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## Spatial Aspects of Agent-Based Modeling of Large Economy

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# **Spatial Aspects of Agent-Based Modeling of Large Economy**

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## **Abstract**

*The paper presents a pilot version of spatial agent-based model simulating the national economy of Russia. The model is supposed to be used for evaluation the effects of industrial and spatial policies.*

*The object of modeling is multi-regional economic space of Russia in its interaction with foreign market. The basic hypothesis is that decisions of agents on microeconomic level lead to spatial changes on macroeconomic level. We consider Arrow-Debreu model with Leontief technologies as a microeconomic prototype of our model and models of stochastically converging equilibrium as the closest macroeconomic prototype.*

*The basic features of the model presented are the following. We explicitly account for space, considering interactions between trading agents located in physical space. Moreover, the model is compatible and exchanges information with an existent multiregional input-output model that uses the identical nomenclature of regions and industries.*

*Agents (firms, households, commodity markets, labour market and foreign market) take decisions on the base of microeconomic models under bounded rationality with the account of transportation costs. Initialization of the model uses some elements of geo-informational approach as well as informational exchange with multiregional input-output model. Agents are located on the map on the base of geographical coordinates of cities, real data on demography and statistical performance of economic activities. Statistical performance is collected mostly across macro-regions and activities and is visualized by graphs. The model is realized on “Lua” programming language.*

*Spatial pattern of interactions among agents is created by two-part transport tariff: the first part is proportional to the amount of commodities and the second part is proportional to the distance between 2 agents and to the amount of deliveries. In the report we illustrate the algorithm of trade between households with the account of transportation costs. The geographic structure of commodity flows is analyzed.*

*The report also presents some results of the experiments accomplished. We studied the influence of transportation costs on the convergence of prices to the state of quasi-equilibrium. Experiments demonstrated that the Law of One-Price is not observed. Prices converge to clusters within regions, which reflect the impact of differences in industrial pattern of regions.*

**Keywords:** Spatial agent-based model, multi-industrial economy, transportation costs.

**JEL classification:** C63, R1, D58

Modeling Russia's economy, with its regional diversity and geographic size, requires taking the factor of space into account, which complicates the representation of economic dynamics. Moreover, in the modern Russian economy location decisions are significantly decentralized; the intensity and pattern of interregional interactions are rather changeable, as well as of interactions of regions with foreign market. An adequate analysis should be based on disaggregated approach with various boundedly rational agents interacting under the conditions of limited information. Thus, a modeler needs such analytical tools that could explicitly account for space and provide compatibility with the available macroeconomic models. Spatial agent-based models satisfy these requirements, providing the representation of asymmetric space of any configuration, which allows studying various features and ways of forming spatial economic systems.

Currently, the most of explicitly spatial agent-based models relate to the field of city and rural land use, transportation and ecology; they are focused on specific engineering problems rather than on general economic ones. A model constructed by Tsekeris and Vogiatzoglou (2011) allows for solve problems of location of agents in the system of several cities. But it does not simulate commodity markets and flows.<sup>1</sup> Large-size macroeconomic agent-based models are rather rare; they do not use the explicit representation of space and real data: these are multi-regional models Eurace@UNIBI<sup>2</sup> and LAGOM RegIO<sup>3</sup>.

Our *aim* is to construct of spatial agent-based model simulating the national economy of Russia. The model is supposed to be used for evaluation the effects of industrial and spatial policies. The paper presents a pilot version of the model. The structure of the model, classes of agents, principles of their interaction are described according to general lines of ODD-protocol.

The *object* of modeling is multi-regional economic space of Russia in its interaction with foreign market. The space is physical; locations of agents are defined by geographical coordinates. The *basic hypothesis* is that decisions of agents on microeconomic level lead to spatial changes on macroeconomic level. We consider Arrow-Debreu model with Leontief

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<sup>1</sup> **Tsekeris T., Vogiatzoglou K.** (2011) Spatial agent-based modeling of household and firm location with endogenous transport costs // *NETNOMICS: Economic Research and Electronic Networking*. V.12 (2).

<sup>2</sup> **Wolf S., Fürst S., Mandel A., Lass W., Lincke D., Pablo-Martí F., Jaeger C.** (2013): A multi-agent model of several economic regions// *Environmental Modelling & Software*. Vol. 44.

<sup>3</sup> **Dawid, H., Harting, P., Neugart, M.** (2013) Cohesion Policy and Inequality Dynamics: Insights from a Heterogeneous Agents Macroeconomic Model // *Bielefeld Working Papers in Economics and Management* No. 26-2013. URL: <http://ssrn.com/abstract=2369187>.

technologies as a microeconomic prototype of our model. Theoretical construction of the model referred to models of stochastically converging equilibrium.<sup>4</sup>

The basic *features* of the model presented are the following. First, we explicitly account for space. We consider interactions between trading agents located in physical space. The agents take into account transportation costs. Location of agents is referred to geographic map of Russia. Moreover, the model is compatible and exchanges information with an existent multiregional input-output model that uses the identical regional and industrial nomenclature.<sup>5</sup>

There are *agents* of the following types: firms, households, commodity markets, labour market and foreign markets. In the current variant firms cover 4 kinds of economic activities: extraction, manufacturing, construction and services. The number of commodity markets is also equal to 4. Firms produce commodities of mono-product industries and sell them to firms and households. They also purchase production factors. Number of commodities is equal to the number of activities. Households perform as sellers. They consume commodities according to their utility functions, earn salaries or unemployment welfares, and receive dividends as firm-owners. Commodity markets play a coordinating role. External markets act as sellers and sellers of commodities. There is no government in the current version of the model. Some of governmental functions are performed by the economic system as a whole. These are re-distribution of money funds (transfers to households, taxation, balancing foreign trade); collection of statistical information. Household seek for jobs at labour market. The choice of job is determined by locations of households relative to firms, by commuting costs, and by conjuncture on labour market. Firms act as employers. Agents take decisions on the base of microeconomic models under bounded rationality.

Agents and their basic relationships are shown on Figure1.

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<sup>4</sup> **Gintis H.** (2007): The Dynamics of General Equilibrium// *Economic Journal*. Vol.117. Iss. 523.

<sup>5</sup> **Gamidov T.G., Domozhirev D.A., Ibragimov N.M.** (2013) Ravnovesnye sostoyaniya otkrytoi mezhhregional'noi sistemy, porozhdyonnoi optimizatsionnoi mezhhregional'noi mezhotraslevoy model'yu (Equilibrium states of an open interregional system generated by an optimization multiregional input-output model)// *Vestnik Novosibirskogo gosudarstvennogo universiteta. Seria: sotcial'no-ekonomicheskiye nauki*. Vol. 13, Iss. 3.

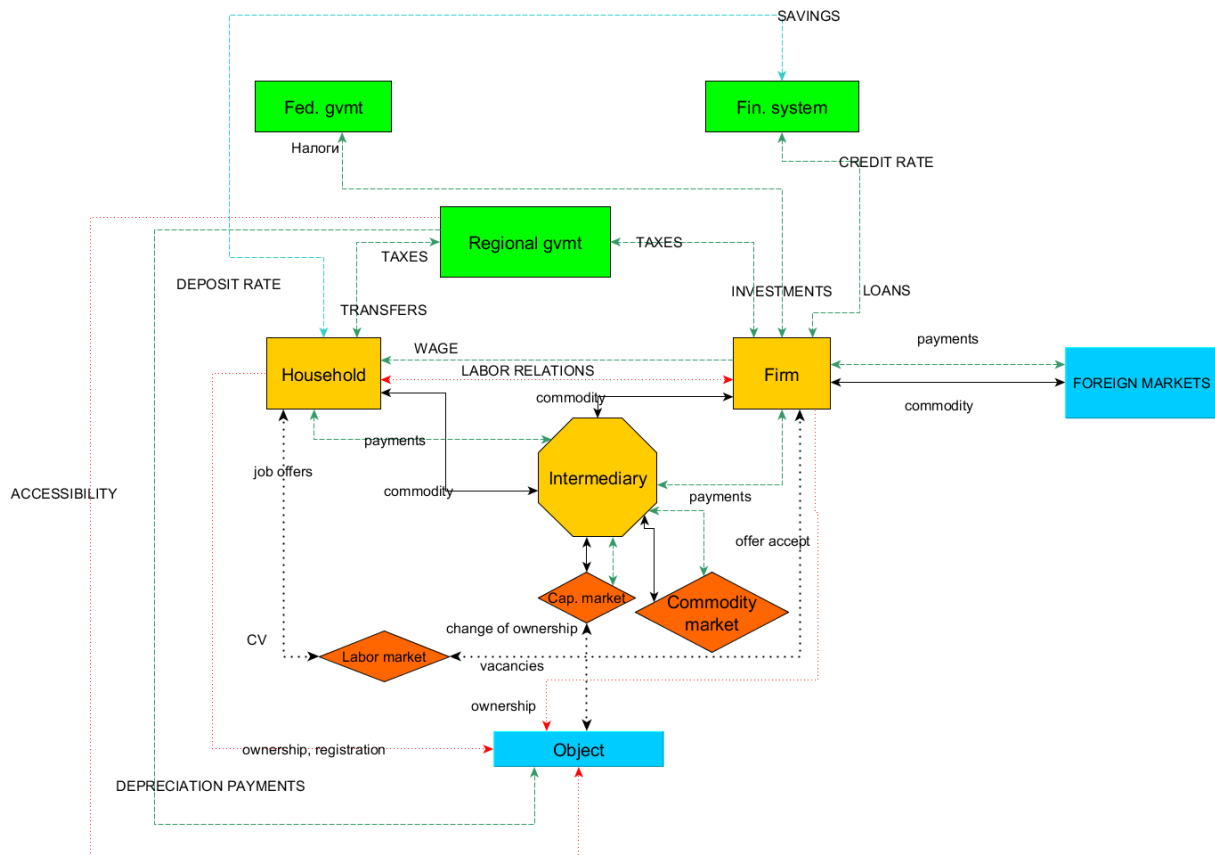


Fig.1. Types of agents and basic relationships in the model.

*The order of events in the model within a single period:*

- The start of the period is announced. Relevant variables are reset at the corresponding start-of-the-period levels.
- The budget makes transfers.
- Households make plans (choose consumption shares by sectors).
- Firms make plans (choose prices of their production and output levels).
- Sellers submit their “(price, quantity)” bundles to the corresponding markets.
- Buyers compare prices (including transport tariffs) from different bundles and make bids on the bundles. The bids are bounded by the available amounts.
- Markets process the bids. If there is an excess demand, then the demand is satisfied proportionally.
- Sellers are notified about realized bundles and the observed demand. Sellers (firms) change their profits.

- Firms adjust their information about the demand.
- Buyers are notified about their purchases. They change their incomes (profits) and the amounts of commodities.
- Buyers adjust their information on prices.
- If there are unsold commodities at the market and there were nonzero purchases, then the trading process return to the stage of making bids.
- Unspent income of households is taken to the budget.
- Dividends are distributed according to ownership shares.
- The end of the period is announced.
- Agents fill in statistical reports.
- The AB system processes the statistics and presents its own reports to the user.
- A new period is started.

*Geographical pattern* of the model is referred to the stylized map of Russia. Hierarchically, it is organized in the following way. The upper level of the hierarchy is formed by three macro-regions (“West”, “Center” and “East”) that consist of united federal districts. Each macro-region includes meso-regions corresponding to 77 federal subjects including cities. Firms and households are on the lower level of hierarchy.

Foreign markets are not installed in this hierarchy: they are characterized by coordinates only and are not attached to regions. There are 3 stylized foreign markets “China”, “Central Asia” and “Europe” having coordinates of Beijing, Alma-Ata and Munich, correspondingly.

Russia’s size is compatible with the Earth’s size, so we do not use a flat map of Russia in order to avoid biases in measuring distances. Distance is measured as a length of the shortest arc between 2 points on the Earth with their coordinates of longitude and latitude.

*Initialization* of the model uses some elements of geo-informational approach as well as informational exchange with multiregional input-output model. Agents are located on the map on the base of geographical coordinates of cities, real data on demography and statistical performance of economic activities. Firms and households are located around the point defined by city’s coordinates according to 2-dimensional normal distribution. The probability for a firm or a household to be located in a specific city is proportional to the city’s

population, while the probability for a firm to be located in a specific region is proportional to the number of firms producing the same commodity in this region.

All technical coefficients for production and consumption functions are based on the input-output model of identical nomenclature. Input coefficients are taken from 3 regional input-output matrices. An amount of capital is calculated from a matrix of bounds on outputs with account of capital intensity. A pattern of final demand from the I-O model is used as coefficients of Cobb-Douglas utility function.

*Visualization* of the model functioning uses animated maps. It is based on a detailed physical map of Russia. It reflects borders of regions, locations of agents, and dynamics of commodity flows. It provides information (outputs, costs, consumption, exports, imports) about any agent chosen.

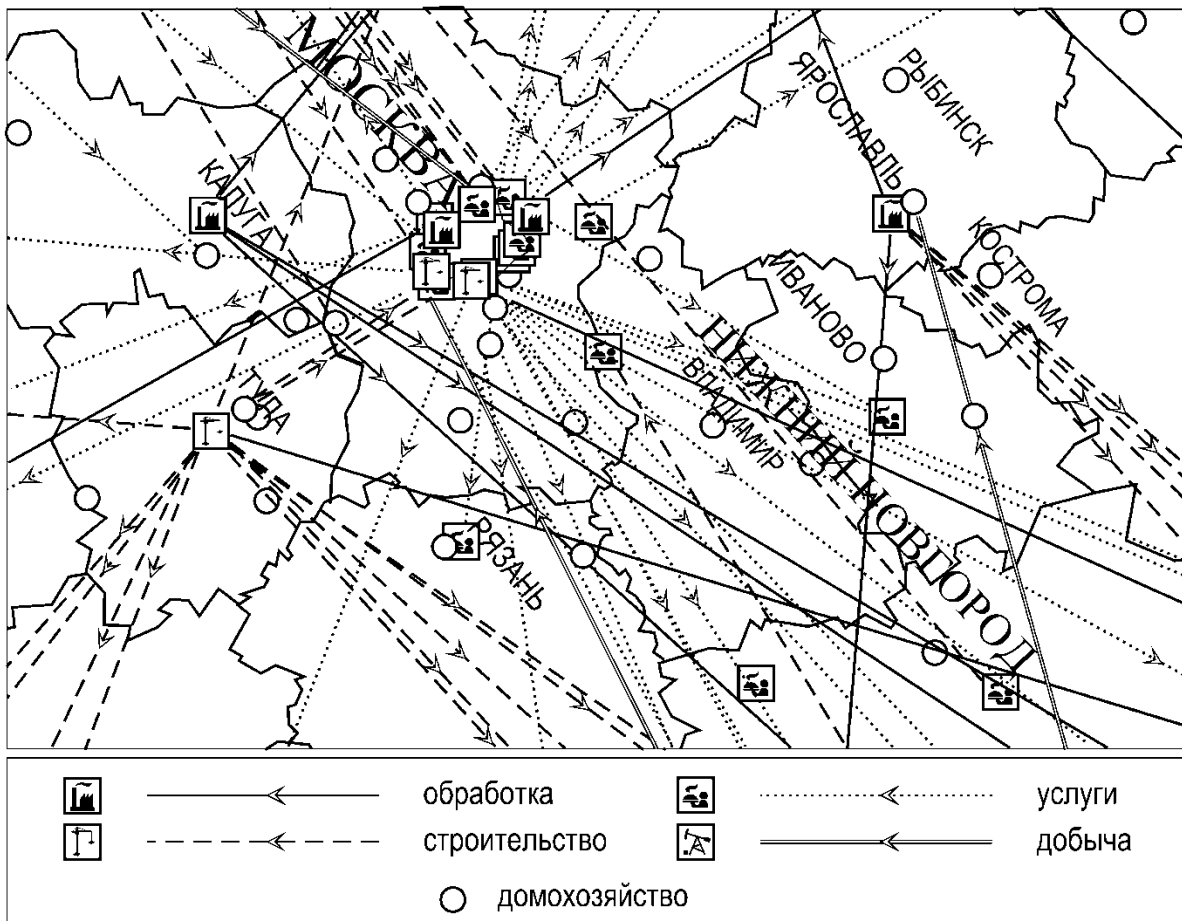


Fig.2. Location of agents and their interactions on the map (flows of different commodities are drawn by arrows of different styles).



*Statistical performance* (such as outputs, profits, consumption per capita, etc.) is collected mostly across macro-regions and activities and is visualized by graphs. Graphs may be updated. The model is realized on “Lua” programming language.

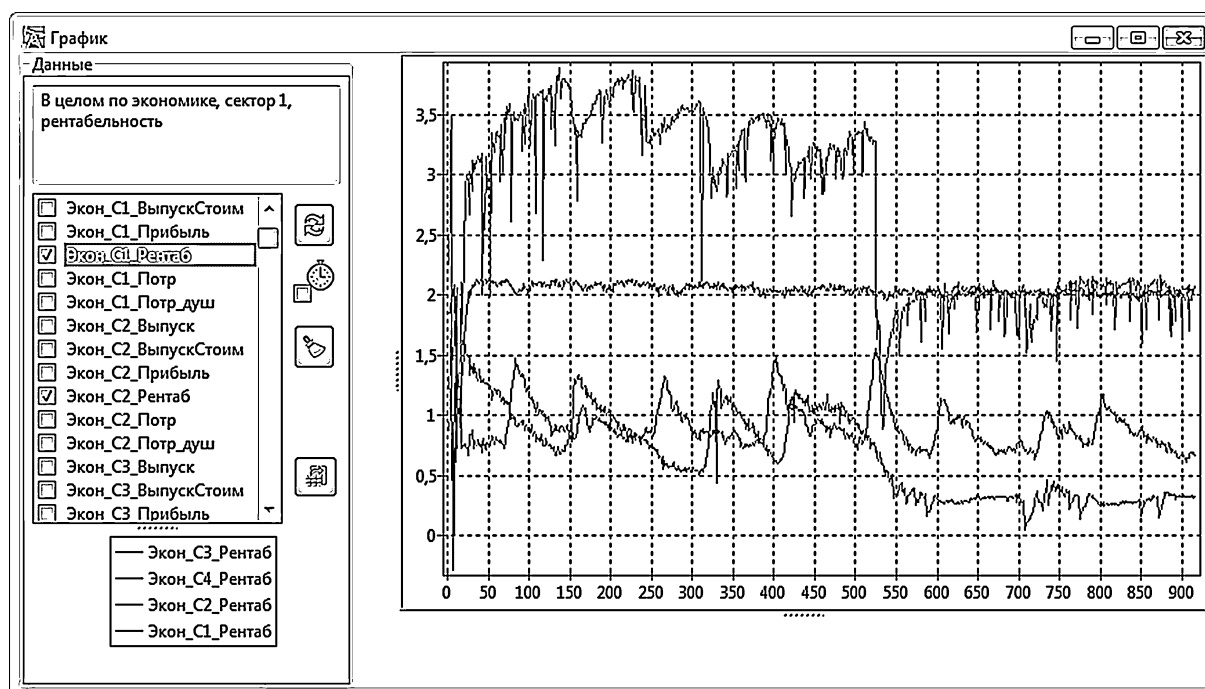


Fig.3. Visualization of the statistics collected in the form of graphs. (Horizontal axis – numbers of periods; vertical axis – statistical indicators)

*Spatial pattern* of interactions among agents is created by two-part transport tariff: the first part is proportional to the amount of commodities and the second part is proportional to the distance between 2 agents and to the amount of deliveries. Transportation costs are different in different industries. Transports are not defined as a separate industry. Fixed exogenous transportation tariffs are similar to taxes.

Trade in each industry takes place through the corresponding commodity market. Trade mechanism is organized with the use of exchange by messages among a commodity market, traders and sellers. During every period some sequence of events happens according to the order described above.

*Internal mechanism of trade with account of transportation costs* may be presented on a stylized example. Initially there are 3 bundles (price, amount) proposed by 3 firms-sellers on market: (2, 12), (4, 24) and (6, 12). One bundle with price 10 and infinite amount is also proposed by foreign market. There are 2 sellers: households A and B. Household A is ready to spend 81 on this market while household B – 152. There are some transportation costs for

each pair seller-household; they are indicated on each line connecting households and bundles on Fig.4. We suppose for simplicity that households “see” all bundles proposed on market and they are fully rational choosing the lowest price with account of transportation costs.

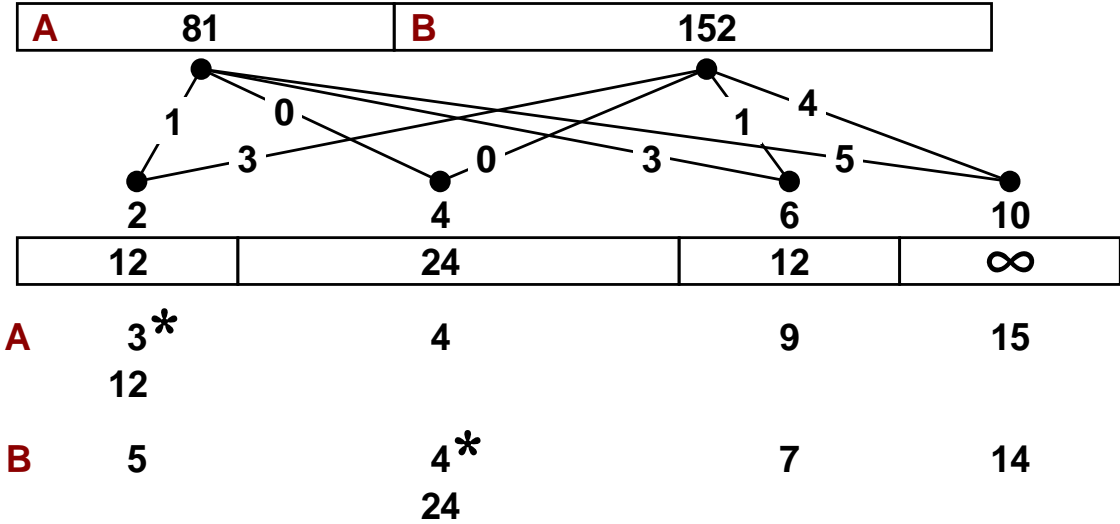


Fig. 4. An example of trade: first iteration.

From the set of bundles proposed the first one fits to household A most of all (price 2; transportation costs 1) while the second one is the best for household B (price 4, transportation costs 0). Households declare the demand that is equal to amount of the bundles they liked because their funds allow to buy them. Thus, 2 bundles leave the market. Next iteration begins. On this iteration the demand of household A is bounded by  $(81-3 \times 12=45)$  while the demand of household B is bounded by  $(152-4 \times 24=56)$ .

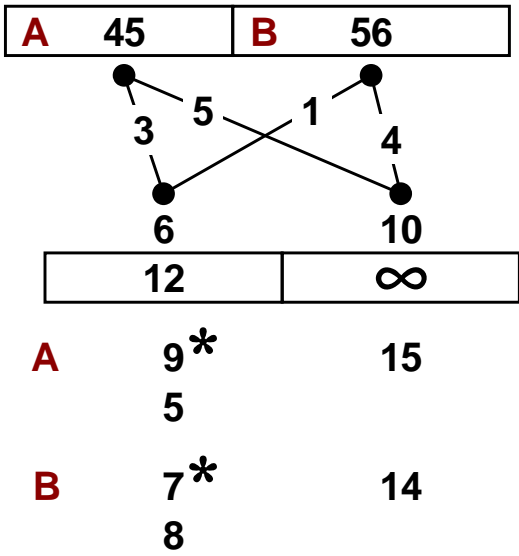


Fig. 5. An example of trade: second iteration.

Now households' funds are not sufficient for purchasing a whole amount of the most attractive bundle. Household A calls for 5 units while household B – for 8 units. Then it turns out to be that the demand declared (13) exceeds the amount of bundle (12). The rest of commodities is distributed proportionally to the calls. Household A receives  $(5 \times 12/13)$  units while household B -  $(8 \times 12/13)$  units.

All standard bundles are sold. Unsatisfied demand  $(45 - 9 \times 5 \times 12/13 = 45/13)$  of household A and  $(56 - 7 \times 8 \times 12/13 = 56/13)$  of household B is satisfied by the infinitely large bundle proposed by foreign market. Households purchase  $3/13$  units and  $4/13$  units, correspondingly, in foreign market. The trade is finished.

The model allows accomplishing *experiments*. The experiments were aimed on analysis of impacts of dramatic changes in import and export prices on geographical location of economic activity. We studied the influence of transportation costs on the convergence of prices to the state of quasi-equilibrium. We considered the average squared deviation of logarithm prices on specific commodity from average weighted logarithm prices over the whole market as an indicator of price dispersion for each commodity market. We did not expect the Law of One Price will work because of the presence of transportation costs, differences in firms' technologies and consumers' preferences of diversity. So this indicator does not need to converge to zero. At the same time, decreasing to some stable level may be an indicator of convergence to quasi-equilibrium.

In experiments behavior of sellers is regulated by 2 parameters: SigmaDS (elasticity  $\sigma_{DS}$  of CES-function; Dixits-Stiglitz-style elasticity of substitution parameter regulating buyers' love for variety) and NPortionsDS (number of portions designated for purchasing different bundles in the amount of expenditures for a specific commodity). The less is SigmaDS and the more is NPortionsDS, the more sellers like diversity. In basic configuration SigmaDS=10, NPortionsDS=9.

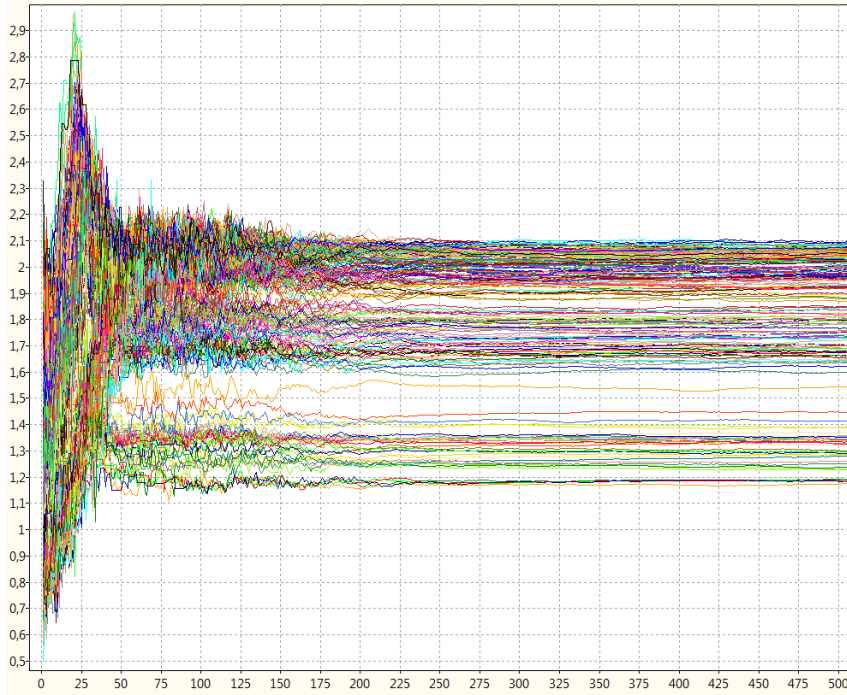


Fig.6. Trajectories of prices in “Services” under basic configuration of parameters.

As the system is functioning, price volatility sharply decreases and becomes stable at rather low mark (less than 0,2%). Price deviations are stabilized at rather high mark (near 30%). Fig. 6 illustrates price trajectories in “Services”. As expected, prices do not come to full convergence. After initial turbulent period prices move parallel. Thus, the system is stabilized and comes to quasi-equilibrium with some occasional fluctuations.

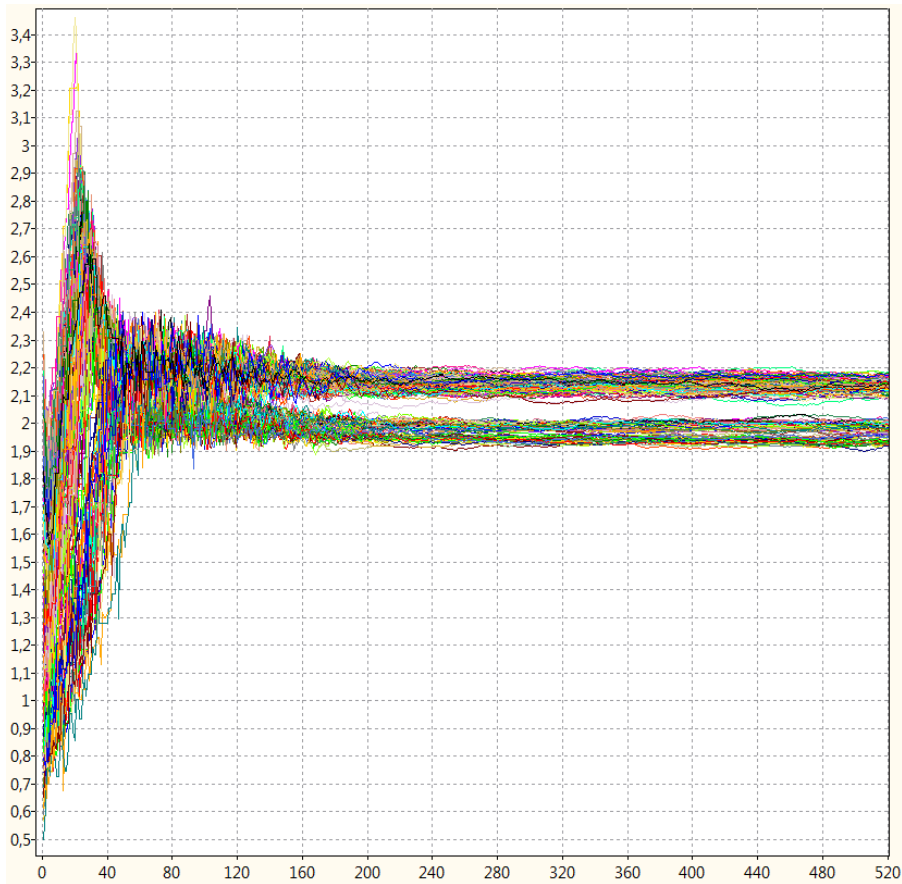


Fig.7. Trajectories of prices in “Services” under transportation costs equal to 0.

The next experiment illustrates the influence of transportation costs on pattern of quasi-equilibrium prices. Under transportation costs equal to zero the volatility of prices increases by 30 % and more in the comparison with basic variant with transportation costs. At the same time average squared deviation of prices becomes less by the factor of 3, but does not converge to zero, that is, full convergence of prices is not observed. Trajectories of prices on Fig. 7 demonstrate convergence to 2 clusters. This may be explained by that firms’ technologies differ in different regions while consumers like diversity of commodities, which in sum leads to rather high differentiation of prices. In the frames of clusters we observe high price volatility, which may be explained by intensive competition among firms.

Thus, experiments demonstrated that the Law of One-Price is not observed. Prices converge to clusters within regions, which reflect the impact of differences in industrial pattern of regions.

The *prospects* of future development of the model refer to adding new types of agents and kinds of economic activities; including federal and regional governments as agents; allowing for mobility of households; including intangible entities; taking transportation networks into account for calculating transportation costs.

*Conclusion.* We presented a pilot version of spatial agent-based model simulating the national economy of Russia.

The basic features of the model presented are 1) explicit account for space, 2) compatibility and informational exchange an existent multiregional input-output model of identical nomenclature.

Spatial pattern of interactions among agents is created by two-part transport tariff. The algorithm of trade between households with the account of transportation costs is presented.

Experiments demonstrated that under absence of transportation costs the Law of One-Price is not observed. Prices converge to clusters within regions, which reflect the impact of differences in industrial pattern of regions.