module of trade flow simulation, a control module and a visualization module.

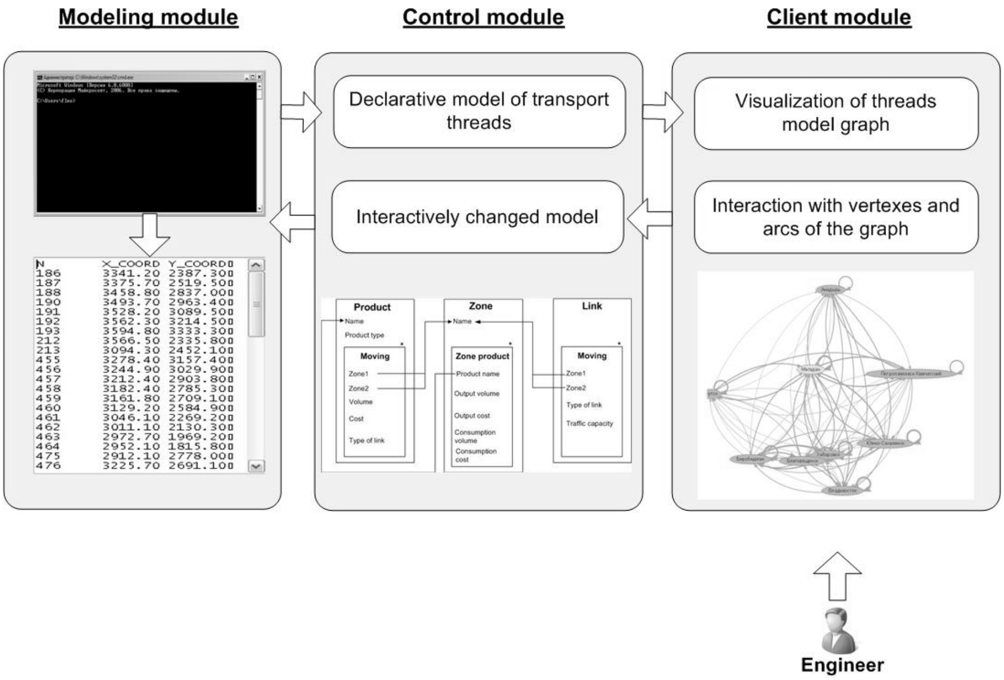

Fig. 1. Interaction architecture of software modules for interactive trade flows service

4 Software implementation and the simulation module of trade flows

Software that implements the described above mathematical model is realized. It is used to find the equilibrium interregional freight traffic in the transport network system of regions. Model implementation is carried out in the MPL language [16] and Octave [17] on the SuperServer 6037R-72RFT+ server platform by SuperMicro company. Software allows us to calculate the equilibrium values of the volume of a freight traffic between the nodes of the transport network.

To use the program the following input information is needed: statistical data on total import and export of products for the regions, the distance between the main transport hubs of regions in the implementation of transport by rail, road and/or sea.

An indicator of "connectedness" of the regions for a specific industry or aggregated for all products is defined as $L_{ij} = \frac{2(x_{ij}+x_{ji})}{E_i+E_j+I_i+I_j}$ where x_{ij} is an outflow from the region of i to the region j and E_k is a total export of products from the region k to all other regions, and I_k is total imports to the region k from all other regions.

Output results of the program are calculated equilibrium values of the freight traffic between transport network nodes, the matrix of interregional flows and "connectivity matrix of regions in the context of NACE classification of economic activities and for all simulated NACE codes.

The computer program provides an output of calculated matrices of interregional flows and indicators of regions "connectedness" for each product and aggregated values of all the goods.

5 Control Module

The trade flow 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 trade flow 14. That format consists of three base types of objects: products, zones and communications. A structure of each type and links between them are provided in the Fig. 2.

The control module uses the http-protocol and asynchronous requests. The visualization module sends an asynchronous http-request to the control module for getting input data from the simulation module. The control module initiates an http-request for getting or calculating data about a state of trade flows. 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 trade flows by obtained data. The control module is different from existing methods for inter-regional flows because it provides interaction between two environments (environment of calculations and environment of visualization) which are on the different platforms.

A declarative representation of the objects which is realized with JSON format is shown on Fig. 2.

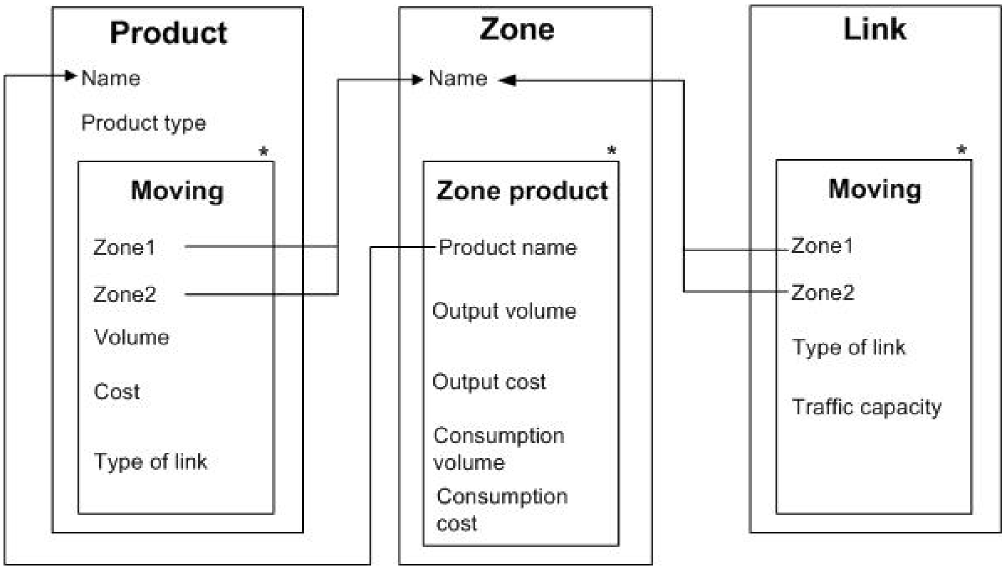

Fig. 2. The declarative model of trade flows

6 Visualization module

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

The visualized transport net allows users to see results of mathematic 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 trade flows [19]. 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.

The parametrical 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.

Interactive editing of the graph supposes a change of the parameters vertexes and arcs of the graph. (Fig. 3). 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.

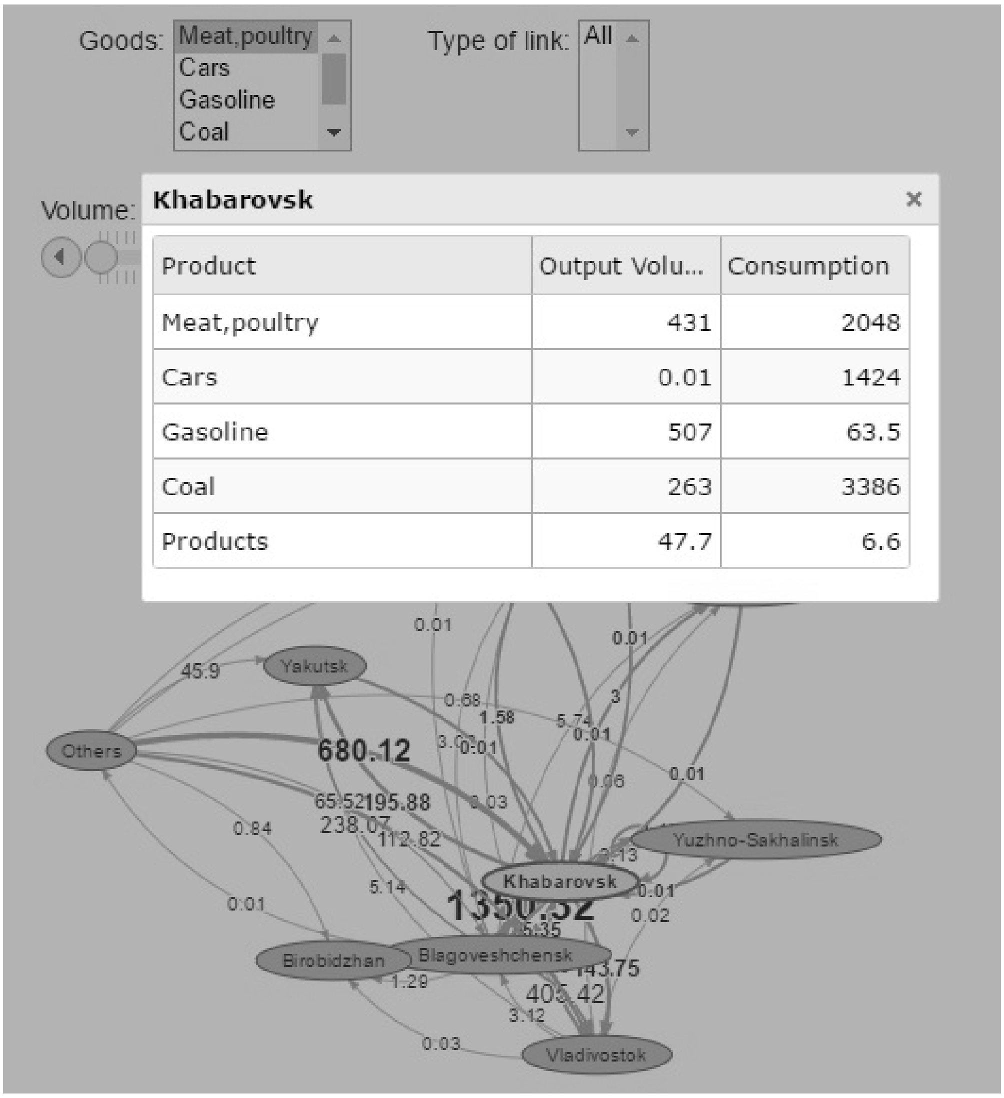

Fig. 3. Editing the parameters of the model

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.

7 Visualization and the analysis of solution

Software for interactive interregional trade simulation is used to determine the equilibrium interregional freight traffic in the transport network of railway, road and sea transport of the Far Eastern regions of Russia. As input data we have used information from official statistical handbooks of Rosstat from different years "The regions of Russia. Socio-economic indicators of the interregional trade". The main products (commodities) are foodstuffs, fuel, goods for technical purposes.

Administrative centers of nine Far East regions are considered: Primorsky Krai (Vladivostok), Khabarovsk (Khabarovsk), the Amur Region (Blagoveshchensk), the Jewish Autonomous Region (Birobidzhan), the Republic of Sakha - Yakutia (Yakutsk), Magadan region (Magadan), Sakhalin region (Yuzhno-Sakhalinsk), Kamchatka region (Petropavlovsk-Kamchatsky), Chukotka Autonomous Okrug (Anadyr). These cities are considered as the centers of economic activities described by the model. Estimates of the distances between regions are shown in Table 1, which are corresponded by the shortest paths between the administrative centers of the regions in the transport network of railway, road and sea transport of the Far East of Russia.

The visual presentation of the data is shown in Fig. 4.

Currently we have made modeling for 25 products for various purposes: food, fuel, technical supplies and others. The result of the simulation determines the most probable movements of goods between the regions of the Russian Far East. In a case of incomplete statistical data the use of mathematical modeling allowed us to obtain interpretable results with economic sense and forecast the most probable distribution of the flow of goods between the regions of the Russian Far East.

The presented approach allows us to determine characteristics of relationship of economies of the Far East regions of Russia in the conditions of the existing spatial structure of production placement. These relationships are accompanied by spatial non-uniformity and strong product differentiation. A new structure of the region's economy relationships is possible when parameters of the economic area are changing (transport, energy infrastructure, and spatial structure of production and consumption of the gross regional product).

8 Conclusion

The paper describes mathematical model and the software package that are designed for interactive simulation of interregional trade. The software package is a cloud-service and consists of three main modules: the simulation module of trade flows, the control module and visualization module. The mathematical model of trade flows is the basis of the simulation module. It is implemented on a high-performance computing platform due to high computational complexity of the modeling process in a case of huge dimension of a problem. Control and visualization modules are implemented on the cloud platform IACPaaS using a multi-agent approach. The interaction between the high-performance computing platform and the IACPaaS platform is carried out using a http-protocol with dynamic asynchronous requests. The software package is designed for professionals from various ministries and departments dealing with the problem of optimizing the

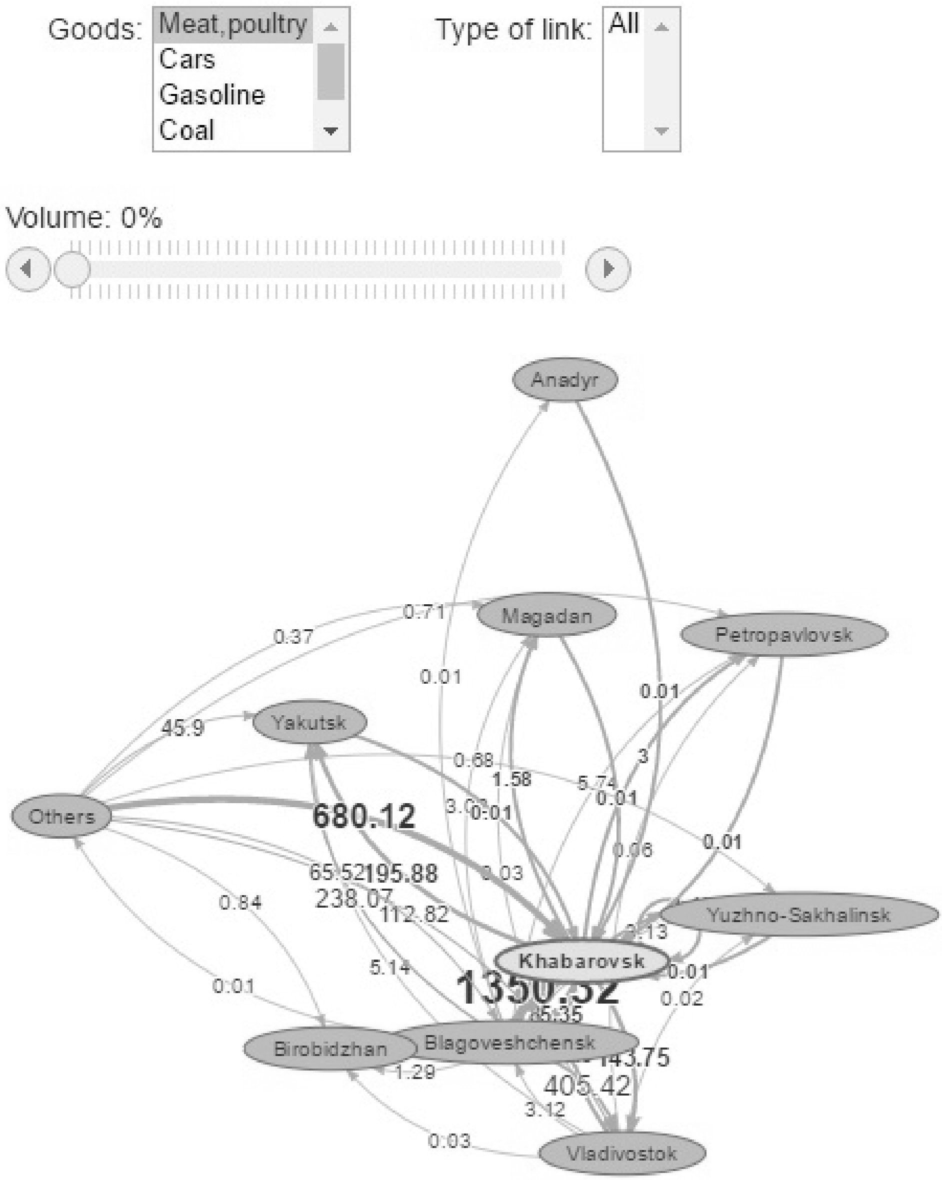

Fig. 4. Visualization of trade flows

planning and interregional flows industries products based on their multi-product in multimodal transport networks, and can be used for interregional trade simulation in different regions of Russia.

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