ISSN 2587-814X (print), ISSN 2587-8158 (online)
Russian version: ISSN 1998–0663 (print), ISSN 2587–8166 (online)

Vol. 16 No. 4 – 2022

BUSINESS INFORMATICS

HSE SCIENTIFIC JOURNAL

Publisher:
National Research University
Higher School of Economics

The journal is published quarterly

The journal is included
into the list of peer reviewed
scientific editions established
by the Supreme Certification
Commission of the Russian Federation

CONTENTS

Address:
26-28, Shabolovka Street,
Moscow 119049, Russia

Tel./fax: +7 (495) 772-9590 *28509
http://bijournal.hse.ru
E-mail: bijournal@hse.ru

Circulation:
English version – 100 copies,
Russian version – 100 copies,
online versions in English and Russian – open access

Printed in HSE Printing House
44, build.2, Izmaylovskoye Shosse,
Moscow, Russia

ABOUT THE JOURNAL

Business Informatics is a peer reviewed interdisciplinary academic journal published since 2007 by National Research University Higher School of Economics (HSE), Moscow, Russian Federation. The journal is administered by HSE Graduate School of Business. The journal is published quarterly.

The mission of the journal is to develop business informatics as a new field within both information technologies and management. It provides dissemination of latest technical and methodological developments, promotes new competences and provides a framework for discussion in the field of application of modern IT solutions in business, management and economics.

The journal publishes papers in the areas of, but not limited to: modeling of social and economic systems, digital transformation of business, innovation management, information systems and technologies in business, data analysis and business intelligence systems, mathematical methods and algorithms of business informatics, business processes modeling and analysis, decision support in management.

The journal is included into the list of peer reviewed scientific editions established by the Supreme Certification Commission of the Russian Federation.

The journal is included into Scopus, Web of Science Emerging Sources Citation Index (WoS ESCI), Russian Science Citation Index on the Web of Science platform (RSCI), EBSCO.

International Standard Serial Number (ISSN): 2587-814X (in English), 1998-0663 (in Russian).

ABOUT THE HIGHER SCHOOL OF ECONOMICS

Consistently ranked as one of Russia's top universities, the Higher School of Economics (HSE) is a leader in Russian education and one of the preeminent economics and social sciences universities in Eastern Europe and Eurasia.

Having rapidly grown into a well-renowned research university over two decades, HSE sets itself apart with its international presence and cooperation.

Our faculty, researchers, and students represent over 50 countries, and are dedicated to maintaining the highest academic standards. Our newly adopted structural reforms support both HSE's drive to internationalize and the groundbreaking research of our faculty, researchers, and students.

Now a dynamic university with four campuses, HSE is a leader in combining Russian educational traditions with the best international teaching and research practices. HSE offers outstanding educational programs from secondary school to doctoral studies, with top departments and research centers in a number of international fields.

Since 2013, HSE has been a member of the 5-100 Russian Academic Excellence Project, a highly selective government program aimed at boosting the international competitiveness of Russian universities.

ABOUT THE GRADUATE SCHOOL OF BUSINESS

HSE Graduate School of Business was created on September 1, 2020. The School will become a priority partner for leading Russian companies in the development of their personnel and management technologies.

The world-leading model of a 'university business school' has been chosen for the Graduate School of Business. This foresees an integrated portfolio of programmes, ranging from Bachelor's to EMBA programmes, communities of experts and a vast network of research centres and laboratories for advanced management studies. Furthermore, HSE University's integrative approach will allow the Graduate School of Business to develop as an interdisciplinary institution. The advancement of the Graduate School of Business through synergies with other faculties and institutes will serve as a key source of its competitive advantage. Moreover, the evolution and development of the Business School's faculty involves the active engagement of three professional tracks at our University: research, practice-oriented and methodological.

What sets the Graduate School of Business apart is its focus on educating and developing globally competitive and socially responsible business leaders for Russia's emerging digital economy.

The School's educational model will focus on a project approach and other dynamic methods for skills training, integration of online and other digital technologies, as well as systematic internationalization of educational processes.

At its start, the Graduate School of Business will offer 22 Bachelor programmes (three of which will be fully taught in English) and over 200 retraining and continuing professional development programmes, serving over 9,000 students. In future, the integrated portfolio of academic and professional programmes will continue to expand with a particular emphasis on graduate programmes, which is in line with the principles guiding top business schools around the world. In addition, the School's top quality and all-encompassing Bachelor degrees will continue to make valuable contributions to the achievement of the Business School's goals and the development t of its business model.

The School's plans include the establishment of a National Resource Center, which will offer case studies based on the experience of Russian companies. In addition, the Business School will assist in the provision of up-to-date management training at other Russian universities. Furthermore, the Graduate School of Business will become one of the leaders in promoting Russian education.

The Graduate School of Business's unique ecosystem will be created through partnerships with leading global business schools, as well as in-depth cooperation with firms and companies during the entire life cycle of the school's programmes. The success criteria for the Business School include professional recognition thanks to the stellar careers of its graduates, its international programmes and institutional accreditations, as well as its presence on global business school rankings.

DOI: 10.17323/2587-814X.2022.4.7.18

Peculiarities of applying methods based on decision trees in the problems of real estate valuation

Mikhail B. Laskin [a]
E-mail: laskinmb@yahoo.com

Lyudmila V. Gadasina [b]
E-mail: l.gadasina@spbu.ru

[a] St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS)
Address: 39, 14 line, Vasilevskiy Island, St. Petersburg 199178, Russia

[b] St. Petersburg State University, Center for econometrics and business analytics (CEBA)
Address: 7/9, Universitetskaya emb., Saint-Petersburg 199034, Russia

Abstract

The increasing flow of available market information, the development of methods of machine learning, artificial intelligence and the limited capabilities of traditional methods of real estate valuation are leading to a significant increase of researchers' interest in real estate valuation by applying methods based on decision trees. At the same time, the distribution of real estate prices is well approximated by a lognormal distribution. Therefore, traditional methods overestimate the predicted values in the region below the average of the available data set and underestimate the predicted values in the region above the average. This article shows the reasons for these features and proposes an adaptive random forest algorithm which corrects the results of the basic algorithm prediction by revising the bias of these predicted values. The results were tested on the real estate offer prices in St. Petersburg.

Keywords: decision trees, random forest, real estate market, price-forming factors, market value apprising

Citation: Laskin M.B., Gadasina L.V. (2022) Peculiarities of applying methods based on decision trees in the problems of real estate valuation. *Business Informatics*, vol. 16, no. 4, pp. 7–18.
DOI: 10.17323/2587-814X.2022.4.7.18

Introduction

The number of publications devoted to non-traditional methods of real estate valuation, focused on large samples of data, and, in particular, methods of machine learning, has significantly increased recently.

The interest of researchers in this topic is understandable: the changed information environment and the wide choice of specialized application packages allow us to consider what was not previously available from evaluation methods; see for example [1–6]. The method of hedonic pricing, linear regression models, logarithmic or partial-logarithmic dependence are considered in [7–10]. Data mining techniques, such as neural networks [11–15] and Support Vector Machines [16] are proposed, the results of such methods as decision trees, naive Bayesian classifier and ensemble algorithm AdaBoost are compared [17]. This paper discusses the prediction biases that arise from the application of decision tree based methods in real estate valuation and proposes an algorithm to correct for these biases. Interest in this group of methods is confirmed by [18–21]. Researchers are turning to machine learning methods, in particular decision tree based methods, under conditions where there is an extensive set of input data and there are no a priori assumptions about the form of the function $F(\cdot)$, describing the dependence $V = F(x_1, x_2, ..., x_n)$ between the output or dependent variable V, which is usually the price, and predictors $x_1, x_2, ..., x_n$, which are the price-forming factors.

The advantage of decision tree based methods is that knowledge of the type of function $F(\cdot)$ is not required. However, this does not mean that the specific properties of real estate price distributions do not affect the results of such algorithms. The method of constructing a single decision tree consists in successive decomposition of the entire predictor domain into subsets of smaller size. Each element of such a subset is assigned a value of the arithmetic average of the values of the dependent variable on such a subset. This is an iterative procedure, known as recursive decomposition:

1. At each step, the datasets are divided into subsets.

2. Each of the subsets obtained on the previous step is, in turn, divided. In general, there will be a decomposition of the space of independent variables (predictors) $x_1, x_2, ..., x_n$ into some number (for example, m) of non-intersecting domains $R_1, R_2, ..., R_m$.

3. Outcome variable V values predicted as the same value for all observations in the domain R_j, $j = 1, 2, ..., m$. This value is equal to the average of all responses that fall into R_j. At each step, dividing provides a minimum of root mean square deviations of RSS (residual sum of squares):

$$RSS = \sum_{j=1}^{m} \sum_{i \in R_j} (V_i - \hat{V}_{R_j})^2,$$

where $\hat{V}_{R_j}$ is the response average value of the training observations from the set R_j.

From the computational point of view, it is not feasible to consider all combinations of decompositions to the greatest possible depth. Therefore, the basic principle of "greedy" algorithms is used: the optimal division (in terms of RSS minimum) is determined only at the current step. The depth of decomposition can be as large as the volume of data allows. Possible rules for stopping: by the number of steps, by the number of elements in subsets (tree sheets), by reaching a pre-determined improvement in the result at the next step.

The model of interest is division with resulting sets $R_1, R_2, ..., R_m$ containing a "sufficiently large number of elements" and the response values standard deviation being not too large from its average value within the predetermined accuracy in each set.

1. Methodology

In the problems of real estate valuation, the application of the decision tree method generates additional opportunity. It allows you to split a set of objects into subsets with less variance, with more homogeneous objects within each of them. They can be studied separately. It should be noted that decision tree based algorithms can operate with both real and factor predictors.

Thus, the advantages of using decision trees are:

1. Clear model interpretation.

2. Such an algorithm reflects people's decision-making process.

3. For one decision tree there is a visual graphical representation.

4. Decision trees easily operate with factor and rank variables.

The disadvantage of such algorithms is low prediction accuracy; dispersion within each decomposition set is not small enough – on leaves). This drawback can be eliminated by applying ensemble decision tree based methods, e.g. random forest, gradient or stochastic boosting. Such algorithms do not produce interpretable results, but they allow you to analyze the importance of predictors in predicting the response and allow you to operate with factor variables. This paper considers the random forest method.

Decision tree based algorithms should be applied for real estate evaluation taking into account the peculiarities of the target variable V, since there are reasons to assume that it is a lognormally random variable. Apparently, Aichinson and Brown [22] first pointed out this fact, and later this observation was confirmed in research such as [4]. Research [23, 24] gives a theoretical substantiation of the reasons for this kind of distribution appearance.

A random variable V is called log-normally distributed with parameters μ and σ, if the random variable $\ln(V)$ is normally distributed with the same parameters. In this case math ematical expectation $E(V) = e^{\mu+\sigma^2/2}$, median $Median(V) = e^{\mu}$, and mode $Mode(V) = e^{\mu-\sigma^2}$. The fraction of empirical distribution values to the left of $E(V)$ (less than the mathematical expectation) can be estimated as

$$\frac{1}{2} + \Phi\left(\frac{\sigma}{2}\right),$$

where $\Phi(\cdot)$ is a Laplace function. The fraction of such values depends on the standard deviation and increases with its growth.

Thus, if we consider the hypothesis that the results of decision tree based algorithms prediction are also log-normally distributed, and moreover, form a joint lognormal distribution with the observed values in the sense of a two-dimensional normal distribution of logarithms, then it becomes clear that decision tree based methods are better applied not to the prices of real estate objects, but to their logarithms. Since at each step the standard deviations of RSS from the mean values in the subsets R_1, R_2, ..., R_m, are minimized, within which the principle of lognormal distribution of the dependent variable V, can be preserved, then in case of ensemble algorithms based on decision trees the prediction of results on the test set will be quite accurate only in the domain of values close to the average values of the responses. In the area of values below the average, the predictions of such algorithms will be overestimated, above the average – underestimated, increasing as we approach the boundaries of empirical distributions. An appropriate diagram showing the relationship between the true and predicted values will, with acceptable prediction accuracy, show scattering clouds extending along some straight line, somewhat displaced relative to the bisector of the first coordinate angle by rotating around a point, with the coordinates of the average response value and the average prediction value. In this case most of the results will be overestimated, because in a lognormal distribution most of the possible values are to the left of the average (less than the average). In this case, for $\ln(V)$, which has a normal distribution, the areas of over- and under-prediction will be about the same by the number of elements. In the described approach, the prediction results remain displaced relative to the true values. This is observed, for example, in [20].

In this paper, we propose to apply an adaptive method based on the correction of the prediction results of the ensemble algorithm random forest. Adaptation consists of the following procedure. The set of initial data is divided into three parts: training, validation and test. The training procedure (selection of parameters) of the random forest algorithm is performed on the first set. Next, we analyze the dependence of the predicted values for the validation set on their true values. The prediction is corrected by rotating the scattering cloud in coordinates (response value is a prediction) by some angle, which removes the displacement from the bisector of the first coordinate angle and recalculates the predicted values. At the third step, the quality of the predictions of the random forest algorithm, taking into account the correction, is checked on the test set.

It should be noted that in any case the estimate of market value will be determined not as the most likely price, but as the average price (if the algorithm was applied to the original prices) or the geometric mean price (if the algorithm was applied to the logarithms of prices).

2. Applying the technique to real market data

Approbation of the procedure we have described was carried out on the following example. Consider the prices for secondary residential real estate in the mass-market sector in St. Petersburg in February 2017 taken from an open source (the advertising publication Real Estate Bulletin No. 1765, February 2017, not indexed in scientometric databases), the total number of records in the dataset after removing incorrect ads was 4294. The random forest method will be used for the predictive model. The dependent (target) variable is the price per square meter of secondary residential real estate in the mass-market sector in St. Petersburg in February 2017 or its logarithm. The predictors are:

- the number of rooms in the apartment – a quantitative variable
- administrative area of the location – a factor variable
- floor – a factor variable
- number of floors in the house – a factor variable
- living space – a quantitative variable
- total area – a quantitative variable
- subway accessibility – a binary variable
- house type – a factor variable
- number of bathrooms, their type – a factor variable.

The calculations were carried out in the open source software R. First of all, let us pay attention to the asymmetric distribution of prices (*Fig. 1*).

The verification of the null hypothesis about following the empirical distribution of prices for one m^2 logarithmically normal distribution is associated with certain difficulties. The sample size is 4294. As was rightly noted in [25], most of the common and fre-

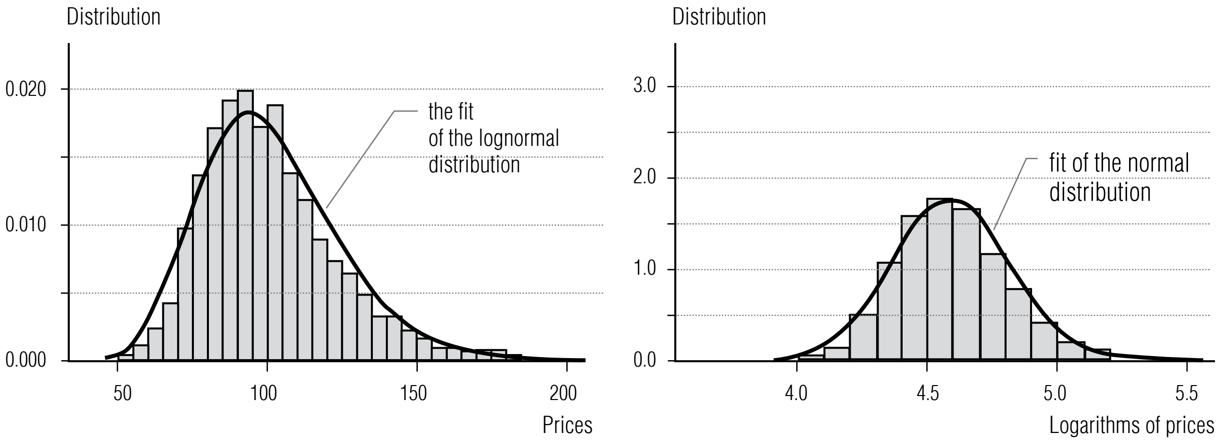


Fig. 1. Prices distribution (left) and their logarithms (right) of secondary residential real estate in St. Petersburg in February 2017.

quently used criteria do not work for samples of the order of even one thousand observations, since their statistics significantly depend on the sample size. Therefore, the question arises of finding, in addition to the visual correspondence shown in *Fig. 1*, additional arguments in favor of a particular type of distribution. In this context, we note the work [26], in which it is proposed to study the relations between the coefficient of asymmetry and the kurtosis of the observed sample in order to advance the null hypothesis about a particular type of distribution. In this paper, the method proposed in [27] was used to test the corresponding hypotheses. The obtained p-value values provide grounds to assume that the observed sample follows a logarithmically normal law; therefore there are grounds to solve the predictive problem in logarithms.

Let us consider sequentially what predictions are obtained by one decision tree, by the random forest algorithm, and then carry out a procedure for correcting the resulting prediction. For this purpose a training set consisting of 2000 records is formed from the initial sample (volume 4294 records) by random selection, as well as a validation set consisting of 1000 records, and the remaining 1294 records form a test set where the model quality is evaluated.

Trained on a random sample of 2000 records, the tree model gives a price prediction diagram (decision tree cut to 11 terminal nodes), shown in the *Fig. 2.*

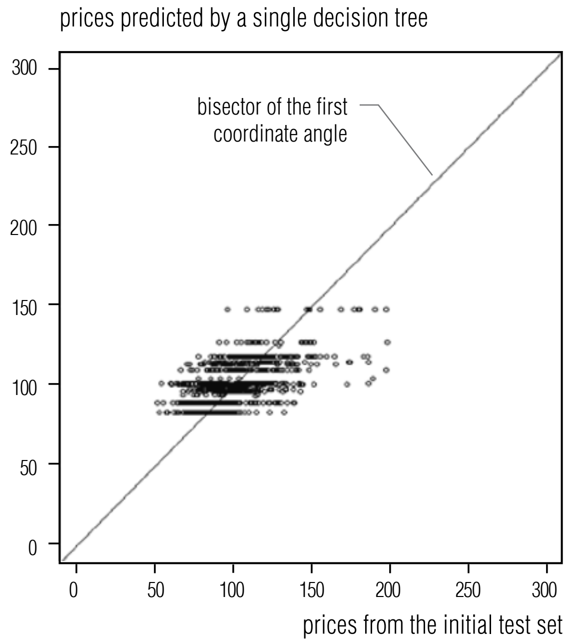


Fig. 2. Prediction diagram on the test set by a single decision tree.

Such decomposition in the evaluation tasks is not meaningless, because it allows us to form groups with a different set of pricing factors in which a group-specific average value and the standard deviation of the observed values from the group average are expected. Predictors that had a significant influence on the formation of the tree were:

♦ administrative district;

♦ building type;

♦ number of floors in the building;

♦ the number and type of bathrooms;

♦ total area;

♦ living area;

♦ metro accessibility;

♦ floor.

The quality of the predictions shown in *Fig. 2* is unsatisfactory – too large ranges of values are predicted to have the same price. (The ideal would be the predictions in *Fig. 2* near the bisector of the first coordinate angle). An effective way to deal with the same predictions is the random forest algorithm. This algirothm builds a large number of trees and averages the results for each object. *Figure 3* shows the result of the random forest algorithm for predicting the price per square meter of secondary residential real estate for the test set. Each tree in the algorithm was built based on 4 predictors, the total number of trees – 200.

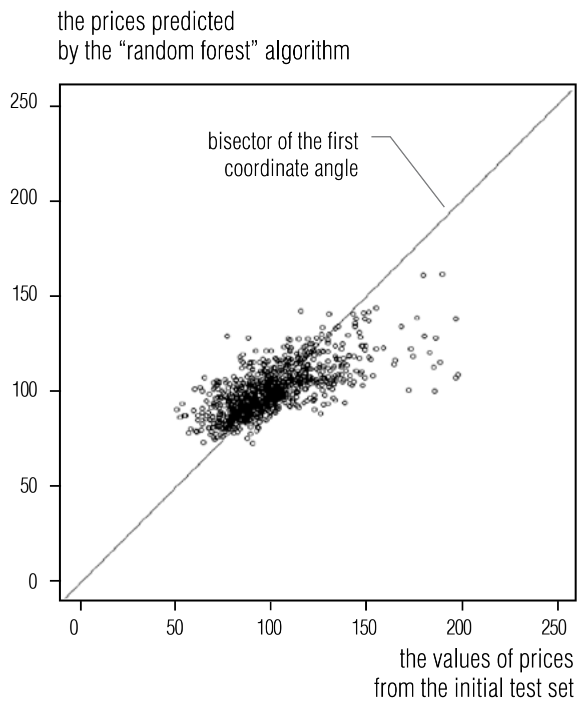


Fig. 3. Diagram of predictions on the test set by the "random forest" algorithm.

A similar figure, with a characteristic displacement of the predictions, can be seen in the article [20] on algorithms based on decision trees when analyzing the real estate market in Ankara. In *Fig. 3* we can see the scatter of the predictions, characteristic of the joint lognormal distribution, that increases with rising price, and the fact that most of the predictions (above the bisector) appear to be overestimated, which is to be expected, given the asymmetric distribution of prices in the original set. Also note that the predictions thus obtained are predictions of average values (mathematical expectations in subsets), and not the market value as the most likely price. The estimate of market value is, in fact, somewhat lower.

Let's apply the adaptive random forest method to the logarithms of prices.

Figure 4 shows the result of the random forest algorithm for predicting the logarithm of the price per square meter of secondary residential property (the number of trees – 200, a random selection of 4 predictors on each tree, a training random sample of 2000 records).

Figure 4 shows that the areas of over- and under-prediction are approximately the same, but the axis of the scattering cloud has a characteristic trend that does not coincide with the bisector of the first coordinate angle. Note that the predictions obtained by potentiating

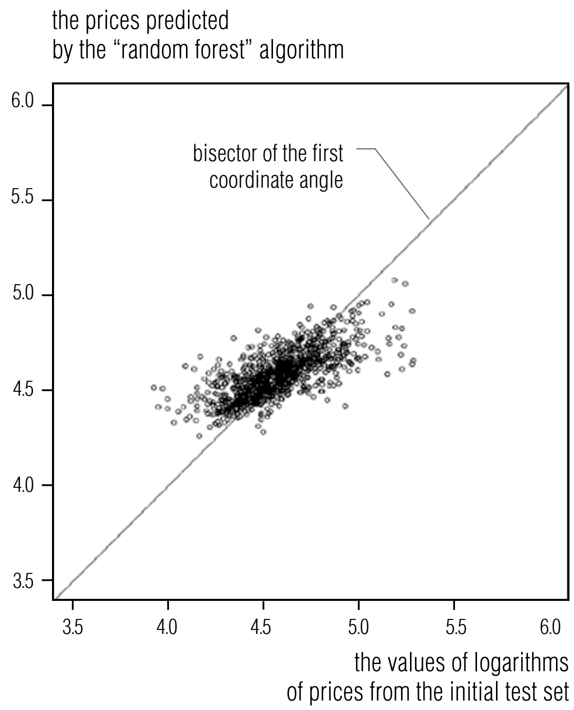


Fig. 4. Diagram of predictions on the test set by the “random forest” algorithm.

the results are predictions of the median values (geometric averages in the subsets R_1, R_2, ..., R_{21}), and not the market value as the most likely price. The estimate of market value in this case is somewhat lower.

The results of the predictions of the random forest algorithm can be corrected by simple transformations of the results. Using the linear regression method, we determine the linear trend of the scattering cloud shown in *Fig. 4*. The result is shown in the *Fig. 5*.

In this example, the trend line equation is

$$\ln(\hat{V}) = 0.40791 \cdot \ln(V) + 2.71920, \qquad (1)$$

where $\ln(V)$ is the observed value of the logarithm of the price;

$\ln(\hat{V})$ is the predicted value of the logarithm of the price.

The statistical characteristics of the obtained trend line: p-value of Student’s test for model coefficients and Fisher’s criterion for the created model is machine zero. The standard error is 0.086, i.e., the parameter spread with probability 0.99 is in the interval ~ +/–26%. The relatively low value of R^2 = 0.5053 does not spoil the situation, because there is no strictly linear relationship between $\ln(\hat{V})$ and $\ln(V)$ in this case, our expectations are related to the multivariate normal distribution of $\mathrm{lln}(\hat{V})$ and $\ln(V)$, for which the linear trend coincides with the major axis of the ellipse of scattering (see more about multidimensional logarithmic normal distribution [27]). Equation (1) corresponds to the line shown in bold black in *Fig. 5.* For the scattering cloud shown in *Fig. 5*, the value of the standard deviation of the observed values from the predicted values is 0.168. It remains for us to correct the predictions shown in *Figs. 3*, *4*, and *5.* For this purpose, all values are centered (horizontal and vertical averages are subtracted). The scatterplot is rotated counterclockwise in the new

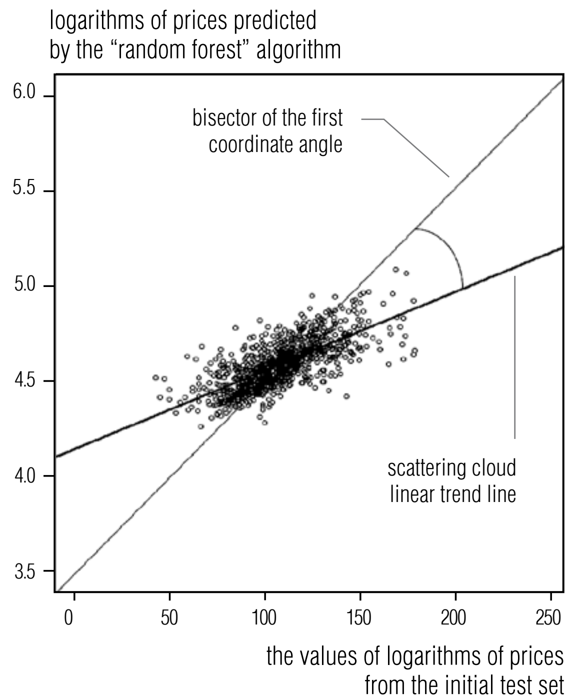


Fig. 5. Diagram of predictions on the test set by the “random forest” algorithm.

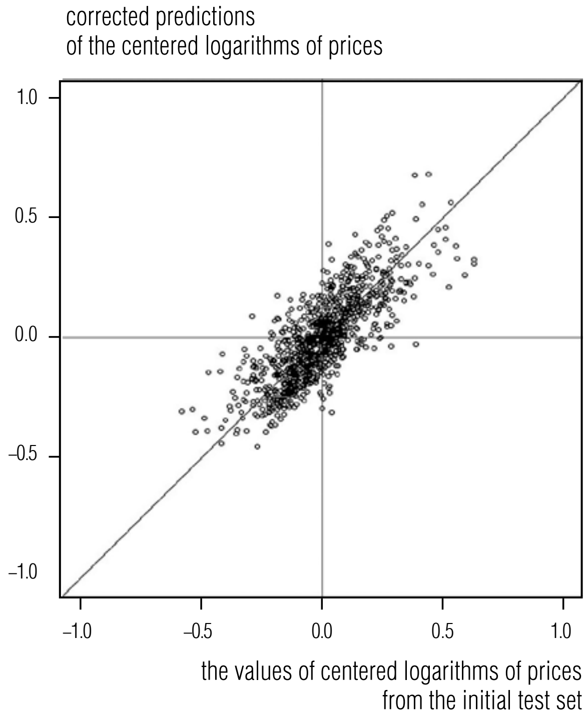


Fig. 6. Corrected predictions on the test set by the "random forest" algorithm.

coordinate system and the angle is the difference between the line given by equation (1) (*Fig. 5*, bold black) and the bisector of the first coordinate angle. Such angle φ is equal to $\frac{\pi}{4} - \text{arctg}(0.40791)$. The result of the rotation is shown in *Fig. 6*.

For the scattering cloud shown in *Fig. 6*, the value of the standard deviation of the observed values from the predicted values is 0.118. Thus, the correction performed gives a better prediction quality.

Now we have two vectors of values: a vector of predictions of centered price logarithms on the test set (we denote it by) and a vector of corrected predictions of centered price logarithms (we denote it by y^*).

In *Fig. 7*, the horizontal axis shows the values of the components of the vector y^*, the vertical shows the values of the vector components y^+.

The set shown in *Fig. 7* has a linear trend of the following form $y^+ = \alpha \cdot y^*$, which is easily determined by using the library function lm of the statistical package R. In this example we get $y^+ = 1.388$. Now we firstly apply sequentially the random forest model already obtained on the training sample and then the prediction correction obtained on the validation set to the test set (1294 records).

Figure 8 shows predictions of centered price logarithms on the verifying set (the random forest model obtained on the training set was applied).

Figure 9 shows corrected predictions of centered price logarithms on the verifying set (using the random forest model obtained on the training set and the correction obtained on the test set).

Here are the necessary formulas and sequence of operations:

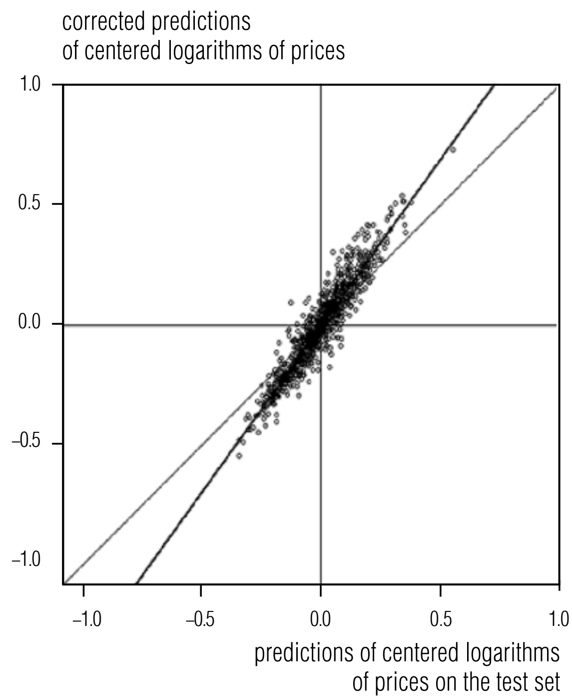


Fig. 7. Correlation of predicted and corrected values.

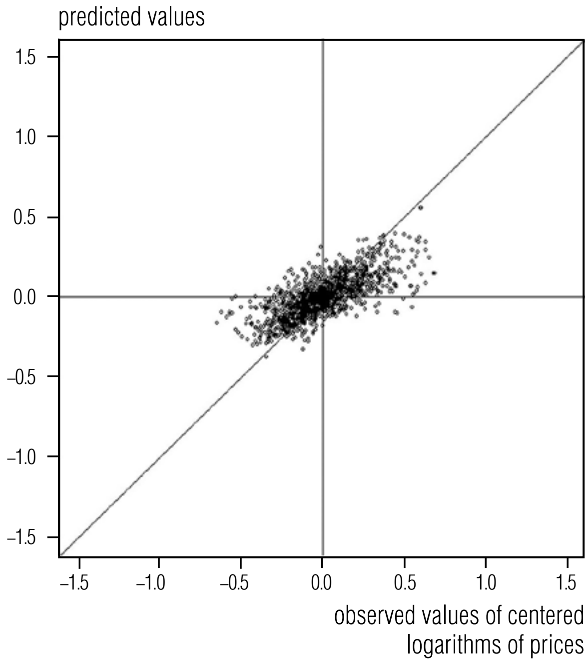


Fig. 8. The correlation between the observed values of centered logarithms of prices and their predicted values by the random forest algorithm.

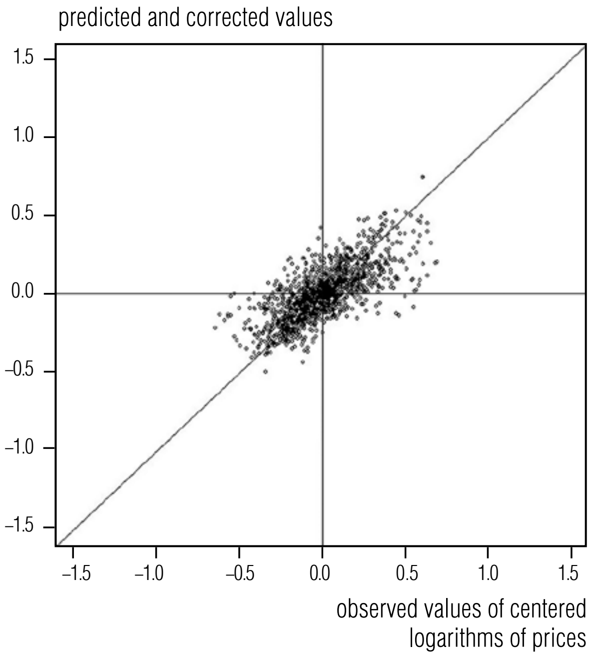


Fig. 9. The correlation of observed values of centered logarithms of prices and their predicted values by the random forest algorithm and corrected by the formula obtained on the test set.

1. Let $\overrightarrow{\ln(V)} = (\ln(V_1), \ln(V_2), \ln(V_3), ..., \ln(V_m))$ are observed values of the logarithms of prices with the average α, $\overrightarrow{\ln(\hat{V})} = (\ln(\hat{V}_1), \ln(\hat{V}_2), \ln(\hat{V}_3), ..., \ln(\hat{V}_m))$ are predicted values on the training set (test, verifying, m – can take different values) values of price logarithms with the average β. Then

$$y_i^* = \ln(\hat{V}_i) - \beta,\ x_i^* = \ln(V_i) - \alpha \text{ and}$$

$$\begin{pmatrix} x_i^+ \\ y_i^+ \end{pmatrix} = (x_i^+, y_i^+) \cdot \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix},$$

where rotation angle

$$\varphi = \frac{\pi}{4} - \operatorname{arctg}(0.40791)$$

(under the arctangent sign is the tangent of the inclination angle of the linear trend of the scattering cloud). See *Figs. 4*, 5, *6.*

2. We compare the predicted and corrected values of the centered logarithms on the validation sample (*Fig. 7*), determine the angular coefficient α of the trend $y^+ = \alpha \cdot y^*$.

3. The predicted and corrected value of y^+ on the test sample is compared with the observed values of centered logarithms of prices x^* (*Figs. 8*, *9*). For the dataset under study, the most significant predictors (when assessing relative importance using the method of features permutation) were the city district, the type of building, the number of floors in the house and the total floor area of the premises. The least important were: the floor location of the premises, the proximity of the subway, the number of rooms.

Conclusion

1. Algorithms based on decision trees predict average values if applied for prices) and average values if applied for logarithms of prices), rather than the most likely values. The market value estimate predicted by

them is somewhat higher than the market value estimate by the most probable value.

2. Due to the lognormal distributions of prices in the original datasets, the predictions constructed using methods based on decision trees require correction. The procedure proposed in this paper allows for such a correction using double cross-validation when a validation subset of the initial data set is selected on which the adaptation of the algorithm is carried out. Then the results are evaluated on the test dataset. The approbation conducted showed the effectiveness of the proposed approach.■

Acknowledgments

The research for this article was supported by a grant from the Russian Science Foundation (project No. 20-18-00365), and by a grant from the Russian Foundation for Basic Research (project number 20-01-00646 A).

References

1. Gu S., Kelly B., Xiu D. (2019) Empirical asset pricing via machine learning. *Chicago Booth Research Paper No. 18-04, 31st Australasian Finance and Banking Conference 2018, Yale ICF Working Paper No. 2018-09.* https://doi.org/10.2139/ssrn.3159577

2. Jim C.Y., Chen W.Y. (2006) Impacts of urban environmental elements on residential housing prices in Guangzhou (China). *Landscape and Urban Planning,* vol. 78, no. 4, pp. 422–434. https://doi.org/10.1016/j.landurbplan.2005.12.003

3. Kok N., Koponen E.-L., Martínez-Barbosa C.A. (2017) Big data in real estate? From manual appraisal to automated valuation. *The Journal of Portfolio Management,* vol. 43, no. 6, pp. 202–211. https://doi.org/10.3905/jpm.2017.43.6.202

4. Ohnishi T., Mizuno T., Shimizu C., Watanabe T. (2011) On the evolution of the house price distribution. *Columbia Business School. Center of Japanese Economy and Business, Working Paper Series, 296.* https://doi.org/10.7916/D8794CJJ

5. Steurer M., Hill R.J., Pfeifer N. (2021) Metrics for evaluating the performance of machine learning based automated valuation models. *Journal of Property Research,* vol. 38, no. 2, pp. 99–129. https://doi.org/10.1080/09599916.2020.1858937

6. Tay D.P., Ho D.K. (1992) Artificial intelligence and the mass appraisal of residential apartments. *Journal of Property Valuation and Investment*, vol. 10, no. 2, pp. 525–540. https://doi.org/10.1108/14635789210031181

7. Anselin L., Lozano-Gracia N. (2008) Errors in variables and spatial effects in hedonic house price models of ambient air quality. *Empirical Economics*, vol. 34, no. 1, pp. 5–34. https://doi.org/10.1007/s00181-007-0152-3

8. Benson E.D., Hansen J.L., Schwartz Jr. A.L., Smersh G.T. (1998) Pricing residential amenities: The value of a view. *The Journal of Real Estate Finance and Economics*, vol. 16, no. 1, pp. 55–73. https://doi.org/10.1023/A:1007785315925

9. Debrezion G., Pels E., Rietveld P. (2011) The impact of rail transport on real estate prices: an empirical analysis of the Dutch housing market. *Urban Studies*, vol. 48, no. 5, pp. 997–1015. https://doi.org/10.1177/0042098010371395

10. Wena H., Zhanga Y., Zhang L. (2015) Assessing amenity effects of urban landscapes on housing price in Hangzhou, China. *Urban Forestry & Urban Greening*, vol. 14, pp. 1017–1026. https://doi.org/10.1016/j.ufug.2015.09.013

11. Do A.Q., Grudnitski G. (1992) A neural network approach to residential property appraisal. *The Real Estate Appraiser*, vol. 58, no. 3, pp. 38–45.

12. Evans A., James H., Collins A. (1992) *Artificial neural networks: An application to residential valuation in the UK*. University of Portsmouth, Department of Economics.

13. McGreal S., Adair A., McBurney D., Patterson D. (1998) Neural networks: the prediction of residential values. *Journal of Property Valuation and Investment*, vol. 16, no. 1, pp. 57–70. https://doi.org/10.1108/14635789810205128

14. Peterson S., Flanagan A. (2009) Neural network hedonic pricing models in mass real estate appraisal. *Journal of Real Estate Research*, vol. 31, no. 2, pp. 147–164. https://doi.org/10.1080/10835547.2009.12091245

15. Worzala E., Lenk M., Silva A. (1995) An exploration of neural networks and its application to real estate valuation. *Journal of Real Estate Research*, vol. 10, no. 2, pp. 185–201. https://doi.org/10.1080/10835547.1995.12090782

16. Kontrimas V., Verikas A. (2011) The mass appraisal of the real estate by computational intelligence. *Applied Soft Computing*, vol. 11, no. 1, pp. 443–448. https://doi.org/10.1016/j.asoc.2009.12.003

17. Park B., Bae J.K. (2015) Using machine learning algorithms for housing price prediction: The case of Fairfax County, Virginia housing data. *Expert Systems with Applications*, vol. 42, no. 6, pp. 2928–2934. https://doi.org/10.1016/j.eswa.2014.11.040

18. Chen T., Guestrin C. (2016) XGBoost: A scalable tree boosting system. *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, pp. 785–794. https://doi.org/10.1145/2939672.2939785

19. Cordoba M., Carranza J.P., Piumetto M., Monzani F., Balzarini M. (2021) A spatially based quantile regression forest model for mapping rural land values. *Journal of Environmental Management*, vol. 289, no. 1, 112509. https://doi.org/10.1016/j.jenvman.2021.112509

20. Yilmazer S., Kocman S. (2020) A mass appraisal assessment study using machine leaning based on multiple regression and random forest. *Land Use Policy*, vol. 99, 104889. https://doi.org/10.1016/j.landusepol.2020.104889

21. Webb G.I. (2000) Multiboosting: A technique for combining boosting and wagging. *Machine Learning*, vol. 40, no. 2, pp. 159–196. https://doi.org/10.1023/A:1007659514849

22. Aitchinson J., Brown J.A.C. (1963) *The Lognormal distribution with special references to its uses in economics*. Cambridge: At the University Press.

23. Rusakov O., Laskin M., Jaksumbaeva O. (2016) Pricing in the real estate market as a stochastic limit. Log Normal approximation. *International Journal of the Mathematical models and methods in applied sciences*, vol. 10, pp. 229–236.

24. Rusakov O., Laskin M., Jaksumbaeva O., Ivakina A. (2015) Pricing in real estate market as a stochastic limit. Lognormal approximation. *Second International Conference on Mathematics and Computers in Sciences and in Industry. Malta, 2015*. https://doi.org/10.1109/MCSI.2015.48

25. Lemeshko B. Yu., Lemeshko S.B., Semenova M.A. (2018) On the issue of statistical analysis of big data. *Bulletin of Tomsk University*, vol. 44, pp. 40–49 (in Russian). https://doi.org/10.17223/19988605/44/5

26. Zhukova G.N. (2016) Identification of the probability distribution by the coefficients of asymmetry and kurtosis. *Automation. Modern Technologies*, vol. 5, pp. 26–33 (in Russian).

27. Laskin M.B. (2020) Multidimensional lognormal distribution in real estate appraisals. *Business Informatics*, vol. 14, no. 2, pp. 48–63. https://doi.org/10.17323/2587-814X.2020.2.48.63

About the authors

Mikhail B. Laskin

Cand. Sci. (Phys.-Math.);

Associate Professor, St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS), 39, 14 line, Vasilevskiy Island, St. Petersburg 199178, Russia;

E-mail: laskinmb@yahoo.com

ORCID: 0000-0002-0143-4164

Lyudmila V. Gadasina

Cand. Sci. (Phys.-Math.);

Associate Professor, St. Petersburg State University, 7/9, Universitetskaya emb., Saint-Petersburg 199034, Russia;

E-mail: l.gadasina@spbu.ru

ORCID: 0000-0002-4758-6104

DOI: 10.17323/2587-814X.2022.4.19.35

Simulation of rates of traffic accidents involving unmanned ground vehicles within a transportation system for the 'smart city'

Andranik S. Akopov
E-mail: akopovas@umail.ru

Levon A. Beklaryan
E-mail: beklar@cemi.rssi.ru

Central Economics and Mathematics Institute, Russian Academy of Sciences
Address: 47, Nakhimovsky prospect, Moscow 117418, Russia

Abstract

This article presents an approach to simulation of the rates of road traffic accidents involving unmanned ground vehicles within a multi-agent intelligent transportation system for the 'smart city.' A new simulation model of an intelligent transport system has been developed which makes it possible to significantly reduce the number of potential road traffic accidents (TAs) and implements the concept of socially-centered management of the urban economy. The software implementation of such a large-scale agent-based model was carried out using the FLAME GPU framework, which allows us to effectively parallelize the agents' behaviour logic and consider their individual decision-making systems when modelling the spacial dynamics of an ensemble of unmanned ground vehicles (UGVs) interacting with other road users: the usual manned ground vehicles (MGVs), unexpected obstacles (e.g., pedestrians, etc.). Various scenarios of such agents' behaviour in an intelligent transportation system are studied, including the occurrence of an accident under certain conditions (e.g., under the high speed and traffic intensity of UGVs, etc.) and various configurations of the digital road network (DRN). We determine the parameter values that provide for the individual decision-making system of UGVs remaining stable with respect to the characteristics of the external environment (including in extreme situations), ensuring the safety of other road users on the scale of the 'smart city.'

Keywords: socially-centered urban management, agent-based modeling, intelligent transportation systems, smart city, simulation of traffic accidents, unmanned vehicles, FLAME GPU

Citation: Akopov A.S., Beklaryan L.A. (2022) Simulation of rates of traffic accidents involving unmanned ground vehicles within a transportation system for the 'smart city'. *Business Informatics*, vol. 16, no. 4, pp. 19–35. DOI: 10.17323/2587-814X.2022.4.19.35

Introduction

Nowadays, the transition to socially-centered management of the urban economy within the development of the 'smart city' [1] is being updated as a complex urban ecosystem that combines a number of interrelated subsystems. Among them, one can highlight intelligent transportation systems as the most important factor providing a safe and comfortable state of the urban population. The importance of rational management for the 'smart city' system is due to the need to transform the urban environment in a direction that ensures a fundamental improvement in road traffic safety. Thus, for instance, the present level of traffic congestion in the Moscow agglomeration, according to various expert estimates, is from 60 to 70% and continues to grow annually (due to an increase in the number of personal vehicles, deficiencies in the characteristics of existing road networks and other factors). The degeneration of the road situation leads to many negative consequences: the occurrence of road traffic accidents (TAs), an increase in the time and cost of delivering marketable products, faster wear of the road surface, environmental degradation and other negative social consequences. Therefore, it is necessary to develop an intelligent information-analytical system for urban economy management which provides the possibility of introducing ground unmanned vehicles (UGVs)[1] and related transportation infrastructure. A clear advantage of the UGV is the ability to organize effective 'car sharing,' i.e. the shared use of unmanned vehicles by many people. The number of required UGVs in such shared use may be relatively small, and the level of security under certain conditions is quite high. In the future, this will make it possible to significantly reduce the number of vehicles on roads and improve the quality of the urban environment. At the same time, we know that accidents regularly occur in Moscow and other large metropolitan areas, including those involving UGVs. Such situations are a significant barrier to the wide dissemination and introduction of UGVs in the urban environment, since, in addition to the high cost of damage from road accidents, there are risks to life and health for all road users.

Previously, in [2–4], the existence of scenarios for accident-free movement of the UGVs ensemble interacting with manned ground vehicles (MGVs) has been shown for various configurations of the digital road networks and other environment characteristics. In particular, in the work [2] general conditions leading to occurrence of such accidents (mainly vehicle manoeuvres in dense traffic conditions) have been determined with the use of the developed agent-based model [5, 6]. Thus, the 'turbulence' and 'crowding' effects arise with an increase in the density of UGVs and MGVs, when some drivers seek to increase their personal space through frequent lane changes, overtaking and braking. As a rule, this leads to an even greater slowdown in traffic, creating difficulties for other road users, their 'pushing out' from their original route, errors dur-

[1] https://www.m24.ru/news/proisshestviya/27042021/163077

ing forced manoeuvres and the occurrence of an accident [7–9]. At the same time, of greatest interest are the particular conditions for the occurrence of accidents involving various agents: UGVs, MGVs, MGVs with anomalous behavior, pedestrians, cyclists, etc., as well as the possibility of developing an individual decision-making system for UGVs that is as stable regarding the environment characteristics. Such the system can be based on modeling and solving emerging problem situations [10, 11], using fuzzy rules in manoeuvres [2] and a phenomenological approach to control of the radius of an agent-UGV's personal space in manoeuvres and unexpected appearance of pedestrian-obstacles [4]. Moreover, it can use optimal routing for UGVs that allows them to avoid possible undesirable interactions with other road users [12–16].

Note that previously the phenomenological approach was proposed for modeling crowd behavior [17], considering the influence of the 'crowd effect' and other environmental characteristics (in particular, its configuration). A multi-agent system for control of UGVs has been developed based on this approach [5, 6]. For this purpose, the large-scale agent-based simulation framework FLAME GPU was used[2] [5, 18, 19]; it makes it possible to efficiently parallelize the logic of agents' behavior and consider their individual decision-making systems when modeling the spacial dynamics of an ensemble of interacting vehicles. On the other hand, the phenomenological approach is based on Dirk Helbing's studies [20, 21], which deal with models of humans and pedestrians' behavior under the influence of social forces.

Within the concept of the 'smart city' development, control systems for unmanned railway vehicles [22, 23] are also of great interest: they can be used to form optimal routs for freight wagons (controlled by unmanned locomotives) for a given set of freight wagons and a list of requests for a cargo transportation. Also, a promising area of research is the use of fuzzy [4, 5] and hierarchical clustering [24] methods to identify problem areas of the urban road network [25] (e.g., traffic jams, accident locations, etc.).

This paper proposes an approach to modeling the rates of accidents and improving road safety within the scale of the 'smart city' by combining computational and expert decision-making methods. A similar approach is also used in strategic management systems [26, 27], and its advantage is the ability to evaluate and generalize trade-offs by experts, obtained, in particular, as a result of optimization experiments with the simulation model so developed. Such an expert assessment allows you to consider the off-model features of an intelligent transportation system, in particular, financial and technological restrictions that affect the possibility of reconfiguring street road networks, as well as legal requirements that can be applied to tasks of the 'smart city.'

The purpose of this article is to develop a new socially-centered approach to urban management based on modeling the dynamics of traffic accidents involving unmanned vehicles within a multi-agent intelligent transportation system of the 'smart city' and implementation on the FLAME GPU framework, as well as determining the conditions under which the UGV's individual decision-making system keeps up resilience to risk factors to ensure the safety of other road users. An information-analytical system for the rational management of the urban economy can be developed based on the proposed model. Furthermore, some recommendations are formulated to increase the transformation of the urban environment (in particular, the transport infrastructure), which is one of the important areas of research in the field of business informatics.

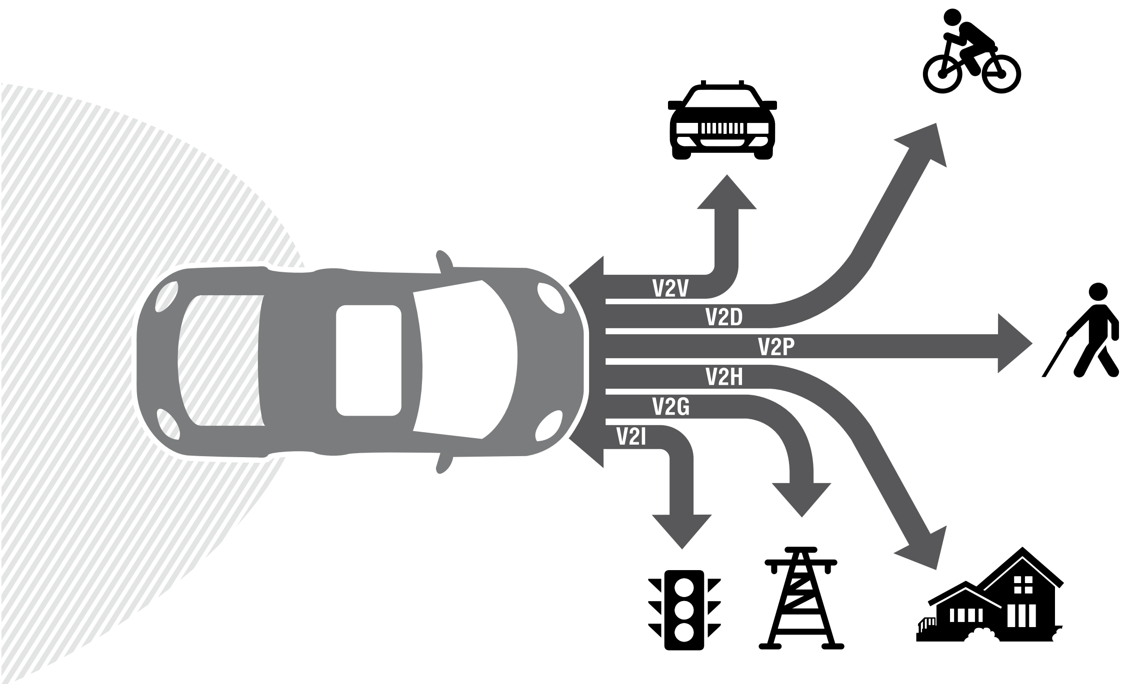
[2] https://flamegpu.com/

1. Description of the model

Previously, an agent-based simulation model of the UGVs' behavior in an interaction with MGVs and other agents of the intelligent transportation system was developed [2, 3]. This model uses a system of finite-difference equations with a variable structure to implement various scenarios for vehicle communications with each other (V2V), with pedestrians (V2P), with the environment (V2I), etc. (*Fig. 1*). Such an approach allows you to consider multiple scenarios of UGVs interaction with other participants of the digital road network (DRN), for instance, MGVs, pedestrians, stationary obstacles, etc., which differ significantly in their velocities and sizes, and which directly affect the decision speed of UGVs.

At the same time, digital road networks such as 'roundabouts" [2] and the 'Manhattan grid' [3] with a limited set of possible configurations were considered. In this paper, we propose to significantly complicate the geometry of digital road networks, bringing it closer to the scale of the 'smart city,' as well as to develop an individual UGV's decision-making system that is as stable as possible regarding risk factors, such as the unexpected appearance of static obstacles, pedestrians, cyclists, etc. (*Fig. 2*).

Such stability is ensured by braking through increasing the radius of the vehicle's personal space (with a subsequent gradual decrease to a normal level) when obstacle objects appear that have different linear speeds, if the path length from the vehicle to the object is sufficient for braking (*Fig. 2a*), or manoeuvering



V2V – interaction of the 'vehicle–vehicle' type
V2D – interaction of the 'vehicle–device' type (i.e. a moving object)
V2P – interaction of the 'vehicle–pedestrian' type
V2H – interaction of the 'vehicle–home' type (i.e. a stationary object)
V2G – interaction of the 'vehicle–grid' type (i.e. a charging station)
V2I – interaction of the 'vehicle–infrastructure' type (i.e. a smart traffic light)

Fig. 1. Illustration of the interaction of a vehicle (V) with various agents of an intelligent transportation system.

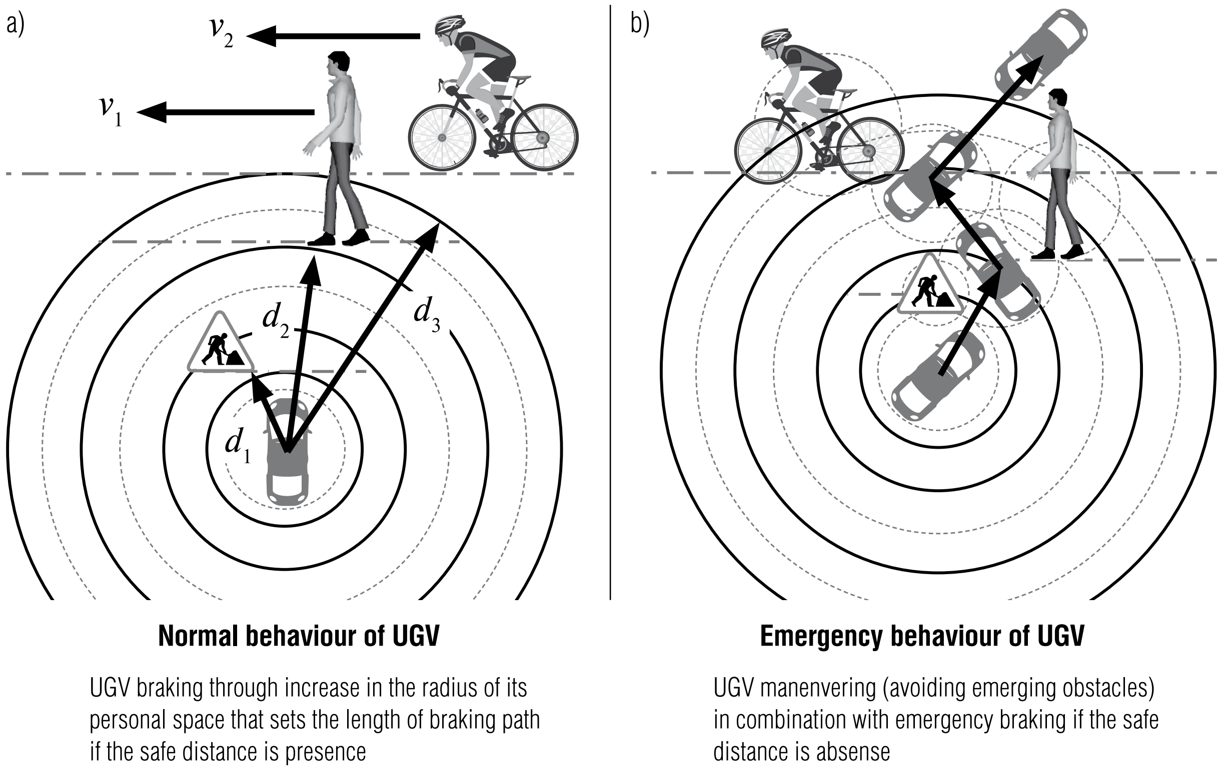


Fig. 2. Illustration of the process of interaction between the vehicle and other agents of the intelligent transportation system:
a) if the safe distance between the vehicle and obstacle is maintained;
b) if the path length is insufficient for emergency braking.

so as to bypass emerging obstacles within its lane in combination with emergency braking (*Fig. 2b*) in the case when the distance between the vehicle and the obstacle that has arisen does not allow avoiding a collision through braking.

If a stationary obstacle (e.g., a road works sign) suddenly appears in front of a vehicle moving at an average speed of 60 km/h, then the decision speed is quite high to avoid an accident by minimally increasing the radius of the vehicle's personal space up to the level d_1 (approximately 20 m in a dry, 30 m in wet and 60 m in icy road surfaces, respectively) if a pedestrian suddenly appears (at an average speed v_1 = 4–7 km/h), then in order to avoid an accident with the UGV, it is necessary to increase the radius of personal space to the level d_2 (approximately 30 m in dry pavement, 50 m in wet and 70 m in icy), and finally, if a fast moving cyclist unexpectedly appears (at an average speed v_2 = 10–15 km/h), then the radius of the personal space of the UGV should be increased to the level d_3(approximately 40 m in dry pavement, 60 m in wet and 80 m in icy). The increase in the radius of the UGV's personal space is caused by decrease in the reaction speed in appearance of a moving obstacle and increase in the UGV's time spent to correctly recognize the corresponding event.

At the same time, various configurations (schemes) of the street road network are possible [25], among which the radial-circular one should be singled out as an example (*Fig. 3*). It should be noted that there are possible configurations of the street road network, for example, extended radial-ring, rectangular, rectangular-diagonal, rectangular-ring, etc.

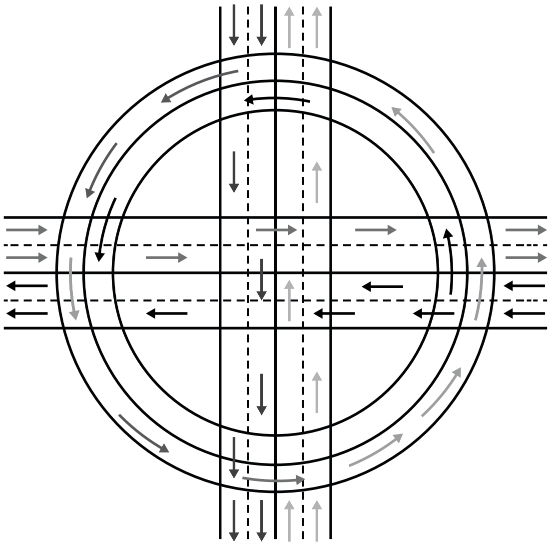


Fig. 3. A simple radial–ring scheme of the street road network.

The arrows in *Fig. 3* show the directions of traffic flows. In such a scheme, each vehicle entering the DRN and staying in decision zones (i.e. at intersections) has two alternative routes of movement (e.g., left-to-right or a detour) that ensure the implementation of outgoing traffic.

Next, an abstract description of the developed model of UGVs' behavior, the spacial dynamics of which correspond to the configuration of a simple radial-ring scheme of the street road network is given (*Fig. 3*).

Here,

- $T = \{t_0, t_1, ..., |T|\}$ is the set of time moments (by minutes),$|T|$ is the total number of time moments; $t_0 \in T$, $t_{|T|} \in T$ are the initial and final time moments;
- $I = \{ i_1, i_2, ..., i_{|I|}\}$ is the set of indices for unmanned ground vehicles (UGVs), where $|I|$ is the total number of UGVs;
- $B = \{1, 2, ..., |B|\}$ is the set of indices of obstacle types:$b = 1$ is an agent-MGV, $b = 2$ is a stationary obstacle (e.g., sign of road works, pit, etc.), $b = 3$ is a pedestrian, $b = 4$ is a cyclist, etc.), which may suddenly appear on the road, where $|B|$ is the total number of types of possible obstacles;
- $J_b = \{j_{b1}, j_{b2}, ..., j_{|Jb|}\}$, $b \in B$ is the set of indices of agent-obstacles belong to the b-type, where $|J_b|$ is the total number of agent-obstacles;
- $U = \{ u_1, u_2, ..., u_{|U|}\}$ is the set of indices of the DRN's characteristics that significantly affect the dynamics and manoeuverability of the agent-UGVs, in particular, the state of the road surface, the illumination level, etc., where $|U|$ is the total number of the DRN's characteristics.

Then, the density of the vehicilar flow around some $\tilde{i}^{th}$-agent-UGV ($\tilde{i} \in I$) at moment t_{k-1} ($t_{k-1} \in T$) is equal to

$$\rho_{\tilde{i}}(t_{k-1}) = \sum_{i=1}^{|I|} m_{\tilde{i}i}(t_{k-1}) + \sum_{b=1}^{|B|} \sum_{j_b=1}^{|J_b|} \tilde{m}_{\tilde{i}j_b}(t_{k-1}), \quad (1)$$

where

$$m_{\tilde{i}i}(t_{k-1}) = \begin{cases} 1, \text{ if } d_{\tilde{i}i}(t_{k-1}) \le R, \\ 0, \text{ if } d_{\tilde{i}i}(t_{k-1}) > R, \end{cases}$$

$$\tilde{m}_{\tilde{i}j_b}(t_{k-1}) = \begin{cases} 1, \text{ if } \tilde{d}_{\tilde{i}j_b}(t_{k-1}) \le R, \\ 0, \text{ if } \tilde{d}_{\tilde{i}j_b}(t_{k-1}) > R, \end{cases} \quad (2)$$

$$i \in I,\ b \in B,\ j_b \in J_b.$$

Here, $\{d_{\tilde{i}i}(t_{k-1}), \tilde{d}_{\tilde{i}j_b}(t_{k-1})\}$ is the Euclidean distance between the $\tilde{i}^{th}$-agent-UGV ($\tilde{i} \in \tilde{I}$) and each other i^{th}-agent-UGV ($i \in I$), as well as between the $\tilde{i}^{th}$-agent-UGV and j_b^{th}-agent-obstacle ($b \in B$, $j_b \in J_b$) at the moment t_{k-1} ($t_{k-1} \in T$), respectively, and the R is the fixed viewing radius chosen to estimate the density of vehicles.

The radius length of the agent-UGV's personal space depends on the density of the surrounding space, as well as on the distance to the agent-obstacle.

The radius of the $\tilde{i}^{th}$-agent-UGV's personal space at moment t_{k-1} ($t_{k-1} \in T$) equals

$$\tilde{r}_{\tilde{i}}(t_{k-1})=\begin{cases}\hat{r}_1, \text{ if } \rho_{\tilde{i}}(t_{k-1})=1 \text{ and } \tilde{d}_{\tilde{i}j_b}(t_{k-1})>l_{bu},\\ \tilde{d}_{\tilde{i}j_b}(t_{k-1}) \text{ if } \rho_{\tilde{i}}(t_{k-1})=1 \text{ and } \tilde{d}_{\tilde{i}j_b}(t_{k-1})\le l_{bu},\\ \dfrac{\hat{r}_1}{\left(\rho_{\tilde{i}}(t_{k-1})\right)^{\eta}}, \text{ if } 1<\rho_{\tilde{i}}(t_{k-1})<\overline{\rho}\\ \text{and } \tilde{d}_{\tilde{i}j_b}(t_{k-1})>l_{bu},\\ \min\left(\tilde{d}_{\tilde{i}j_b}(t_{k-1}),\ \dfrac{\hat{r}_1}{\left(\rho_{\tilde{i}}(t_{k-1})\right)^{\eta}}\right),\\ \text{if } 1<\rho_{\tilde{i}}(t_{k-1})<\overline{\rho} \text{ and } \tilde{d}_{\tilde{i}j_b}(t_k)\le l_{bu},\\ \hat{r}_2, \text{ if } \overline{\rho}\le\rho_{\tilde{i}}(t_{k-1})<\overline{\overline{\rho}} \text{ and } \tilde{d}_{\tilde{i}j_b}(t_k)>l_{bu},\\ \min\left(\tilde{d}_{\tilde{i}j_b}(t_{k-1}),\hat{r}_2\right), \text{ if } \overline{\rho}\le\rho_{\tilde{i}}(t_{k-1})<\overline{\overline{\rho}}\\ \text{and } \tilde{d}_{\tilde{i}j_b}(t_k)\le l_{bu},\\ 0, \text{ if } \overline{\overline{\rho}}\le\rho_{\tilde{i}}(t_{k-1}),\end{cases} \quad (3)$$

$$\tilde{i}\in I,\ b\in B,\ j_b\in J_b,\ u\in U.$$

Here, $\hat{r}_1$ is the initial value of the radius of the agent's personal space corresponding to the normal state of the density of the surrounding space (i.e. in absence of panic); $0\leqslant\eta\leqslant 1$ is some coefficient with the fixed value ($\eta=0.2$); $\hat{r}_2>>\hat{r}_1$ is the value of the radius of the agent's personal space corresponding to the state of high density of the surrounding space; $\{\overline{\rho},\overline{\overline{\rho}}\}$are the threshold values of the densities of the surrounding space; l_{bu}, $b\in B$ is the minimum required distance from the UGV to the j_{bu}^{ths}-obstacles for safe braking, taking into account the state of the road surface and illumination level $u\in U$.

The agent-UGV motion velocity depends on the radius of its personal space and presence of obstacles.

The line speed of the $\tilde{i}^{th}$-agent-UGV when driving in the linear section of the street road network at moment t_{k-1} ($t_{k-1}\in T$) is equal to

$$\tilde{v}_{\tilde{i}}(t_{k-1})=\begin{cases}\lambda\tilde{v}_1, \text{ if } \tilde{r}_{\tilde{i}}(t_{k-1})\in[\hat{r}_1,\ \hat{r}_2],\\ \lambda\psi\,\tilde{v}_{\tilde{i}}(t_{k-2}), \text{ if } \tilde{d}_{\tilde{i}j_b}(t_{k-1})\le l_{bu},\\ 0, \text{ if } \tilde{r}_{\tilde{i}}(t_{k-1})=0,\end{cases} \quad (4)$$

$$\tilde{i}\in I,\ b\in B,\ j_b\in J_b,\ u\in U.$$

Here, $\tilde{v}_1$ is the base velocity of UGV given through the log-normal distribution in a fixed range; $0\leqslant\psi\leqslant 1$ is the coefficient of extreme braking ($\psi=0.01$); λ is the coefficient that determines the ratio of the scales of real and virtual simulation time (considering the real and virtual velocities of the vehicular movement).

The angular velocity of the $\tilde{i}^{th}$-agent-UGV ($\tilde{i}\in I$) when driving in the roundabout section of the street road network at moment t_{k-1} ($t_{k-1}\in T$) is equal to

$$\tilde{v}^{*}_{\tilde{i}}(t_{k-1})=\frac{\tilde{v}_{\tilde{i}}(t_{k-1})}{\tilde{d}_{\tilde{i}O}(t_{k-1})}. \quad (5)$$

Here, $\tilde{d}_{\tilde{i}O}(t_{k-1})$ is the Euclidean distance from the $\tilde{i}^{th}$-agent-UGV ($\tilde{i}\in I$) to the center of the circular motion area (see *Fig. 2a*) at moment t_{k-1} ($t_{k-1}\in T$).

The directional angle required for the angular motion of the $\tilde{i}^{th}$-agent-UGV ($\tilde{i}\in I$) located in a circular motion at moment t_{k-1} ($t_{k-1}\in T$) equals

$$\alpha_{\tilde{i}}(t_{k-1})=\arctan\frac{y_{\tilde{i}}(t_{k-1})-\hat{y}_O}{x_{\tilde{i}}(t_{k-1})-\hat{x}_O}-\lambda\tilde{v}^{*}_{\tilde{i}}(t_{k-1}). \quad (6)$$

Here, $\{\tilde{x}_{\tilde{i}}(t_{k-1}),\tilde{y}_{\tilde{i}}(t_{k-1})\}$ are coordinates of the $\tilde{i}^{th}$-agent-UGV ($\tilde{i}\in I$) at moment t_{k-1} ($t_{k-1}\in T$); $\{\hat{x}_O,\hat{y}_O\}$ are coordinates of the center of the roundabout area.

The offset angle of the $\tilde{i}$-agent-UGV ($\tilde{i}\in I$) to bypass the nearest j_b^{th}-agent-obstacles ($j_b\in J_b$, $b\in B$) at moment t_{k-1} ($t_{k-1}\in T$) equals

$$\omega_{\tilde{i}j_b}(t_{k-1})=\frac{\pi}{4}+ \quad (7)$$

$$+\left|\arctan\frac{y_{j_b}(t_{k-1})-\tilde{y}_{\tilde{i}}(t_{k-1})+\left(r_{j_b}(t_{k-1})+\tilde{r}_{\tilde{i}}(t_{k-1})\right)\sin\frac{\pi}{4}}{x_{j_b}(t_{k-1})-\tilde{x}_{\tilde{i}}(t_{k-1})+\left(r_{j_b}(t_{k-1})+\tilde{r}_{\tilde{i}}(t_{k-1})\right)\cos\frac{\pi}{4}}\right|.$$

Here, $\{x_{j_b}(t_{k-1}),\ y_{j_b}(t_{k-1})\}$, $r_{j_b}(t_{k-1})$, are coordinates and radius of the personal space of the j_b^{th}-obstacle ($j_b \in J_b$, $b \in B$) at moment t_{k-1} ($t_{k-1} \in T$).

The angle specified the direction of movement of the $\tilde{i}^{th}$-agent-UGV ($\tilde{i} \in I$) towards the nearest neighbour (for overtaking) at moment t_{k-1} ($t_{k-1} \in T$) equals

$$\gamma^*_{\tilde{i}j_b}(t_{k-1}) = \left| \arctan \frac{y_{j_b}(t_{k-1}) - y_i(t_{k-1})}{x_{j_b}(t_{k-1}) - x_i(t_{k-1})} \right|. \quad (8)$$

The rebound angle of the $\tilde{i}^{th}$-agent-UGV ($\tilde{i} \in I$) from the nearest j_b^{th}-agent-obstacles ($j_b \in J_b$) at moment t_{k-1} ($t_{k-1} \in T$) equals

$$\gamma_{\tilde{i}j_b}(t_{k-1}) = \pi + \gamma^*_{\tilde{i}j_b}(t_{k-1}). \quad (9)$$

Here,

- ♦ $\tilde{s}_{\tilde{i}}(t_k) \in \{1, 2, 3, 4\}$ is the UGV state: $\tilde{s}_{\tilde{i}}(t_k) = 1$ is the accident state, $\tilde{s}_{\tilde{i}}(t_k) = 2$ is the initial state of the UGV at the entrance to the DRN that is saved when driving on the road linear section, $\tilde{s}_{\tilde{i}}(t_k) = 3$ is the state of the UGV movement in the roundabout area of the DRN at moment t_k ($t_k \in T$), $\tilde{s}_{\tilde{i}}(t_k) = 4$ – the state of the UGV exit from the DRN using a straight section of the road;
- ♦ $\tilde{c}_{\tilde{i}}(t_0) \in \{1, 2, 3, 4\}$ is the UGV type: $\tilde{c}_{\tilde{i}}(t_0) = 1$ is the movement from left-to-right, $\tilde{c}_{\tilde{i}}(t_0) = 2$ is the movement from right-to-left, $\tilde{c}_{\tilde{i}}(t_0) = 3$ is the movement from bottom-to-top, $\tilde{c}_{\tilde{i}}(t_0) = 4$ is the movement from top-to-bottom given at the initial moment ($t_0 \in T$).

Then, the direction of movement of the UGV in the DRN at the moment of time t_{k-1} ($t_{k-1} \in T$) can be calculated like this:

$$\tilde{w}_{\tilde{i}}(t_{k-1}) = \begin{cases} 1, \text{ if } \tilde{c}_{\tilde{i}}(t_0) \in \{1,3\} \text{ and } \tilde{s}_{\tilde{i}}(t_{k-1}) \neq 1, \\ -1, \text{ if } \tilde{c}_{\tilde{i}}(t_0) \in \{2,4\} \text{ and } \tilde{s}_{\tilde{i}}(t_{k-1}) \neq 1, \\ 0, \text{ if } \tilde{s}_{\tilde{i}}(t_{k-1}) = 0. \end{cases} \quad (10)$$

In view of the foregoing, for the considered radial-ring scheme of the digital road network, the space dynamics of the $\tilde{i}^{th}$-agent-UGV ($\tilde{i} \in \tilde{I}$) at moment t_k ($t_k \in T$) is given by the following system of the finite difference equations with the variable structure:

$$\tilde{x}_{\tilde{i}}(t_k) = \begin{cases} \tilde{x}_{\tilde{i}}(t_{k-1}) + \tilde{w}_{\tilde{i}}(t_{k-1})\lambda\tilde{v}_{\tilde{i}}((t_{k-1}), \text{ if I is true} \\ \tilde{x}_{\tilde{i}}(t_{k-1}) + \tilde{v}_{\tilde{i}}(t_k)\cos\left(\pm\tilde{\omega}_{\tilde{i}j_b}(t_{k-1})\right) + \\ + \dfrac{c_1}{d_{\tilde{i}j_b}(t_{k-1})}\cos\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}), \text{ if II is true,} \\ \tilde{x}_{\tilde{i}}(t_{k-1}) + \dfrac{c_1}{d_{\tilde{i}j_b}(t_{k-1})}\cos\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}), \\ \text{if III is true,} \\ \hat{x}_O + \tilde{d}_{\tilde{i}O}(t_{k-1})\cos\left(\lambda\tilde{v}^*_{\tilde{i}}(t_{k-1}) + \tilde{\alpha}_{\tilde{i}}(t_{k-1})\right), \\ \text{if IV is true,} \\ \left(\begin{array}{l} \tilde{x}_{\tilde{i}}(t_{k-1}) + \cos\left(\begin{array}{l} \lambda\tilde{v}^*_{\tilde{i}}(t_{k-1}) + \\ \tilde{\alpha}_{\tilde{i}}(t_{k-1}) \pm \tilde{\omega}_{\tilde{i}j_b}(t_{k-1}) \end{array} \right) + \\ \dfrac{c_2}{d_{\tilde{i}j_b}(t_{k-1})}\cos\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}) \end{array} \right), \\ \text{if V is true,} \\ \tilde{x}_{\tilde{i}}(t_{k-1}) + \dfrac{c_2}{d_{\tilde{i}j_b}(\mathrm{t}_{k-1})}\cos\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}), \\ \text{if VI is true,} \\ \tilde{x}_{\tilde{i}}(t_{k-1}), \text{ if VII is true,} \end{cases} \quad (11)$$

$$\tilde{y}_{\tilde{i}}(t_k) = \begin{cases} \tilde{y}_{\tilde{i}}(t_{k-1}), \text{ if I is true,} \\ \tilde{y}_{\tilde{i}}(t_{k-1}) + \tilde{v}_{\tilde{i}}(t_k)\sin\left(\pm\tilde{\omega}_{\tilde{i}j_b}(t_{k-1})\right) + \\ + \dfrac{c_1}{d_{\tilde{i}j_b}(t_{k-1})}\sin\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}), \text{ if II is true,} \\ \tilde{y}_{\tilde{i}}(t_{k-1}) + \dfrac{c_1}{d_{\tilde{i}j_b}(t_{k-1})}\sin\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}), \\ \text{if III is true,} \\ \hat{y}_O + \tilde{d}_{\tilde{i}O}(t_{k-1})\sin\left(\lambda\tilde{v}^*_{\tilde{i}}(t_{k-1}) + \tilde{\alpha}_{\tilde{i}}(t_{k-1})\right), \\ \text{if IV is true,} \\ \left(\begin{array}{l} \tilde{x}_{\tilde{i}}(t_{k-1}) + \sin\left(\begin{array}{l} \lambda\tilde{v}^*_{\tilde{i}}(t_{k-1}) + \\ \tilde{\alpha}_{\tilde{i}}(t_{k-1}) \pm \tilde{\omega}_{\tilde{i}j_b}(t_{k-1}) \end{array} \right) + \\ + \dfrac{c_2}{d_{\tilde{i}j_b}(t_{k-1})}\sin\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}) \end{array} \right), \\ \text{if V is true,} \\ \tilde{x}_{\tilde{i}}(t_{k-1}) + \dfrac{c_2}{d_{\tilde{i}j_b}(t_{k-1})}\sin\tilde{\gamma}_{\tilde{i}j_b}(t_{k-1}), \\ \text{if VI is true,} \\ \tilde{y}_{\tilde{i}}(t_{k-1}) + \tilde{w}_{\tilde{i}}(t_{k-1})\tilde{\lambda}\tilde{v}_{\tilde{i}}(t_{k-1}), \\ \text{if VII is true,} \end{cases} \quad (12)$$

$$\tilde{i} \in I, b \in B, j_b \in J_b,$$

where

I. $s_i(t_{k-1}) \in \{2, 4\}$ and $\tilde{c}_{\tilde{i}}(t_0) \in \{1, 2\}$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) > \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for all $(j_b \in J_b)$, that corresponds to the conditions for the UGV movement of the in the linear section of the DRN in the direction of **left-to-right or right-to-left** (when entering or leaving the DRN) and absence of obstacles, i.e. when the distance between this UGV and other agents exceeds the sum of the lengths of the radiuses of their personal spaces;

II. $s_i(t_{k-1}) \in \{2, 4\}$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) \le \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for the nearest $(j_b \in J_b)$ and $\gamma^*_{\tilde{i}j_b}(t_{k-1}) = 0$, that corresponds to the conditions of the UGV movement in the linear section of the DRN (in any direction) and **presence (appearance) of an obstacle** located ahead of the given UGV (i.e., occupying the same lane at a critically close distance), which causes manoeuvering in the form of overtaking or bypassing this obstacle;

III. $s_i(t_{k-1}) \in \{2, 4\}$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) \le \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for the nearest $(j_b \in J_b)$ and $\gamma^*_{\tilde{i}j_b}(t_{k-1}) > 0$, that corresponds to the conditions for the vehicular movement on the linear section of the CPC (in any direction) and **presence of an obstacle** that is not ahead of this vehicle (i.e., located behind or on the side at a critically close distance), which causes manoeuvering in the form of increasing the distance relative to this obstacle (i.e. accelerating, braking or avoiding a collision);

IV. $s_i(t_{k-1}) = 3$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) \le \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for all $(j_b \in J_b)$, that corresponds to the conditions for the UGV movement **in the circular motion area** of the DRN and absence of obstacles;

V. $s_i(t_{k-1}) = 3$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) \le \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for the nearest $(j_b \in J_b)$ and $\gamma^*_{\tilde{i}j_b}(t_{k-1}) > 0$, that corresponds to the conditions for the vehicle movement in the circular motion area of the DRN and **presence (appearance) of an obstacle** located in front of this vehicle, which causes manoeuvering in the form of overtaking or bypassing this obstacle;

VI. $s_i(t_{k-1}) = 3$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) \le \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for the nearest $(j_b \in J_b)$ and $\gamma^*_{\tilde{i}j_b}(t_{k-1}) > 0$, that corresponds to the conditions for the vehicular movement in the circular motion area of the DRN and presence of an obstacle that is **not in front of this vehicle**, which necessitates manoeuvering in the form of increasing the distance relative to this obstacle;

VII. $s_i(t_{k-1}) \in \{2, 4\}$ and $\tilde{c}_{\tilde{i}}(t_0) \in \{3, 4\}$ and $\tilde{d}_{\tilde{i}j_b}(t_{k-1}) > \tilde{r}_{\tilde{i}}(t_{k-1}) + r_{j_b}(t_{k-1})$ for all $(j_b \in J_b)$itions for the UGV movement in the linear section of the DRN in the direction of **bottom-up or top-down** (when entering or leaving the DRN) and no obstacles.

Next, the software implementation of the proposed model (11)–(12) using FLAME GPU will be presented.

2. Software implementation

The software implementation of the traffic model of interacting UGVs with other road users allows us to study the rate of road accidents under various configurations of the digital road network (DRN) (*Fig. 4*).

The choice of the best street road network configuration should be based on a combination of computational and expert decision-making methods. The use of the simulation model we developed makes it possible to form a set of trade-offs for the implementation of the intelligent transportation system of the 'smart city' and its modes of operation. At the same time, genetic optimization algorithms [2, 3], scenario analysis methods [4, 5], etc., can be used to improve the values of the objective functions of the system: the total output traffic and the number of potential accidents. Further, based on the methods of expert assessment [26, 27], practical recommendations can be obtained on the transformation of the configuration of the DRN and using UGVs with characteristics that provide the required safety level of the 'smart city.'

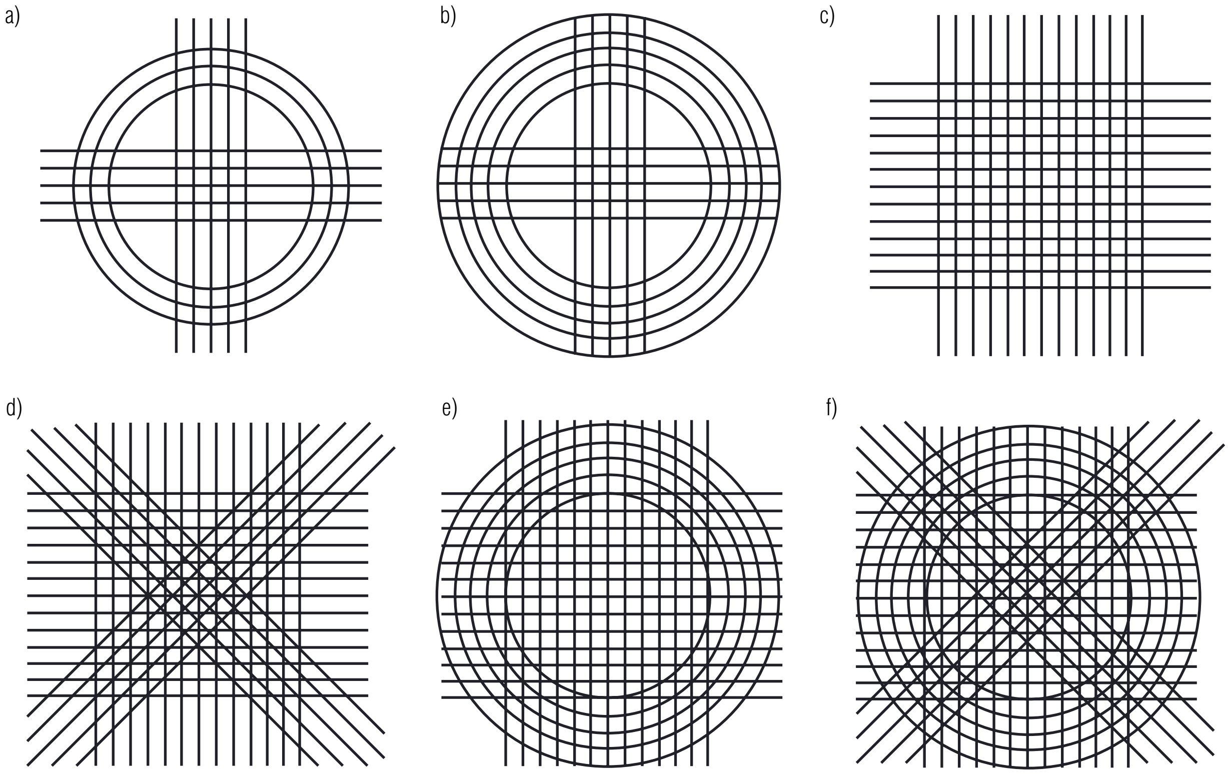


Fig. 4. DRN configurations: a) simple radial–annular, b) extended radial–circular, c) rectangular, d) rectangular–diagonal, e) rectangular–circular, f) rectangular–diagonal–circular.

The software implementation of such a model was made using the FLAME GPU framework (https://flamegpu.com/) that provides efficient parallelization of the behavior logic of interacting agents and their individual decision-making systems.

Table 1 provides a description of the functions developed in C++ using the FLAME GPU.

Table 1 contains mainly two types of functions: FLAMEGPU_STEP_FUNCTION and FLAMEGPU_AGENT_FUNCTION. Functions of the first type are executed at each moment of simulation time at the level of the central processing unit (CPU), and functions of the second type are executed in parallel computing mode using graphics processing units (GPUs). Thus, the logic of each agent behavior is parallelized (including control if the velocity, manoeuvering, etc.). As a result, the simulation model we developed makes it possible to investigate the behavior of an ensemble of UGVs, MGVs, and other agents in the scale of the 'smart city' (i.e., to simulate traffic that includes tens and hundreds of thousands of interacting road users). The visualization of the spacial dynamics of agents is carried out using the **OpenGL** that is a special application programming interface (API) providing the ability to draw multiple objects, both stationary and mobile (*Fig. 5*).

As a result, it is possible to visualize the spacial distribution of agents in the DRN and assess the composition and state of road users (UGVs, MGVs, vehicles in the accident state, etc.), which significantly simplifies the validation process for the model developed.

Table 1.

Basic computational procedures and functions of the traffic simulation model

Function name	Appointment	Input messages	Output messages
FLAMEGPU_INIT_FUNCTION (init_function)	Model initialization. Formation of the configuration of the DRN in accordance with the specified value of the control parameter of the model. Generation of the initial population of agents (UGVs and MGVs).	No	No
FLAMEGPU_STEP_FUNCTION (basic output)	Generation of new agents (UGVs and MGVs) and their arriving to the DRN with a given intensity. Formation of agents–obstacles (for example, pedestrians) in the road sections of the DRN.	No	No
FLAMEGPU_STEP_FUNCTION (agents_data_updating)	Implementation of the hierarchical clustering algo–rithm to identify problem areas of the DRN to UGVs can bypass the emerging traffic jams. Saving data on the spacial location of agents and their characteristics for the further visualization using the OpenGL.	No	No
FLAMEGPU_AGENT_FUNCTION (density_estimation, flamegpu::MessageSpatial2D, flamegpu::MessageNone)	Assessment of the traffic density around the agent–vehicle, changing the radius of the agent's personal space and its speed when interacting with other agents (e.g., reducing the radius of the agent's personal space in high–density traffic and increasing it when there are obstacles). Computing the direction angle and distance to the nearest agent for the purpose of the further manoeuvering (overtaking or braking). Monitoring emergency situations (accidents).	Agent Data	No
FLAMEGPU_AGENT_FUNCTION (update_agent_state, flamegpu::MessageNone, flamegpu::MessageSpatial2D)	Calculation of the resulting characteristics of the model (e.g., the total number of accidents, output traffic). Transfer of data about the agent–vehicle to other road users.	No	Agent Data
FLAMEGPU_AGENT_FUNCTION (agent_move, flamegpu::MessageNone, flamegpu::MessageNone)	Spacial movement of the agent in the DRN in accordance with the given rules of individual decision– making, e.g. entry (or exit) into (or outside) the DRN at the rectilinear movement, roundabout, manoeuvering, etc.	No	No
void display()	Visualization of the DRN and spacial dynamics of agents using the OpenGL at each moment of simulation time.	No	No

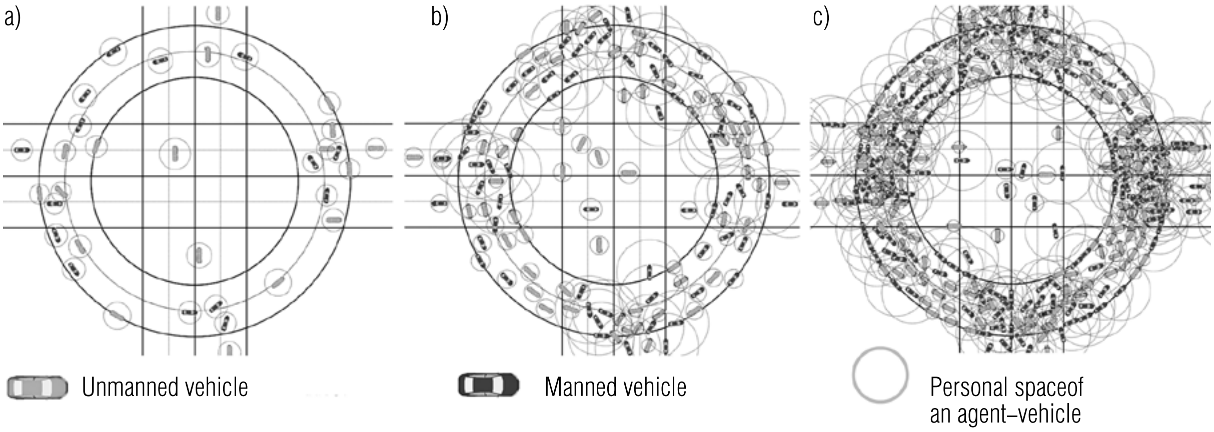


Fig. 5. Spacial dynamics of agents in a simple radial–annular DRN:
a) low–intensity traffic, b) medium–intensive traffic, c) high–intensity traffic.

3. Results of numerical experiments

Table 2 presents the resulting characteristics of the simulation model: the total output traffic (TOT) and number of vehicles in the accident state (VAS), calculated for the final time point (60 min.) under various scenarios and in absence of extreme situations, i.e. in conditions of sufficient visibility, with a dry road surface, absence of unexpected obstacles in the form of pedestrians, etc.:

- **Scenario 1.** *Low-intensity and low-speed movement of UGVs.* The vase velocity of UGVs and MGVs equals to 45–65 km/h, the intensity of vehicles arrival to the DRN is 1 vehicle every 10 sec.
- **Scenario 2.** *Medium-intensive and medium-speed movement of UGVs.* The vase velocity of UGVs and MGVs equals to 65–90 km/h, the intensity of vehicles arrival in the DRN is 5 vehicles every 10 sec.

Table 2.

Outbound traffic and number of potential accidents in absence of emergencies

DRN configurations	Scenario 1		Scenario 2		Scenario 3	
	TOT (traffic)	VAS (accidents)	TOT (traffic)	VAS (accidents)	TOT (traffic)	VAS (accidents)
Simple radial–annular	706	0	905	2	2810	6
Expanded radial–annular	851	0	1321	2	3100	6
Rectangular	1010	0	1532	2	3520	8
Rectangular–diagonal	1205	0	1720	2	3610	8
Rectangular–ring	1305	0	1850	2	3750	10
Rectangular–diagonal–ring	1530	0	2120	2	4111	12

- **Scenario 3.** *High-intensity and high-speed movement of UGVs.* The base speed of UGVs and MGVs: 100–120 km/h, intensity of vehicle arrival to the DRN is 10 vehicles every 10 sec.

Table 3 presents the resulting characteristics of the simulation model in the presence of extreme conditions (i.e., in conditions of insufficient visibility, wet road surface, unexpected appearance of pedestrians, cyclists and other obstacles on the roadway, etc.).

Figure 6 shows the rate of traffic accidents (cumulatively) for the Scenario 3 (*Table 3*), i.e. in high-intensity and high-speed movement of UGVs in extreme situations. At the same time, *Fig. 6* shows the quantitative characteristics of traffic congestion caused by the effects of the 'turbulence' and 'crash' that described in [6, 17], earlier.

As shown in *Fig. 6*, the rate of road accidents (i.e. the number of vehicles in the accident state) is associated with an increase in the number and average density of traffic congestion. Thus, the growth in the total number and scale of traffic jams in the DRN under conditions of high-intensity and high-speed traffic is the most important factor causing accidents, including those involving the UGV, which periodically have collisions with unexpected obstacles. A similar phenomenon is explained by attempts to manoeuvre (e.g., extreme braking, overtaking, etc.) from the side of vehicles, which, in conditions of traffic congestion, often leads to accidents. However, as follows from *Table 3*, a reduction in the velocity limit (up to 45–65 km/h) and the density of vehicles arriving at the DRN (up to 0.1 vehicles per second) ensures the high level of road safety even in extreme situations.

Conclusion

The article presents an approach to simulation of the road traffic accident rates with the participation of unmanned ground vehicles within a multi-agent intelligent transportation system of the 'smart city' (*Fig. 1*). We suggest a model of the UGVs ensemble movement in the digital road network (DRN) with the implementation on the example of a simple radial-ring scheme of the street road network (*Fig. 3*). Such a model, using a system of finite-difference equations with variable structure (11)–(12), makes it possible to study the

Table 3.

Outbound traffic and number of potential accidents in extreme situations

DRN configurations	Scenario 1		Scenario 2		Scenario 3	
	TOT (traffic)	VAS (accidents)	TOT (traffic)	VAS (accidents)	TOT (traffic)	VAS (accidents)
Simple radial–annular	655	2	870	2	2800	12
Expanded radial–annular	760	2	1210	4	3100	14
Rectangular	980	0	1310	6	3462	14
Rectangular–diagonal	1110	0	1622	8	3423	16
Rectangular–ring	1210	2	1780	8	3554	18
Rectangular–diagonal–ring	1400	2	2100	10	3780	20

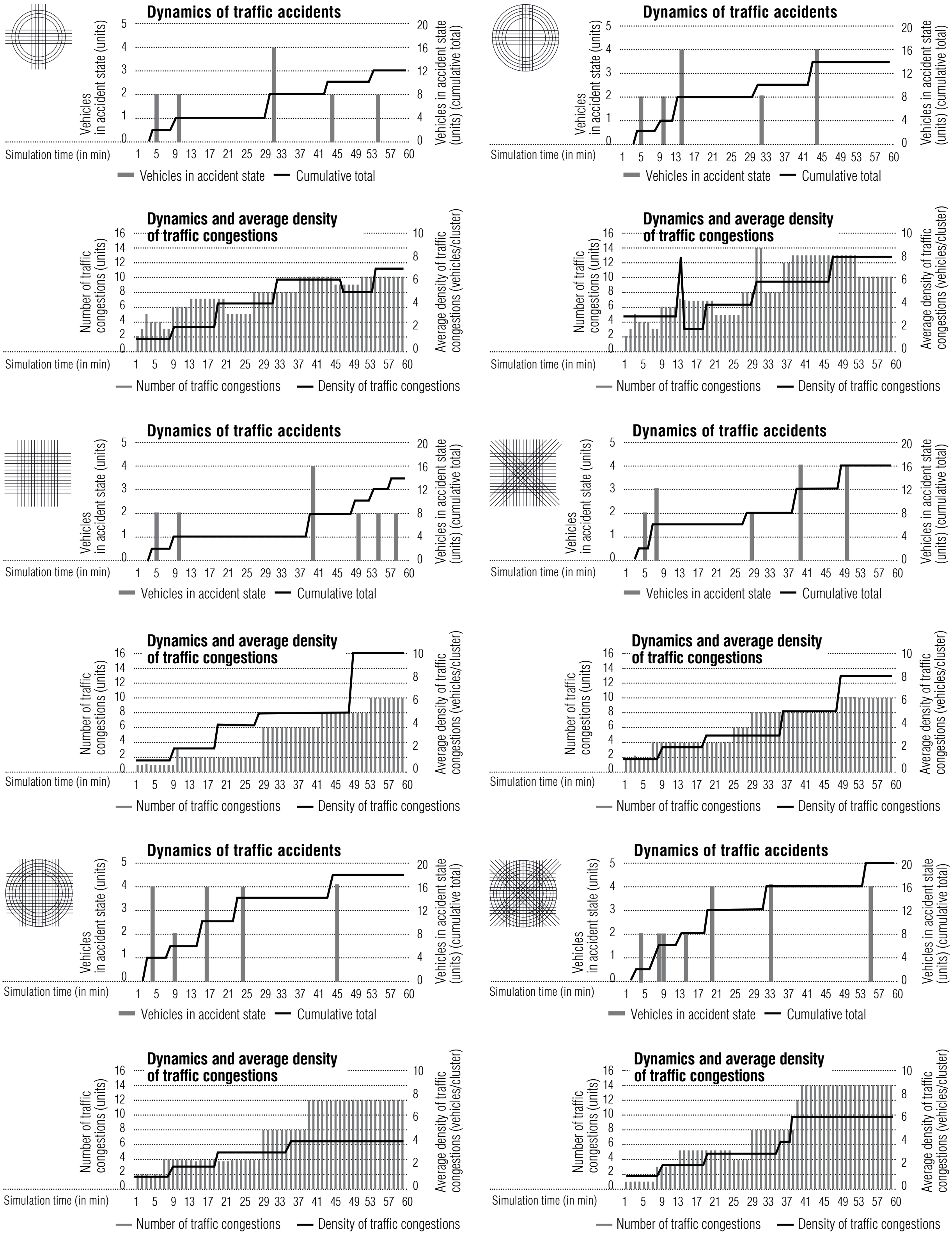


Fig. 6. Dynamics of accidents and characteristics of traffic congestions under different configurations of the digital road network (DRN): the occurrence of new accidents is interconnected with the appearance of traffic jams and an increase in their average density and depends on the DRN's geometry.

spacial dynamics of agent-UGVs interaction with various obstacles as MGVs, unexpectedly emerging pedestrians, etc. for various configurations of the DRN (*Fig. 4*). At the same time, each agent-UGV has an individual decision-making system for manoeuvering aimed at preventing emergency situations, in particular, by changing the radius of the personal space of the agent-UGV, reducing speed, bypassing unexpected obstacles, etc. (*Fig. 2*). The proposed simulation model was implemented using the large-scale agent-based simulation framework FLAME GPU, which made it possible to study the behavior of the UGVs ensemble interaction with other agents, including under high traffic conditions (*Fig. 5*). The numerical results (*Fig. 6*, *Tables 2–3*) so obtained confirm the possibility of achieving the required level of road safety even in extreme situations.

Further research will be aimed at solving the problems of optimal routing of UGVs within the DRN to minimize the impact of traffic congestion and forced manoeuvering on the accident rates. ■

Acknowledgments

The reported study was funded by RFBR, project number 19-29-06003.

References

1. Makarov V.L., Bakhtizin A.R., Beklaryan G.L., Akopov A.S. (2019) Simulation modelling of the smart city system: Concept, methods and cases. *National Interests: Priorities and Security*, vol. 15, no. 2 (371), pp. 200–224 (in Russian). https://doi.org/10.24891/ni.15.2.200

2. Akopov A.S., Beklaryan L.A., Thakur M. (2022) Improvement of maneuverability within a multiagent fuzzy transportation system with the use of parallel biobjective real-coded genetic algorithm. *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 8, pp. 12648–12664. https://doi.org/10.1109/TITS.2021.3115827

3. Akopov A.S., Beklaryan L.A., Beklaryan L.A. (2021) Simulation-based optimization for autonomous transportation systems using a parallel real-coded genetic algorithm with scalable nonuniform mutation. *Cybernetics and Information Technologies*, vol. 21, no. 3, pp. 127–144. https://10.2478/cait-2021-0034

4. Akopov A.S., Beklaryan A.L. (2021) Scenario simulation of autonomous vehicles motion in artificial road network using FLAME GPU. *Artificial societies*, vol. 16, no. 1 (in Russian). https://doi.org/10.18254/S207751800014028-9

5. Akopov A.S., Beklaryan L.A., Beklaryan A.L., Belousov F.A. (2021) Simulation of motion of an ensemble of unmanned ground vehicles using FLAME GPU. *Informacionnye Tehnologii*, vol. 27, no. 7, pp. 369–379 (in Russian). https://doi.org/10.17587/it.27.369-379

6. Akopov A.S., Beklaryan L.A., Khachatryan N.K., Beklaryan A.L., Kuznetsova E.V. (2020) Multi-agent control system for unmanned ground vehicles. I*nformacionnye Tehnologii,* vol. 26, no. 6, pp. 342–353 (in Russian). https://doi.org/10.17587/it.26.342-353

7. Andreev K.P., Kildishev A.A., Terentiev V.V., Shemiakin A.V. (2019) Safety assessment of transport units by means of computer simulation. *Byulleten' transportnoj informacii,* no. 1 (283), pp. 20–23 (in Russian).

8. Kolotov V.V., Kolyuzhnov V.V. (2011) Intelligent transport system and road situation modelling. *Vestnik komp'yuternyh i informacionnyh tekhnologij,* no. 12 (90), pp. 53–56 (in Russian).

9. Astarita V., Pasquale Giofré V. (2019) From traffic conflict simulation to traffic crash simulation: Introducing traffic safety indicators based on the explicit simulation of potential driver errors. S*imulation Modeling Practice and Theory*, vol. 94, pp. 215–236. https://doi.org/10.1016/j.simpat.2019.03.003

10. Kravchenko T.K., Isaev D.V. *Decision support systems.* Moscow: Urait, 2017 (in Russian).

11. Brännström M., Coelingh E., Sjöberg J. (2010) Model-based threat assessment for avoiding arbitrary vehicle collisions. I*EEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 3, pp. 658–669. https://doi.org/10.1109/TITS.2010.2048314
12. Cheng S., Li L., Guo H.-Q., Chen Z.-G., Song P. (2020) Longitudinal collision avoidance and lateral stability adaptive control system based on MPC of autonomous vehicles. *IEEE Transactions on Intelligent Transportation Systems,* vol. 21, no. 6, pp. 2376–2385. https://doi.org/10.1109/TITS.2019.2918176
13. Petrović D., Mijailović R., Pešić D. (2020) Traffic accidents with autonomous vehicles: Type of collisions, manoeuvres and errors of conventional vehicles' drivers. T*ransportation Research Procedia,* vol. 45, pp.161-168. https://doi.org/10.1016/j.trpro.2020.03.003
14. Wang H., Huang Y., Khajepour A., Zhang Y., Rasekhipour Y., Cao D. (2019) Crash mitigation in motion planning for autonomous vehicles. *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 9, pp. 3313–3323. https://doi.org/10.1109/TITS.2018.2873921
15. Wang J., Wu J., Li Y. (2015) The driving safety field based on driver–vehicle–road interactions. *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 4, pp. 2203–2214. https://doi.org/10.1109/TITS.2015.2401837
16. You F., Zhang R., Lie G., Wang H., Wen H., Xu J. (2015) Trajectory planning and tracking control for autonomous lane change maneuver based on the cooperative vehicle infrastructure system. *Expert Systems with Applications*, vol. 42, no. 14, pp. 5932–5946. https://doi.org/10.1016/j.eswa.2015.03.022
17. Akopov A.S., Beklaryan L.A. (2015) An agent model of crowd behaviour in emergencies. *Automation and Remote Control*, vol. 76, no. 10, pp. 1817–1827. https://doi.org/10.1134/S0005117915100094
18. Richmond P., Walker D., Coakley S., Romano D. (2010) High performance cellular level agent-based simulation with FLAME for the GPU. *Briefings in Bioinformatics*, vol. 11, no. 3, pp. 334–347. https://doi.org/10.1093/bib/bbp073
19. Heywood P., Richmond P., Maddock S. (2015) Road network simulation using FLAME GPU. In: *Euro-Par 2015: Parallel-Processing Workshops. Lecture Notes in Computer Science*, vol. 9523. Springer, Cham, pp. 430–431. https://doi.org/10.1007/978-3-319-27308-2_35
20. Helbing D. (2001) Traffic and related self-driven many-particle systems // *Reviews Of Modern Physics*, vol. 73, no. 4, pp. 1067–1141. https://doi.org/10.1103/RevModPhys.73.1067
21. Helbing D., Buzna L., Johansson A., Werner T. (2005) Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. *Transportation Science*, vol. 39, no. 1, pp. 1–24. https://doi.org/10.1287/trsc.1040.0108
22. Khachatryan N.K., Akopov A.S. (2017) Model for organizing cargo transportation with an initial station of departure and a final station of cargo distribution. *Business Informatics*, vol. 1, no. 39, pp. 25–35. https://doi.org/10.17323/1998-0663.2017.1.25.35
23. Belousov F.A., Khachatryan N.K., Nevolin I.V. (2022) Reduction of dimension in the problem of optimal management of a freight cars fleet using unmanned locomotives. *Business Informatics*, vol. 2, no. 16, pp. 7-20. https://doi.org/10.17323/2587-814X.2022.2.7.20
24. Mullner D. (2013) fastcluster: Fast hierarchical, agglomerative clustering routines for R and Python. *Journal of Statistical Software*, 53, no. 9, pp. 1–18. https://doi.org/10.18637/jss.v053.i09
25. Kostsov A.V., Bakhirev I.A., Borovik E.N., Martyakhin D.S. (2017) *Transport planning of cities. Textbook*. Moscow: A-project (in Russian).
26. Kravchenko T.K., Isaev D.V. (2016) Making strategic decisions under risk and uncertainties. *Finance: Theory and Practice*, vol. 20, no. 4, pp. 22–31 (in Russian). https://doi.org/10.26794/2587-5671-2016-20-4-22-31
27. Isaev D.V. (2022) Making strategic management decisions based on a combination of computation and expert methods. *Proceedings of the XXIII All-Russian Symposium "Strategic Planning and Development of Enterprises"*, Moscow: CEMI RAS, pp. 174–176 (in Russian). https://doi.org/10.34706/978-5-8211-0802-9-s2-10

About the authors

Andranik S. Akopov

Dr. Sci. (Tech.), Professor; Professor of the Russian Academy of Sciences;

Chief Researcher, Laboratory of Dynamic Models of Economy and Optimization, Central Economics and Mathematics Institute, Russian Academy of Sciences, 47, Nachimovky Prospect, Moscow 117418, Russia;

E-mail: akopovas@umail.ru

ORCID: 0000-0003-0627-3037

Levon A. Beklaryan

Dr. Sci. (Phys.-Math.), Professor;

Chief Researcher, Laboratory of Dynamic Models of Economy and Optimization, Central Economics and Mathematics Institute, Russian Academy of Sciences, 47, Nakhimovsky Prospect, Moscow 117418, Russia;

E-mail: beklar@cemi.rssi.ru

ORCID: 0000-0001-5695-4450

DOI: 10.17323/2587-814X.2022.4.36.49

Multi-trend trade system for financial markets

Sergey V. Bukunov
E-mail: sergeybukunov@yandex.ru

Olga V. Bukunova
E-mail: bukunovaolga@yandex.ru

Saint Petersburg State University of Architecture and Civil Engineering
Address: 4, 2nd Krasnoarmeiskaya Street, Saint Petersburg 199005, Russia

Abstract

At present, more and more people are beginning to be interested in the field of investment. This is due to the growth in incomes of the population, on the one hand, and development of financial technologies, on the other hand. The problematic situation is analyzed in this article and the main known models, algorithms and indicators used to build trading strategies are considered. A conservative trading strategy based on trend indicators is proposed. The strategy can be an alternative to the popular conservative "buy and hold" strategy. Exponentially moving averages of various orders that reveal the presence of trends of variable duration in the price dynamics of a financial asset are used as system indicators. A distinctive feature of the proposed trading system is the combination in one approach of the trading method that generates trade signals and the rules for position size management. The article contains results of testing a proposed trading strategy based on historical data. A comparative analysis of the results obtained with the results of the "buy and hold" strategy and the strategy based on two exponential moving averages of different orders is carried out. The proposed system can be easily integrated into automated trading systems. The R language was used for data processing and visualization.

Keywords: financial markets, technical analysis, trade system, trend indicators, data visualization, R language

Citation: Bukunov S.V., Bukunova O.V. (2022) Multi-trend trade system for financial markets. *Business Informatics*, vol. 16, no. 4, pp. 36–49. DOI: 10.17323/2587-814X.2022.4.36.49

Introduction

Real estate, bank deposits, currency, as well as securities (mainly stocks and bonds) are traditionally among the most popular investment tools used by non-professional investors to save and accumulate their capital. However, real estate prices in Russia have risen significantly over the past few years. As a result, the "entry threshold" to this market has increased, on the one hand, and the profitability of investments in real estate has decreased, on the other hand. At the same time, bank deposit rates systematically declined. Despite the fact that there was a trend towards an increase in the average deposit rates in 2021, the average amounted to 6.1% per annum during 2021 [1], which was significantly lower than the average annual inflation rate of 8.38%, for the same time period [2].

As a result, there has been an outflow of Russian funds from bank deposits to the stock market over the past few years. Thus, according to experts of the Russian National Rating Agency, the net outflow of funds held by Russians in banks amounted to 1.5 trillion rubles for the period from January 01, 2021 to January 11, 2021 [3].

At the same time, according to the Moscow Exchange, as of July 6, 2021, the number of individuals with brokerage accounts was about 13 million people, and the total inflow of funds from individuals into various financial market instruments amounted to 1.1 trillion rubles over 12 months [4].

However, investments in financial markets are traditionally among the most complicated activities [5]. The main reason is the high volatility of prices for financial assets due to the simultaneous impact of a very large number of both objective and subjective factors on them. It is high volatility that has caused a sharp increase in the use of algorithmic trading in exchange assets trading [6–9] because a person often does not physically have time to respond to rapid changes in stock quotes. The share of transactions made by trading robots on the Moscow Exchange has long exceeded 50% of the total number of transactions [10].

Trading robots are computer programs that make transactions for the purchase / sale of securities according to embedded algorithms. In turn, any algorithm implements a trading system (trading method), which is a set of rules for opening and closing positions. Obviously, it is the trading system that determines the efficiency of the trading robot.

The range of approaches to creating trading systems is quite wide:

- undamental analysis [11];
- technical analysis [12];
- statistical analysis [13, 14];
- text mining [15];
- fractal analysis [16, 17];
- machine learning with neural networks [18, 19];
- computer analysis [6–9].

It should be noted that trading systems based on technical and computer analysis are most widely used in algorithmic trading. Among such trading systems, we can identify:

- trend systems – based on trend indicators (for example, moving averages) and designed to apply on strong stable trends;
- countertrend systems – based on the different oscillators (for example, RSI, %R, stochastics etc.) and designed to apply in periods of price consolidation (no trend (flat));
- breakdown systems – systems based on the idea of breaking through key support/resistance levels formed in conditions of price consolidation;
- combined systems – various combinations of the previous systems.

The development and use of automated trading systems are only possible for professional market participants and these are rather complicated processes [20–23]. For this reason, companies have entered the financial market in recent years that develop and sell computer programs for algorithmic trading. Big investment and brokerage companies also do not stand aside. For example, the FINAM investment holding constantly presents the results of a dozen different investment strategies on its portal [24]. The company offers its clients to join to them to save their labor costs for developing investment decisions. However, all of these products are, in fact, "black boxes" because the developers do not disclose the trading strategies that underlie them.

Almost all trading systems that work on one or another indicator of technical or computer analysis have one common problem – the problem of stability, or robustness. The robustness of a trading system is usually understood as the ability of an algorithm to maintain profitability for a sufficiently long time, regardless of the type of changes in market prices [21]. The volatility of modern financial markets leads to the need for constant reconfiguration (optimization) of the parameters of the algorithms underlying trading systems. At the same time, the more parameters the used trading method contains, the faster the optimization will be required. At the same time, if we take as an axiom the random nature of pricing in financial markets, then we cannot create a stable trading system with optimized parameters on a random price sequence. That is why any "black box" sooner or later begins to bring losses to its owners.

The consumers of these software products, as a rule, are that part of inexperienced investors who naively believe that they will be able to increase their fortune quickly and easily with the help of these "black boxes."

Another segment of investors uses in their practice more conservative strategies such as "buy and hold." The "buy and hold" trading system is a simple system without any parameters, and it is matched to the market perfectly. The profitability of the strategy will always exactly match the profitability of the financial asset: there will be large volatility of profitability, with strong price fluctuations; the volatility of profitability will be low with low price fluctuations.

High volatility is a distinctive feature of modern financial markets. Therefore, such strategies can lead to significant losses or to the "freezing" of investments for long periods of time. Typical examples of such situations are the price dynamics for the GAZPROM shares and for VTB Bank shares shown in *Figs. 1, 2.*

The graphs presented show that investors who bought GAZPROM shares in 2007–2008 were able to return their investments only after fourteen years, and investors who bought VTB Bank shares at the same time were unable to sell their shares with a profit during the review time.

The purpose of this work is to develop and test a conservative trading strategy based on popular trend indicators which can be used by non-professional investors when working on the stock exchange.

1. A brief overview of trend strategies

Any trend strategy is based on trend indicators [23, 25, 26]. The main purpose of this group of indicators is to determine the presence of an up-trend or a downtrend in the price dynamics for a financial asset. The disadvantages of trend indicators include the delay of the buy/sell signals relative to price changes generated by them. In addition, trend indicators work well on strong, well-defined trends, but these have been quite rare in recent years. Nevertheless, it was shown in [27] that the time for prices to stay in a particular trend is from

Fig. 1. Price dynamics for GAZPROM shares for the period from 2007 to 2021.

Fig. 2. Price dynamics for VTB shares for the period from 2007 to 2021.

25% to 30% even in the modern highly volatile Russian stock market. Therefore, the popularity of trend strategies is still quite high.

At the present time, a quite large number of trend strategies have been developed. Most trend strategies are based on the use of moving averages (MA). There are several types of this trend indicator, but the most popular are the simple moving average (SMA) and the exponential moving average (EMA).

The main parameter of the moving average is the averaging period *n*. Moving averages with a small value of *n* are usually called short-term MA. Moving averages with a large value of *n* are usually called long-term MA. When choosing an EMA order, you need to understand that the smaller this order, the more sensitive the EMA to price changes and the faster it reveals new trends. But, on the other hand, a short EMA changes its direction more often and, accordingly, it gives false signals more often. A slow EMA gives false signals less often, but it also reacts more slowly to a trend change.

Another way of choosing the order of the EMA is to link it to the cyclical nature of the market. When we identify the duration of the cycle, the order of the EMA should be equal to half of the dominant market cycle. For example, if a 26-day cycle is identified, then a 13-day EMA should be used to analyze such a market. However, the problem with this approach is that the cycles very often change their periodicity and even disappear altogether sometimes.

Therefore, investors often use a simple rule for choosing an EMA order: the longer the trend they are trying to find, the larger the EMA order should be. Most often *n* values are used in the range from 10 to 20 in real trading. Fibonacci numbers are used as the EMA order quite often.

The first trading systems using moving averages used the following rules:

♦ buy when the MA rises and the price closes above MA;

♦ sell when the price closes below MA.

Another version of the simplest trend trading system is as follows:

♦ buy when the short-term moving average crosses above the long-term moving average;

♦ sell when the short-term moving average crosses the long-term moving average downwards.

In [28] the trading method based on the intersection of two moving averages is proposed. Such an approach is used as a reference technique of this kind quite often. The technique uses a 9-day moving average as the short-term moving average, and an 18-day moving average is used as the long-term moving average. Many traders use other values for the averaging order to improve trading results with this strategy [19].

However, such approaches give relatively good results in markets with a pronounced trend component only. A lag of the moving averages leads to false signals and losses when the prices enter in a range.

One way to increase this kind of trending systems efficiency in markets with an implicit trend component is to use different kinds of filters. Filters are some rules that reject some trading system signals. Examples of the simplest filters: the price must close on the other side of the EMA several times (usually twice), or the price must break through the MA by a certain percentage. However, any filters are a "double-edged sword": by reducing losses, they also reduce profits. In addition, filters detract from the main advantage of the moving average – its ability to catch the trend at an early stage.

An intersection of three moving averages with different orders (for example, 4-, 9- and 18-day MA) is often used as a filter [23]. Trading signals come at those moments when all three MAs turn in the same direction. It is clear that this approach will miss a significant part of the trend, so it only makes sense to use it in markets with very strong trends.

In [29] the author's Triple Choice trading system is described, which is a combination of trend indicators and oscillators. In the system, EMA is used to identify trends, and oscillators are used to generate trading signals.

In [19] the TEMA (Triple Exponentially Moving Average) indicator is considered as a possible indicator for building trend trading systems instead of classical moving averages. This indicator is an advanced version of exponential smoothing.

Moving Average Convergence Divergence (MACD) is another way to improve a trend indicator that consists of three MAs [23, 25]. The MACD indicator consists of two lines: solid (MACD line) and dotted (signal line). MACD line is the difference between two MAs of different orders. It reacts to price changes faster. The signal line is the moving average of the MACD line. It reacts to price changes more slowly.

By crossing the MACD line and the signal line we can decide on a change in the trend. Such a system generates many fewer false signals than a system using a single moving average.

The rules for opening/closing positions using this indicator are as follows

- buy when the fast MACD line rises above the signal line;
- sell when the fast MACD line falls below the signal line.

The MACD indicator is included in most programs for technical analysis and trading terminals. The algorithm for its calculation is as follows:

1. Calculation of the 12-day EMA.
2. Calculation of the 26-day EMA.
3. Calculation of the difference between the 12-day and 26-day EMA and plotting it on the chart as a solid line (fast MACD line).
4. Calculation of the 9-day EMA fast line and plotting it on the chart as a dotted line (slow or signal line).

Some users of the MACD indicator try to optimize it by using other values (not 12, 26 and 9) for the order of the moving averages used to calculate the indicator. In particular, the combination (5, 34 and 7) is popular.

Some investors try to align the MACD indicator to market cycles. However, many analysts question the idea that financial markets are cyclical. If we still consider cycles, then it is believed that the order of the first EMA should be one quarter of the dominant cycle, and the order of the second EMA should be half of it. The third EMA is a smoothing tool, so it is not necessary to correlate it with a cycle.

Some investors adjust the MACD indicator until it produces the desired (but not necessarily correct) result for them.

Quite often, in real trading, not the standard MACD indicator is used, but the MACD histogram. This indicator has historically been considered as one of the best indicators in the arsenal of investors. It represents the difference between the MACD line and the signal line.

A graphical representation of both variants of the MACD indicator is shown in the *Fig. 3*.

The MACD histogram generates two types of trading signals. The first is the direction of the slope of the histogram. The second is the divergence between the MACD histogram and the price chart. The second signal does not appear on the charts very often, but it is considered as a very strong signal [25].

The rules for opening/closing positions using MACD histogram are as follows:

- buy when the MACD histogram goes from negative to positive;
- sell when the MACD histogram goes from positive to negative;
- sell when price makes a new high and there is a lower high on the MACD histogram (bearish divergence);
- buy when price makes a new low and there is a higher low on the MACD histogram (bullish divergence).

The indicator of directional movement ADX is often used to identify the presence of a trend [23]. This indicator is also included in most

Fig. 3. Graphical representation of the MACD indicator and the MACD histogram.

technical analysis software. The calculation of the indicator is rather complicated. It is based on a methodology for assessing not only the direction of the trend, but also its strength.

2. Multi-trend trade method

A strategy that generates trade signals based on the presence of various duration trends in price dynamics is proposed in this article.

There are three models to describe the price dynamics of a financial asset: an uptrend (the price is growing), a downtrend (the price is falling) and a neutral trend (flat – there is no directional movement in the price). Depending on the time interval, short-, medium- and long-term trends are distinguished.

Under the proposed approach, the position size can vary from 0% (no investment, free cash ratio is 100%, all trends are down) to 100% (all free cash is invested, all trends are up).

In general, the formula for calculation of the position size γ is as follows:

$$\gamma = \alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3, \qquad (1)$$

where α_i – coefficients for the presence of long-, medium- and short-term trends, respectively;

β_i – weight coefficients of the influence of long-, medium- and short-term trends, respectively.

The following condition is satisfied for the weight coefficients:

$$\sum_{i=1}^{3}\beta_i = 1.$$

The α_i coefficients take the following values: in the case of an up-trend $\alpha_i = 1$, in the case of a downtrend $\alpha_i = 0$ and in the case of no trend (flat) $\alpha_i = 0.5$.

Position size calculation example. Suppose that at the current moment of time the following situation has developed for the traded financial asset: no long-term trend ($\alpha_1 = 0.5$), no medium-term trend ($\alpha_2 = 0.5$), the short-term trend is downtrend ($\alpha_3 = 0$), and the following values are used for weight coefficients of the influence of trends:

- long-term trend, $\beta_1 = 0.5$;
- medium-term trend, $\beta_2 = 0.3$;
- short-term trend, $\beta_3 = 0.2$.

Then the position size is:

$$\gamma = 0.5 \cdot 0.5 + 0.3 \cdot 0.5 + 0.2 \cdot 0.0 = 0.4.$$

i.e., the size of the current position should be equal to 40% and free cash should be equal to 60%. If, for example, the position size is 70%, then it is necessary to sell 30% of the position at the current market price in order to adjust the position size to the required value (40%).

The presence of trends was determined by the slope of the corresponding exponential moving average. The advantage of exponential averaging over simple or weighted averaging is that in exponential averaging each of the prices of the analyzed time interval is given its own "weight." Moreover, the greatest weight is assigned to the last price (as the most significant), and the least weight is assigned to the first one.

To calculate the exponential moving average of the *n*-th order at the *i*-th time moment, the following iterative formula was used [25]:

$$EMA\ (i,\ n) = kP_i + (1 - k)\ EMA\ (i - 1,\ n), \quad (2)$$

where $k = 2 / (n + 1)$ – smoothing factor;

P_i – the price of a financial asset at the i-th time moment.

As an initial approximation for the iterative formula (2), we can take a simple moving average over a similar averaging period *n*.

An example of EMAs of various orders, calculated using formula (2), is shown in *Fig. 4*. From the chart it can be seen that EMAs smooth out price fluctuations. At the same time, the greater the order of EMA (the value of *n*), the more smoothly its graph changes.

To identify the presence of the trend, the method of determining the slope of the exponential moving average of the corresponding order was used. For example, to determine the presence of a trend in an interval of 21 days,

Fig. 4. An example of EMAs of various orders.

a 21-day exponential moving average is calculated. If the slope of the calculated moving average is positive, then it is concluded that there is an up-trend on the interval of 21 days and, therefore, the corresponding coefficient $\alpha_i = 1$. If the slope of the exponential moving average is negative, then we have a downtrend (the corresponding coefficient $\alpha_i = 0$). If the exponential average is a horizontal line (slope = 0), then this means that there is no trend in the price dynamics in the time interval of 21 days (the corresponding coefficient $\alpha_i = 0.5$).

The presence of a slope was determined by four consecutive EMA values at different points in time:

- if $EMA_i > EMA_{i-1} > EMA_{i-2} > EMA_{i-3}$ – slope is positive ($\alpha_i = 1$);
- if $EMA_i < EMA_{i-1} < EMA_{i-2} < EMA_{i-3}$ – slope is negative ($\alpha_i = 0$);
- for any other ratio of EMA values, it was considered that there is no slope ($\alpha_i = 0.5$).

The following values for the order of averaging n and weight coefficients of the influence of trends (β_i coefficients in formula (1)) were used in this work:

- short-term trend: $n = 8$, $\beta = 0.2$;
- medium-term trend: $n = 21$, $\beta = 0.3$;
- long-term trend: $n = 55$, $\beta = 0.5$.

Thus, the maximum weight (0.5) was given to the long-term trend.

As a result, the position is managed in the following way. At each new time moment (new week, new day, new hour, etc.), new values of three EMAs of the corresponding orders are calculated using formula (2). After that, the parameters of short-, medium- and long-term trends (α_i coefficients in formula (1)) are determined and a new position size α is calculated using formula (1). If the value of α has increased, then the required amount of the traded asset is bought. If the value of α has decreased, then the required amount of the traded asset is sold.

3. Data source

The portal of the financial holding "FINAM" was used as a source of data on prices for financial assets [24]. This resource allows you to get a history of quotes of all financial assets traded on the Moscow Exchange for an arbitrary period. The data can be saved both in a text file (file with the .txt extension) and in a csv file (a file with the .csv extension).

4. Technologies

The functional programming language R [30, 31] used to implement all the necessary calculations and to visualize the results. In recent years, this language has become one of the most popular tools for data processing and visualization in the field of Big Data and Data Science.

The basic tools of the R language as well as the capabilities of the dplyr, lubridate, and ggplot2 libraries were used for data processing and data visualization.

5. Results

Below are the results of testing the proposed trading system for the shares of four Russian companies from various sectors of the economy traded on the Moscow Exchange: Sberbank (SBER ticket), Novolipetsk Iron and Steel Company (NLMK ticker), Akron (AKRN ticker) and Yandex (YNDF ticker). The testing period was one year from December 15, 2020 to December 15, 2021. One day was used as the time frame.

In *Figs. 5–8*, the left charts show the price dynamics of the corresponding asset, and the right charts show the change in the return on investment in this asset (profit or loss) if you were to use the strategy considered above.

The figures presented clearly show the effect of the proposed trading system. It lies in the

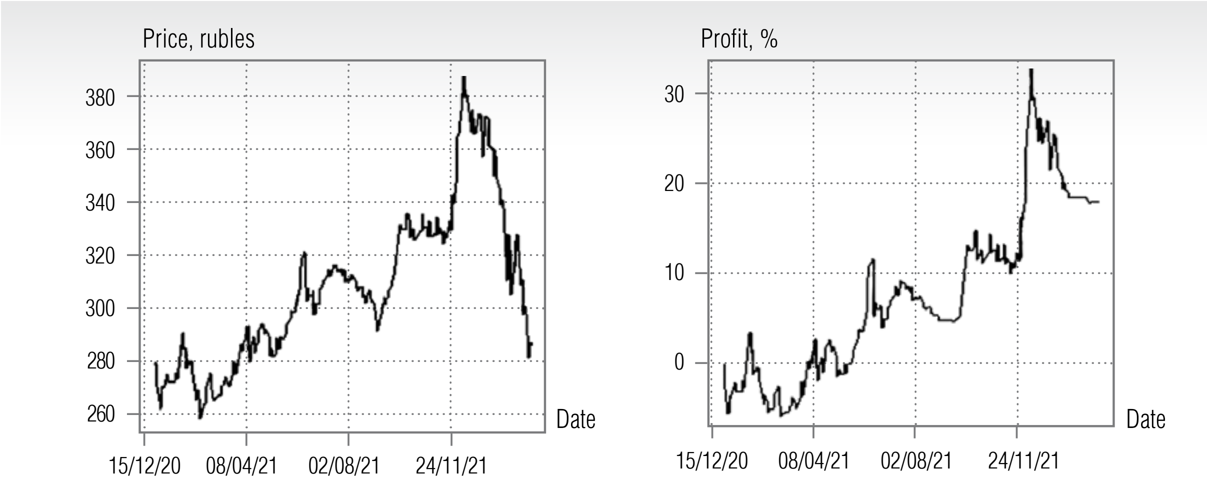


Fig. 5. The test resultsfor Sberbank share.

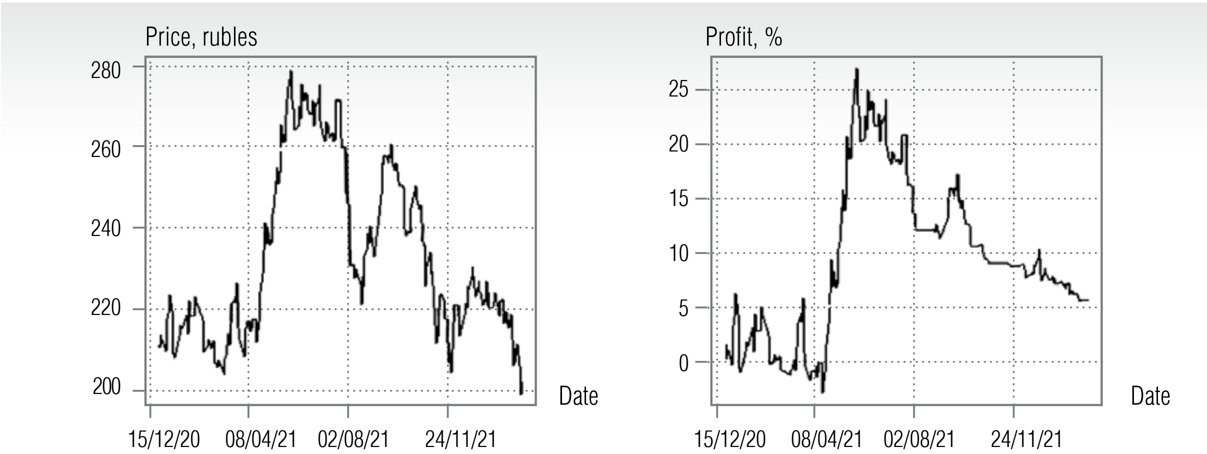


Fig. 6. The test results for Novolipetsk Iron and Steel Company share.

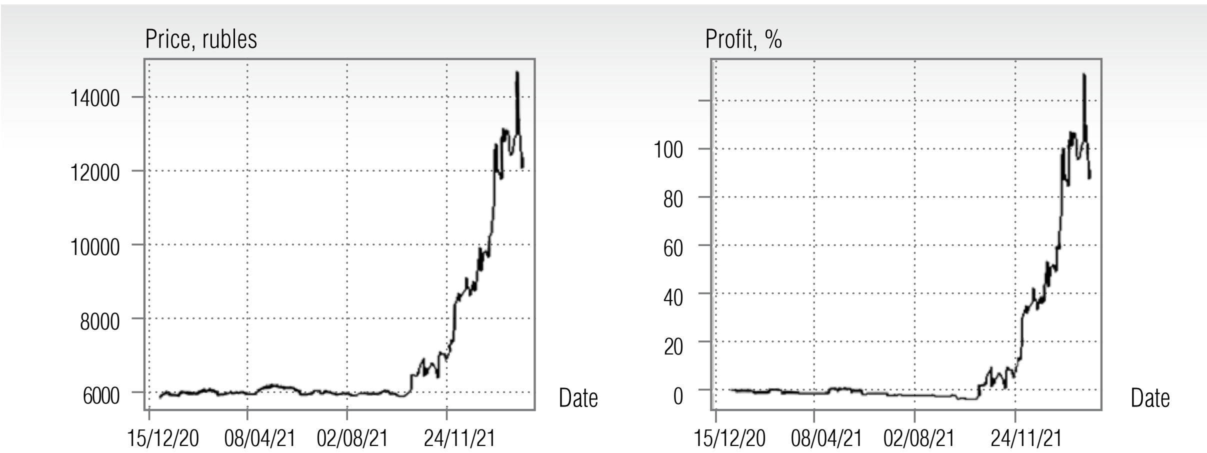


Fig. 7. The test results for Akron share.

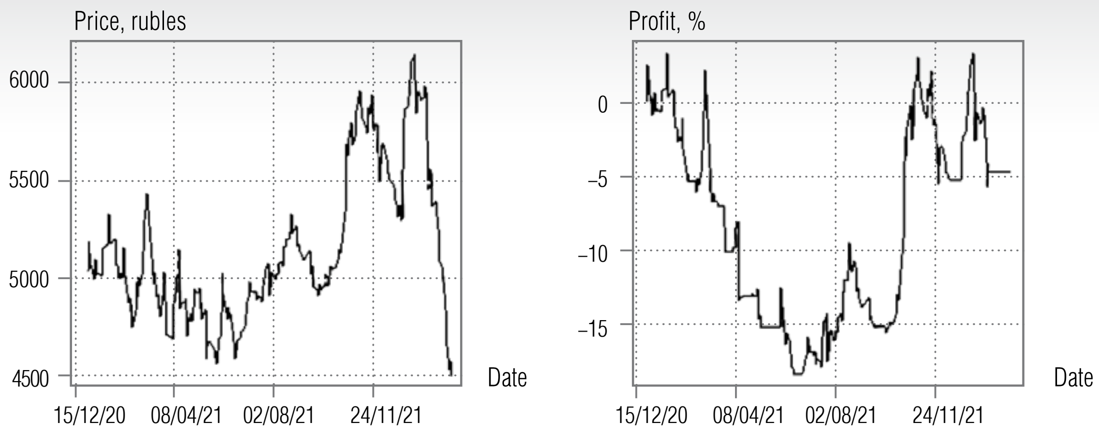


Fig. 8. The test results for Yandex share

fact that the profit chart is not an exact copy of the price chart (as opposed to the use case of "buy and hold" strategy). The difference between the charts is due to the fact both the opening and closing of a position is not carried out immediately in full, but in parts as each of the three trends forms.

One consequence of this approach is to obtain lower losses in the case of generating false signals. For example, if the system reacted to a false signal with 20% of the funds, then when the position is closed with a loss, this loss will be five times less than in a case when all 100% of the funds were involved in this unsuccessful transaction.

But, on the other hand, the same reason (formation of a position in parts) can also lead to a shortfall in profit at the initial stage of opening a position.

However, the main advantage of the proposed approach compared to the "buy and hold" strategy lies in the complete closing of the position with a big price drop, which leads to limiting losses. This effect is especially pronounced for the shares of Sberbank and Yandex (*Figs. 5, 8*). The charts clearly show that at the end of 2021, all positions were closed (horizontal lines on the right profit charts). As a result, it was possible to avoid significant losses in the event of a subsequent strong decline in prices for these assets.

To quantify the quality of the proposed system, *Table 1* presents summary results on the return on investment in selected assets, which could be obtained by using this strategy in real exchange trading.

Table 1.

The summary test results

Share ticket	Strategy profit, %	Strategy "Buy and hold" profit, %
SBER	17.61	2.85
NLMK	5.53	–4.04
AKRN	91.24	108.30
YNDF	–4.67	–10.66

For comparison, *Table 1* shows the return on investment in the same assets that would have been obtained using the "buy and hold" strategy. Based on the data in the table, we can conclude that in most cases (with the exception Akron stock) the use of the proposed strategy allows you to get significantly better results in terms of profitability compared to the conservative strategy.

It can be seen the strategy gives good results in areas with pronounced trends. Such a result is quite expected because the strategy is based on trend indicators. The higher the volatility of an asset is, the worse the results obtained are.

It should be noted that the purpose of this work was to develop a relatively simple trading strategy that can be considered as an alternative to the conservative "buy and hold" strategy and not to oppose the proposed strategy to other existing strategies. As noted at the beginning of the article, currently there are a very large number of different strategies. However, firstly, not all developers disclose the details of their strategies, and secondly, it is necessary to test different strategies on the same data sets to make a correct comparative analysis.

Such an analysis is beyond the scope of this work. Nevertheless, as an example, the results of the proposed strategy were compared with the results obtained in [19] using one of the most popular strategies described in paragraph 1. This strategy is based on the intersection of two moving averages of different orders. In particulary, 9-day and 20-day EMAs were used in [19]. The stock quotes of the American company AJG for the period from November 12, 2012 to November 10, 2021 were used as the data set. The profitability of the conservative "buy and hold" strategy was 125%. The profitability of the strategy for two EMAs was 82.99%. The profitability of the proposed strategy amounted to 134.63%.

Conclusion

An original trading strategy for working on financial markets is proposed. The strategy is based on trend indicators. A distinctive feature of the strategy is the combination of the trading method (rules for opening/closing a position) and the position size control system in one approach.

The results of testing the strategy on historical data showed that such strategies can bring investors returns that exceed those of conservative strategies even in today's highly volatile markets. Such strategies can also be considered as an alternative to both high-frequency robots and bank deposits for long time trading.

The strategy can be easily integrated into an automated trading system for short time trading. ■

References

1. *Average deposit rate in Moscow* (2022). Available at: https://www.sravni.ru/vklady/srednyaya-stavka-po-vkladam (accessed 10 January 2022) (in Russian).
2. *Inflation rate statistics in Russia* (2022). Available at: https://bhom.ru/inflation/rus/ (accessed 19 January 2022) (in Russian).
3. *Analysts estimated the net outflow of funds of Russians from banks* (2022). Available at: https://www.rbc.ru/finances/17/12/2020/5fd8b80a9a79472f7ea2739b (accessed 02 February 2022) (in Russian).
4. *Individuals invested more than 1 trillion rubles in securities on the Moscow Exchange* (2022). Available at: https://www.moex.com/n34977 (accessed 10 February 2022) (in Russian).
5. Sharpe W.F., Alexander G.J., Baily J.V. (1998) *Investments*. New Jersy: Prentice Hall.
6. Cartea A., Jaimungal S., Penalva J. (2015) *Algorithmic and high-frequency trading*. Cambridge: Cambridge University Press.
7. Chan E.P. (2017) *Machine trading: Deploying computer algorithms to conquer the markets*. New Jersey: Wiley.

8. Chan E.P. (2013) *Algorithmic trading: Winning strategies and their rationale*. New Jersey: Wiley.
9. Klimin P.Y., Bukunov S.V. (2021) Computer modeling of modern financial markets. In Proceedings of the *Information Technologies and Intelligent Decision Making Systems (ITIDMS2021), CEUR Workshop Proceedings*, Aachen. Available at: http://ceur-ws.org/Vol-2843/paper014.pdf (accessed 15 February 2022).
10. *Robots helped the Moscow Exchange set a record in March* (2022). Available at: https://1prime.ru/Financial_market/20200417/831279655.html (accessed 18 February 2022) (in Russian).
11. Kolmykova L.I. (2007) *Fundamental analysis of financial markets*. Saint-Petersburg: Piter (in Russian).
12. Schwager J.D. (1996) *Technical analysis*. NY: Wiley.
13. Aleinik T.S., Klyanina L.N. (2018) Statistical analysis of minimal risk securities portfolio. *Engineering Bulletin of the Don*. №1. Available at: http://ivdon.ru/magazine/archive/n1y2018/4771/ (accessed 15 February 2022) (in Russian).
14. Davey K.J. (2014) *Building winning algorithmic trading system: A trader's journey from Data Mining to Monte Carlo simulation to live trading*. New Jersey: Wiley.
15. Andrianova E.G., Novikova O.A. (2018) The role of text mining methods in automating stock market predicting. *Cloud of Science*, vol. 5, no. 1. Available at: https://cloudofscience.ru/publications/archive/cos_5_1/ (accessed 15 January 2022) (in Russian).
16. Burlakov V.V., Dementieva E.M., Dzyurdzya O.A. (2020) Fractal analysis as a method for predicting the dynamics of the value of the securities of enterprises, taking into account their hidden innovative potential. *Bulletin of RGGU. Chapt. "Economics. Management. Right"*, no. 3. https://doi.org/10.28995/2073-6304-2020-3-87-98 (in Russian).
17. Palyuvina A.S. (2019) Fractal analysis of the market based on the Hurst coefficient. *Economics Vector,* no. 4 (in Russian).
18. Kudryavtsev O.E., Mamedzade Kh.M., Rodochenko V.V., Chivchyan A.A. (2017) Efficiency analysis of options trading strategies on the Moscow Exchange using machine learning methods. *Engineering Bulletin of the Don*, no. 1. Available at: http://ivdon.ru/magazine/archive/n1y2017/4069/ (accessed 20 March 2022) (in Russian).
19. Stepanov A. (2021) *Comparison of the trading efficiency of a robot based on neural networks with some trading algorithms*. Available at: https://vc.ru/finance/318680-sravnenie-effektivnosti-torgovli-robota-na-neyronnyh-setyah-s-nekotorymi-torgovymi-algoritmami (accessed 10 June 2022) (in Russian).
20. Durenard E.A. (2013) *Professional automated trading. Theory and practice*. New Jersey: Wiley.
21. Chebotarev Yu. A. (2011) *Trading robots on the Russian stock market*. Moscow: SmartBook (in Russian).
22. Kaufman P. (2013) *Trading systems and methods*. New Jersey: Wiley.
23. Solabuto N.V. (2010) *Trading: trading systems and methods*. Saint-Petersburg: Piter (in Russian).
24. *FINAM* (2022). Available at: http://www.finam.ru/ (accessed 28 February 2022) (in Russian).
25. Naiman E.L. (2000) *Trader-Investor*. Kiev: VIRA-R (in Russian).
26. *Top-10 trend indicators* (2022). Available at: http://www.gurutrade.ru/blogs/10-luchshikh-triendovykh-indikatorov (accessed 20 February 2022) (in Russian).
27. Bukunov S.V. (2020) Verification of the applicability of trend strategies in modern financial markets. In Proceedings of the *International Science and Technology Conference "FarEastCon 2020"*. Singapore: Springer Nature Singapore Pte Ltd. P. 879–886. https://doi.org/10.1007/978-981-16-0953-4_85
28. Lebo Ch., Lukas D. (2017) *Computer analysis of future markets*. Moscow: Alpina Business Books (in Russian).

29. Elder A. (2010) *Trading for a living: Psychology. Trading tactics. Money management.* Moscow: Alpina Publishers (in Russian).

30. Grolemund G., Wickham H. (2017) *R for Data Science*. Boston: O`Reilly Media Inc.

31. R Core Team (2022) *R: A language and environment for statistical computing*. Available at: https://www.R-project.org/ (accessed February 2022).

About the authors

Sergey V. Bukunov

Cand. Sci. (Tech.), Associate Professor;

Associate Professor, Saint Petersburg State University of Architecture and Civil Engineering, 4, 2nd Krasnoarmeiskaya Street, Saint Petersburg 199005, Russia;

E-mail: sergeybukunov@yandex.ru

ORCID: 0000-0002-5983-0637

Olga V. Bukunova

Cand. Sci. (Tech.), Associate Professor;

Associate Professor, Saint Petersburg State University of Architecture and Civil Engineering, 4, 2nd Krasnoarmeiskaya Street, Saint Petersburg 199005, Russia;

E-mail: bukunovaolga@yandex.ru

ORCID: 0000-0002-5721-1795

DOI: 10.17323/2587-814X.2022.4.50.67

Choosing the type of business model to implement the digital transformation strategy of a network enterprise

Yury F. Telnov
E-mail: Telnov.YUF@rea.ru

Aleksey A. Bryzgalov
E-mail: Bryzgalov.AA@rea.ru

Petr A. Kozyrev
E-mail: Kozyrev.PA@rea.ru

Daria S. Koroleva
E-mail: Koroleva.DS@rea.ru

Plekhanov Russian University of Economics
Address: 36, Stremyanny Lane, Moscow 117997, Russia

Abstract

The digital transformation of enterprises and organizations in modern conditions is carried out through the development and implementation of new business models based on various digital technologies which are collectively accumulated as part of digital business platforms. Insufficient development of methods and means of choosing adequate business models for the functioning of network enterprises at the present time, depending on the competitive strategy used, production technologies, digital maturity, and security policy, determines the relevance of this study. The aim of the work is to develop a method to justify the rational choice of the type of business model of digital transformation of a network enterprise under the conditions of multi-criteria evaluation of various factors of obtaining network effects, digital maturity and ensuring economic and information security. To achieve the goal, methodological approaches are used as approaches to solve the problem: to formalize the business model based on the St. Gallen framework, to classify business models of the working group on business models Industry 4.0 to build a knowledge-based system using fuzzy sets of production rules. A method is proposed for classifying the types of business models of a network enterprise depending on the competitive strategy applied, the stage of the life cycle of products and services provided, the type of production and the method of using digital business platforms. In accordance with the classification of the working group on business models of Industry 4.0, network effects are determined for the main roles of participants in network interaction for each type of business model. A conceptual multi-criteria model for choosing the type of business model has been developed, implemented in the form of sets of production rules of a knowledge-based system which include an assessment of network effects, digital maturity, commercial risks and information security risks.

Keywords: business model, digital transformation strategy, digital platform, network enterprise, network effects, digital maturity, commercial risks, information security risks, multi-criteria choice, knowledge-based system

Citation: Telnov Yu.F., Bryzgalov A.A., Kozyrev P.A., Koroleva D.S. (2022) Choosing the type of business model to implement the digital transformation strategy of a network enterprise. *Business Informatics*, vol. 16, no. 4, pp. 50–67. DOI: 10.17323/2587-814X.2022.4.50.67

Introduction

One feature of economic development in modern conditions is the creation of business ecosystems based on the use of digital platforms within which there is a radical transformation of business models and business processes of enterprises and organizations. Such transformations are called digital transformation of enterprises; it involves "qualitative changes in the business models of economic activity, and significant socio-economic effects from their implementation" [1].

According to the Strategy of the Ministry of Industry and Trade of Russia, "Digital transformation of industry is a priority for the development of the domestic economy, providing high adaptability in the formation of business models and the operation of production processes through the integration of end-to-end digital technologies" [2]. In [3] it is argued that "Digital transformation represents a sharp reduction in transaction costs due to platforms as a result of the emergence of new business models. Combining the capabilities of technology and the traditional scope of the organization leads to the emergence of new products and processes with fundamentally different qualities." Work [4] emphasizes the role of digital transformation in the transition to digital business "based on a comprehensive transformation of the company's activities, its business processes, competencies and business models, the fullest use of digital technology capabilities in order to increase competitiveness, create and build value in the digital economy." As the Working Group on "Digital Business Models in Industry 4.0" (BMWK) defines Industry 4.0: "Business models are the foundation of entrepreneurial success. They embody the corporate mission and corporate strategy, and are the basis for investment decisions and organizational management" [5].

In [6] it is argued that innovations in business models bring a more tangible effect compared to innovations separately in products, processes and technologies. In this regard, a business model is not just a scheme of monetization of the company's income, but the entire set of business processes, technologies and personnel organization which determines the scheme of interrelated material, information and financial flows from the perspective of the overall strategy of digital transformation, taking into account technological and resource constraints. Therefore, the rational choice of the type of business model is a determinant condition for the success of the digital transformation of enterprises. The purpose of this paper is to develop a method to justify the rational choice of the type of business model for digital transformation of a network enterprise under the conditions of multi-criteria evaluation of various factors of network effects, digital maturity and economic and information security.

Aspects of creating business models based on multilateral digital platforms are discussed in articles [7–9]. A key conclusion of the analysis of existing business models is that digital services depend on the organization of value networks in which all participants in network interactions receive economic effects (network effects). Methods and models for creating network businesses using digital platforms are developed in [10–12]. Application of various business models has a significant impact on the change of organizational schemes of interaction of the enterprises participating in joint activity, in the creation of network enterprises [13].

One of the main conditions for the successful selection and application of a business model is its alignment with the defining strategy of digital transformation. Digital transformation strategy can be considered both in the classical sense of competitive strategy implementation: broad differentiation, cost leadership, optimal costs, focused strategies (segmentation) [14], and in the narrow sense as a way (direction) of applying digital technologies to implement business models and create new competitive business potential. In the first case, the choice of business model is determined by the competitive strategy; in the second case, the type of business model, on the contrary, determines the methods of digitalization of all related processes [15–17].

The study of its application at different stages of the life cycle of products and services plays an important role in the choice of a business model of interaction of enterprises in the ecosystem [18]. Consideration of features of the type of production: single, serial, mass production is also important when choosing the type of business model for creating network enterprises [19].

Given the above-mentioned features of business model application related to the analysis of competitive strategy, life cycle of products and services, as well as type of production, it is advisable to develop a classification of business models which would allow the preliminary choice of a business model for application. A more in-depth analysis of the application of various business models involves a study of the economic potential of enterprises to assess the possibility of digital transformation according to the chosen business model.

Economic analysis of the potential of the network enterprise is reduced to an assessment of the possible network effects [12, 20, 21] which can be obtained as a result of creating a network enterprise and assessment of the resources used, reflecting, on the one hand, its digital maturity in terms of knowledge of modern digitalization technologies, and on the other hand, aimed at preventing violations of economic and information security.

Works [7, 22, 23] are devoted to measuring the digital maturity of an organization for digital transformation. The key issue is the selection of indicators for measuring digital maturity. The most important indicators of digital maturity include: the level of digital culture and personnel competencies, the quality of organization of processes and products, access to data, and the organization of an information infrastructure [3].

On the other hand, the assessment of digital maturity should be conducted in conjunction with an analysis of the risks of default in the implementation of commercial transactions, the risks of selecting strategic partners and suppliers of components and materials, the risks of marketing errors in assessing internal market prospects, the risks of a long time to bring a new product to market [2], as well as information security risks [24–26].

To implement an appropriate choice of business model of the network enterprise, this article proposes the development of a method that, on the one hand, allows the best way to realize the strategic objectives of the digital transformation of the enterprise and provides high network effects, and on the other hand, makes it possible to assess the readiness of the enterprise to implement this or another type of business model, given the sufficiency of the economic potential of the enterprise.

From this point of view, the paper proposes a classification of the types of business models on the basis of compliance of the business model with the competitive strategy, stage of the life cycle, type of production and method of application of digital business platforms based on classifications [5, 6], and a multi-criteria model of business model type selection for its implementation in terms of obtaining network effects, sufficiency of digital maturity and minimizing commercial risks and information security risks using a knowledge-based system [27, 28]. The need for knowledge-based systems (expert systems) is due to the qualitative nature of the evaluation factors of the network effects, the level of digital maturity, commercial risks and information security risks, creating the need to formalize the selection process of the network enterprise business model based on the knowledge base of fuzzy rules and the application of the logical inference mechanism.

1. Classification of business model types

Modern concepts of the definition of business models combine the external side of the application, aimed at the implementation of value chains and monetization of financial flows, and the internal side, aimed at the organization of all interrelated business processes [9].

To the greatest extent, this concept of business model is reflected in the interpretation of Osterwalder [29]. In this model, on the one hand, material flows and on the other hand, financial flows are reflected. In the material flow, the output of the business model determines the receipt of value by the final consumer through various channels of distribution of products and services, and the input, respectively, the receipt of necessary material resources through various sources for the production of the required value.

The financial flow reflects in the opposite direction of the value chain the cash flows associated with the receipt and use of income to pay for the resources invested. And the financial flow may not always be directly related to the material flow of value creation, for example, as a consequence of the income from related advertising; nevertheless, one way or another, both flows are tied to a common model of value creation. Osterwalder's model in many respects reflects the classical scheme of business organization, in which the producing company is in the center, and suppliers and subcontractors are considered as business partners, on the one hand, and consumers and users, on the other hand.

In digital business, the network business model affects the functioning of enterprises along the entire value chain. Therefore, the efficiency of a network enterprise is determined not only by the efficiency of the parent enterprise, but also by the efficiency of all interrelated participants, which is called network effects. If the network effects for the participants of the network enterprise will not be obtained, such business model is doomed to failure: the interacting enterprises will not be interested to form a common structure within the unified business concept.

For reflection of network interaction of the enterprises within the limits of the uniform business model, there is the widely applied St. Gallen model [30, 31] in which for each participant of network interaction (for each role in a value chain) the independent model by means of four dimensions is defined: Who (Customer), What (Value proposition, value offer, product or service), How (How — Value Chain, Internal value chain as set of interconnected activities), and Value (Revenue mechanism, Cost structure and income mechanisms applied, etc.). A unified business concept is considered taking into account the network effects for all interacting participants of the value chain. If at least one of participants of interaction does not receive the effect, the business model ceases to be viable. Due to the possibility of the best reflection of network interactions and effects in the future, we will use the model of St. Gallen.

The Working Group on "Digital Business Models in Industry 4.0" is currently developing the use of the St. Gallen framework to formalize digital business models. In the digital business models of Industry 4.0, the key digital technology on which the new business organization is based is the use of digital platforms, and other technologies are based on the use of the Internet of Things, big data and artificial intelligence technology.

The use of the Internet of Things technology makes it possible to implement feedback from technological equipment and manufactured products into the loop of operational production management, which, on the one hand, makes it possible to implement a real-time management process and, on the other hand, to accumulate large amounts of data for analysis and improvement of all interconnected production and business processes. In this case, a new service business model of consumer-producer relations is formed instead of traditional commodity trading.

The use of digital platforms opens up opportunities to integrate network enterprise participants in common business processes, and intelligent technologies together with the Internet of Things technology allow to us to create multi-agent systems, in many cases automating the interaction of value chain participants with minimal staff participation.

In accordance with the above, the BMWK project identifies four types of Industry 4.0 business models based on different ways of applying digital business platforms [5] (*Table 1*).

These types of models reflect a service approach to the organization of customer needs and ultimately implement mediated relationships between consumers and producers through digital platforms that take on intermediary functions (marketplace, digital data platform). However, the variety of business models based on digital platforms is much broader [32, 33]. Therefore, the types of business models of the Industry 4.0 reviewed can be considered as technological frameworks (type models) for the construction of more complex models [34, 35] in which the types of business models examined can be combined.

One of the most successful works on the presentation of more complex archetypes of business models is [6] which differentiates business models according to their purpose: the integration of participants in the value chain, customer service products and services, consulting based on data.

In a broader context, the use of digital platforms makes it possible to manage more complex end-to-end value chains through integration business models that emphasize a special role for one of the enterprises, called

Table 1.

Business models of Industry 4.0

No.	Name of the type of business model Industry 4.0	The essence of the model	Technological principles used	Network effects of the business model
1.	IIoT platform provider	Collection of product use data throughout the product lifecycle, an on–demand data service, getting a data analysis service to improve the product.	Industrial Internet of Things, Data collection and analysis, Machine Learning	**Platform operator/provider:** The revenue model is directly proportional to the number of connected IIoT hardware units and the amount of data being transmitted and analyzed in the value chain. **User:** Outsourcing activities that are not part of its core business. **Service Provider:** Optimize resource utilization with multiple orders from the platform, reducing equipment downtime.
2.	Value adding services in operation	Leasing a finished product or equipment	Industrial Internet of Things, Data collection and analysis, Machine Learning, Multi–Agent Technologies	**Technologies Provider of solutions for IIoT:** Expanding the value proposition by organizing interactions between value chain participants, providing a platform for application development needed to integrate IIoT equipment. **User:** User can outsource activities that are not part of their core business. **Service Provider:** Optimize product usage by analyzing data from the IIoT platform and, as a result, improve the user experience as a result of new insights. **Produce:r** Based on the data received from the service provider on the use of the product by the user, optimizes the product and its processes. **Technical service network:** Reduces transaction costs in the value chain due to direct product delivery from the manufacturer bypassing the owner–service provider **IIoT Equipment Integrator:** Expanding the value proposition to include installation, development and integration of IIoT applications and technologies
3.	Marketplace (Brokerage Platform)	The platform that conditions the connection between suppliers and consumers	Data collection and analysis, Multi–agent Technologies	**The platform (Marketplace) Provider:** The revenue model is directly proportional to the number of connected Buyers and Product Suppliers and the balance of sufficient supply and demand on the trading floor. **Component Buyer:** Fast delivery and minimizing the risk of default by selecting reliable suppliers and being able to replace them quickly in case of unforeseen circumstances. **Product supplier:** Increased ordering, reduced transaction costs in the value chain.

No.	Name of the type of business model Industry 4.0	The essence of the model	Technological principles used	Network effects of the business model
4.	Data trustee	Collection of relevant data to optimize products or use additional data for research and development	Collection and analysis of secure data, Artificial Intelligence and machine learning	**Trusted data storage:** Expanding the value proposition by providing and engaging anonymous data from manufacturers on a digital platform. **Data producer:** Generating revenue from submitted data on a secure, neutral platform. **Producer accessing data:** Gaining access to an integrated base of primary and aggregated data, in a secure and standardized way. **System integrator:** Gaining revenue from supporting integrated data protection technologies. **Supplier of smart RFID devices** Revenue model is directly proportional to the number of connected pieces of equipment and the volume of data transmitted and analyzed.

the Integrator. In this type of business model, there are no intermediaries where a manufacturing company entrusts the marketing of its products to a trading company and does not get into the heart of the trading process. The Integrator business model type assumes that the "vendor" is embedded in the overall value chain, for example through its own or integrated online stores. Meanwhile, customers and other participants are embedded in the value chain by actively participating in the innovative development of products and all related processes. Production becomes decentralized to different markets with a focus on customer types.

The subtypes of integration business models are:

- The business model of crowd sourced innovation which is characterized by the union of all stakeholders of joint activities in the development of new products. In this case, there is a close integration of efforts of many participants of the joint project: customers, marketers, designers, technologists, suppliers, logisticians, distributors in product development, taking into account the subsequent implementation of the entire value chain.
- The "Production as a Service" business model. In this model, the customer becomes the key figure in determining the design of the products, the components of the manufactured products and the technologies used. The production processes must be individualized with respect to the customer, i.e. a single production is realized.
- The business model "Mass customization" involves adapting customer-selected variants of product types to their needs. In this case, serial production is carried out in accordance with consumer categories.

From the point of view of representation of service business models (Servitization), models of continuous customer service during the whole period of operation (Life-long partnerships), organization of services related to the end product, which is leased to the customer (Product as a service), and services based on the provision and analysis of end-use data, when the relevant process is outsourced to the service provider (Manufacturer) are considered (Result as a service).

Data-driven consulting business models (Expertise as a service) are based on trusted data access models related to analytics on digital data platforms that are collected through the Internet of Things and include the following subtypes:

- Fulfillment of requests for analytics of accumulated large amounts of data.
- Product-related consulting that complements product sales with advice and consultancy based on the company's own experience with products in other companies.
- Consulting related to the process of implementing related enterprise digital transformation processes.

The diversity of business models of network enterprises poses the problem of their choice depending on the corporate strategy of the company, product lifecycle and type of production (mass, serial, single). The classification model of business model types is presented in *Table 2*, which establishes the relationship between business model type and corporate strategy, product lifecycle stage, production type and Industry 4.0 business model type, reflecting the way digital business platforms are applied.

Competitive strategies determine the nature of the use of business models [35–37]. For example, strategies of broad product differentiation or market segmentation by various consumer categories are associated with the need to continuously update the product range, bring new types of goods and services to market, customize existing types and perform cyclical work on design and technical preparation of production. In this regard, the development and renewal of product types requires business models of integration and trusted data access which more closely connect all stakeholders of joint activities.

Thus, the initial stage of the lifecycle on the formation or development of requirements determines the application of the crowdsourcing model based on big data analysis, and at the stage of design and technical preparation of production – the model of production as a service or the model of mass customization of production, depending on the type of production.

A competitive cost-saving strategy focuses on improving the efficiency of operational processes. Therefore, various digital service business models will be most appropriate for these purposes. In this case, the application of the "Product as a Service" business model type will be more typical for single production, and the "Process as a Service" business model will be more typical for batch production.

Finally, the implementation of the market segmentation strategy is largely driven by consulting models and corresponding Industry 4.0 business models for data trustee.

As a result of the analysis of applying business model possibilities according to the classification table, it may turn out that some combination of corporate strategy, life cycle stage and production type may correspond to several alternative or complementary business models. In this case, it is necessary to conduct a more detailed analysis which will prove the necessity and possibility of applying a particular type of digital business model, taking into account the multi-criteria evaluation of various factors of obtaining network effects, digital maturity, economic and information security.

Table 2.

Classification of business model types

Type of business model	Integration of value chain participants			Customer service f or products and services			Data-driven consulting			
	Crowd sourced innovation	Production as a service – embedding the consumer in the develop–ment process	Mass customi–zation – adapt–ing the product to customer categories	Solution main–tenance – Life–long partnerships	Product as a service – Payment for use and access – re–source sharing	Process as a service – Process Outsourcing	Product Management Consulting (Consultations on the operation of products)	Consulting on organization of processes (produc–tion)	Intermediary services	Process efficiency analysis
Corporate strategy	Wide differentiation			Economy on costs			Market segmentation, value added services			
Product lifecycle stage	Product requirement, design, devel–opment	Design and Technical Production Preparation	Design and Technical Production Preparation	Operation, Maintenance	Operation, Maintenance	Operation, Maintenance	Operation, Maintenance	Design and Technical Production Preparation	Operation	Product requirement, design, development
Type of production	Single	Single	Serial	Single	Single	Serial	—	—	—	—
Industry 4.0 Business Model	Data trustee model	Value adding services in operation model	Value adding services in operation model	IIoT platform provider model	IIoT platform provider model	IIoT platform provider model	Data trustee model	Data trustee model	Marketplace Model	Data trustee model

2. Multi-criteria model for selecting the type of business model

Any management decision is usually considered from the position of assessment of necessity and possibility of its implementation. The need for realization of the decision is usually justified by the set of competitive advantages that result from its implementation, and the possibility is conditioned by an analysis of the sufficiency of various resources for implementation. For the business model of the network enterprise, these competitive advantages correspond to a set of network effects obtained by the participants of the value chain based on the digital platform. The assessment of the feasibility of implementation, on the other hand, is determined by the sufficiency of potential in the form of an assessment of digital maturity and risks of adverse effects related to the violation of economic and information security.

The variety of qualitative and uncertain factors in the feasibility of different types of business models leads to the construction of a multi-criteria model for selecting the type of business model and its implementation using a knowledge-based system that includes a knowledge base of production rules and a fuzzy inference mechanism to evaluate and convolution of expertise [27, 28].

The use of the mathematical instrument of fuzzy logic in comparison with the simpler methods of expert assessments used in scoring models facilitates the qualitative assessment of the factors with the help of linguistic variables which translate quantitative values of the evaluated indicators into fuzzy values on formalizable interval scales [38–41]. Thus, with the help of linguistic variables, it is possible to reflect the experts' experience in evaluating the factors in the knowledge base of fuzzy production rules. In addition, the system of fuzzy rules is used to display multilevel models of evaluation in which the assessment of intermediate factors is carried out with the help of appropriate subsets of rules.

A multi-criteria model for selecting the type of business model for the subsequent construction of a knowledge-based system in the form of an "AND – OR" graph is presented in Figure 1. It is assumed that this model evaluates one type of business model which receives a satisfactory or unsatisfactory value for use with some coefficient of confidence on a scale of [0, 1]. Satisfactory use of the type of business model is recognized when it exceeds some threshold value, for example, 0.8. If there are several applicants for the choice of business model type, the type with the highest confidence coefficient is selected.

The multi-criteria model uses the following designations of factors – fuzzy variables with values "satisfactory" or "unsatisfactory," for which the confidence coefficient is set on a scale of [0, 1]:

BM – choice of a business model;

NE – the network effect of the value chain (network enterprise);

NE_1 – the network effect of the first enterprise participating in the value chain (the first participant);

NE_k – network effect of the *k*-th enterprise participating in the value chain (*k*-th participant);

D – digital maturity;

DC – digital culture level;

PC – personnel competence level;

BP – quality of organization of business processes;

Prod – product quality;

Data – data availability;

Infra – IT infrastructure organization;

R – risks;

ES – commercial risks;

Trans – the risk of default in commercial transactions;

Sup – the risk of choosing strategic partners and suppliers of components and materials;

Mark – the risk of marketing mistakes in assessing internal market prospects;

Dead – the risk of a long time to bring a new product to market;

IS – information security risks;

Secr – the risk of violation of trade secrets;

Pers – the risk of personal data breach

Own – violations of data ownership rights.

Consider the mapping of the business model type selection model as a set of knowledge-based system production rules in more detail.

At the top level of the model, the Productive Rule of Conjunction of Network Effects (*NE*), Digital Maturity (*D*) and Risk (*R*) factors determines a satisfactory or unsatisfactory assessment of the target variable "Choice of a Business Model" (*BM*):

$$NE \text{ and } D \text{ and } \neg R \rightarrow BM, \qquad (1)$$

where → – implication sign, ¬ – the sign of negation.

This production rule in its expanded form has the form:

$$\text{IF } NE = \text{“satisfactory” and } D = \text{“satisfactory” and } \neg R = \text{“satisfactory” THEN } BM = \text{“satisfactory”}. \qquad (2)$$

Each factor represents a term with a value of "satisfactory" or "unsatisfactory". If at least one of the factors takes an unsatisfactory score, then the type of business model receives an unsatisfactory score. In this sense, the condition that all factors must be satisfied in order for the production rule to work must be satisfied. Otherwise, the target variable receives an unsatisfactory value.

In this case, the factor associated with the assessment of network effects reflects the resulting competitive advantages of the value chain formed, and factors of assessment of digital maturity and commercial risks and risks of information security reflect the possibility of its implementation.

Similarly, product conjunction rules are defined for network effects (*NE*), risks (*R*), commercial risks (*ES*) and information security (*IS*).

Thus, the rule of estimation of network effects is formed from the conjunction of estimates of network effects from the participation of all stakeholders (enterprises) in the value chain (network enterprise) for the type of business model under consideration:

$$NE_1 \text{ and } NE_2 \text{ and } \dots NE_k \rightarrow NE. \qquad (3)$$

The composition of participants in the value chain of each type of business model will differ depending on the nature of the network enterprise, so k – the number of chain participants (enterprises participating in the network enterprise) has a variable value.

The composition of the components determining the network effect of each type depends on the role played by the value chain participant in the business model (*see Table 1*). For example, a product supplier gets a network effect by increasing the number of orders and reducing transaction costs in the value chain. The number of components of the network effect can be different for each participant. In general, the network effect estimates for the i-th participant is calculated as the conjunction of the results of checking the terms of the j-th effect components:

$$NE_i = \wedge_j NE_{i,j}. \qquad (4)$$

The assessment of risks in the product rule (1) is interpreted in terms of their logical negation by ensuring the economic and information

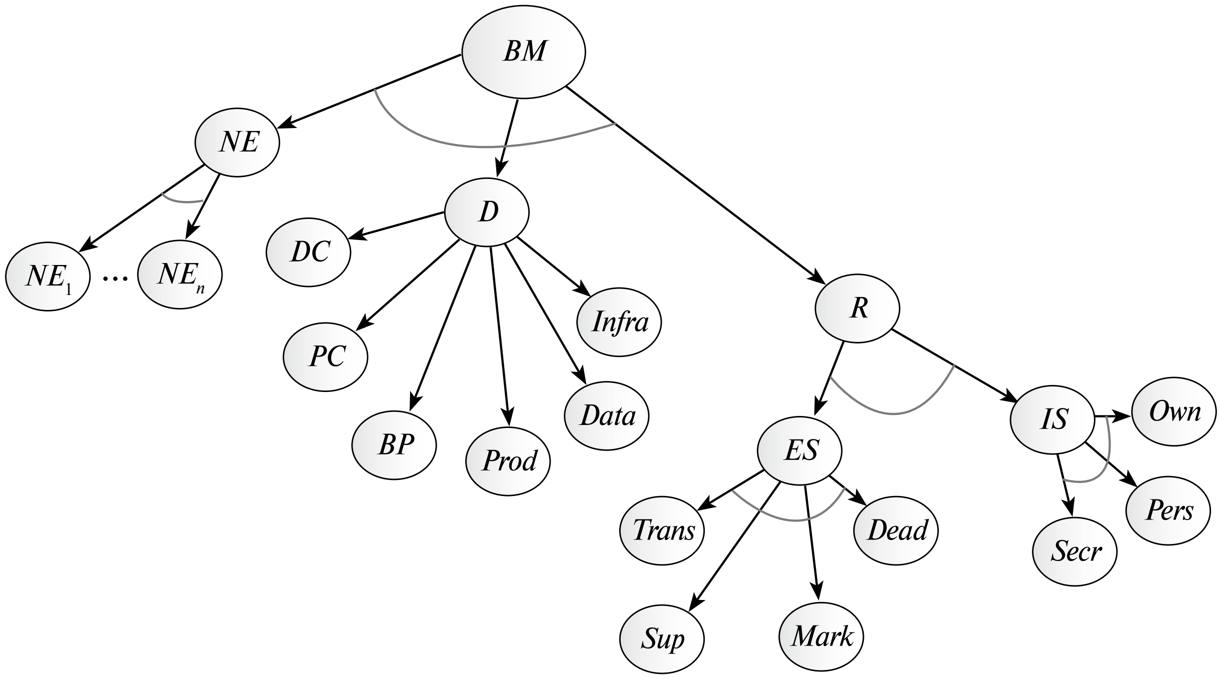


Fig. 1. Multi–criteria model of business model type selection
(the arc crossing the subordinate factors to the superior factor denotes conjunction of factors;
non–crossing arcs of subordinate factors denote disjunction).

security of the digital platform, and, accordingly, the risks are associated with the possibility of security violations. Thus, the assessment (R) depends on the conjunction of factors associated with commercial risks leading to a violation of economic security (ES) and information security (IS).

$$ES \text{ and } IS \rightarrow R. \qquad (5)$$

Accordingly, commercial risks (ES) are determined by the conjunction of estimates of the risk of default in commercial transactions ($Trans$), the risk of choosing strategic partners and suppliers of components and materials (Sup), the risk of marketing mistakes in assessing the internal market perspective ($Mark$), and the risk of a long time to bring a new product to market ($Dead$):

$$Trans \text{ and } Sup \text{ and } Mark \text{ and } Dead \rightarrow ES. \qquad (6)$$

The composition of commercial risks is defined in the Strategy of digital transformation of manufacturing industries [2].

Similarly, the risk of information security breach (IS) depends on the conjunction of the risks of violation of trade secrets ($Secr$), personal data ($Pers$), and data ownership rights (Own):

$$Secr \text{ and } Pers \text{ and } Own \rightarrow IS. \qquad (7)$$

The most significant risks associated with cybersecurity in the Internet environment are highlighted as risks of information security violation.

Each of the above risk factors must be associated with a certain digital platform service, the work of which should be aimed at eliminating the risk factor. In this regard, to assess the risk for one or another factor ($FactR_i$) when selecting the type of business model, it is necessary to obtain an expert assessment of the quality (reliability) of the service (*Serv*) used to eliminate the risk factor, which receives a fuzzy confidence coefficient on a scale [0, 1] and correlates with the assessment of the risk factor:

$$Serv_i \rightarrow FactR_i, \quad (8)$$

where $FactR_i \in \{Trans, Sup, Mark, Dead, Secr, Pers, Own\}$.

An expanded representation of a production rule looks like this:

$$\text{IF } Serv_i = \text{"satisfactory" THEN} \oplus < FactR_i, \text{"satisfactory"}, F_i\,(FactR_i)>, \quad (9)$$

where $\oplus$ – fuzzy value addition operator;

F_i – an membership function that calculates the confidence coefficient for a variable on the [0, 1] scale.

The nature of the membership function is determined by the type of variable $FactR_i$, in the simplest case some number in the interval [0, 1].

The digital maturity factors used to assess the type of business model $FactM_j$, unlike the risk factors, have an additive reinforcing nature. Therefore, their impact on the overall assessment of digital maturity D is considered using product rules separately:

$$FactM_j \rightarrow D, \quad (10)$$

where $FactM_j \in \{DC, PC, BP, Prod, Data, Infra\}$.

An expanded representation of a production rule looks like this:

$$\text{IF } FactM_j = \text{"satisfactory" THEN} \oplus < D, \text{"satisfactory"} F_j\,(D)>, \quad (11)$$

where $\oplus$ – fuzzy value addition operator;

F_j – a membership function that calculates the confidence coefficient for a variable on the scale [0, 1]. The nature of the membership function is determined by the type of variable $FactM_j$, in the simplest case some number in the interval [0, 1].

In this case, each $FactM_j$ production rule forms some fuzzy confidence coefficient estimate of the D (Digital Maturity) variable individually on the [0, 1] scale and reflects the value of the sufficiency sign.

The rules for evaluating each factor separately can be expanded into an independent knowledge base of rules interpreting linguistic variables, resulting in a fuzzy assessment of the confidence factor on the scale [0, 1]. Then the additive evaluation of the confidence coefficient of the maturity factor is carried out by the algorithm of fuzzy addition with recursion:

For *i* from 1 to 6:

$$1.\ CF(D_1) = CF(Fact_1),$$
$$2.\ CF(D_i) = CF(D_{i-1}) + CF(FactM_j) - CF(D_{i-1}) \cdot CF(FactM_j), \quad (12)$$

where $CF(Variable)$ – the confidence coefficient extraction function for the value of the fuzzy variable.

In the business model maturity assessment algorithm, you need to set an acceptable confidence threshold value, such as 0.8, at which the Digital Maturity variable gets a satisfactory value.

In the assessment of other factors – fuzzy variables of a multi-criteria model of business model type evaluation connected conjunctively can also get fuzzy values. To combine the fuzzy numbers for these factors, a multiplicative rule is used, such as choosing the minimum confidence coefficient:

$$CF(Left\ part\ of\ rule) = \min\{CF(NE_1), CF(NE_2), \ldots, CF(NE_k)\}. \quad (13)$$

When combining the confidence coefficients of the left and right parts of product rules (implications), either the minimum confidence coefficient is chosen or the fuzzy multiplication of the left and right confidence coefficients is performed.

In order to accept a positive assessment of the final choice of the type of business model one can also set a threshold level of confidence coefficient, for example, 0.8.

The implementation of a multi-criteria model for assessing the choice of the type of business model under conditions of fuzzy interpretation of qualitative factors using the tools of knowledge-based product system, together with the implementation of a preliminary classification of model types according to certain characteristics, will formalize the decision-making process to justify an effective strategy for the digital transformation of enterprises.

Conclusion

Analysis of approaches to the application of business models of network enterprises showed their diversity, determining the need to develop methods and tools to justify a rational choice of the type of business model in accordance with the strategy of digital transformation of the enterprise and the expected network effects, digital maturity, commercial risks and information security risks.

For representation of the components of a business model, one applies the framework St. Gallen which allows us to map processes of reception of network effects for all participants of the network enterprise. For the types of business models identified by the Industry 4.0 Business Model Working Group, the sources of network effects for the different roles of enterprises in the value chain are identified.

This paper proposes a method for substantiating the rational choice of the type of business model of a network enterprise based on a preliminary classification of business model types according to the characteristics of compliance with the competitive strategy of the enterprise, the stage of the life cycle of products and services, the type of production, the business model used Industry 4.0, and the subsequent multi-criteria assessment of the applicability of business model, taking into account the assessment of the resulting network effects, digital maturity, commercial risks and information security risks. As a tool to implement the multi-criteria model of business model type selection presented, it is proposed to use a knowledge-based system with a set of production rules implementing fuzzy inference on qualitative factors (variables).

The novelty of the proposed method for justifying a rational choice of the type of business model of network enterprise lies in the improvement of classification and development of a multi-criteria model of choice of the type of business models for the network enterprise, implemented with the help of a knowledge-based system with a fuzzy inference mechanism. The practical significance of the results obtained is determined by the possibility of applying the developed method in the implementation of modern digital platforms in the real practice of economic activities of network enterprises. In future research, it is necessary to continue refinement of the methods of formalization of qualitative assessment of diverse factors of applying business models for network enterprises. ■

References

1. Abdrahmanova G.I., Byhovskij K. B., Gokhberg L. M., Rudnik P.B., Veselitskaya N.N., Vishnevskij K.O., Zinina T.S. (2021) *Digital transformation of industries: initial conditions and priorities: report for the 22th Apr. International Scientific Conference on Problems of Economy and Society Development*. Moscow: HSE (in Russian).

2. Ministry of Industry and Trade of the Russian Federation (2021) *Strategy for digital transformation of manufacturing industries to achieve their "digital maturity" by 2024 and for the period until 2030* (in Russian).

3. Potapova E.G., Poteev P.M., Shklyaruk M.S. (eds.) (2021) *Strategy for digital transformation: write to implement*. Moscow: RANEPA (in Russian).

4. Cenzharik M.K., Krylova Yu.V., Steshenko V.I. (2020) Digital transformation of the company: strategic analysis, factors of influence and models. *Vestnik Sankt-Peterburgskogo universiteta. Ekonomika*, vol. 36, no. 3, pp. 390–420 (in Russian). https://doi.org/10.21638/spbu05.2020.303

5. Federal Ministry for Economic Affairs and Climate Action (Germany) (2019) *Digital business models for Industrie 4.0. Result paper*. Available at: https://www.bmwk.de/Redaktion/EN/Publikationen/Industry/digital-business-models-industry-4-0.pdf (accessed 31 August 2022).

6. Weking J., Stocker M., Kowalkiewicz M., Bohm M., Krcmar H. (2018) Archetypes for industry 4.0 business model innovations. Proceedings of the *24th Americas Conference on Information Systems, AMCIS 2018. New Orleans, LA, USA, 16–18 August 2018* (eds. A. Bush, V. Grover, S. Schiller). Association for Information Systems (AIS), pp. 1–10.

7. Zolotuhina Yu.V., Adamenko A.A., Kryzhanovskaya O.A. (2021) Choice of a business transformation strategy by organizations – participants of information interaction in the digital economy. *Natural-Humanitarian Studies*, vol. 37, no. 5, pp. 116–123 (in Russian). https://doi.org/10.24412/2309-4788-2021-537-116-123

8. Serova L.S., Strakhovich E.V., Churakova I.Yu. (2017) Multi-sided platforms in the evolution of micro-enterprise business models. *Upravlenets (The Manager)*, vol. 68, no. 4, pp. 53–60 (in Russian).

9. Ryndina S.V. (2020) *Business models of digital economy*. Penza: PGU (in Russian).

10. McIntyre D., Srinivasan A., Afuah A., Gawer A., Kretschmer T. (2021) Multisided platforms as new organizational forms. *Academy of Management Perspectives*, vol. 35, no. 4, pp. 566–583. https://doi.org/10.5465/amp.2018.0018

11. Vakeel K.A., Malthouse E.C., Yang A. (2020) Impact of network effects on service provider performance in digital business platforms. *Journal of Service Management*, vol. 32, no. 4, pp. 461–482. https://doi.org/10.1108/JOSM-04-2020-0120

12. Tucker C. (2019) Digital data, platforms and the usual [antitrust] suspects: Network effects, switching costs, essential facility. *Review of Industrial Organization*, vol. 54, no. 4, pp. 683–694. https://doi.org/10.1007/s11151-019-09693-7

13. Telnov Yu.F., Kazakov V.A., Danilov A.V. (2021) Technology for designing innovative processes for creating products and services of a network enterprise using an i4.0 knowledge-based system. *Business Informatics*, vol. 15, no. 4, pp. 76–92. https://doi.org/10.17323/2587-814X.2021.4.76.92

14. Porter M.E. (1998) *Competitive strategy: Techniques for analyzing industries and competitors*. N.Y.: Free Press.

15. Kraus N., Kraus K. (2021) Digitalization of business processes of enterprises of the ecosystem of Industry 4.0: virtual-real aspect of economic growth reserves. *WSEAS Transactions on Business and Economics*, vol. 18, pp. 569–580. https://doi.org/10.37394/23207.2021.18.57

16. Ritter T., Pedersen C.L. (2020) Digitization capability and the digitalization of business models in business-to-business firms: Past, present, and future. *Industrial Marketing Managemen*t, vol. 86, pp. 180–190. https://doi.org/10.1016/j.indmarman.2019.11.019

17. Bouncken R.B., Kraus S., Roig-Tierno N. (2021) Knowledge and innovation-based business models for future growth: Digitalized business models and portfolio considerations. *Review of Managerial Science*, vol. 15, no. 1, pp. 1–14. https://doi.org/10.1007/s11846-019-00366-z

18. Yang M., Evans S. (2019) Product-service system business model archetypes and sustainability. *Journal of Cleaner Production*, vol. 220, pp. 1156–1166. https://doi.org/10.1016/j.jclepro.2019.02.067

19. Turner C., Moreno M., Mondini L., Salonitis K., Charnley F., Tiwari A., Hutabarat W. (2019) Sustainable production in a circular economy: A business model for re-distributed manufacturing. *Sustainability*, vol. 11, no. 16, pp. 42–91. https://doi.org/10.3390/su11164291

20. Hinz O., Otter T., Skiera B. (2020) Estimating network effects in two-sided markets. *Journal of Management Information Systems*, vol. 37, no. 1, pp. 12–38. https://doi.org/10.1080/07421222.2019.1705509

21. Falkner C.F., Munck af Rosenschöld O. (2021) *Network Effects and Valuation: Examining the platform-mediated business model of international tech companies in order to test for an exponential association between revenue and user base*. Lund University. Available at: https://lup.lub.lu.se/student-papers/search/publication/9050810 (accessed 29 August 2022).

22. Teichert R. (2019) Digital transformation maturity: A systematic review of literature. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, vol. 67, no. 6, pp. 1673–1686. https://doi.org/10.11118/actaun201967061673

23. Belyaeva E.S., Ershov A.Yu., Ershova I.G. (2021) Parameters for assessing the digitalization of a business model in the context of economic transformation. *Industrial Economics*, vol. 12, no. 5, pp. 1128-1133 (in Russian). https://doi.org/10.47576/2712-7559_2021_5_12_1128

24. Prinsloo J., Sinha S., von Solms B. (2019) A review of industry 4.0 manufacturing process security risks. *Applied Sciences*, vol. 9, no. 23, article no. 5105. https://doi.org/10.3390/app9235105

25. Culot G., Fattori F., Podrecca M., Sartor M. (2019) Addressing industry 4.0 cybersecurity challenges. *IEEE Engineering Management Review*, vol. 47, no. 3, pp. 79–86. https://doi.org/10.1109/EMR.2019.2927559

26. Corallo A., Lazoi M., Lezzi M. (2020) Cybersecurity in the context of industry 4.0: A structured classification of critical assets and business impacts. *Computers in Industry*, vol. 114, article no. 103165. https://doi.org/10.1016/j.compind.2019.103165

27. Bolotova L.S. (2012) *Artificial intelligence systems: Knowledge-based models and technologies*. Moscow: Finance and Statistics (in Russian).

28. Telnov Yu.F. (2004) *Reengineering of business-processes. Component-based methodology.* Moscow: Finance and Statistics (in Russian).

29. Osterwalder A. Pignuer Y. (2010) *Business model generation: A handbook for visionaries, game changers, and challengers*. Hoboken, NJ: John Wiley and Sons.

30. Gassmann O., Frankenberger K., Csik M. (2014) *The business model navigator: 55 models that will revolutionise your business*. Harlow, UK.

31. Gassmann O., Frankenberger K., Csik M. (2013) *The St. Gallen business model navigator: Working Paper.* University of St. Gallen.

32. Queiroz M.M., Pereira S.C.F., Telles R., Machado M.C. (2019) Industry 4.0 and digital supply chain capabilities: A framework for understanding digitalisation challenges and opportunities. *Benchmarking: An International Journal*, vol. 28, no. 5, pp. 1761–1782. https://doi.org/10.1108/bij-12-2018-0435

33. Frank A.G., Mendes G.H.S., Ayala N., Ghezzi A. (2019) Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. *Technological Forecasting and Social Change*, vol. 141(C), pp. 341–351. https://doi.org/10.1016/j.techfore.2019.01.014

34. Rosa P., Sassanelli C., Terzi S. (2019) Towards circular business models: A systematic literature review on classification frameworks and archetypes. *Journal of Cleaner Production*, vol. 236, article no. 117696. https://doi.org/10.1016/j.jclepro.2019.117696

35. Puglieri F.N., Salvador R., Romero-Hernandez O., Filho E.E., Piekarski C.M., de Francisco A.C., Ometto A.R. (2022) Strategic planning oriented to circular business models: A decision framework to promote sustainable development. *Business Strategy and the Environment*, vol. 31, no. 7, pp. 3254–3273. https://doi.org/10.1002/bse.3074

36. Borowski P.F. (2021) Digitization, digital twins, blockchain, and Industry 4.0 as elements of management process in enterprises in the energy sector. *Energies*, vol. 14, no. 7, article no. 1885. https://doi.org/10.3390/en14071885

37. Mancha R., Gordon S. (2022) Multi-sided platform strategies for organizations: transforming the business model. *Journal of Business Strategy*, vol. 43, no. 3, pp. 175–183. https://doi.org/10.1108/JBS-09-2020-0203

38. Zadeh L.A. (1965) Fuzzy sets. *Information and Control*, vol. 8, no. 3, pp. 338–353.

39. Mamdani E.H. (1974) Application of fuzzy algorithms for control of simple dynamic plant. *Proceedings of the Institution of Electrical Engineers*, vol. 121, no. 12, pp. 1585–1588. https://doi.org/10.1049/piee.1974.0328

40. Beklaryan G.L., Akopov A.S., Khachatryan N.K. (2019) Optimisation of system dynamics models using a real-coded genetic algorithm with fuzzy control. *Cybernetics and Information Technologies*, vol. 19, no. 2, pp. 87–103. https://doi.org/10.2478/cait-2019-0017

41. Akopov A.S., Beklaryan L.A., Thakur M. (2022) Improvement of maneuverability within a multiagent fuzzy transportation system with the use of parallel biobjective real-coded genetic algorithm. *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 8, pp. 12648–12664. https://doi.org/10.1109/TITS.2021.3115827

About the authors

Yury F. Telnov

Dr. Sci. (Econ.), Professor;

Head of the Department of Applied Information Technologies and Information Security, Plekhanov Russian University of Economics, 36, Stremyanny Lane, Moscow 117997, Russia;

E-mail: Telnov.YUF@rea.ru

ORCID: 0000-0002-2983-8232

Aleksey A. Bryzgalov

Assistant, Plekhanov Russian University of Economics, 36, Stremyanny Lane, Moscow 117997, Russia;

E-mail: Bryzgalov.AA@rea.ru

ORCID: 0000-0002-5001-4326

Petr A. Kozyrev

Senior Lecturer, Department of Applied Information Technologies and Information Security, Plekhanov Russian University of Economics, 36, Stremyanny Lane , Moscow 117997, Russia;

E-mail: Kozyrev.PA@rea.ru

ORCID: 0000-0002-8021-2665

Daria S. Koroleva

Assistant, Plekhanov Russian University of Economics, 36, Stremyanny Lane, Moscow 117997, Russia;

E-mail: Koroleva.DS@rea.ru

ORCID: 0000-0002-0051-0655

DOI: 10.17323/2587-814X.2022.4.68.81

Development of a rating system assessing the quality of the service provided by drivers in a taxi aggregator company

Timofey Ya. Shevgunov [a]
E-mail: shevgunov@gmail.com

Zhanna A. Vavilova [a]
E-mail: vavilova.zhanna@internet.ru

Tatiana K. Kravchenko [b]
E-mail: tkravchenko@hse.ru

Liubov L. Levchenko [b]
E-mail: lllevchenko@edu.hse.ru

[a] Moscow Aviation Institute (National Research University)
Address: 4, Volokolamskoe Shosse, Moscow 125993, Russia

[b] HSE University
Address: 20, Myasnitskaya Street, Moscow 101000, Russia

Abstract

This paper deals with the problem of quantitative description and improvement of the quality of the service provided by taxi aggregator companies working on the Russian market. This problem seems to be insufficiently addressed in open research publications due to its high specificity, though some research aiming at searching the quality metrics have been conducted for some companies worldwide. The goal of the current research is mathematical formalization of a rating system assessing the driver service quality that allows one to design a parametrically tunable model. The proposed mathematical model of the rating system is described by means of a state graph where the transition from a vertex to another happens when the explicitly written conditions are satisfied. We show that the rating evaluation for a driver remaining in the active can be carried out by means of linear filtration performed as digital signal processing of the time series consisting of the scores which are given to the driver by their passengers. The type and waveform of the filter impulse response is suggested. The A/B-test conducted for the group of drivers working with a taxi aggregator proved the fact that the integral metric of service quality is sensitive to changes in the parameters of the proposed rating system; this eventually led to a decrease in the rate of taxi rides accompanied with a negative client experience. The rating system model developed can be utilized to increase the quality of the service provided by the taxi aggregator by means of more effective differentiation of the drivers, while the subsequent optimization of the rating system parameters can serve as a tool for achieving indicators supporting the strategic goals of the company.

Keywords: taxi aggregator, driver rating, rating system, digital signal processing, linear filtering, state graph

Citation: Shevgunov T.Ya., Vavilova Zh.A., Kravchenko T.K., Levchenko L.L. (2022) Development of a rating system assessing the quality of the service provided by drivers in a taxi aggregator company. *Business Informatics*, vol. 16, no. 4, pp. 68–81. DOI: 10.17323/2587-814X.2022.4.68.81

Introduction

The service industry of a modern megalopolis exists and evolves in an environment of robust competition for customers. Companies have to carefully monitor the sentiment and customer preferences of active and potential client groups, react to changes quickly, constantly monitor the quality of services provided, search for growth directions and seek to increase consumer value of their products. The automobile passenger market or, to put it simply, passenger taxi market is quite large, diverse by client segments and has its own history. Since the beginning of the 2000s, the advancing taxi aggregator companies inexorably push aside and gradually supersede classic taxi companies with a taxi depot and phone operator. Undoubtedly, the cause of this phenomenon is the advancement of digital technology resulting in universal availability of mobile Internet in cities. Historically, the first taxi aggregator in Russia was Uber, which entered the market in 2009; then Yandex.Taxi and Gett-taxi appeared in 2011. Over the course of the following ten years, the Russian taxi aggregator market has been continuously expanding; new companies have appeared, including regional and local ones.

Broadly speaking, a taxi aggregator is a platform that provides services by arranging taxi rides based on a two-way mobile application connecting passenger demand with driver supply [1], in other words, an aggregator company provides communication between passengers and drivers.

A typical aggregator company should seek to maintain the positive value of its brand among customers and to improve the quality of services provided, thus facilitating an increase in brand loyalty and retention of customers for as long as possible. The specific aspect of the taxi aggregator business is the fact that it is important for a company to maintain loyalty of both passengers and drivers at the same time so as to accommodate the interests of both groups. Drivers are one of the key profit-generating resources in the business model of taxi aggregators. Due to increasing demand of core customers, the companies study and test various methods to attract qualified drivers (i.e. those who provide good quality service to passengers) and to subsequently retain them in the company. A rating system (RS) is one of the methods used to evaluate quality and promote the company's attractiveness for drivers. For most taxi aggregators, RS is the main method of quality control over drivers' service to customers. The score in such RS directly affects the driver's income and ability to continue working with the platform in general, so it becomes the key factor for most of the drivers. In study [2], it is noted that taxi aggregators use a rating system as a tool to motivate drivers to maintain the quality service level standardized by companies. Note that the scores are given not by the company's own experts, but by its clients (passengers).

Considering the importance of the rating system for formation of driver and passenger loyalty, attraction, retention and motivation of drivers, we may set the task to develop a driver RS from the perspective of most parties concerned. The drivers would like to get a transparent and comprehensible RS, which would be sensitive to factors that depend on the drivers' own efforts. The passengers would like to get an illustrative RS to be able to pre-evaluate the quality of drivers offered to them. An aggregator would like to get an RS that increases driver motivation by rewarding their actions aimed at service improvement or by punishing them for their breach of safety and quality rules. Also, RS should be able to provide the aggregator with interpretable and quantifiable feedback signals from passengers which may be used, after processing, for preparation and implementation of changes in the aggregator's terms of service.

The RS that would be almost ideal for all parties concerned should meet the following requirements:

- it should influence the driver as a motivating factor: rewards and punishments;
- it should provide a scalar value, which is calculated on a comprehensible basis with substantive rationale;
- it should feature functions of parameterization and configuration;
- it should provide a special starting period allowing drivers to adapt to the system;
- it should provide for comprehensible feedback to the platform in order to make further modifications;
- it should be sensitive to changes in the driver's behavior: if a driver changes his or her behavior pattern, the RS should detect such a change within a short period of time.

RS improvements may potentially improve the quality of service provided by the aggregator as well as the effectiveness of driver differentiation, and also promote formation of a comfortable working environment for drivers.

The purpose of RS development as part of the current task is to improve the effectiveness of driver differentiation by quality of services provided during rides, and, as a result, to improve the quality of service and customer satisfaction.

It is important to note that the problem of developing an RS for taxi aggregators receive little attention in scientific literature. This is due to the quite narrow focus of such a research subject. Thus, studies [3, 4] address selection of indicators for sensitive qualitative evaluation of passenger preferences in taxi service quality evaluation. In study [5], a selection of metrics is proposed for evaluation of service quality based on entropy, and study [6] contains a discussion of the influence of the service quality indicators used on passenger behavior. Particular attention should be given to analysis of regional passenger markets in a megalopolis in the Middle East [7].

The main source of information for this study is the research [8] done by one of the coauthors of this study which provides a comprehensive analysis of the problem of RS development for the benefit one of the taxi aggregators in Russian market. The informational background provided by the abovementioned research was used in this study in depersonalized form.

1. Taxi aggregator service quality

Since one of the strategic goals of most companies conducting business in a highly competitive environment is to increase its market share, each aggregator company is interested in looking for effective ways to attract and retain new drivers and passengers, i.e. to uphold their satisfaction and loyalty. At least once a year, a typical aggregator company conducts comprehensive research of brand loyalty through online interviews of clients.

To measure brand loyalty, one of the most simple and common methods is used, the *Net Promoter Score* (*NPS*). *NPS* determines a loyalty index: the intention of users to recommend the platform, readiness to convey their personal experience of interaction with the company to new clients. Respondents are asked to evaluate their readiness to recommend the platform to other people on a score from 0 to 10 (where 0 means "not ready to recommend," and 10 means "ready to recommend"). After that, respondents are separated into three categories: 1) promoters (score 9–10); 2) neutrals (score 7–8); 3) and detractors (score 0–6). Then the *NPS* index is calculated according to a formula (1):

$$NPS = P_p - P_c, \qquad (1)$$

where P_p is the percentage of promoters in the total number of respondents;

P_c is the percentage of detractors in the total number of respondents.

NPS values are distributed in the [−100%, 100%] range, and the higher the *NPS* value is, the more loyal the audience is and the more ready it is to recommend the platform.

The success of this metric is defined by its simplicity (users are asked only one question and offered an intuitive evaluation scale) and correlation with long-term growth of the company [9], which allows one to set measurable KPIs for increasing brand loyalty.

The designated metric for measurements of customer satisfaction is the *Customer Satisfaction Index* (*CSI*). This index defines the degree to which the platform meets the requirements and expectations of the market and the degree of customers' satisfaction from interaction with the company. The calculation takes account of certain company-defined attributes such as: the company's goodwill, customer value, expectations, perceived quality, which affect the consumer satisfaction and, as a result, consumer loyalty to the company. Each attribute has its weight, i.e. importance among all attributes according to respondent's opinion, and a rating, which are both given by respondents on a 1 to 5 scale. The calculation algorithm can be described with the following formula:

$$CSI = \frac{100\%}{K} \sum_{i=1}^{k} W_i \cdot P_i, \qquad (2)$$

where K is the number of analyzed attributes;

W_i is attribute weight;

P_i is attribute rating.

CSI values are distributed in [0%, 100%] range; the higher *CSI* value is, the more satisfied the customers are by interaction with the company.

For comprehensive research of customers' loyalty to a brand, *NPS* and *CSI* values are considered in conjunction. There are two types of *NPS* and *CSI*: by market and by own base. *NPS* and *CSI* by market are calculated based on data received from all customers who were interviewed via a pre-selected Internet platform, and then the company's position among competitors is identified. *NPS* and *CSI* by own base are calculated based on responses of customers of a particular service, and such values demonstrate the change of the company's attractiveness among the most active audience.

Survey among own base of drivers has shown that the *CSI* index of market leaders, i.e. companies working under such brands as Yandex. Taxi, Uber, City-Mobil, showed almost no change during the six months from December 2020 to June 2021 and remained within 40–50% range, as shown in *Fig. 1.* The latter six months of 2021 have shown a certain decline of Uber and City-Mobil indices as compared to Yandex.Taxi as the leading aggregator.

Figure 2 compares the dynamics of *NPS* by own base for drivers of City-Mobil, Uber, Yandex.Taxi for the period from December 2020 to December 2021. On the diagram, it can be observed that the *NPS* index of Yandex and Uber is much higher than City-Mobil, which is indicative of a low satisfaction of City-Mobil drivers from interaction with the aggregator. City-Mobil drivers point out the following downsides: low fares (and therefore low income), problems with supervision and

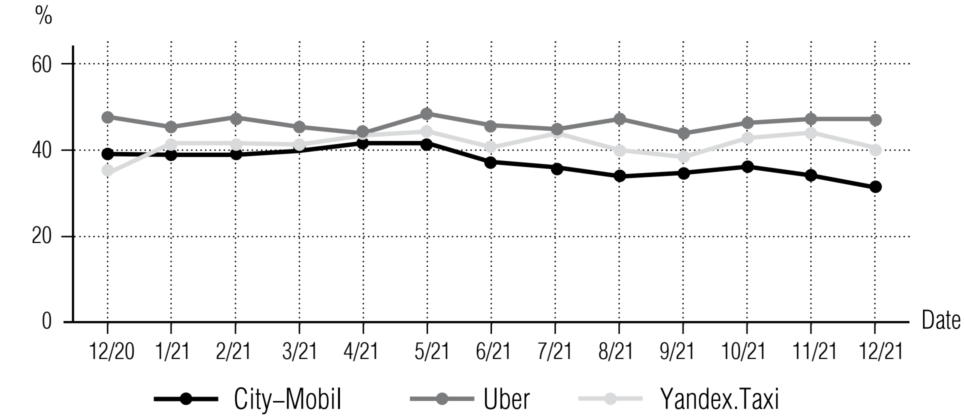


Fig. 1. Dynamics of passenger CSI by own base
for City–Mobil, Uber, Yandex.Taxi (December 2020 – December 2021).

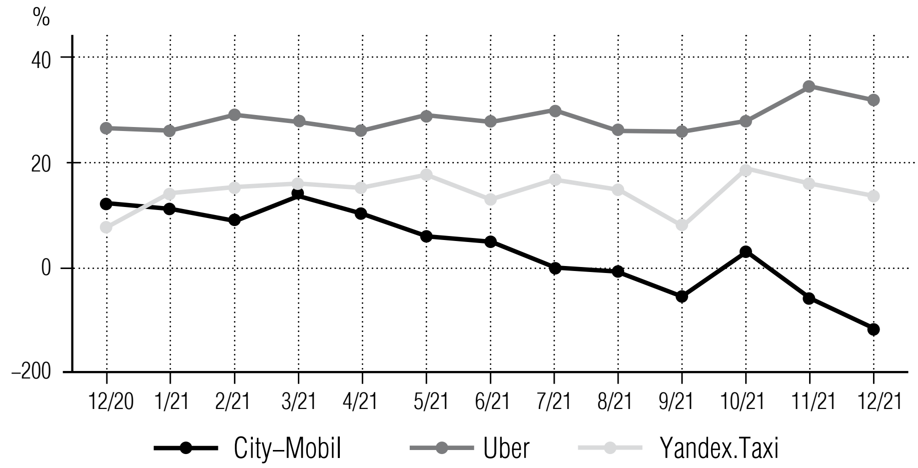


Fig. 2. Dynamics of NPS by own base for drivers
of City–Mobil, Uber and Yandex.Taxi (December 2020 – December 2021). Source: City–Mobil.

low number of orders in general (compared to Yandex.Taxi and Uber).

The above-mentioned indices are designed to evaluate the perceived quality of platforms based on one-time passenger surveys carried out by taxi aggregators. Apparently, the formula of service quality evaluation for a company should be defined in a more strict way and calculated on dynamically obtained data, to which the company would have access at any time.

After each ride, a passenger is invited to rate the ride in the aggregator's client mobile app on a scale from 1 to 5 stars. Customers can put a rating immediately after the ride, or they can get back to it after a while. The passenger may also select tags from the list provided or write his or her own comment to substantiate the rating. Depending on the rating given, the offered tags are changed: examples of tags for different ratings are shown in *Fig. 4.*

The quality of service over time by days or by weeks may be evaluated by a *Bad Trips Rate* (*BTR*) value, which is calculated using the formula:

$$BTR = P_{BT}, \tag{3}$$

where P_{BT} is the percentage of bad rides from the total number of rides.

Bad rides include all rides, where: 1) the passenger has put a rating of 1–3 (such scores are perceived as a signal of unsatisfactory platform use experience); 2) the passenger has contacted customer support with a problem from "Quality Standard Violations" and/or "Safety Standards Violations." Categories "Quality Standard Violations" and "Safety Standards Violations" include all problems related to drivers' behavior and skills (rudeness, smoking in the vehicle, aggression, traffic violation, illness, inadvertence, etc.), vehicle condition (dirtiness inside the vehicle, bad smell, technical issues, etc.) or order procedures (monetary cheating of the client, no ride given, failure to pay change in cash, etc.)

Unfortunately, this metric should not be used as a quality indicator for a certain driver, because additional research has shown that it depends strongly on the driver's number of rides: the more rides, the lower *BTR* value.

In order to evaluate quality of a certain driver without reference to the number of rides, one more special metric can be used: *CAD* (*Conversion after Driver*), which is customer conversion to another ride after a ride with a certain driver. *CAD* is calculated according to the formula:

$$CAD = \frac{ns_d}{N_d} \cdot 100\%, \tag{4}$$

where ns_d is the number of passengers who took another ride within less than 60 days after a ride with driver *d*;

N_d is the number of passengers who took a ride with driver *d*.

The results of analysis of this metric can be used to categorize drivers into two groups with maximum difference in their influence on passenger loyalty.

The first group consists of drivers with high conversion rate $CAD \in [80\%, 100\%]$. Such drivers take orders with high rates, work fewer hours per day on average (6 or less), are highly discriminative in ride selection. But the main thing is that they do rides of higher quality. Also, such drivers work longer with the aggregator.

The second group consists of drivers with low conversion rate: $CAD \in [0\%, 20\%]$. Such drivers have lower income, work more hours per day on average (seven or more), are less discriminative in ride selection, but do rides of lower quality according to feedback and ratings given by passengers. Such drivers remain with the aggregator for a shorter period of time.

Driver rating can be called the quality indicator of service provided by the driver with regard to satisfaction of passengers from the services provided. That's why for a passenger, driver rating is a signal of how well a certain driver can satisfy a ride request in terms of safety and comfort. When making an order, passengers pay attention to the rating and would likely reject the ride with a driver who has a low rating (according to their value judgment).

Research of drivers' attitudes towards ratings [8] has shown that around 60% of drivers check their rating on a daily basis, since they realize its importance for successful work. They intend to maintain a high rating by keeping the vehicle clean both inside and outside, keeping smells in the normal range, by politeness and proper conduct, careful driving and passenger care. Research has also shown that drivers are often unable to find out why they got a bad rating, so they treat the idea of a rating system negatively and think that some passengers use it to humiliate and discriminate against drivers. As a result, a drop in their rating spoils their mood and doesn't motivate them to improve their quality of service.

2. Rating system model

Currently, all major companies in the Russian taxi aggregator market have their own driver rating system which makes calculations based on classical approaches of time series analysis.

Time series is a collection of observations generated sequentially over time [10]. Thus, ratings of a certain driver *d* obtained from passengers are a random value which forms a discrete random time series that can be denoted as: $\{r_d[t]\}$, where $r_d \in \{1, 2, 3, 4, 5\}$. The time series $\{r_d[t]\}$ can be treated as an implementation of a certain random process quantified by the driver's ratings $r_d[t]$ generated by a hidden probabilistic mechanism. In this study, we do not make assumptions on the nature of the process under consideration, in particular regarding its stationary or a more complex non-stationary behavior [11, 12].

Let us define the axis of discrete running time *t*, integer values of which will mean sequence numbers of rides done by drivers. Let us denote the rating of driver *d* at the moment of time *t* as $R_d[t]$. Value $R_d[t]$ is formed on the basis of processing a time series of $r_d[t]$ ratings with account taken of the following variables:

$S_d[t]$ means the driver's state in RS;

$Am_d[t]$ means the number of the drivers' amnesties at the moment of time *t*;

TH is the threshold value $R_d[t]$, at which the driver is allowed to work with the platform;

$TA_d[t]$ is the moment of the driver's latest amnesty since the decrease of his/her rating below the threshold value;

MA means the maximum number of amnesties for a driver;

NA means the duration of adaptation and recovery period;

RN means a novice's rating during the adaptation period;

RA means the driver's rating immediately after amnesty, which is valid during the recovery period.

2.1. Monitoring of driver state within the platform

The variable describing the driver state monitored by RS assumes values from a finite alphabet {*N*, *A*, *B*, *C*}:

N (*newbie*) – the driver works with the platform and has a newbie status;

A (*active*) – the driver works with the platform in rating calculation mode;

B (*blocked*) – the driver is blocked: this state appears when $R_d[t] < TH$ on a certain step;

C (*correction*) – the driver works with the platform in a recovery period, i.e. within a certain period after amnesty.

Figure 3 demonstrates a finite state machine graph implementing the driver's transition between the states. The square brackets contain the conditions for transition to another state. If neither of the transition conditions is met, the driver's state remains the same: $S_d[t] = S_d[t-1]$.

$\{N, A, C\}$ forms a subset of states, in which the driver is allowed to do rides, and time t increases by one with every ride. States in this subset differentiate by rating calculation method and time duration measured by the number of rides during which the driver can remain in every state. The driver may potentially stay in active state A for an infinite period of time, unless and until an exit condition is triggered due to a low rating. At the start of work of each unique driver d, the system performs initialization: $Am_d[t] = 0$, $TA_d[t] = 0$. The accepting state of the graph is state B, in which the driver loses the ability to do rides if the number of amnesties received by him/her has not exceeded the maximum number of amnesties MA set in the system. If the number of amnesties received by the driver does not exceed MA, then the driver may leave this state if he makes an amnesty request. $REQA$ denotes a Boolean variable assuming 'true' value when a driver makes such a request. After that, the driver usually has to undergo additional training provided by the aggregator in order to get the amnesty officially, and only after that he/she would be able to work with the platform again. However, the process of such training will not be reviewed in this study, and the state graph actually demonstrates this event as continuation of the driver's work in state C after the amnesty.

2.2. Linear rating calculation model

Linear digital filtration is a simple but effective way to process the time series of ratings given by passengers to a driver. Such a procedure allows for effective smoothing of a sequence of ratings by generating an average value. This provides an opportunity to reduce the influence of random situational factors on the overall driver rating.

The formula for calculation of the current value of rating $R_d[t]$ depends on the driver's state $S_d[t]$, as shown in (5):

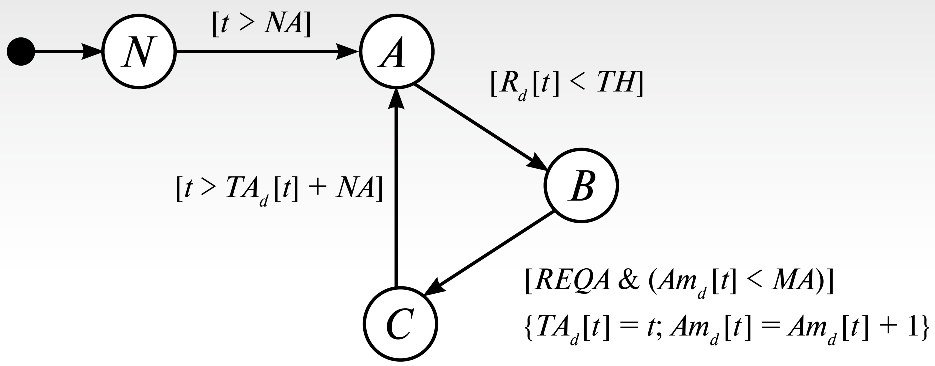


Fig. 3. Driver state graph in the rating system.

$$R_d[t] = \begin{cases} \sum_{n=-\infty}^{+\infty} w[n] r_d[t-n], \\ (S_d[t] = A) \vee (S_d[t] = B); \\ RN, NS_d[t] = N; \\ RA, S_d[t] = C; \end{cases} \quad (5)$$

where $w[n]$ are the ratios of a weighing function, which, taken together, comprise an impulse response function (*IRF*) of an equivalent linear time-invariant (*LTI*) filter [13] that converts the input digital signal $r_d[t]$ into output signal $R_d[t]$ by linear digital convolution.

The choice of *IRF* $w[n]$ completely defines the *LTI* filter's behavior, and in certain situations, in case of quite general qualitative description of the desired conversion, it happens to be possible to set requirements for *IRF*. Since, in order to form the driver rating $R_d[t]$ in active state (A) based on observation over his/her ratings $r_d[t]$ for a certain preceding period of time, the *LTI* filter responsible for such formation must perform a smoothing conversion. In this case, the following requirements apply to its *IRF*.

Firstly, the applied *LTI* filter must be a causal system [14], i.e. at $n < 0$: $w[n] = 0$, which is due to the impossibility of knowing the values of the input signal in future moments of time when calculating the output value in the current moment of time.

Secondly, *IRF* readings must be non-negative: $\forall n : w[n] \geq 0$, which is due to the semantic content of overall rating as a result of accumulation of a time series of rating values.

The third requirement for the filter's *IRF* is the condition of its norming:

$$\sum_{n=-\infty}^{+\infty} w[n] = 1, \quad (6)$$

which allows one to receive values of rating $R_d[t]$ within the range of rating values $r_d[t]$.

The simplest selection of *IRF* for calculation and semantic interpretation is an *IRF* implementing a smoothing filter of a simple moving average, *SMA*, calculated based on the last W readings of the input signal:

$$w[n] = SMA_W[n] = \begin{cases} \frac{1}{W}, \ 0 \leq n \leq W-1, \\ 0, \ n \geq W. \end{cases} \quad (7)$$

Table 1 shows driver rating calculation methods used by major taxi aggregators present in the Russian market as of January 2022.

Table 1.

Rating calculation by major aggregators in the Russian market in January 2022

Aggregator company	Smoothening method	Averaging window width *W*	Threshold value *TH*	Adaptation period *NA*
Yandex.Taxi [16]	Weighted moving average	150	4.4	50
Uber [17]	Simple moving average	500	4.6	100
Gett [18]	Simple moving average	150	4.6	50
City–Mobil [19]	Simple moving average	200	4.6	30

3. Example of a driver's rating evaluation

As an example, let us consider the following parameters of a rating system: we use a simple moving average window (7) with parameter W = 200, threshold value TH = 4.6, adaptation period duration NA = 30 and maximum number of amnesties MA = 3. *Figure 4* shows the rating time series of a driver from the group with high conversion rate. It can be noted that such a driver's rating has never decreased to less than the threshold value marked by the dashed line on the diagram. The initial section of continuous rating 4.9 is due to the adaptation period. In addition, the diagram shows the value of the estimated rating which can be obtained by using the first line of formula (5) without regard to the driver's actual state in the system.

Figure 5 shows the rating time series of a driver from the group with a low conversion rate. It can be noted that such a driver's actual rating has never decreased below the threshold value marked by the dashed line on the diagram, immediately upon expiration of the adaptation period. After an amnesty, the recovery period has started, during which the driver's rating was set equal to RA = 4.7.

4. Estimation of rating system effectiveness

A/B test carried out in February 2022 [15] provided an opportunity to check whether or not the theoretical evaluation of the effect of implementing the new rating system is confirmed by actual changes of service quality metrics.

The A/B test was carried out on a group of drivers who had done at least 250 rides in City-Mobil for the period from November 2021 to January 2022 in St. Petersburg [8]. The test was carried out during five weeks, since in that period drivers were getting enough ratings for calculation of overall rating in various ways. In

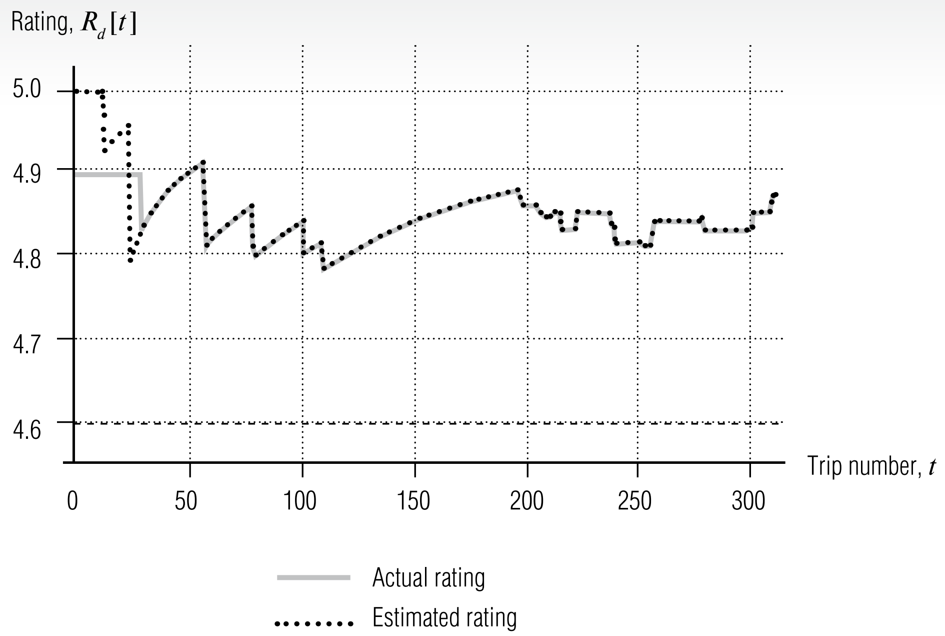


Fig. 4. Variation of rating of a driver with high conversion rate.

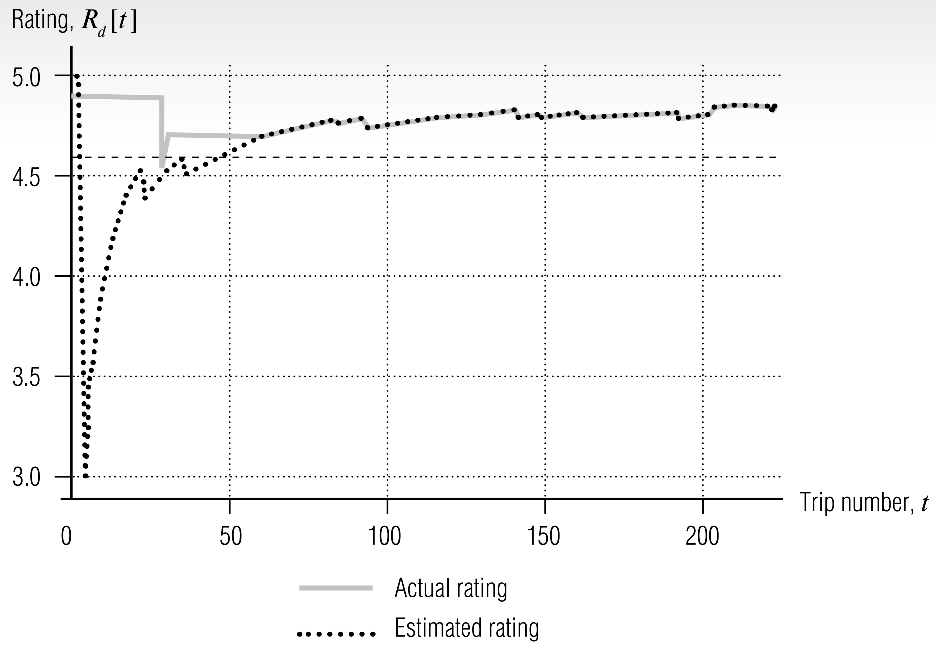


Fig. 5. Variation of rating of a driver with low conversion rate.

that period, a sufficient quantity of observations was accumulated for evaluation of statistical significance.

For test group A, the rating was calculated with the use of an RS having the following parameters: $W = 100$, $T = 4.6$, $A = 2$. For test group B, the rating was calculated with the use of preselected parameters: $W = 200$, $T = 4.6$, $A = 3$. The main metric that was checked for variation was the driver's *BTR*. Such a choice is due to the fact that the drivers selected for testing had almost an equal number of rides. The hypothesis for the A/B test was formulated as follows: the *BTR* value in a test group would undergo statistically significant reduction, because the rating would become more sensitive due to the reduction of moving average window width, and drivers would monitor the quality of service provided better, while the main parameters of drivers, such as a driver's number of rides per day, percentage of accepted orders from the total number of orders, do not change.

The selected drivers were randomly split into groups A and B in 50/50 percentage. Five weeks later, the results were analyzed. The metric in test group A turned out to be 23.52% less than in test group B, while the main parameters showed almost no change. The values obtained for the main metric for the groups are shown in *Fig. 6.*

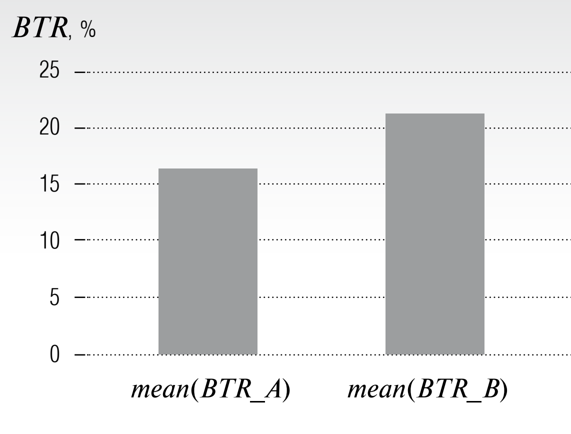


Fig. 6. Comparison of average *BTR* values of two groups of drivers.

Nevertheless, it is also important to check the statistical significance of the observed variation in order to make sure that it was not caused by a mere accident. It was required to check null hypothesis H_0 about equality of average distributions $\{BTR\}_A$ and $\{BTR\}_B$, i.e. H_0: $mean(BTR_A) = mean(BTR_B)$. In this case, a parametric test was used for hypothesis check – Student's t-test. As a result, the estimated value $p = 0.034$ attests to the fact that the null hypothesis is rejected when choosing typical significance level $\alpha = 0.05$, since $p < \alpha$.

Therefore, variations in the metric by groups may be deemed statistically significant, while $mean(BTR_A) > mean(BTR_B)$. This allows us to conclude that the approach reviewed in this study provides an opportunity to build a rating system in which variation of parameters can have a statistically significant influence on the quality of service provided by the taxi aggregator.

Conclusion

The rating system model proposed in this study is built upon the driver state graph, which implements the driver's transition between states upon fulfillment of expressly defined conditions. The method of driver rating calculation depends on the driver's current state. It was shown that for the basic active state of the driver, the task can be formalized as a task to determine a digital filter described by its impulse response function. The basis of digital filtering of a time series of ratings is formed by a smoothing procedure intended to form a value which would integrally reflect the quality of service provided by the driver within a certain period of time. This provides an opportunity to reduce the influence of random and situational factors on the overall driver rating. The advantage of the resulting rating system model is that its adaptation can be achieved by using a limited set of parameters that define its operation: the form and duration of impulse response function of a digital filter, threshold value of rating, permitted number of amnesties, duration of periods of driver's adaptation and recovery after amnesty.

The results of effectiveness analysis of the proposed rating system performed on actual data through an A/B-test on a group of drivers have shown that the new rating system would allow a company to improve service quality indicators by at least 5% due to selection of other parameters of the rating system. This may potentially improve such an indicator as lasting value of a company due to the attraction of new drivers and passengers. It is important to note that development of a mathematically formalizable model of a rating system is an important step that opens up opportunities for further research in this direction, and specifically for optimization of rating system parameters in order to obtain quality indicators ensuring the achievement of strategic business goals of a taxi aggregator company. ■

Acknowledgments

The theoretical part of the research was funded by the state assignment of the Ministry of Science and Higher Education of the Russian Federation, project no. FSFF-2020-0015.

References

1. *Analytical report on market competition of information exchange between passengers and taxi driver (taxi aggregator market)*. The Federal Antimonopoly Service of Russia. Available at: https://fas.gov.ru/documents/678673 (accessed 10 October 2022) (in Russian).

2. Rosenblat A., Stark L. (2016) Algorithmic labor and information asymmetries: A case study of Uber's drivers. *International Journal of Communication*, vol. 10, pp. 3758–3784. https://doi.org/10.2139/ssrn.2686227

3. Yao Z.-G., Ding X.-D. (2011) Measuring passenger's perceptions of taxi service quality with weighted SERVPERF. *Applied Mechanics and Materials*, vol. 97–98, pp. 1181–1184. https://doi.org/10.4028/www.scientific.net/AMM.97-98.1181

4. Alonso B., Barreda R., dell'Olio L., Ibeas A. (2018) Modelling user perception of taxi service quality. *Transport Policy*, vol. 63, pp. 157–164. https://doi.org/10.1016/j.tranpol.2017.12.011

5. Li Q.-H., Song W. (2011) Service quality evaluation model for taxi industry based on entropy weight and TOPSIS method. Proceedings of the *International Conference on Machine Learning and Cybernetics (ICMLC 2011). Guilin, China, 10–13 July 2011*, vol. 3, pp. 1043–1047. https://doi.org/10.1109/ICMLC.2011.6016914

6. Techarattanased N. (2015) Service quality and consumer behavior on metered taxi services. *International Journal of Economics and Management Engineering*, vol. 9, no. 12, pp. 4242. https://doi.org/4246. 10.5281/zenodo.1110471

7. Shaaban K., Kim I. (2016) Assessment of the taxi service in Doha. *Transportation Research. Part A: Policy and Practice*, vol. 88, pp. 223–235. https://doi.org/10.1016/j.tra.2016.04.011

8. Levchenko L.L. (2022) *Development of a rating system to evaluate quality of drivers' performance for a ride-hailing company.* Diploma dissertation. Moscow: HSE University. Available at: https://www.hse.ru/ba/bi/students/diplomas/page12.html/624082719 (accessed 10 October 2022) (in Russian).

9. Reichheld F. (2013) *The one number you need to grow.* Harvard Business Review. Available at: https://hbr.org/2003/12/the-one-number-you-need-to-grow (accessed 1 October 2022).

10. Box G., Jenkins G., Reinsel G., Ljung G. (2015) *Time series analysis: Forecasting and control.* Fifth Edition. Wiley.

11. Guschina O. (2022) Cyclostationary analysis of electric power in a resonant circuit under periodic excitation. Proceedings of the *2022 Systems of Signals Generating and Processing in the Field of on Board Communications. Moscow, Russia, 15–17 March 2022.* P. 1–5. https://doi.org/10.1109/IEEECONF53456.2022.9744264

12. Efimov E. (2022) On the effect of a signal delay on cross-spectral correlation function // Proceedings of the *2022 Systems of Signals Generating and Processing in the Field of on Board Communications. Moscow, Russia, 15–17 March 2022.* P. 1–6. https://doi.org/10.1109/IEEECONF53456.2022.9744308

13. Holton T. (2021) *Digital signal processing: Principles and applications*. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/9781108290050

14. Oppenheim A., Schafer R. (2009) *Discrete-time signal processing*, 3rd ed. Pearson.

15. Kohavi R., Tang D., Xu Y. (2020) *Trustworthy online controlled experiments: A practical guide to A/B testing*. Cambridge, UK: Cambridge University Press.

16. *Section "Rating" of the knowledge base for taxi driver in application Yandex.Pro.* Yandex.Pro. Available at: https://pro.yandex/ru-ru/ufa/knowledge-base/taxi/app/raiting (accessed 8 May 2022) (in Russian).

17. *How does the rating work.* Uber. Available at: https://www.uber.com/cz/ru/drive/basics/how-ratings-work/ (accessed 8 May 2022) (in Russian).

18. *Rating*. Gett. Available at: https://driver.gett.ru/information/rating/ (accessed 6 May 2022) (in Russian).

19. *Rating of Citymobile.* Citimobile. Available at: https://ct-mobil.ru/rating/ (accessed 8 May 2022) (in Russian).

About the authors

Timofey Ya. Shevgunov

Cand. Sci. (Eng.);

Associate Professor, Radio Engineering Department, Moscow Aviation Institute (National Research University),

4, Volokolamskoe Shosse, Moscow 125993, Russia;

E-mail: shevgunov@gmail.com

ORCID: 0000-0003-1444-983X

Zhanna A. Vavilova

Cand. Sci. (Eng.);

Associate Professor, Radio Engineering Department, Moscow Aviation Institute (National Research University),

4, Volokolamskoe Shosse, Moscow 125993, Russia;

E-mail: vavilova.zhanna@internet.ru

Tatiana K. Kravchenko

Dr. Sci. (Econ.), Professor;

Professor, Department of Business Informatics, Graduate School of Business, National Research University Higher School of Economics, 20, Myasnitskaya Street, Moscow 101000, Russia;

E-mail: tkravchenko@hse.ru

ORCID: 0000-0002-6479-6250

Liubov L. Levchenko

MSc Student, Graduate School of Business, National Research University Higher School of Economics, 20, Myasnitskaya Street, Moscow 101000, Russia;

E-mail: lllevchenko@edu.hse.ru

DOI: 10.17323/2587-814X.2022.4.82.104

Macroeconomic production function of Russia and estimation of the marginal rate of technical substitution in the unprecedented socio-economic realities of 2020–2022

Anton A. Afanasiev
E-mail: aanton@cemi.rssi.ru

Olga S. Ponomareva
E-mail: fondf@cemi.rssi.ru

Central Economics and Mathematics Institute, Russian Academy of Sciences
Address: 47, Nakhimovsky Prospect, Moscow 117418, Russia

Abstract

In the period 2020–2022 the Russian economy has been facing the new, unprecedented challenges of coronavirus and sanctions. In order to analyze the current state of affairs, we are offering an econometric study of Russia's macroeconomic production function for 1990–2022 and an estimation of the marginal rate of technical substitution under internal and external restrictions associated with the spread of the Wuhan coronavirus (SARS-CoV-2) and the conduct of Russia's special military operation in Ukraine, accompanied by increased sanctions pressure on the Russian economy. We have obtained several significant results. In the years 1991–1996 the marginal rate of technical substitution was increasing, and in 1997–2020 it was decreasing except for 2008–2009 and 2015. In the context of the Wuhan coronavirus pandemic, the main reasons for the Russian economy's decline in 2020 and growth in 2021 were, first of all, fluctuations in the world crude oil price, and not the Wuhan coronavirus pandemic as such. We did not find any evidence that the decline in the world crude oil price in 2020 was caused by a decrease in demand from China, since Russian oil exports to China increased. Contrary to many negative forecasts, the results of our forecasting of Russia's GDP for 2022 show that under sharply increased sanctions pressure, with the world price of Urals oil at $60 per barrel, the average growth rate will be 0%, while at $70 it will be 4%, and at $80 it will be 7%. Under the reduced demand for Russian gas and the shutdown of the Nord Stream 1 gas pipeline, the forecast volumes of gross natural gas production by Gazprom (excluding Gazprom Neft) in the Tyumen Region for 2022, based on the exponential production function studied by econometric methods, range from 364 to 392 billion cubic meters. Using the example of Great Britain, where in 2021 the average actual export prices for Russian oil and gas were the lowest compared to other Western European countries, we discuss the economic inexpediency of setting marginal prices for Russian energy products by Western consumers.

Keywords: Russian economy, macroeconomic production function, world oil price, econometric forecasting, coronavirus restrictions, production capacities, natural gas production, oil and gas export, sanctions, price cap, UK economic and trade policy

Citation: Afanasiev A.A., Ponomareva O.S. (2022) Macroeconomic production function of Russia and estimation of the marginal rate of technical substitution in the unprecedented socio-economic realities of 2020–2022. *Business Informatics*, vol. 16, no. 4, pp. 82–104. DOI: 10.17323/2587-814X.2022.4.82.104

Introduction

An econometric study of the macroeconomic production function is one of the most important components of economic analysis and forecasting the dynamics of the development of any country's national economy, including Russia, especially in the unprecedented socio-economic realities of 2020–2022, i.e. under internal and external restrictions associated with the Wuhan coronavirus (SARS-CoV-2) pandemic and the conduct of Russia's special military operations in Ukraine, accompanied by increased sanctions pressure on the Russian economy from many of Russia's Western and overseas neighbors. A number of studies by Russian and foreign scientists are devoted to the study and the analysis of economic and mathematical models of production functions (for example, [1–6]). In our publications [7–9], we have studied the production function of the Russian economy in regard to the world price of Brent crude oil for 1990–2019. It is commonly known that 2019 was marked by the appearance, and 2020 was marked by the active spread of the Wuhan coronavirus, later named SARS-CoV-2 by virologists [9]. The socio-economic crisis which appeared during the pandemic did not bypass Russia. After some restoration of the world economy in 2021, the socio-economic crisis began to flare up again from the end of February 2022. That was mainly due to the sharply increased external economic and foreign policy pressure on the Russian national economy from the majority of Western countries, which disagreed with the launch of Russia's special military operation in Ukraine on February 24, 2022. Thus, it seems relevant to offer an econometric study of the macroeconomic production function of Russia for the period 1990–2021, covering the first two years of the pandemic, and to predict Russia's GDP for the first year of reinforced sanctions (2022).

1. Production function and statistics

For 1990–2021, we are offering an econometric study of the macroeconomic production function in regard to the world price of Brent crude oil [7–9]

$$Y_t = A(n_t Z_t)^{\gamma} V_t^{1-\gamma} e^{\delta O_t} \quad (1)$$

by the least squares method based on the statistical data of *Table 1*,

where Y_t is Russian GDP in constant 1990 prices for year t;

Z_t is average annual value of Russian economy fixed assets in constant 1990 prices for year t;

n_t is the average annual rate of use of production capacities in Russian industry for year t;

V_t is the average annual number of people employed in the national economy for year t;

O_t is the world price of Brent crude oil in 2010 US real dollars for year t.

Statistical data is presented in *Table 1*. Methodological features of the processing of time series of initial data for the purpose of their comparability are given below.

Average annual value of fixed assets. The calculation of the average annual value of fixed assets for 2020–2021 in constant prices was carried out according to the same methodology as in our previous works [7–9] (*Table 2*). Note that the value of the average annual price index in capital construction (now for investment products), which we calculated for 2020 using the Rosstat methodology (1.055), differs slightly from the value presented by Rosstat itself (1.057) due to the possible clarification of statistical data.

Average annual number of people employed in the national economy. Due to the 2016 change of the methodology for calculating the average annual number of people employed in the national economy by Rosstat, in order to proceed to an accurate comparison with the data for previous years, we calculate the values for 2017–2021 based on Rosstat's average annual growth rates for these years.

Average annual rate of use of production capacities in Russian industry. We also note that in 2020–2021 there was a significant multidirectional dynamic of the average annual rate of use of production capacities according to the Russian Economic Barometer (REB), the data of which we have been using since 1992 [10, p. 11], and according to Rosstat. Thus, according to the Russian Economic Barometer, the average annual rate of use of production capacities increased from 79% in 2020 to 84% in 2021, which is the highest since 1992 [13]. At the same time, the average rate of use of production capacities of industrial enterprises (OKVED C + D + E) n_{Rt} decreased from 62% in 2020 to 59% in 2021. To calculate it based on Rosstat data, we used the formula

$$n_{Rt} = \frac{n_{Ct} Z_{Ct} + n_{Dt} Z_{Dt} + n_{Et} Z_{Et}}{Z_{Ct} + Z_{Dt} + Z_{Et}},$$

where n_{Ct}, n_{Dt}, n_{Et} are arithmetic averages of the average monthly rate of use of production capacities for 12 months in year t according to OKVED C, D and E, respectively;

Z_{Ct}, Z_{Dt}, Z_{Et} are the average annual availability of fixed assets at constant prices in year t according to OKVED C, D and E, respectively.

This difference in the dynamics of the indicator may be explained by the fact that manufacturing enterprises predominate in the sample of the Russian Economic Barometer [14], and in the Rosstat sample fixed assets of extractive industries have the largest weight (38%), and extractive industries account for the largest decrease in the level of use of the average annual production capacity: from 64% in 2020 to 59% in 2021 (*Table 3*). At the same time, we do not know whether the Rosstat sample includes oil and gas companies, since Rosstat does not publish data on their production capacities. Thus, in our econometric study of function (1) for 1990–2021 we consider two values of the average annual rates of use of production capacities in 2021: the first is 84% according to the Russian Economic Barometer, and the second is the value equal to 75% which is obtained by multiplying the value of

Table 1.

Statistical data for 1990–2022

Year (t)	O_t, \$/bb	n_t,%	Z_t, million rubles	V_t, thousands of people	Y_t, billion rubles
1990	28.65	100	1871649	75325	644
1991	24.50	100	1957288	73848	612
1992	23.14	73	2009054	72071	523
1993	19.72	74	2030396	70852	478
1994	18.91	61	2014984	68484	417
1995	18.57	60	1995229	66441	400
1996	22.90	54	1983823	65950	386
1997	22.22	54	1967098	64639	391
1998	15.48	55	1953216	63642	371
1999	22.10	62	1953747	63963	394
2000	35.54	66	1962932	64517	434
2001	31.89	69	1976006	64980	456
2002	32.99	70	1993845	65574	477
2003	36.24	73	2015564	65979	512
2004	45.05	74	2040209	66407	549
2005	62.07	76	2074736	66792	584
2006	72.72	78	2119496	67174	632
2007	76.18	80	2169707	68019	686
2008	94.95	77	2229842	68474	722
2009	64.13	65	2292706	67463	665
2010	79.64	72	2350079	67577	695
2011	99.97	78	2416816	67727	725
2012	101.61	79	2499424	67968	750
2013	99.21	78	2581327	67901	760
2014	91.59	77	2644159	67813	765
2015	53.65	75	2673133	68389	744
2016	46.98	77	2696319	68430	742
2017	55.91	79	2730170	68127	753
2018	70.01	78	2762511	68016	771
2019	64.37	79	2853595	67388	781
2020	42.73	79	2976450	65953	757
2021	70.04	84/75	3081807	67155	793
2022 (forecast)	60/70/80 *	85/76	3205079	66845	See *Table 6*

Sources: for 1990–2019 see [9], for 2020–2021 see Tables 2, 3 [10, p. 11], [11, pp. 49, 260], [12],Rosstat website (https://rosstat.gov.ru/labour_force).

* For 2022 the price forecast of Urals crude oil is presented in nominal US dollars (i.e. excluding the depreciation of t he US dollar) instead of Brent oil price.

Table 2.

Average annual value of fixed assets of the Russian economy in constant 1990 prices for 2020–2021 (for a full range of enterprises and organizations)

Year		2020	2021
At full book value in actual prices, million rubles [1)]	Availability at the beginning of the reporting year	344 257 518	372 337 039
	Commissioning of new fixed assets	18 505 278	22 863 184
	Liquidated fixed assets	1 275 458	1 515 663
	Availability at the end of the reporting year	361 804 806	397 315 582
Producer price index for capital construction, year as a multiple of the preceding year [2)]		1.055	1.051
Index of actual revaluation of fixed assets,year as a multiple of the preceding year [3)]		0.984	1.029
At full book value in comparable prices of 1990, million non-denominated rubles [3)]	Availability at the beginning of the reporting year	2 928 336	3 024 564
	Commissioning of new fixed assets	165 949	194 993
	Liquidated fixed assets	69 720	80 507
	Availability at the end of the reporting year	3 024 564	3 139 049
	Average annual value	2 976 450	3 081 807

Source: [1)] EMISS database (https://fedstat.ru/), [2)] Authors' calculations according to Rosstat methodology,
[3)] The authors' calculations according to the methodology [7–9].

the indicator for 2020 according to the Russian Economic Barometer (79%) by the growth rate of the indicator for 2021 according to Rosstat (59%/62% = 0.952) (see *Table 3*).

2. Results of the econometric study: econometric and economic analysis

The results of the econometric study of function (1) are presented in *Table 4* and in *Figs. 1, 2.*

1. For the time period 1990–2020, which includes the first year of the coronavirus pandemic, the OLS estimates of the coefficients of the production function (1) remain almost unchanged compared to 1990–2019: the coefficient of neutral technical progress A slightly increases from 0.00058 to 0.00059, the elasticity of GDP with respect to fixed assets γ remains at the level of 0.80, and the coefficient at the world price of Brent oil δ remains equal to 0.003. In 1990–2020, all arguments of the production function remain statistically significant according to Student's t-test (*Figs. 1, 2*). Compared to 1990–2019, the values of t-statistics of the coefficient of neutral technical progress and elasticity of GDP

Table 3.

Average annual rate of use of production capacities in Russian industry

Years	n_{Ct}	n_{Dt}	n_{Et}	Z_{Ct}	Z_{Dt}	Z_{Et}	n_{Rt}	$\frac{n_{Rt}}{n_{Rt-1}}$	Recalculation REB's n_t
2020	64	61	60	43 390 182	40 706 473	30 820 307	62.14	–	79
2021	59	60	59	47 718 229	45 125 113	33 547 120	59.19	0.95247798	75
2022 (9 month)	58	61	62	n/a	n/a	n/a	60.00	1.013725079	76

Sources: EMISS database (https://fedstat.ru/), Rosstat website (https://rosstat.gov.ru/leading_indicators), [10, p. 11].

Note: We calculate the rate of use of production capacities for 9 months of 2022 based on fixed assets for 2021.

Table 4.

Results of an econometric study of production function (1) for 1990–2021

Time period, years	Coefficients and (in brackets) t-statistics			R^2	DW
	A	δ	γ		
1990–2019	0.00058 (–41)	0.80 (13)	0.003 (7)	0.96	1.24
1990–2020	0.00059 (–47)	0.80 (15)	0.003 (7)	0.96	1.24
At the average annual rate of use of production capacities $z_{2021} = 84\%$					
1990–2021	0.00067 (–47)	0.75 (14)	0.003 (7)	0.96	1.18
At the average annual rate of use of production capacities $z_{2021} = 75\%$					
1990–2021	0.00060 (–49)	0.79 (15)	0.003 (7)	0.96	1.22

Sources: for 1990–2019 see [9], for the remaining years we have made calculations based on the data *in Table 1*.

Note. Econometric study results for the time intervals from 1990 up to 2000–2018 see [9], *Figs. 1, 2*.

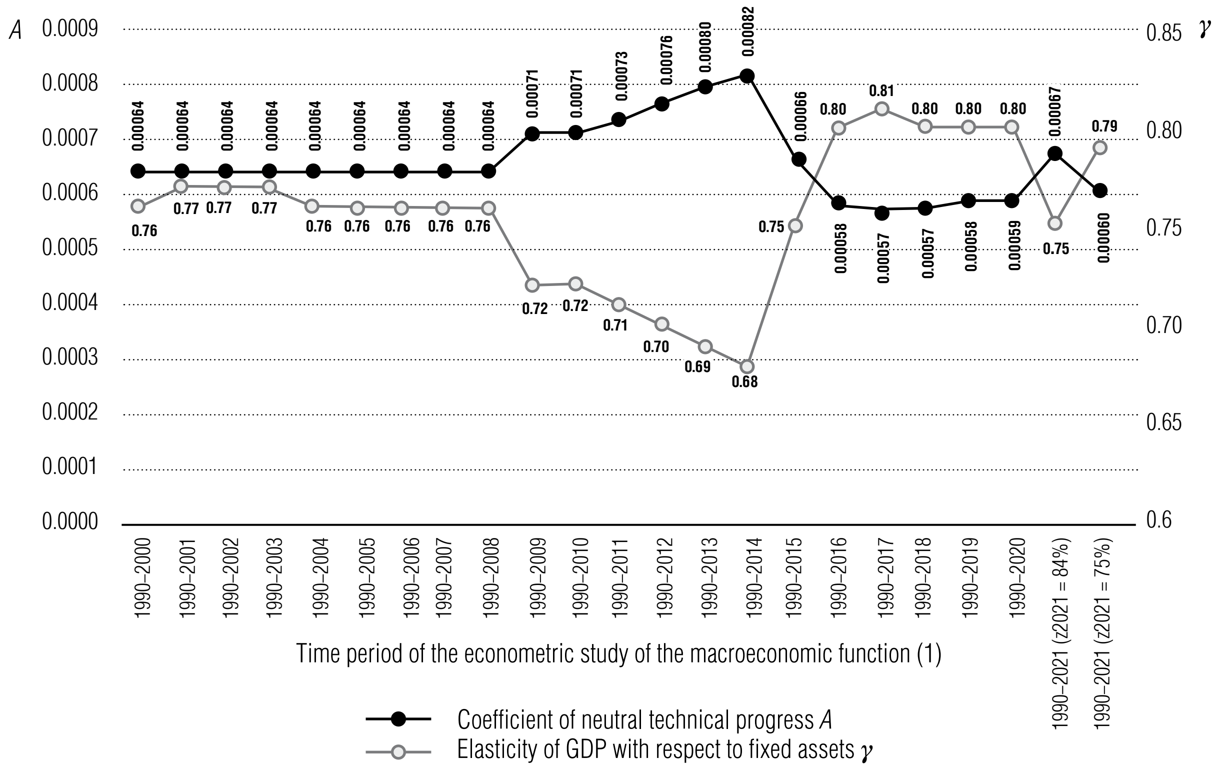


Fig. 1. Coefficients *A* and γ of function (1) for 1990–2021.

Source: [9] and *Table 4*.

with respect to fixed assets increases, and the value of *t*-statistics of the coefficient of the world price of Brent oil remains unchanged. The values of the coefficient of determination ($R^2 = 0.96$) and Durbin-Watson test ($DW = 1.24$) remain at the same level.

2. For the time period 1990–2021, which includes the first and the second coronavirus pandemic years, we offer two options for an econometric study of the parameters of the production function (1). That is due to significant differences in the directions of dynamics of the average annual rate of use of production capacities in the Russian industry for 2020–2021 published by the Russian Economic Barometer and Rosstat.

2.1. At the average annual rate of use of production capacities of 84% in 2021, published by the Russian Economic Barometer, for 1990–2021 the coefficient of neutral technical progress goes up to 0.00067, the elasticity of GDP with respect to fixed assets decreases to 0.75 and the coefficient at the world price of Brent crude oil remains unchanged at the level of 0.003 (*Figs. 1, 2*). The coefficient of determination remains at the level of the previous year ($R^2 = 0.96$), while the value of the Durbin-Watson statistics declines ($DW = 1.18$).

2.2. At the average annual rate of use of production capacities of 75% in 2021, which we calculated by multiplying the 2020 REB's rate by the Rosstat's rate of decline in the level of average annual rate of use of production capacities, there is a slight change in two parameters of the production function compared to 2020. Thus, the coefficient of neutral technical progress rises from 0.00059 to 0.00060, the elasticity of GDP with respect to fixed assets falls from 0.80 to 0.79, and the coefficient at

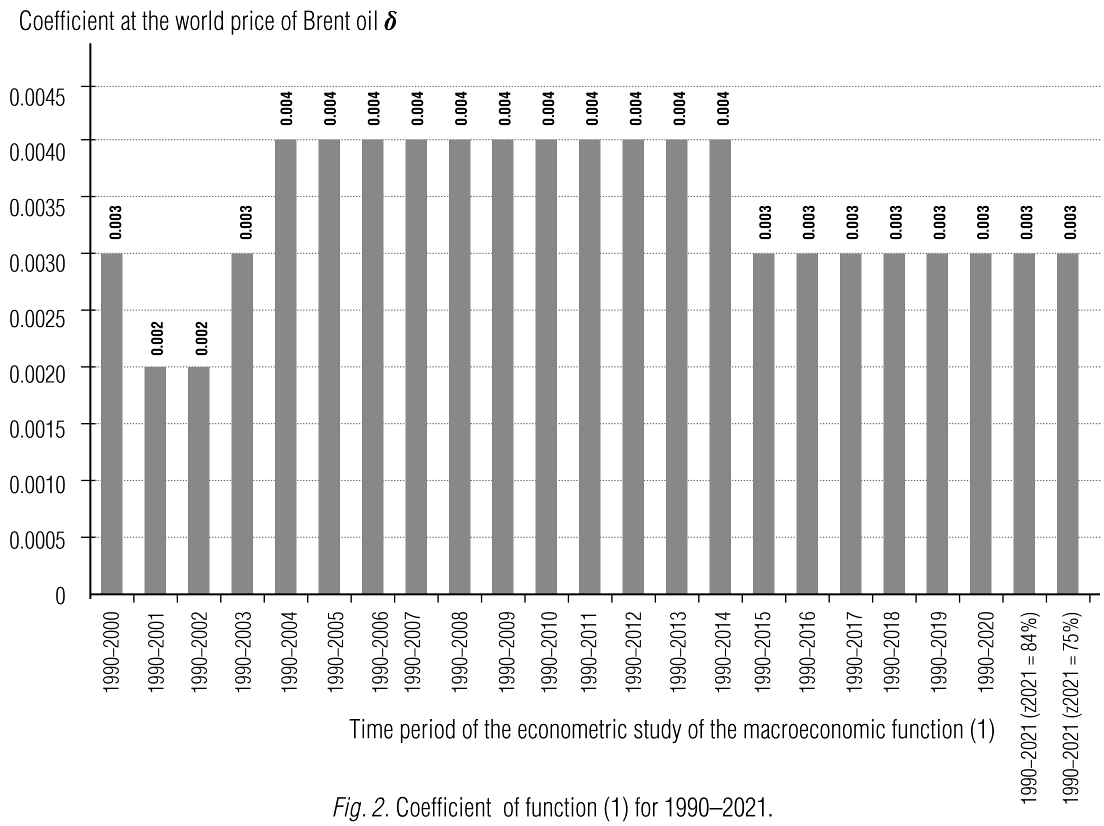


Fig. 2. Coefficient of function (1) for 1990–2021.

Source: [9] and *Table 4*.

the world price of Brent oil does not change and remained at the level of 0.003 (*Figs. 1, 2*). The coefficient of determination also remains unchanged (R^2 = 0.96), while the value of the Durbin-Watson statistics slightly decreases (DW =1.22).

Thus, during 1990–2021, at the two considered values of the rate of use of production capacities of Russian industrial enterprises, the degree of dependence of Russia's GDP on the world crude oil price remains unchanged. The rate of 75% has almost no effect on the contribution of labor and capital to the expanded reproduction of GDP and the innovation-driven activity of the economy. However, at the rate of 84%, the innovation-driven activity of the national economy accelerates, the contribution of capital to the expanded reproduction of the Russian economy falls, and the contribution of labor, on the contrary, increases, i.e. there is a certain substitution of capital for labor. In this regard, it seems to us relevant to assess the marginal rate of technical substitution of factors in the Russian economy.

3. Marginal rate of technical substitution for 1990–2020

Let us calculate the marginal rate of technical substitution of labor for capital according to the formula [15]

$$MTRS_t = \frac{\gamma}{1-\gamma} \cdot \frac{V_t}{n_t z_t}, \qquad (2)$$

for 1990–2020 on the basis of the statistical data from *Table 1* and the OLS estimate of elasticity of GDP with respect to fixed assets of function (1) for 1990–2020. The calculation results are presented in *Table 5* and *Fig. 3*.

Table 5.
Marginal rate of technical substitution of factors in 1990–2020

Years	$\frac{\gamma}{1-\gamma}$	$\frac{n_t Z_t}{V_t}$	$MTRS_t$
1990	4	24.8	0.161
1991	4	26.5	0.151
1992	4	20.3	0.197
1993	4	21.2	0.189
1994	4	17.9	0.223
1995	4	18.0	0.222
1996	4	16.2	0.246
1997	4	16.4	0.243
1998	4	16.9	0.237
1999	4	18.9	0.211
2000	4	20.1	0.199
2001	4	21.0	0.191
2002	4	21.3	0.188
2003	4	22.3	0.179
2004	4	22.7	0.176
2005	4	23.6	0.169
2006	4	24.6	0.163
2007	4	25.5	0.157
2008	4	25.1	0.160
2009	4	22.1	0.181
2010	4	25.0	0.160
2011	4	27.8	0.144
2012	4	29.1	0.138
2013	4	29.7	0.135
2014	4	30.0	0.133
2015	4	29.3	0.136
2016	4	30.3	0.132
2017	4	31.7	0.126
2018	4	31.7	0.126
2019	4	33.5	0.120
2020	4	35.7	0.112

Source: the authors' calculations based on formula (2) and data from *Tables 1, 4*.

As is known, in a market economy under a constant volume of output and *caeteris paribus*, the marginal rate of technical substitution of production factors tends to decrease. And although we are considering the marginal rate under a changing volume of GDP, we can draw the following conclusions. In 1991–1996, there is an increasing trend in this indicator, which, in our opinion, is associated with the structural transformation of the Russian economy under the transition from a centrally-planned to a market economy, accompanied by a large-scale denationalization of property. For 1997–2020 in general, there is a downward trend, with the exception of 2008–2009 and 2015. In 2008–2009, the Russian national economy, like the entire world economy, experienced the financial and economic crisis, and the growth of the marginal rate of technical substitution was the result of the adaptation of the Russian economy to its consequences. Since 2014, after the reunification of Crimea with Russia, the Russian economy has been subjected to significant external economic pressure from most of Western countries, and therefore some increase in the marginal rate of technical substitution in 2015 illustrates the adaptation of the Russian economy to the new sanctions, and this adaptation turned out to be quite successful. It should be noted that in 2020, during the Wuhan coronavirus pandemic, the marginal rate continued to decrease, which indirectly indicates that the Russian economy was more easily able to adapt to the coronavirus than to the 2014 sanctions, although both were accompanied by economic recession.

4. *Ex-post* forecasts of Russian GDP for 2020–2021: causes for the decline in 2020 and growth in 2021

As we noted earlier, a distinctive feature of the macroeconomic production function (1) in 2001–2019 is not only the closeness of the *ex-post* forecast GDP values to the actual ones,

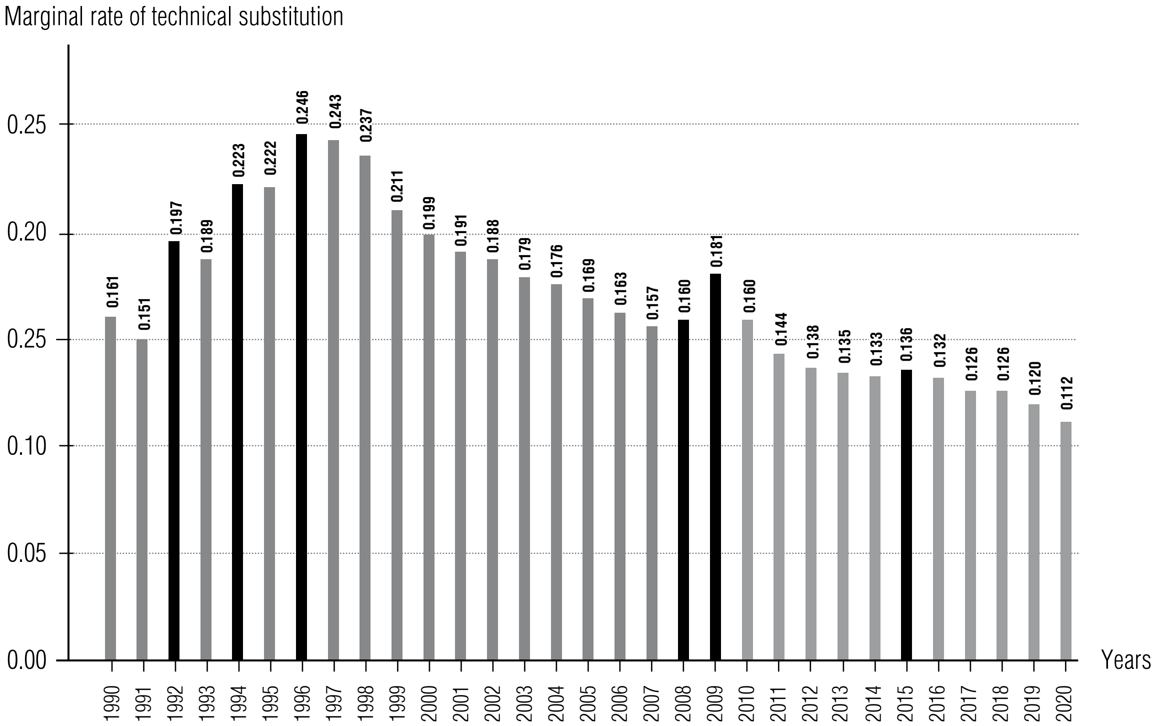


Fig. 3. Estimation of the marginal rate of technical substitution in Russia based on function (1) in 1990–2020.
Source: *Table 5.*

but also the coincidence of the dynamics of the *ex-post* forecast output with the dynamics of the actual one [7–9]. Such proximity and the same direction of dynamics are also observed in 2020–2021 (*Table 6*, *Fig. 4*).

Indeed, *ex-post* forecasts for all training samples show a decrease in Russia's GDP in 2020 and its growth in 2021, and at a rate of use of production capacities of 84% the *ex-post* forecast GDP grows faster than at a 75% (*Table 6*). Thus, it becomes clear why the average errors of the *ex-post* forecast for the test samples until 2021 at the 84% rate exceed the average errors at the 75% rate. The average errors for the test samples up to 2020 are in the range from 0.5% to 6.6%. Against the backdrop of constancy of OLS estimates of the macroeconomic production function (1) in 1990–2020, the main reason for the decline in GDP for 2020 was the fall in world oil prices from $64.37/bbl. in 2019 to $42.73/bbl in 2020. Thus, we cannot say that the Wuhan coronavirus spread was the main reason for the economic downturn in Russia. At the same time, the quarantine and isolation restrictions imposed by the central and regional authorities from late March to early June 2020 had a noticeable negative impact on the activities of public catering establishments, trade in non-food products, services and some types of transport [16, p. 252, 260; 17]. The greatest damage was inflicted on small and medium-sized enterprises in the above mentioned as well as in other sectors of the national economy.

There is a widely held view that COVID-19, which emerged in late 2019 in Wuhan, China, and the strict quarantine and isolation restrictions imposed by the PRC authorities, led to a decrease in demand for oil and petroleum products from China, which greatly contributed to a decrease in the world price of oil and a global recession [18]. However, the following fact testifies against this point of view. Accord-

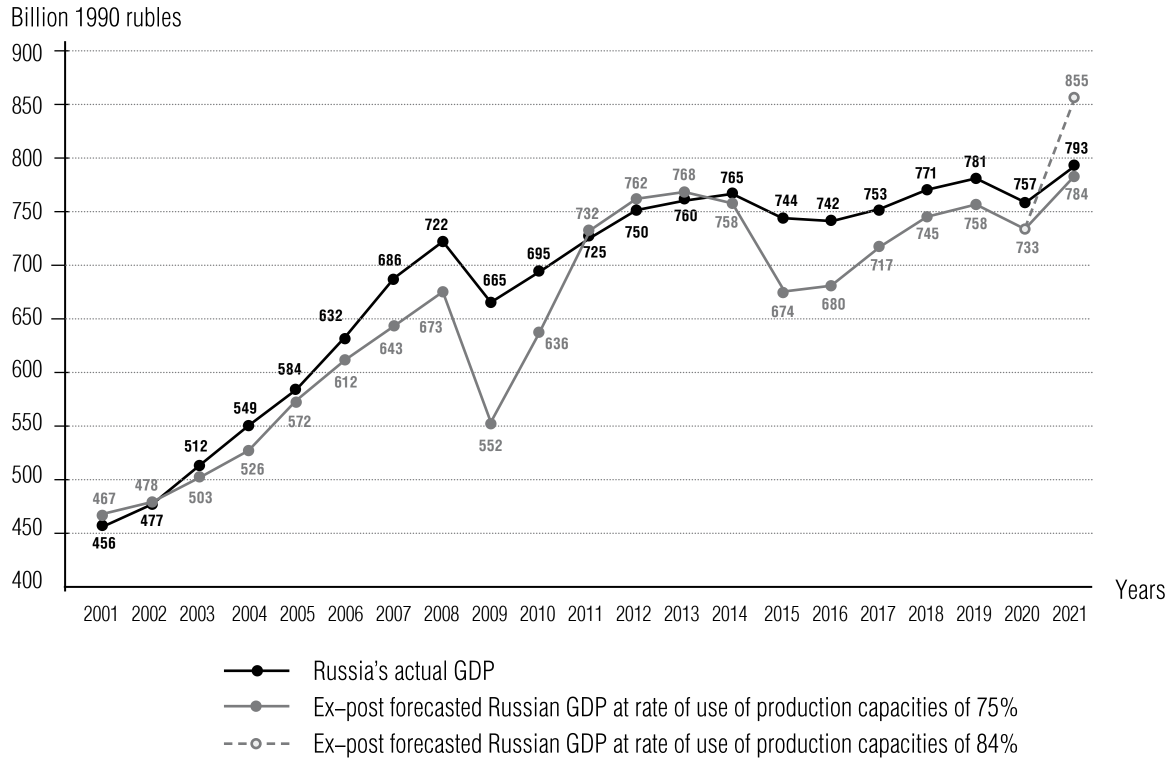


Fig. 4. Dynamics of the *ex-post* forecasted and actual Russian GDP for 2001–2021 at 75% and 84% rate of use of production capacities in 2021.

ing to the Russian Federal Customs Service[1], exports of Russian crude oil to China increased from 70.6 million tons in 2019 to 75.3 million tons in 2020 (in 2021, exports amounted to 71.0 million tons), and Russian natural gas exports increased from 0.3 billion m³ in 2019 to 3.5 billion m³ in 2020 and to 8 billion m³ in 2021. Thus, in 2020 there was an increase in Chinese demand for oil and gas from Russia, despite strict quarantine in China. That does not support the idea that the Wuhan coronavirus is one of the main reasons for the fall in the world oil price through a decrease in Chinese demand for it. Our point of view is also confirmed by the results of an econometric study [19], which did not reveal a direct impact of the Wuhan coronavirus spread on the world market and the price of oil; it revealed only an inverse relationship between the frequency of the pandemic's mention in Internet search engines and the world oil price.

Returning to the forecast strength of Russia's macroeconomic production function (1), it should be noted that the increase in *ex-post* forecast GDP in 2021 was mainly due to an increase in the world oil price from $42.73/bbl. in 2020 to $70.04/bbl in 2021. In addition, growth was facilitated by an increase in the average annual number of employees from 66 million people in 2020 to 66.9 million people in 2021. *Ex-post* forecast GDP growth in the first version of the forecast was strengthened by

[1] See the website of the Federal Customs Service of the Russian Federation (http://stat.customs.gov.ru/analysis).

Table 6.

Russian GDP forecasts for 2022 and *ex-post* forecasts for 2019–2021

Forecast for year	Urals crude oil world price, USD dollars per barrel	Rate of use of production capacities, %	Learning samples from 1990 to year:																					
			2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Ex-post forecasted GDP, billion 1990 rouble																								
2019			758	740	744	759	784	778	778	784	784	787	789	776	766	759	755	777	791	792	791			
2020			733	725	726	733	743	741	741	742	742	735	735	730	723	716	713	742	762	764	763	761		
2021		75	784	764	768	786	815	809	808	815	816	821	823	808	795	787	784	806	820	822	821	819	818	
2021		84	855	833	838	857	888	881	881	888	889	890	892	876	861	851	846	877	898	901	899	897	896	
Forecasted GDP, billion 1990 roubles																								
2022	60	75	793	777	780	794	816	811	811	816	816	815	816	805	794	785	781	810	829	831	830	827	826	823
2022	60	84	863	846	850	865	888	883	883	888	888	883	885	871	858	848	843	881	907	910	908	905	903	880
2022	70	75	815	794	798	817	847	840	840	847	848	851	853	837	824	815	811	837	855	857	855	853	852	849
2022	70	84	888	866	870	890	922	915	915	922	923	922	924	907	891	880	875	910	935	938	936	933	932	909
2022	80	75	839	812	818	841	879	871	870	879	880	889	891	871	855	845	841	865	881	883	882	880	879	876
2022	80	84	913	885	891	916	957	948	947	957	958	963	966	943	925	913	907	941	964	967	965	962	961	939
Forecasted GDP growth rate, year as a multiple of the preceding year																								**Average rate**
2022	60	75	1.01	1.02	1.02	1.01	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	**1.00**
2022	60	84	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	**1.00**
2022	70	75	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.03	1.04	1.04	1.04	1.04	1.04	1.04	**1.04**
2022	70	84	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	**1.04**
2022	80	75	1.07	1.06	1.06	1.07	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	**1.07**
2022	80	84	1.07	1.06	1.06	1.07	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	**1.07**
Ex-post forecast errors																								
2020			3.2%	4.2%	4.0%	3.1%	1.9%	2.1%	2.1%	1.9%	2.0%	2.9%	2.9%	3.6%	4.5%	5.4%	5.8%	2.0%	0.7%	1.0%	0.8%	0.5%		
2021		75	1.1%	3.7%	3.2%	0.9%	2.8%	2.0%	1.9%	2.8%	2.9%	3.5%	3.7%	1.8%	0.3%	0.8%	1.2%	1.6%	3.4%	3.7%	3.5%	3.3%	3.2%	
2021		84	7.8%	5.1%	5.6%	8.1%	12.0%	11.1%	11.1%	12.0%	12.1%	12.3%	12.5%	10.4%	8.6%	7.3%	6.7%	10.6%	13.3%	13.6%	13.4%	13.1%	12.9%	
Average ex-post forecast errors																								
2020			4.4%	6.6%	6.5%	4.9%	4.4%	4.6%	4.9%	5.2%	5.6%	6.0%	6.6%	5.1%	4.8%	5.1%	6.0%	2.5%	0.9%	0.8%	1.0%	0.5%		
2021		75	4.3%	6.5%	6.3%	4.7%	4.3%	4.4%	4.7%	5.0%	5.4%	5.8%	6.3%	4.8%	4.3%	4.6%	5.3%	2.4%	1.4%	1.8%	1.9%	1.9%	3.2%	
2021		84	4.6%	6.5%	6.4%	5.1%	4.9%	5.0%	5.3%	5.7%	6.1%	6.5%	7.1%	5.6%	5.2%	5.4%	6.1%	3.9%	3.4%	4.0%	5.2%	6.8%	12.9%	

Note. *Ex-post* forecast errors and their average values are calculated using the formulas [9. p. 27–28]. The forecast GDP growth rate for 2022 is calculated as the ratio of the forecasted GDP for 2022 to the *ex-post* forecasted GDP for 2021.

an increase in the average annual rate of use of production capacities from 79% in 2020 to 84% in 2021, and in the second version of the forecast, GDP growth was somewhat weakened by a decrease in this rate to 75% in 2021 (*Fig. 4*). The average *ex-post* forecast errors of function (1) for 2021 vary from 1.4% to 6.5% (at a rate of use of production capacities of 75%) and from 3.4% to 12.9% (at a rate of use of production capacities of 84%).

Thus, according to the results of the econometric study of function (1) and *ex-post* forecasting based on it, the main reasons for the decline of Russian GDP in 2020 and growth in 2021 were fluctuations in the world oil price.

At the same time, since the end of February 2022, the Russian economy has been subjected to multiply increased sanctions pressure due to the disagreement of the governments of a number of European and American countries with the Russia's special military operation in Ukraine which started on February 24, 2022. This sanctions pressure was further exacerbated by explosions organized by international terrorists at vital Russian and international transport infrastructure facilities, which partially disabled the Crimean Bridge and completely deactivated Gazprom's main pipeline gas transportation facilities, Nord Stream 1, and one of the two lines of Ready-to-operate Nord Stream 2 (in accordance with the terminology adopted by the company, hereinafter *PJSC Gazprom* means the parent company and *Gazprom* means the group that includes the parent company and its subsidiaries).

The current difficult conditions require from the Russian economy as well as from the Russian government and Russian businesspersons new solutions to successfully and effectively overcome the negative consequences of foreign economic, political and financial restrictions imposed and newly introduced from abroad. Among them we can point out the increase in the well-being of the population and the maintenance of positive rates of economic growth. Meanwhile, according to Rosstat estimates, Russia's GDP in the first half of 2022 decreased by 0.4% compared to the same period in 2021 [20, p. 6]. It seems to us extremely important and relevant to give a forecast of Russia's GDP for 2022 based on the macroeconomic production function (1) that we have studied.

5. Econometric forecasting of Russian GDP for 2022

For the purposes of forecasting Russia's GDP for 2022, we chose the values of the factors of the macroeconomic production function (1) as follows (*Table 1*).

1. *Average annual value of fixed assets.* We assume that the average annual value of fixed assets in 1990 constant prices is growing at the same average annual rate as in 2020 and 2021. For these years, the average annual rate was 4%. Then the forecasting average annual value of fixed assets of the Russian economy (in constant 1990 prices) for 2022 will be equal to 3 205 079 million rubles (*Table 1*).

2. *Average annual rate of use of production capacities in the Russian industry.* For 2022 the rate of use of production capacities of Russian industrial enterprises was calculated, as for 2021, in two versions. In the first option, we use REB's data – the average value for 7 months of 2022, equal to 85% [10, p. 11]. In the second option, we calculate the average rate value according to the level growth rate according to Rosstat, which is the ratio of the average rate value for 9 months of 2022 to the average rate value for 12 months of 2021 (*Tables 1* and *2*).

3. *Average annual number of people employed.* The forecast rate of change in the average annual number of people employed in the Russian economy in 2022 was calculated as the ratio of the average number of labor force aged 15 years and older in the 1st half of 2022 (74 795.356 thousand people) to the same

indicator for 2021 (75 142.615 thousand people). This rate is equal to 0.995. Thus, the forecast average annual number of employees for 2022 will be equal to 66.845 thousand people (*Table 1*). In turn, the average labor force for the 1st half of the year is calculated on the basis of Rosstat data[2] as the arithmetic mean of the labor force for the 1st and 2nd quarters of the corresponding year (Q1 2021 – 75 034.1 thousand people, Q2 2021 – 75 251.2 thousand people, Q1 2022 – 74 698.4 thousand people, Q2 2022 – 74 892.4 thousand people). The expected decline in the number of people employed in the economy for 2022 is to some extent due to the outflow of some insignificant part of the labor force from Russia to abroad in March and October 2022.

4. *World crude oil price*. Instead of the world price of Brent oil in 2010 US dollars, we consider the world price of Urals oil (excluding the depreciation of the US dollar). That is due to the significant discrepancy (discount) formed in 2022 between the quotations of these two oil types. We will consider three scenarios for the world price of Urals oil: \$60, \$70, and \$80 per barrel (*Table 1*). The first scenario is consistent with the irresistible desire of US Treasury Secretary Dr. Janet Yellen to purchase Russian oil by all over the world at any price less than \$60 per barrel [21]. The third scenario corresponds to the forecasts for 2022 of the Ministry of Finance of Russia [22, p. 36]. And the second scenario is the average of the other two.

So, function (1) gives the following forecasts of Russia's GDP for 2022 with errors range from 1.5% to 7% (*Table 6*, *Fig. 5*). At a world price of Urals crude oil of \$60 per barrel and at a rate of use of production capacities of 76% and 85%, GDP growth rates will range from –1% to 2%. At a world crude oil price of \$70 per barrel and the rate of use of production capacities of 76% and 85%, the growth rate of GDP will range from 3% to 4%, and at a price of \$80 per barrel and the rate of use of production capacities of 76% and 85%, the growth rate will range from 6% to 8%.

In other words, at both rates of use of production capacities and at a price of \$60 per barrel, the average growth rate of Russian GDP will be equal to 0%, at \$70 per barrel there will be a natural growth of the economy with an average rate of 4%, and at \$80 per barrel, the average economic growth rate will be equal to 7% (*Table 6*).

Thus, at world prices for Urals oil ranging from \$60 to \$80 per barrel, the macroeconomic function of Russia (1) does not predict any significant economic downturn, contrary to the negative forecasts of some of our foreign colleagues, in particular, English ones, expecting a fall in Russia's GDP of at least 6% [23]. Our forecasts are consistent with the point of view of Academician S. Yu. Glazyev, who, speaking at the Moscow Academic Economic Forum on May 16, 2022, expressed the following idea: "Now Western forecasting centers are imposing a suicidal trajectory on us. Some say – minus 10% of GDP, others already say – minus 20% of GDP. This bacchanalia of negative forecasts should not program us for failure" [24, 25].

6. Discussion and forecasting of natural gas production by PJSC Gazprom in the Tyumen region for 2022

It should be noted that we consider the rate of use of production capacity only in industry, since data is not collected for other sectors of the Russian economy, including air transport, trade of imported goods and the banking system, which were affected to some extent by sanctions. In addition, the rate of use of pro-

[2] See Rosstat website (https://rosstat.gov.ru/labour_force).

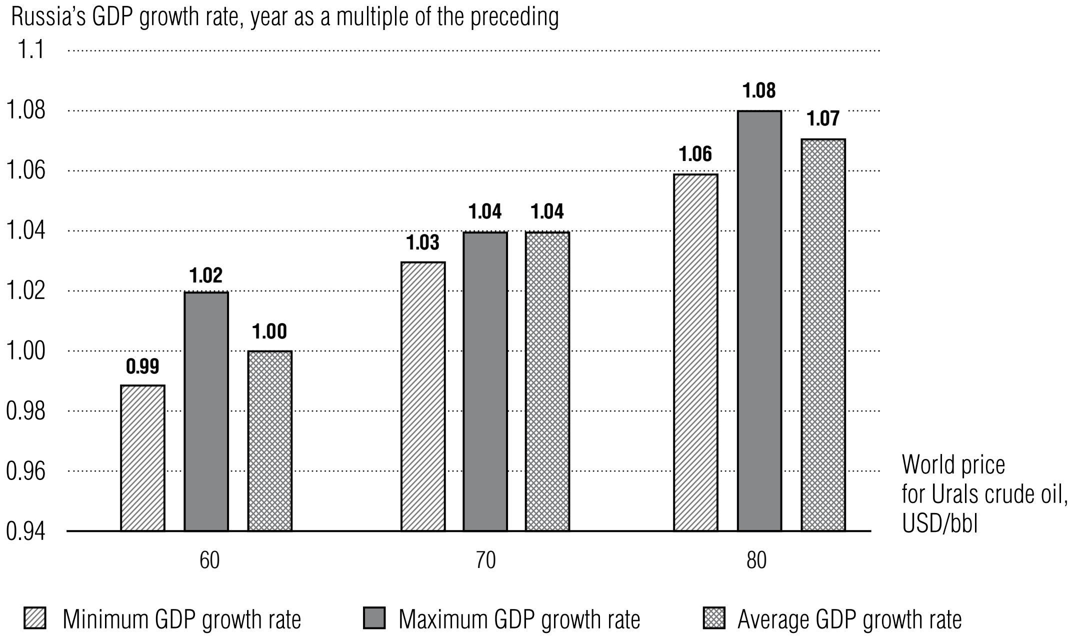


Fig. 5. Forecast of Russia's GDP growth rates in constant 1990 prices for 2022 at different values of the world price of Urals oil.
Source: *Table 6.*

duction capacity, which we are considering for 2022, may not take into account the capacities of oil and gas producing enterprises, including PJSC Gazprom subsidiaries reporting to Rosstat on the annual forms 1-TEK (oil) and 2-TEK (gas). When in the first half of 2022 the volume of production of Russian oil increased by 3.3% (according to Rosstat [26, p. 21]) and the volume of its export rose by 10–12% (according to various estimates [27, slide 3]) compared to the same period previous year, the volume of natural gas production decreased by 6.6% (according to Rosstat [26, p. 21]) and the volume of its export to non-CIS countries fell by 31% (according to Gazprom [28]) compared to the same period previous year. In this regard, the real rate of use of production capacities in 2022 may be lower than the value considered by us, and, therefore, the growth rates forecast of Russia's GDP may be somewhat lower. Indeed, as a result of the refusal of many European consumers to purchase Russian gas in 2022, caused by the disagreement of the governments of their countries with the conduct of Russia's special military operation in Ukraine, their unwillingness to buy gas from PJSC Gazprom for Russian rubles, as well as the disabling of two strings Nord Stream 1 and one line of Nord Stream 2, the volumes of gas produced by PJSC Gazprom have significantly decreased. Obviously, the main reduction in gas production will occur in the Tyumen region, where, as of January 1, 2022, PJSC Gazprom produced more than 90% of its gas. According to the forecasts [29] made on the basis of the production function of the form [30]:

$$\mathit{\Gamma}_t = e^{\alpha} \mathit{\Phi}_{t-1}^{\beta+\gamma G_{1963,\,t-2}} \qquad (3)$$

where $\mathit{\Gamma}_t$ is gross natural gas production for year t;

$\mathit{\Phi}_t$ is the average annual value of fixed assets in constant 1990 prices for year t;

$G_{1963,\ t-1}$ is cumulative natural gas production since 1963 up to year $t-1$;

and according to the statistical reports of Gazprom [3], in 2022 natural gas production by Gazprom (excluding Gazprom Neft) in the Tyumen region will be range from 364 to 392 billion m^3 (*Fig. 6*, *7*).

We give these forecasts for 2022 on the basis of training samples for 1985–1991 and 1985–1993, since in the test time intervals of 1992–2021 and 1994–2021 function (3) has the smallest average *ex-post* forecast errors among all training samples (*Figs. 8*, *9*).

It should be noted that in [32], on the basis of an econometric study of function (3), the sustainability of the goals of the strategic development of the Gazprom gas production complex in the Tyumen region since 1985 was substantiated. This stability is due to stability of the parameters of function (3) over time, as well as the proximity and similarity of the directions of the dynamics of the actual and *ex-post* forecast gas production (*Fig. 6*). The negative dynamics of *ex-post* forecast production observed since 2015 and fluctuations in actual production relative to its curve (*Fig. 6*) indicate a forced strategic reduction in gas production by Gazprom due to several causes: (1) the uncertainty of export supplies to Europe, which increased sharply after the reunification of Crimea with Russia, (2) lack of delays in the commissioning of export pipeline capacities, (3) a refusal to buy Russian gas by some European consumers against the backdrop of Russia's special military operation in Ukraine, and, finally, (4) the disabling of Nord Stream 1 as a result of explosions organized by international terrorist groups that benefit from the destruction of long-term cooperation in the gas sector between Russia and Europe. It should be noted that all these negative actions of unfair competition are aimed at weakening one of the most efficient global oil and gas companies – Russian Gazprom, which, as empirically proven in [33, 34], since 1993 in the field of gas production has been a highly efficient energy company characterized by growing coefficient of neutral technical progress, declining unit cost of gas production at new fields and minimal production costs, the marginal and average values of which coincide and do not depend on the volumes of gas produced. We emphasize that, unlike the Russian Gazprom, we are not aware of similar econometric studies on other domestic and foreign oil and gas companies that would justify the increasing trend of their innovation-driven development and their being at the point of minimum cost for a quarter of a century.

At the same time, despite all these temporary difficulties, Russian Gazprom has been, is and will be a reliable supplier of natural gas, able to meet the demand for it from both Russian and foreign consumers in a timely manner.

In this regard, it is impossible to ignore the fact that in 2021–2022 a significant part of Western and overseas consumers of Russian oil and gas are striving to agree on a "price cap" (maximum price) for these energy resources or to completely abandon them. For many centuries, these Russia's foreign partners have been trying to buy Russian raw materials as cheaply as possible, and in return to sell small volumes of manufactured products at the highest possible prices. Here, the most illustrative example is the United Kingdom, whose principles of economic policy towards Russia were quite accurately disclosed by Dr. Adam Smith back in the 18th century. Smith wrote: "To Russia, for example, we send fine linen and other

[3] Statistics for 1985–2008 and the methodology for recalculating fixed assets into comparable prices are given in [30, 31]. For 2021, fixed assets were taken into account in accordance with RAS of Gazprom Dobycha Nadym LLC and Gazprom Dobycha Yamburg LLC (receipt of own fixed assets and the difference between leased fixed assets at the end and at the beginning of the year, taking into account their actual revaluation by PJSC Gazprom and its subsidiaries), as well as the commissioning of new fixed assets of PJSC Severneftegazprom. Fixed assets of LLC Gazprom Dobycha Urengoy and LLC Gazprom Dobycha Noyabrsk were not taken into account due to the lack of statistical information.

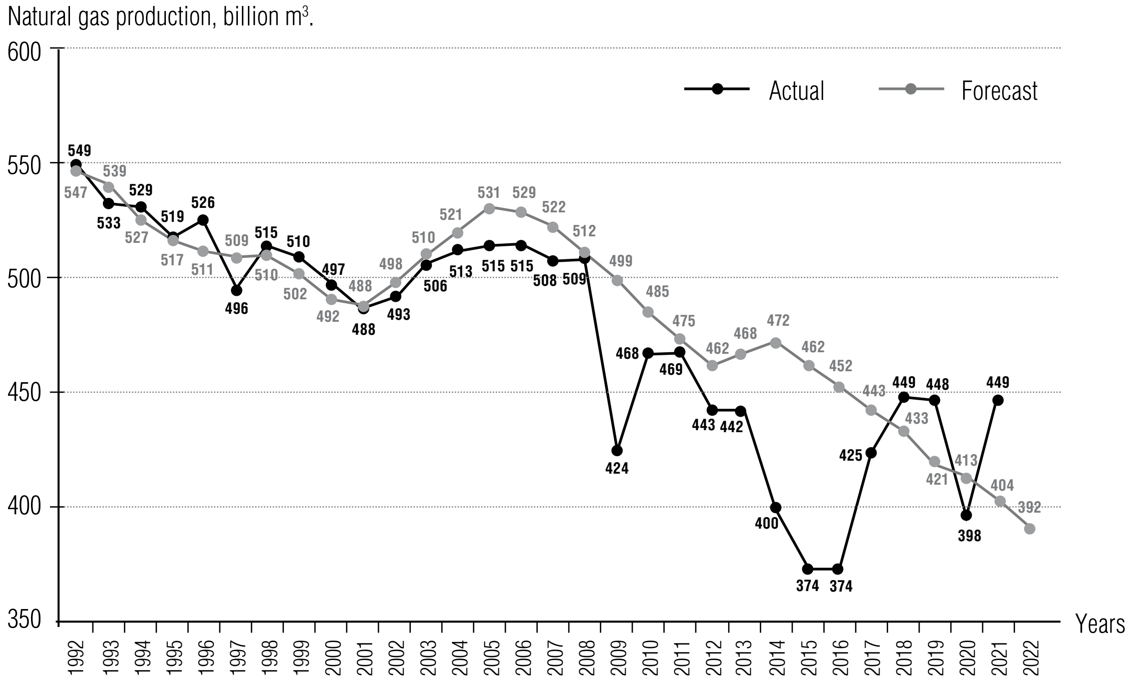


Fig. 6. Forecast for 2022, *ex-post* forecast for 1992–2021 and actual gross natural gas production by Gazprom (without Gazprom Neft) in the Tyumen region according to function (3) studied in 1985–1991, billion cubic meters.

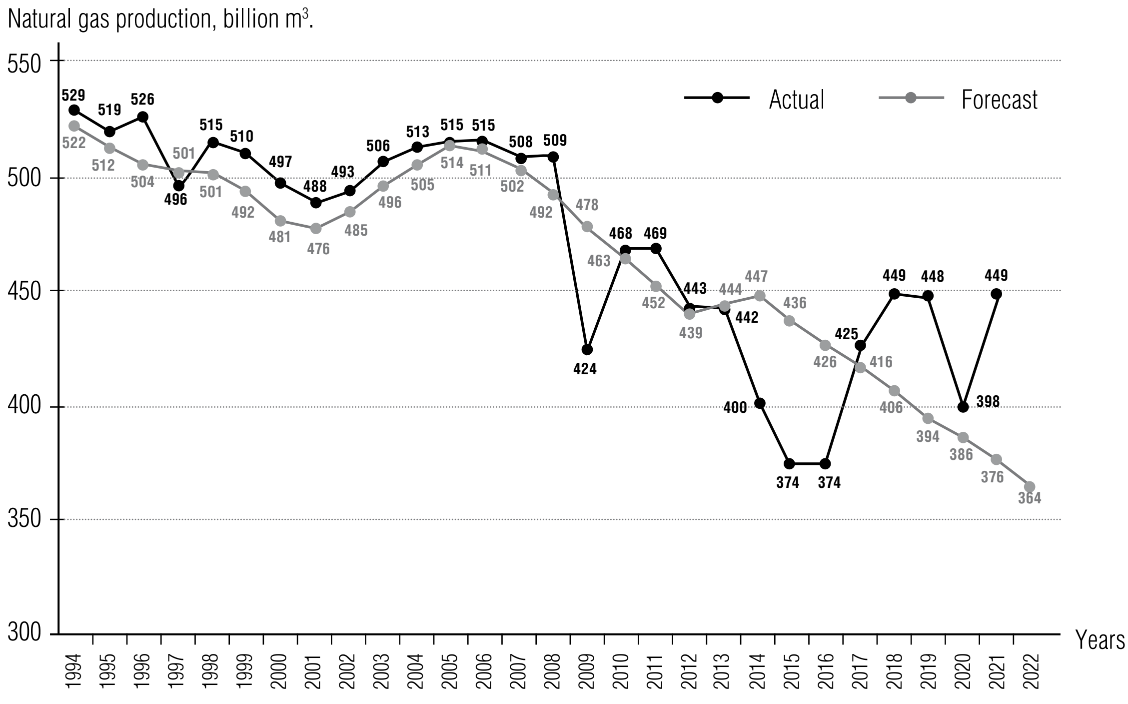


Fig 7. Forecast for 2022, *ex-post* forecast for 1994–2021 and actual gross natural gas production by Gazprom (without Gazprom Neft) in the Tyumen region according to function (3) studied in 1985–1993, billion cubic meters.

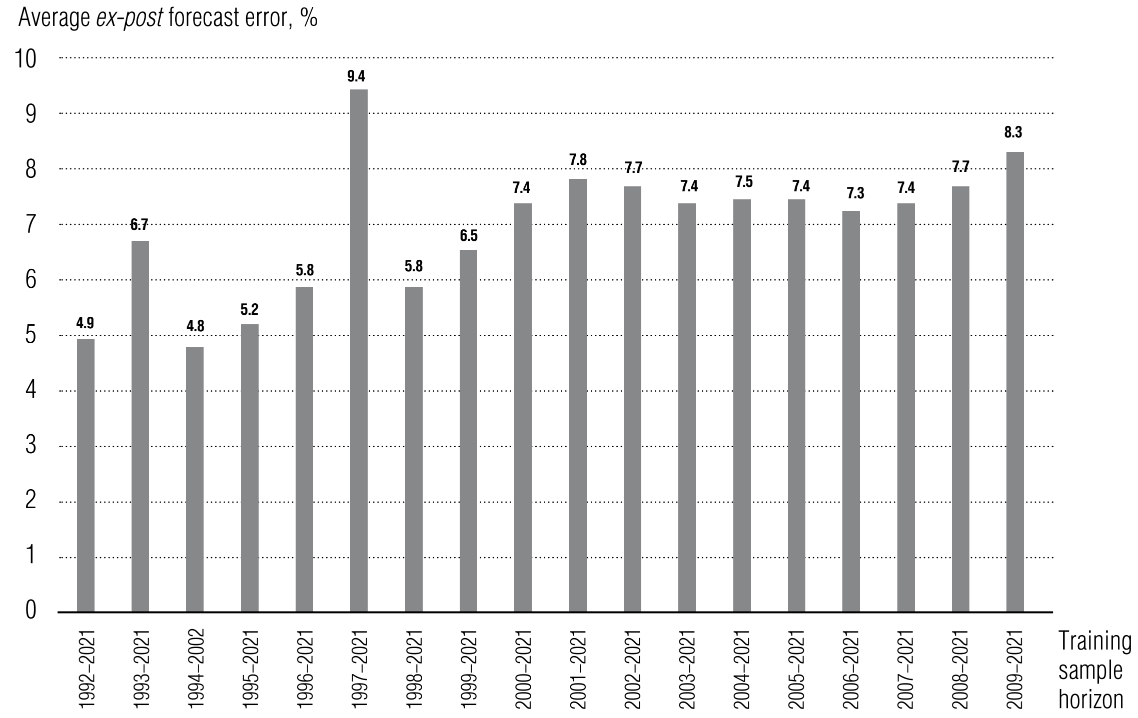


Fig. 8. Arithmetic mean of *ex-post* forecast errors of gross natural gas production by Gazprom (excluding Gazprom Neft) in the Tyumen region for 1992–2021 based on the training samples of function (3), studied from 1985 to 1991–2008.

Note. The average *ex-post* forecast errors are calculated using the formulas [9, p. 27–28].

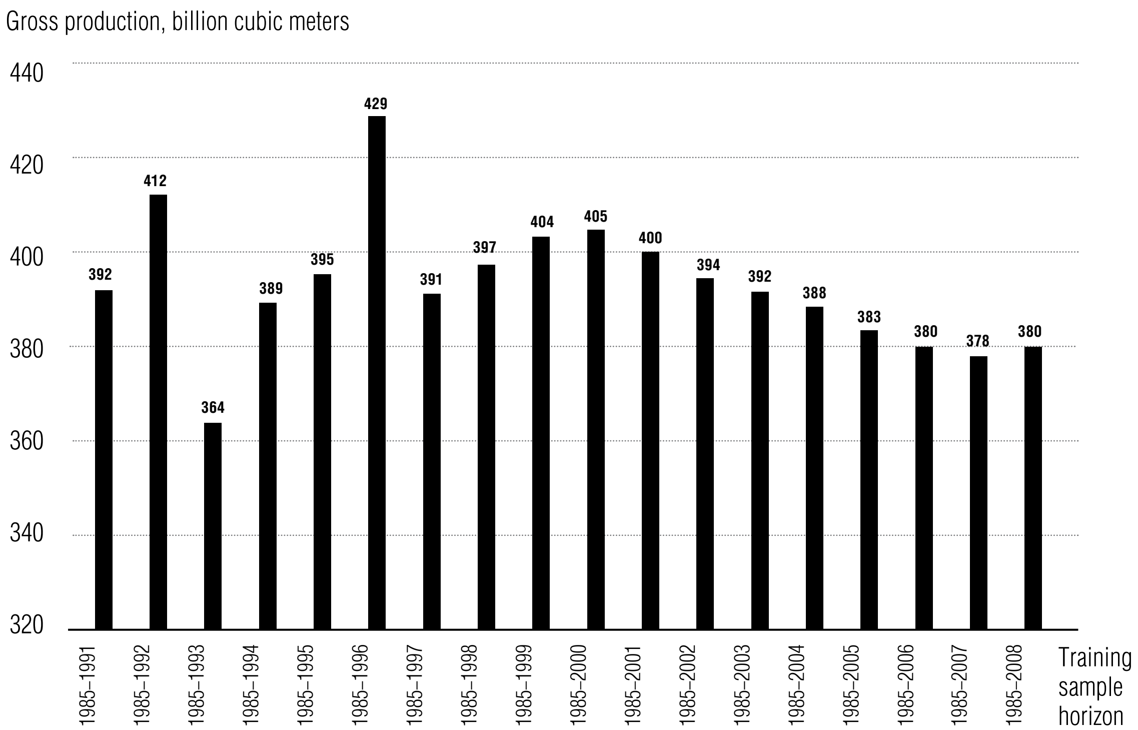


Fig. 9. Forecasts of gross natural gas production by Gazprom (excluding Gazprom Neft) in the Tyumen region for 2022 based on training samples of function (3) from 1985 to 1991–2008.

manufactured goods, and for a small quantity of these receive, in return, great quantities of unmanufactured goods. This kind of trade is very advantageous, because goods in an unmanufactured and rude state afford employment and maintenance to a great number of persons" [35, p. 247].

The economic and trade policy of England remains the same today. Thus, according to the Federal Customs Service of Russia[4], in 2021 Russia exported 12.3 million tons of goods to the United Kingdom in the amount of $22.3 billion at an average actual export price of 1.810 dollars per ton, and imported from it 0.5 million tons of goods worth $4.7 billion at an average actual import price of $9.393 per ton. The bulk of Russian exports were pearls and precious metals ($17.3 billion), fuel and energy minerals and ores ($3.7 billion), and most (at least three-quarters) of imports from the UK amounted to finished goods (at least $3.5 billion).

We should note that Russia sells oil and gas to the United Kingdom at a significant discount, i.e. much cheaper than to other Western European countries. Thus, calculations based on the data of the Russian Federal Customs Service show that in 2021 the average export price of Russian natural gas in gaseous state supplied to the United Kingdom ($131.56 per thousand cubic meters) was approximately at the same level of the average price of gas supplied by Russia to the allied Belarus ($131.78 per cubic meters) (*Fig. 10*). In 2020, the average price of Russian gas for the British, which amounted to $105.96 per thousand cubic meters, was even lower than for the Belarusians ($130.73 per thousand cubic meters). In 2021, Belgium was in second place in terms of the cheapness of Russian natural gas: the average export price for it was $143 per thousand cubic meters. Moreover, according to the Russian Federal Customs Service, in 2021, the average export prices for Russian liquefied natural gas and crude oil to the United Kingdom amounted to $185 and $457 per ton, respectively, which are lower than the average export prices of these energy resources sold by Russia to Belgium ($197 and $547 per ton), to France ($198 and $477 per ton), to the Netherlands ($236 and $463 per ton) and to Germany (oil – $483 per ton), which are geographically closer to Russia (*Fig. 10*).

Against this background, the desire of the British government to refuse to import cheap Russian energy resources or to buy them even more cheaper does not look economically justified. The recent seizure of Russian assets in the UK is even more unjustified. In early November 2022, the British government seized Russian assets worth £18 billion [23], comparable in size to the volume of all Russian exports to the UK in 2021 ($22.3 billion). Thus, Russia, having a positive trade balance with the UK and a number of other states and leaving the income from its net exports in these countries instead of investing in the growth of its own national economy, incurs significant losses over the years [36], which, as we may see, increased manifold in 2022 after the arrest of Russian foreign exchange reserves and other assets in many European countries and the United States.

Under these new conditions, Russia has the opportunity to revise its economic policy, to lower its centuries-old export dependence on raw materials and to transit to a new technical order [25] taking into account the active use of its significant production and rich scientific potential.

Conclusion

In this paper, we offered an econometric study of Russia's macroeconomic production function (1) in the unprecedented socio-eco-

[4] See the website of the Federal Customs Service of the Russian Federation (http://stat.customs.gov.ru/analysis).

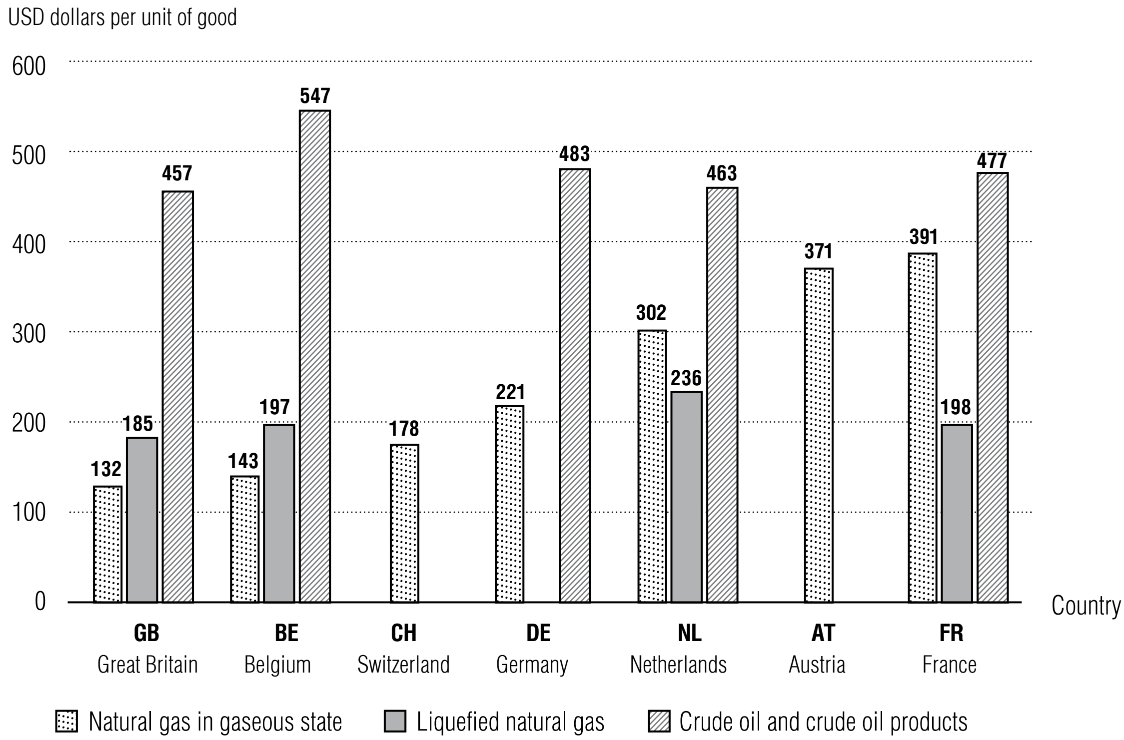


Fig. 10. Average export prices for Russian energy resources for Western European countries in 2021, USD per ton (natural gas in gaseous state – USD per thousand cubic meters)

Source: calculations based on data from the Federal Customs Service of Russia (http://stat.customs.gov.ru/analysis).

nomic realities 2020–2022, i.e. under internal and external restrictions associated with the Wuhan coronavirus (SARS-CoV-2) pandemic and the conduct of Russia's special military operation in Ukraine, accompanied by increased sanctions on the Russian economy from many Western countries. We also estimated the marginal rate of technical substitution for 1990–2020. The results of our econometric study, *ex-post* forecasting for 2020–2021 and forecasting for 2022 show the following:

1. In 1991–1996 there was an increase in the marginal rate of technical substitution, and in 1997–2020 we observed its decrease except for 2008–2009 and 2015. Its growth in the early 1990s we explain by the structural transformation of the Russian economy in the context of the transition from centrally-planned to market economy, accompanied by a large-scale denationalization of property. Increase in the marginal rate of technical substitution in 2008–2009 was a consequence of the reaction of the Russian economy to the global financial and economic crisis, and in 2015 it was a consequence of the adaptation of the national economy to external sanctions pressure that began after the reunification of Crimea with Russia.

2. During the Wuhan coronavirus pandemic, the main reasons for the Russian economy's decline in 2020 and growth in 2021 were fluctuations in the world oil price: its decline in 2020 and increase in 2021. Our analysis refutes the widespread view that one of the main reasons for the decline in the world oil price in 2020

was the reduction in Chinese demand for it, as the export of crude oil from Russia to China increased in 2020 compared to 2019.

3. Contrary to many negative forecasts, the results of our forecast of Russia's GDP for 2022 based on the macroeconomic production function (1) show that under a sharply increased sanctions pressure, at the world price of Urals crude oil at $60 per barrel, the average growth rate will be 0%, at $70 per barrel, natural economic growth will be observed at an average rate of 4%, and at $80 per barrel, the average economic growth rate will be equal to 7%. The average forecast errors range from 1.5% to 7%.

4. Under reduced demand for Russian gas and the shutdown of the Nord Stream 1 gas pipeline, the forecast volumes of gross natural gas production by Gazprom (excluding Gazprom Neft) in the Tyumen Region for 2022 based on the exponential production function studied by econometric methods (3) range from 364 to 392 billion cubic meters. Average forecast errors do not exceed 5%.

5. Using the example of Great Britain, where in 2021 the average actual export prices for Russian oil and gas were the lowest compared to other Western European countries, we discuss the economic inexpediency of setting marginal prices for Russian energy products by Western consumers.

6. Under the current new conditions, Russia has the opportunity to revise its economic policy, reduce its centuries-old export dependence on raw materials and transit to a new technological order using Russia's significant production and rich scientific potential.

The results of our study may be used by relevant ministries and departments, large companies and other interested organizations for economic analysis and forecasting of the national economic and sectoral dynamics, as well as for developing the foundations of Russia's new economic policy under the new unprecedented coronavirus and sanctions conditions. ■

Acknowledgments

We express our sincere gratitude to professor Dr. Valery G. Grebennikov (1938–2021), professor Dr. Yuri E. Stsepinsky (1935–2022) and professor Dr. Edouard F. Baranov (1939–2022) for helpful discussions and valuable advice as well as to Ph. D. Natalia A. Tikhonov (Fedorenko) for editing the English version of this paper.

References

1. Grebennikov V.G. (1968) On some problems of the interconnection between the national income rates of growth and savings rates. *Economics and Mathematical Methods*, vol. 4, no. 4, pp. 583–596 (in Russian).
2. Grebennikov V.G. (1969) Use of the production function for the analysis of the long-term trends of the us economic growth. In: *Methods and Models of the Long-Term Analysis*. Moscow: CEMI AS USSR, pp. 51–77 (in Russian).
3. Kleiner G.B. (1986) *Production functions: Theory, methods, applications*. Moscow: Financy i Statistika. 238 p. (in Russian).
4. Makarov V.L. (1999) *Computable general equilibrium model of the Russian economy (RUSEC)*. Preprint. wp/99/069. Moscow: CEMI RAS (in Russian).
5. Baranov E.F., Bessonov V.A. (2018) A view at the Russian economic transformation. *Voprosy Ekonomiki*, vol. 11, pp. 142–158 (in Russian). https://doi.org/10.32609/0042-8736-2018-11-142-158

6. Byvshev V.A. (2022) Assessment of the construction of scientific and technological progress to the real GDP of Russia. *Economics of Contemporary Russia*, no. 3 (98), pp. 46–64 (in Russian). https://doi.org/10.33293/1609-1442-2022-3(98)-46-64

7. Afanasiev A.A., Ponomareva O.S. (2014) The aggregate production function of Russian economy in 1990–2012. *Economics and Mathematical Methods*, vol. 50, no. 4, pp. 21–33 (in Russian).

8. Afanasiev A.A., Ponomareva O.S. (2020) The macroeconomic production function of Russia in 1990–2017. *Economics and Mathematical Methods*, vol. 56, no. 1, pp. 67–78 (in Russian). https://doi.org/10.31857/S042473880006708-7

9. Afanasiev A.A., Ponomareva O.S. (2021) Wuhan coronavirus (SARS-CoV-2) spread in Russia: macroeconomic production function in regard to Brent crude oil price. *Market economy problems*, no. 1, pp. 24-46 (in Russian). https://doi.org/10.33051/2500-2325-2021-1-24-46

10. *Statistical series of REB. Industry*. Supplement to the monthly bulletin "Russian Economic Barometer" for September 2022 (in Russian). Available at: https://www.imemo.ru/files/File/magazines/REB_month/statistics/2022/2022_09_reb_stat_ru.pdf (accessed 10.11.2022).

11. *Russian Statistical Yearbook 2020*: Stat .book/Rosstat (2020) Moscow. 700 p. (in Russian).

12. *World Bank Commodity Price Data* (The Pink Sheet). Available at: https://thedocs.worldbank.org/en/doc/5d903e848db1d1b83e0ec8f744e55570-0350012021/related/CMO-Historical-Data-Annual.xlsx (accessed 15.09.2022).

13. Aukutsionek S., Zhukov O. (2022) The 2021 surveys of industrial enterprises: results and forecasts. *Russian Economic Barometer*, no. 2(86), pp. 3–7 (in Russian). https://doi.org/10.20542/reb.rus-2022-2-3-7

14. Aukutsionek S., Dyomina N. (2022) Outline of REB surveys and clarification to the series. *Russian Economic Barometer*, no. 2(86), pp. 13–18 (in Russian).

15. Brown M. (1971) *On the theory and measurement of technological change*, translated by Valery V. Zotov, edited by Valery G. Grebennikov and Grigory G. Pirogov. Moscow, Statistika, 208 p. (in Russian).

16. *National accounts of Russia in 2013–2020*: Stat .book/Rosstat (2021). Moscow (in Russian).

17. Afanasiev A.A., Ponomareva O.S. (2022) Econometric study of the Russian economy production function and estimation of the marginal rate of substitution of factors in regard to Wuhan coronavirus period (1990–2020). In: *System modeling of social-economic processes: The Material 45th Anniversary international scientific school-seminar*, ed. by I.N. Shchepina. Voronezh, «Istoki», pp. 148–158 (in Russian). https://doi.org/10.5281/zenodo.7404549

18. International Energy Agency (2020) *Oil Market Report – February 2020*. Available at: https://www.iea.org/reports/oil-market-report-february-2020 (accessed 05.06.2022).

19. Nepp A.N., Zykov A.S., Yegorova Yu.V. Oil in the age of coronavirus: hysteria or explainable fall? *Economics and Mathematical Methods*, vol. 59 (in press) (in Russian).

20. *Socio-economic situation in Russia 2022, January-August* (2022) Moscow, Rosstat (in Russian).

21. Lawder D. (2022) US Treasury Secretary reveals Russian oil price cap target, *Reuters*, October 13, 2022. Available at: https://www.reuters.com/markets/europe/yellen-says-russian-oil-price-cap-60-range-would-allow-moscow-some-profit-2022-10-12/ (accessed 10.11.2022).

22. Ministry of Finance of the Russian Federation (2022) *The main directions of the budget, tax and customs tariff policy for 2023 and for the planning period of 2024 and 2025.* Moscow. Available at: https://storage.consultant.ru/ondb/attachments/202209/28/ONNP_73J.pdf (accessed 10.11.2022) (in Russian).

23. His Majesty's Government (2022) *News story. UK sanctions on Russia top £18 billion for the first time. New figures reveal the full effect of UK sanctions on Russia*, 10 November 2022. Available at: https://www.gov.uk/government/news/uk-sanctions-on-russia-top-18-billion-for-the-first-time (accessed 10.11.2022).

24. Kazakova D., Kolebakina-Usmanova E. (2022) Sergei Glazyev: "The Bacchanalia of Negative Forecasts Should Not Program Us for Failure", Business Electronic Newspaper *Business Online*, May 1. Available at: https://www.business-gazeta.ru/article/550442 (accessed 05.06.2022) (in Russian).

25. Glazyev S.Yu. (2022) Changing technological patterns: information, digital, intellectual and cognitive technologies. *Plenary presentation at the International Academic Economic Forum* May 16, 2022, Moscow. Available at: https://www.youtube.com/watch?v=PSESiZZ4aRk&t=5526s (accessed 05.06.2022) (in Russian).

26. *Socio-economic situation in Russia 2022, January-July* (2022) Moscow, Rosstat (in Russian).

27. *Indices of the Institute for Problems of Natural Monopolies*. Monitoring the state of the industry. June 2022. Available at: http://ipem.ru/content/Индексы/индекс_ИПЕМ%202022%20июнь.pdf (accessed 10.11.2022) (in Russian).

28. *Gas production and supplies: results for six months*. Release. July 1, 2022. Available at: https://www.gazprom.com/press/news/2022/july/article554547/ (accessed 10.11.2022).

29. Afanasiev A.A. (2022) Econometric forecast of Gazprom natutal gas production in Tyumen region for 2022. In: *System modeling of social-economic processes: The Material 45th Anniversary international scientific school-seminar*, ed. by I.N. Shchepina. Voronezh, «Istoki», pp. 159–162 (in Russian). https://doi.org/10.5281/zenodo.7406120

30. Afanasyev A.A. (2008) Natural gas production in Tyumen region: economic-and-mathematic modelling and forecasting. *Gas Industry of Russia*, no. 4(12), pp. 5–10.

31. Afanasiev A.A. (2009) Production Functions of Natural Gas Production Industry in Krasnoyarsk Territory. *Economics and Mathematical Methods*, vol. 45, no. 3, pp. 3–11 (in Russian).

32. Afanasiev A.A. (2014) Sustainable strategic goals of a Global Energy Company: Key for Gazprom's future. *Gazovaya promyshlennost*, no. 704, pp. 10–20 (in Russian).

33. Afanasiev A.A. (2018) Econometric analysis of Gazprom production efficiency in 1993–2016. *Oil & Gas Journal Russia*, nos. 1–2(123), pp. 74–80 (in Russian).

34. Afanasyev A.A. (2009) Pareto-efficiency, cost minimization, and innovations: the key Gazprom policies targeting gas production. *Gas Industry of Russia*, no. 3(15), pp. 30–37.

35. Smith A. (1896) *Lectures on Justice, Police, Revenue and Arms delivered in the University of Glasgow by Adam Smith and reported by a Student in 1763,* and edited, with an introduction and notes, by Edwin Cannan. Oxford: Clarendon Press, 293 p.

36. Lvov D.S., Afanasiev A.A. (2007) Does Russia need a Stabilization Fund? *Financial business*, no. 1, pp. 8–15 (in Russian).

About the authors

Anton A. Afanasiev

Dr. Sci. (Econ.);

Professor, Leading researcher, Central Economics and Mathematics Institute, Russian Academy of Sciences, 47, Nakhimovsky Prospect, Moscow 117418, Russia

E-mail: aanton@cemi.rssi.ru

ORCID: 0000-0002-5680-7896

Olga S. Ponomareva

Senior Researcher, Central Economics and Mathematics Institute, Russian Academy of Sciences, 47, Nakhimovsky Prospect, Moscow 117418, Russia

E-mail: fondf@cemi.rssi.ru

24th YASIN (APRIL) INTERNATIONAL ACADEMIC CONFERENCE ON ECONOMIC AND SOCIAL DEVELOPMENT

Dear colleagues,

HSE University is pleased to announce a call for proposals to take part in the **24th International Academic Conference on Economic and Social Development** (hereinafter the "24th Yasin Conference" or the "Conference").

The Conference will be held jointly with Russian corporations, as well as research and consulting institutions.

The key events of the 24th Yasin Conference will be taking place in Moscow from April 4 to 14, 2023.

At the 24th Yasin Conference, reports on new research results will be presented and discussed. These reports will be selected through reviews of proposals (the requirements can be found below). Furthermore, the Conference's programme traditionally features expert discussions of the most pressing economic, social, internal and external issues, involving state officials and leading Russian and foreign experts, as well as honorary reports by distinguished academics from all over the world and various associated events.

The Conference's events will be held in Russian or English. Certain discussions will be bilingual and will feature simultaneous translation services.

With a view to involve participants from Russia's various regions and all over the world, as well as bearing in mind that certain epidemiological restrictions still may be in effect, the 24th Yasin Conference will be held in a hybrid format. Most sections and other events will be held face-to-face, but there is an option for some speakers and other participants to join streaming sessions online.

For the 24th Yasin Conference, as was in previous years, a call will be announced for proposals to support participation in the Conference of young academics from Russia's regions.

24th YASIN (APRIL) INTERNATIONAL ACADEMIC CONFERENCE ON ECONOMIC AND SOCIAL DEVELOPMENT

The sections of the 24th Yasin Conference will be focused on the following areas:

- Arctic Studies;
- Public Administration, Local Self-government and NGOs;
- Demography and Job Markets;
- Instrumental Methods in Economic and Social Research;
- Macroeconomics and Macroeconomic Policy;
- International Relations;
- Management;
- Methods in Economics Research;
- Global Economy;
- Science and Innovation;
- Education;
- Political Processes;
- Law in the Digital Age;
- Healthcare;
- Regional and Urban Development;
- Smart City;
- Social and Economic History;
- Social Policy;
- Sociocultural Processes;
- Sociology;
- Theoretical Economics;
- Financial Institutes, Markets and Payment Systems;
- Firms and Markets;
- Digital Economy.

We kindly invite you to join the Conference as a listener.

To submit your application as a listener, please,
register at the HSE University's Conference system until **March 31, 2023**:
http://conference.hse.ru

Conference fees.

Listeners have to pay conference fee to attend the events of the XXIV Yasin (April) International Academic Conference on Economic and Social Development.

The amount of fee is RUB **2,000** (by March 1, 2023) or RUB **2,500** (after March 1, 2023).

The detailed information about the Conference is available at the official web-site: https://conf.hse.ru/