

MATHEMATICAL METHODS AND MODELS IN ECONOMIC RESEARCH

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SIMULATION MODEL OF THE FORMATION AND DEVELOPMENT OF THE ALL-RUSSIAN AGRARIAN COMMODITY MARKET IN THE SECOND HALF OF THE 18TH – EARLY 20TH CENTURY

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Abstract

The paper analyzes the model of the grain balance's dynamics in different regions and assesses the efficiency and development of the grain market during 18-19 centuries. It is stated, that in the context of annual grain transportation the overall yearly import and export of grain to and from a region are influenced by the surplus and shortage of grain in various areas. Regions with more than 5% surplus of grain are identified as exporting regions, while those with more than 5% shortage are identified as importing regions. Among the main factors affecting grain trade are the model accounts, the transportation distance, transportation capabilities, epidemic situations, money supply sufficiency, government trade policies, and international trade conditions. The model's effectiveness was tested by comparing model-derived optimal trade scenarios with actual historical data over a 55-year period (1802-1856). It is stated, that the model was found to adequately describe the grain export dynamics to foreign countries in at least 72% of cases. Regional grain balances in 18-19 centuries were assessed. It is revealed, that grain production and consumption varied greatly due to unstable agricultural yields and changing population demands. Surplus grain was often exported even from regions with overall negative grain balances by reducing local consumption or using lower-quality substitutes. Market development over time characterized with the features: 1) from the 1830s onwards, there was a noticeable improvement in the grain market as more regions could consistently export grain, leading to a more interconnected market; 2) by the late 19th century, interregional grain trade became more active, indicating a well-developed market. The comparison between the optimal model and actual historical data helps identify discrepancies and understand the development level of the grain market. It is proved, that the model's strength lies in its ability to work with estimated values and limited precise data, providing a robust tool for historical economic analysis.

Keywords: simulation model, model of agrarian market, grain prices, factors of economic dynamics, social impact of the grain market.

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Introduction

Effective management of modern socio-economic processes requires comprehensive short- and long-term characteristics of the processes being managed. In most cases, it is extremely difficult to obtain the necessary analytical data in sufficient volume and in advance of making a management decision. Naturally, obtaining information about an object is not always aimed at supporting management activities; for example, specific historical or theoretical research also demands the most complete information. The task of timely obtaining comprehensive information about a socio-economic process can be facilitated by creating and using a model of the object.

Among the various ways of constructing such models, a method that does not require extensive knowledge of the precise characteristics of the object at the initial stages seems noteworthy. This approach is usually justified when there is no adequate formal theoretical description of the process under study. Initially, a highly aggregated model reflecting the main characteristics of the process is created. After establishing its adequacy, as research progresses and results are compared with the development of the real process, the model's parameters can be gradually refined and detailed. The aim of the article is to describe the author's simulation model of the formation of the All-Russian agrarian commodity market in the second half of the 18th – early 20th century. The problem of the All-Russian agrarian market formation in 18th – 19th century were studied with periodic intensity. Among the last works we can mention papers, devoted to mathematics-statistical analysis of agrarian market (Polovyi M. 2023a; Polovyi M. 2023b)

Methodology

A 161-year period from 1754 to 1914 was taken for model construction. The lower time boundary of the study is marked by an important event in the development of trade and the formation of capitalist relations in Russia – the abolition of internal customs in the mid-18th century (1754). The start of the First World War and the subsequent change in conditions and forms of socio-economic development determine the upper boundary of the studied period. The simulation model of the formation of a unified agrarian commodity market is considered for the European part of Russia. The model's step is one year. It is detailed into 11 major economic-geographical regions covering the entire territory of the European part of the Russian Empire, excluding the Grand Duchy of Finland, the Kingdom of Poland, and Transcaucasia (Mironov, B.N., 1985; Drobizhev, V.Z., Kovalchenko, I.D., Muravyov, A.V., 1973).

For the construction of the model, annual data on the following quantitative factors were used: prices of rye, oats, wheat, barley, and buckwheat in eleven regions of European Russia from 1754-1914 (data gaps for the latter three crops average 37% of the total period); exports of rye, oats, wheat, and barley abroad; prices of these grains in England, Holland, Denmark, France, and Prussia; their yields; the volume of money supply in Russia. Additionally, annual values of such factors as the condition of domestic and foreign trade transport routes, government trade policy, foreign political situation, and epidemiological situation in the country were assessed (Mironov, B.N., 1985; Fortunatov, A., 1893; Kashkarov, M. 1898; Kaufman, I. I., 1909; Nebolsin, G., 1850; Georgievskiy, P. N., 1885; Beveridge, W.H., 1965; Friis, A., Glamann, K., 1958; Posthumus, N.W., 1943; Rogers, J.E.T., 1902; Tooke, T., Newmarch, W., 1838-1857; Tooke, T., 1824).

To evaluate some indicators, data on Russia's population, the size of the Russian army and navy, and sown areas were used. Based on a previous study of the relationship between grain prices and socio-economic factors, as well as a preliminary analysis of the interrelationships between factors of grain production and consumption, a modeling concept was developed and a complete verbal description of the interconnected dynamics of grain market factors was created (Arkhangelsky, G. I., 1874; Derbek, F. A., 1905; Lodyzhensky, K. P., 1886; Kitanina, T. M., 1987; Istomina, E. G., 1982; Yatsunsky, V.K., 1957; Kabuzan, V.M., 1971; Rashin, A.G., 1956; Vodarsky, Ya.E., 1973; Arsenyev, K., 1848).

Among the developed initial premises and principles of the model for the formation and development of the agrarian commodity market, the following should be mentioned:

1. Regarding the period of interest, the statement "greater or lesser degree of market development" (according to various characteristics) may be closer to the truth than the opposition "no market – there is a market."

2. For the known socio-economic conditions in Russia, it is possible to hypothetically model the situation of an "ideal" grain market for these conditions – a market that fully utilizes all available trade resources.

3. The most important feature of the "ideal" market is ideally established connections that could be defined as the realization of the ability to transport goods in the time possible to the area with high prices from the area with low prices. The existence of such connections leads, in particular, to the minimization of commodity surpluses in exporting regions.

4. A balance simulation model, mainly considering the deviation coefficients of the real situation from the "ideal" grain market, allows the best study of the features and dynamics of the formation of the All-Russian grain market.

Based on the indicated premises and experience in constructing a simulation model of rye price dynamics in Russia in the second half of the 18th century, we built a model of the formation of the agrarian commodity market in the European part of Russia in the second half of the 18th – early 20th centuries, following the type of J. Forrester's models with the following characteristics:

Using the modeling concept, verbal model descriptions, and block diagrams, the structure of the model for the formation and development of the All-Russian agrarian commodity market was determined, and the level variables and independent variables considered in the model were defined. The level variables include the volume of grain production and consumption in each of the 11 studied regions of European Russia from 1754-1914; volumes of interregional grain transport and grain exports from regions abroad. Other factors – regional prices of rye, wheat, oats, barley, and buckwheat, considered as indicators of interregional and foreign grain transports; total annual export volumes of the mentioned five grains from Russia; prices of rye, wheat, oats, barley, and buckwheat in the largest trading centers of the world; average yields of these five grains in European Russia; the volume of the money supply in Russia; the epidemiological situation in Russia; the condition of internal and external trade transport routes; government trade policy; foreign political situation – are considered independent variables.

The relationships of the model's variables are initially described in natural language and then formalized with simple finite-difference equations. For example, the total volume of grain available in a given region in a given year is determined by summing the grain produced in the current year and the grain left over from the previous year. The volumes of interregional grain transport (and grain transport abroad) are determined in several stages (and also recorded as equations):

1. Regions with grain surpluses are identified, and the total possible export (TPE) is determined for each region. A region with a grain surplus is considered one where the grain surplus exceeds 5% of annual consumption.

2. Regions requiring grain imports in a given year are identified. These are considered regions where the grain deficit exceeds 5% of consumption. The total import needs (TIN) for each respective region are also determined. Regarding foreign exports, the total need is assumed to equal the volume of grain actually exported in a given year (this is an independent variable).

3. The possibility of profitable export-import of goods (PEIG) among the regions identified in steps 1 and 2 with grain surpluses and deficits is determined by the ratio of regional grain prices (sequentially for each pair of regions) considering distances between regions.

4. The volumes of transport are determined considering the volumes of TPE and TIN based

on the principle of optimizing commodity flows with the criterion of maximizing profit (iterations of export options starting from the pairs of regions with the maximum PEIG).

Due to the peculiarities of the proposed method of model creation, some additional restrictions were taken in accordance with this methodology (Chen J. and Roth, J. 2024) connected with possible zero values for some variables. Some constraints are imposed on the indicated relation: Grain import into any region is mutually exclusive with export from this region (i.e., there was either a grain deficit and it was imported, or there were significant grain surpluses and it was exported from this region). Obviously, in reality, the situation was more complex (in the presence of significant surpluses in the region as a whole, grain could be imported into some of its areas, and similarly, in the case of a clear grain deficit, grain could be exported from the region. However, these "uncharacteristic" grain movements canceled each other out, and thus, they can be ignored in the aggregated model. If market connections established, the volume of grain equal to the difference between production and consumption (if it is positive) should be exported to other regions or abroad. With optimally ("ideally") established market connections, there should be no commodity surpluses (or their amount should tend to a minimum).

Description of the model:

As a result of identifying the relationships between the structural components of the model, the balance equations for the increments of the level variables of the model, as well as the initial values of the level variables, were determined.

The process of formation and development of the All-Russian agrarian commodity market is described by the following system of equations:

$$G_n^t = G_n^t(npou3\theta) + G_n^t(ocm)$$

$$G_n^t(npou3\theta) = U_n^t \cdot Su_n^t$$

$$G_n^t(ocm) = G_n^{t-1} - B_{n \rightarrow (1 \div N, a)}^{t-1} + BB_{n \leftarrow (1 \div N)}^{t-1} - C_n^{t-1}$$

$$C_n^{t-1} = CP_n^{t-1} + TAX_n^{t-1} + SEED_n^{t-1},$$

where G_n^t is the total grain in the current year t in the n -th region ($n \in \{1, 2, \dots, N\}$, $N=11$; $G_n^t(npou3\theta)$ is the grain produced in this region in the current year t . The volume of grain production is a function of the sown areas and yield in the region; $G_n^t(ocm)$ is the leftover grain from the previous year; U_n^t is the yield in the n -th region; Su_n^t is the area of sown fields under grain in the region, where G_n^{t-1} is the total grain produced in the previous year in this region; $B_{n \rightarrow (1 \div N, a)}^{t-1}$ is the total export of grain for the previous year from this region n to all other regions ($1 \div N, a$) except, obviously, this region, and abroad a ; $BB_{n \leftarrow (1 \div N)}^{t-1}$ is the import of grain into this region from all other regions in the previous year. The arrows \leftarrow, \rightarrow indicate the direction of grain movement from region to region; C_n^{t-1} is the annual grain consumption in the previous year in the region n . The volume of grain consumption in the region is primarily determined by the population size, and it is assumed that there were some qualitative differences in the levels of consumption among different social classes and associated "layers" – for example, the wealthy could

consume grain from higher quality flour than the lower classes. These differences are generally accounted for as follows: it is assumed that peasants consumed 100% of the quantitative norm of medium-quality grain consumption, townspeople – 150%, and nobles – 200%; CP_n^{t-1} is the total grain consumption by the region's population for food; TAX_n^{t-1} is all state grain purchases and collections (usually for military needs); $SEED_n^{t-1}$ is seed and reserve stocks. In most cases, these can be taken as constant given the preservation of the sown areas.

Certain restrictions are imposed on the modelling relations:

Importing grain into any region apparently excludes exporting grain from that region – i.e., either a grain shortage is observed, and it is imported, or significant grain surpluses exist, and it is exported from that region.

Obviously, in reality, the situation was more complex – with significant overall surpluses in the region, grain could be imported into certain areas, and similarly, with a clear grain shortage, grain could be exported from the region. However, these "uncharacteristic" grain movements canceled each other out ("balanced") and could thus be neglected in the model.

In the presence of market connections, the volume of grain equal to the difference between production and consumption (if positive) should be exported to other regions or abroad.

Given the imperfections of transport and communication in the studied era, as well as the possible existence of local unaccounted factors that contributed to increasing or, conversely, decreasing export volumes, it is considered possible for exporting regions, in the presence of a high profit margin, to increase export volumes by 5-10% of the consumption norm or, conversely, not fully utilize export opportunities – increasing "excess" stocks by 5-10% of the consumption norm. Similarly, for grain-importing regions, it is considered possible to "under-import" grain by 5-10% of the consumption norm or to import excess grain of approximately the same volume; in both cases, this is associated with the anticipated profit margin – if the price difference was small, large import volumes were not always profitable, and conversely, a high profit margin contributed to the influx of even objectively excess grain sold at a lower price than local grain.

With optimally established market connections, there should be no surplus goods (or their quantity should tend towards a minimum).

The comparison of optimally possible interregional and foreign transportations under the given actual conditions with the real ones allows us to determine the degree of discrepancy between the existing grain market and the developed and well-formed "ideal" market. The smaller this discrepancy, the closer the market connections can be considered, and the more developed the grain market appears.

Model Verification and Discussion of Simulation Results

The verification of the model's adequacy could not be conducted by comparing the calculated and actual values of the level variables since the model is intended to recreate the optimal ("ideal") situation in grain trade and therefore may not reflect the real situation in terms of numerical values of the variables. Therefore, the model's operability was verified by comparing the following characteristics of the model situation and the real situation: 1) the model's capabilities of regions for grain export abroad and the actual export volumes; 2) the model and actual directions of interregional transportations. Finally, the consistency of the trends in changes between the calculated and actual values of the state variables was assessed.

The model's operability was tested over a 55-year interval (1802-1856).

The verification of the model's adequacy based on the data on grain export volumes showed that in 37 out of 51 cases (no export occurred during 4 years of the Napoleonic wars), the total grain balance of the exporting regions exceeded the volume of grain actually exported abroad. In the remaining years, the grain balance of the exporting regions was negative. In 43 out of 50 cases, an increase in the calculated grain balance was accompanied by an increase in export volumes. Thus, in no less than 72% of cases, the model adequately describes the dynamics of grain exports abroad.

Among the main directions of interregional transportations, the import into the Northern and Central Non-Black Earth regions stands out unequivocally. According to available information, these regions were in extreme need of grain imports in 64% and 70% of cases, respectively, and imported grain from neighboring or more distant regions (e.g., the Northern region from the Eastern and sometimes from the Central Black Earth region). In the remaining years, the grain shortage in these regions did not exceed the critical level of 5% of consumption. The coincidence of the calculated and actual import needs of the importing regions (import or self-sufficiency) and the export possibilities of the exporting regions (considering a 5-10% adjustment for high profit margins of over 60-80% – see above) was 76.5% (39 years out of 51), i.e., the error in assessing the directions and saturation of interregional transportations was 23.5%.

The conducted study of the model's sensitivity and numerical experiments with it allow us to draw the following conclusions.

The grain production volumes in the regions of European Russia experienced significant fluctuations throughout the studied period. The main factor influencing the variability of the total grain harvests was the crop yields, which were very unstable due to the relatively low level of agriculture. This was particularly characteristic of the period from 1754 to the early 1870s, which was marked by low yields (on average 3.8 chetverts/ha, with a minimum yield of 1.7 and a maximum yield of 6.4 chetverts/ha). Only the last 50 years of the period under consideration are characterized by a reduction in the range of variation of total harvests to $\pm 11\%$ of the average, whereas the preceding nearly century-long period was characterized by an annual variation range of up to $\pm 31\%$.

The gradual expansion of sown areas in almost all regions (only in the Northern and Central Non-Black Earth regions did the sown areas decrease in the last 60 years of the period under consideration to almost the level of the mid-18th century, and in the Central Black Earth region, this process affected the last thirty years), as well as the improvement of agriculture (transition in many regions from the fallow system to the three-field system, fertilization) and the expansion of grain crops in old arable lands, were the main factors of the positive trend in the dynamics of total grain harvests.

The study of the model showed that grain consumption in the regions depended not only on the population size of the region but also significantly on the occupations of the residents. Under the influence of this factor, the total consumption could decrease by 17-41%. Alongside population growth, the expansion of sown areas was also a factor in the increase of total consumption, particularly significantly affecting the consumption in the Eastern, Volga, Southeastern, Southwestern, Steppe, Left-Bank Ukrainian, and in the first century of the period, the Central Black Earth regions. This factor also noticeably influenced the total consumption in the Baltic region due to the high density of sowing per unit area. The fluctuations in the number of the army and navy had the least impact on the dynamics of the total needs of the regions, as the grain expenditures for the needs of the army and navy ranged from 0.69% to 2% of the total grain requirement in different years.

The grain balance of the regions deserves separate consideration. Serious fluctuations in crop yields and, consequently, in the total harvest led to many years with a negative balance even in the grain-exporting regions, while at the same time resulting in several years with a positive balance in regions that were traditional consumers of imported grain, such as the Northern and Central Non-Black Earth regions.

This state of the grain balances changed the initial notion that exports were possible only from regions with a positive grain balance. It is reliably known that there was at least export abroad and, judging by the price ratios, there must have been imports into the Northern and Central Non-Black Earth regions during years characterized by a dominance of negative regional balances. Apparently, the grain necessary for such export could only be obtained by replacing part of the grain ration with lower-quality grain or its substitutes. Considering that for almost the entire studied period, the consumption norm for a person was 2 chetverts of flour per year (approximately 300 kg in flour equivalent), and currently, the norm is considered to be 115 kg in flour equivalent per year, it can be assumed that it was possible to reduce grain consumption to about 1.5 – 1.25 chetverts per person by additionally introducing forest products, livestock products, and vegetables (the latter to a lesser extent due to their limited distribution at the time). The differentiation of grain producers, while not saving their upper echelon (primarily large landowners of the Southwestern, Steppe, and Left-Bank Ukrainian regions) from crop failures, nevertheless gave them grain surpluses for export even in low-yield years due to larger sown areas. Thus, in cases primarily determined by price ratios and high profit margins, up to 29% of the region's total necessary consumption could be included in the volume of potential grain export.

Another feature of the regional grain balances is their interconnected movement – until the second half of the 1830s – early 1840s, they change in sign almost uniformly across all regions (though some differences appear when determining export capabilities and import needs – an additional category of "self-sufficient" regions is added, which do not need grain imports and have nothing to export without additional incentives). In general, about 60% of the years in the studied period are characterized by such coordinated movement of grain balances. This situation arises due to the previously mentioned exceptionally strong influence of crop yields on total harvests in this part of the period. With the gradual development of agriculture, such dependence becomes less fatal.

From the mid-1830s, a new stage in the development of the internal grain market apparently begins, as the conditions of its existence significantly change – whereas earlier imports into needy regions could mostly only be made from regions with negative grain balances, which naturally entailed additional difficulties, now the balances of the regions differentiate, and in almost 90% of the years of the remaining studied period, both positive and negative balances exist simultaneously each year. This confirms our previously expressed view that a unified market in European Russia first emerged around the 1830s-1840s – as we can see, it is from this time that conditions for profitable interregional grain transportation began to form.

Moreover, the following pattern in the dynamics of regional grain balances is observed – it becomes somewhat orderly again in the 1850s, and then in the second half of the 1860s – the first half of the 1870s, after which there is another period of "stratification" of balances according to the economic orientation of the regions. According to model calculations, the dynamics of the needs of the Central Non-Black Earth region are captured by exporting regions only by 25% in the second half of the 1820s – the first half of the 1830s. According to model calculations, mass interregional transportation sporadically becomes possible from the late 18th century and has the capacity to meet the needs of regions from the 1830s onwards. In the 1830s-1840s, the deviation of the total transportation volumes from the consumption norm of importing and exporting regions (limited to 5% in both directions) does not exceed $\pm 10\%$. Further, the same situation repeats as with the balances – in the second and third quarters of the 19th century, interregional transportation diminishes despite the acute need for it (though lesser in some years – for example, in 1847-1849, a cholera epidemic spread in Russia, claiming about a million lives, and thus the overall need for grain in European Russia decreased by 1.4%). The activation of interregional transportation is observed from the late 1870s – early 1880s and continues almost until the end of the studied period.

Conclusions

The comparison of the optimally possible interregional and international transportation under given actual conditions with the real transportation allows us to determine the degree of inconsistency of the existing grain market with the formed and well-developed "ideal" market. The smaller this inconsistency, the closer the market ties and the more developed the grain market appears.

The undeniable advantages of this approach to building a simulation model include the method's insensitivity to the lack of a large number of precise data and the possibility of constructing the model even based on estimated parameter values.

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