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VIRTUAL SCENARIOS OF DEMOGRAPHIC IMPACT ON ECONOMIC GROWTH

Introduction. As you know, developed economies try to automate production processes as much as possible, which in turn increases their capital intensity. However, such automation significantly reduces the dependence of enterprises on human resources. This has a twofold impact on the economy: on the one hand, it increases labor productivity and economic efficiency, and on the other hand, demographic changes, such as an aging population and a shrinking labor force, become less critical for economic growth. However, in the long run, population decline may lead to a decline in domestic demand, which creates additional challenges for economic development.

In countries with a low level of production automation, the demographic situation plays a more significant role. In such countries, population growth rates directly affect the formation of labor resources and, consequently, economic growth. However, rapid population growth in the context of limited investment in human capital and low technological development can lead to unemployment, deteriorating living standards, and growing social inequality.

Taking demographic changes into account when modeling economic growth is crucial for obtaining realistic forecasts and developing effective economic policies. Demographic factors, such as population growth rates, fertility rates, life expectancy, and the structure of age groups, directly affect the dynamics of labor resources and capital accumulation.

Methodology. We chose an endogenous model of economic growth that takes into account foreign trade and investment, as well as its modification that divides the economy into sectors with an emphasis on their interaction, as described in detail in [1-3].

In the model, the main factors of production are private capital K_{pr}, public capital K_{gov}, human capital (knowledge) H, labor L and the variable factor R. Variable factor R in a single-sector production model is responsible for the land factor N. A modified Cobb-Douglas function of the form:

$$Y_p = AK_{pr}{}^{\alpha}K_{gov}{}^{\beta}H^{\gamma}N^{\varphi}L^{1-\alpha-\beta-\gamma-\varphi}, \qquad (1)$$

where α – is the coefficient of elasticity of private capital, β – public capital elasticity coefficient, γ – human capital elasticity coefficient, φ – elasticity of the variable factor, in this case, land [2; 3].

In the multisectoral model, the factor R depends on the sector. For the primary sector Y_{agr} land is a factor, similar to the single-sector model. For the secondary sector Y_{ind} factor is the output of the primary sector Y_{agr}. For the tertiary sector Y_{serv} factor is the output of the secondary sector Y_{ind}.

For a multisectoral model, the production function takes the form:

$$\begin{aligned} Y_p = {} & A_1K_{agr}{}^{\alpha1}K_{gov}{}^{\beta1}H_{agr}{}^{\gamma1}\ N^{\varphi1}L_{agr}{}^{1-\alpha1-\beta1-\gamma1-\varphi1} + \\ & A_2K_{ind}{}^{\alpha2}K_{gov}{}^{\beta2}H_{ind}{}^{\gamma2}\ Y_{agr}{}^{\varphi2}L_{ind}{}^{1-\alpha2-\beta2-\gamma2-\varphi2} + \\ & A_3K_{serv}{}^{\alpha3}K_{gov}{}^{\beta3}H_{serv}{}^{\gamma3}\ Y_{ind}{}^{\varphi3}L_{serv}{}^{1-\alpha3-\beta3-\gamma3-\varphi3}, \end{aligned} \qquad (2)$$

wherein $Y_p = Y_{agr} + Y_{ind} + Y_{serv}$, similarly $K_{pr} = K_{agr} + K_{ind} + K_{serv}$ and $H = H_{agr} + H_{ind} + H_{serv}$, $L = L_{agr} + L_{ind} + L_{serv}$.

Capital in the model is divided into private and public, which allows for a more accurate accounting of the differences in the functions and role of each sector in the process of economic growth. Investments are made through aggregate savings, which reflect the ability of the economy to effectively channel resources for development. Thus, capital dynamics can be described through three key indicators: private sector capital intensity, which determines the volume of private investment; public sector capital intensity, which characterizes investments in public infrastructure and public goods; and aggregate savings per unit of labor, which is the main source of investment in the economy.

This approach allows for a deeper exploration of the interrelationships between private and public investment, as well as their joint impact on labor efficiency and long-term economic growth [2; 3].

The innovation sector generates new knowledge by the production function:

$$\Delta H = BK_{rd}{}^{v}L_{rd}{}^{1-v}, \quad (3)$$

where K_{rd} – capital raised in the innovation sector, L_{rd} – labor involved in the innovation sector, v – capital elasticity in the innovation sector. Total capital in the economy K_{full} can be found by the formula: $K_{full} = K_{rd} + K_{pr} + K_{gov}$, similar to labor: $L_{full} = L_{rd} + L$.

Full single-sector multivariate model in general form [2; 3]:

$$\begin{cases} k_{pr}{}^{\bullet} = i_{in} + i_f - (d_{pr} + n)k_{pr}, \\ k_{gov}{}^{\bullet} = g - (d_{gov} + n)k_{gov} + tx, \\ m^{\bullet} = sAk_{pr}{}^{\alpha}k_{gov}{}^{\beta}h^{\gamma}n_N{}^{\varphi} - (g + nm + i_{in} + i_{out}), \\ h^{\bullet} = Bk_{rd}{}^{v}l - nh, \end{cases} \quad (4)$$

where k_{pr} – capital intensity of the private sector, d_{pr} – amortization rate of private capital, n – average growth rate of the employed labor force, i_{in} – domestic investment per unit of labor, i_f – foreign investment per unit of labor, k_{gov} – capital intensity of the public sector, g – taxes per unit of labor, d_{gov} – depreciation ratio for public capital, tx – net government international transfers, m – total savings per unit of labor, s – savings rate, n_N – land factor per unit of labor, i_{out} – external investment per unit of labor.

For a multisectoral modification, the formula for the derivative of total savings per unit of labor is as follows:

$$\begin{aligned} m^{\bullet} &= A_1\frac{L_{agr}}{L}k_{agr}{}^{\alpha 1}k_{gov}{}^{\beta 1}h_{agr}{}^{\gamma 1}n_N{}^{\varphi 1} \\ &+ A_2\frac{L_{ind}}{L}k_{ind}{}^{\alpha 2}k_{gov}{}^{\beta 2}h_{ind}{}^{\gamma 2}y_{arg}{}^{\varphi 2} \\ &+ A_3\frac{L_{serv}}{L}k_{serv}{}^{\alpha 3}k_{gov}{}^{\beta 3}h_{serv}{}^{\gamma 3}y_{ind}{}^{\varphi 3} - \\ &- (g + nm + i_{in} + i_{out}). \end{aligned} \quad (5)$$

The labor factor, or labor force, is one of the key elements of economic growth. The labor force ensures productivity in all sectors of the economy by creating goods and services. The growth of the working-age population contributes to the increase in the country's production capacity, which can stimulate economic growth.

The amount of labor in an economy is determined by many demographic and social factors, including births, deaths, and migration. High fertility rates ensure long-term replenishment of the labor force, although their impact becomes noticeable only decades later, when the new generation reaches working age. Low mortality, especially among the working-age population, helps to maintain a stable labor force. Migration also plays a key role: immigration can increase the number of workers in a country, compensating for demographic decline, while emigration, on the contrary, reduces the labor force, which is often a challenge for countries with low birth rates. All of these factors interact to shape the labor force dynamics in each individual economy.

In the considered model (4), in addition to the production function, the labor factor is present in the main system of equations in the form of the coefficient n, which corresponds to the average growth rate of labor L. In the form of a formula, this can be written as:

$$n = \frac{dL/dt}{L} \quad (6),$$

where dL/dt – growth of labor (labor force) in the period t. Assuming that the unemployment rate is constant, i.e. $e = const$, then this coefficient can be written using the population indicator P as:

$$n = \frac{dP/dt}{P} \quad (7).$$

To model population dynamics in the country, it is proposed to use the Verhulst model [4]. The Verhulst model, also known as the logistic equation, has significant advantages for modeling population dynamics because it takes into account the limited resources and shows how the population approaches its ecological maximum (carrying capacity). Unlike exponential models, which assume unlimited growth, the logistic model realistically reflects slowing growth rates due to competition for resources such as food, water, housing, and jobs. This makes it particularly useful for analyzing demographic processes in a country's economy, as it allows to assess the impact of population overcrowding and predict the consequences for economic development. In addition, the model is easy to implement and interpret, making it a convenient tool for long-term planning..

In general, the Verhulst model looks like this:

$$\frac{dP}{dt} = rP(1 - \frac{P}{K_e}), \quad (8)$$

where r – population growth rate, K_e – specific capacity of the environmental niche. Taking into account that population growth depends on birth and death rates, as well as the fact that the model does not take into account migration processes, it is proposed to modify expression (8) as follows:

$$\frac{dP}{dt} = (r_b - r_d)P\left(1 - \frac{P}{K_e}\right) + \frac{(a-b)P^2}{K_e}, \quad (9)$$

where a – immigration rate, b – emigration rate. $Q = \frac{(a-b)P^2}{K_e}$ – population growth due to migration processes, r_b – birth rate, r_d – mortality rate.

By integrating equation (9), we can obtain the solution of the logistic equation with the migration factor, which is as follows:

$$P = \frac{e^{(r_b-r_d)t}P_0K_e}{\frac{-P_0((r_b-r_d)-(a-b))(1-e^{(r_b-r_d)t})}{(r_b-r_d)} + K_e}, \quad (10)$$

where P_0 – initial value of the population size.

In model (4), we use equation:

$$n = (r_b - r_d)\left(1 - \frac{P}{K_e}\right) + \frac{(a-b)P}{K_e}. \quad (11)$$

Unemployment is an economic condition in which a part of the working-age population cannot find a job, although they are actively looking for one. It is one of the key indicators of a country's economic health, reflecting the level of labor utilization. Unemployment leads to lower incomes, weaker consumer demand, and losses for the economy due to unused production potential.

The main causes of unemployment are structural changes in the economy, technological progress, economic crises, and seasonal fluctuations. According to these reasons, there are several types of unemployment. Frictional unemployment occurs when people change jobs or look for their first job. Structural unemployment is associated with a mismatch between the skills of workers and the requirements of the labor market. Seasonal unemployment is typical for industries with periodic employment, such as agriculture or tourism. Cyclical unemployment is caused by general economic downturns, when demand for goods and services decreases, leading to job losses.

Cyclical unemployment is closely related to the phases of the economic cycle. During periods of recession or downturn, unemployment rises due to reduced production and lower investment as companies are forced to lay off workers due to falling demand. On the contrary, during an economic recovery, unemployment falls due to the creation of new jobs and increased consumer demand. This cyclicality requires active government intervention through monetary and fiscal policy to mitigate economic fluctuations and stabilize the labor market.

To take into account complex cycles, we use the modified Theil-Wage model [5-6] of the form:

$$\hat{y}_{t+h|t} = (l_t + hb_t)s_{t+h+(k+1)}$$
$$l_t = \alpha(y_t/s_t) + (1-\alpha)(l_{t-1} + b_{t-1})$$
$$b_t = \beta(l_t - l_{t-1}) + (1-\beta)b_{t-1}$$
$$s_t = s_{t1-m1} * s_{t2-m2} * \dots * s_{tn-mn},$$
$$s_{t1} = \gamma_1(y_t/(l_{t-1} + b_{t-1})) + (1-\gamma_1)s_{t1-m1}$$
$$s_{t2} = \gamma_2(y_t/(l_{t-1} + b_{t-1})s_{t1}) + (1-\gamma_2)s_{t2-m2}$$
$$\dots$$
$$s_{tn} = \gamma_n(y_t/(l_{t-1} + b_{t-1})s_{t1} * \dots * s_{tn}) +$$
$$+ (1-\gamma_n)s_{tn-mn}, \quad (12)$$

where l_t – time series level equation, b_t – trend equation, $s_{t1}, s_{t2}, \dots, s_{tn}$ – seasonality/cyclicity equations, coefficients α, β та $\gamma_1, \gamma_2, \dots, \gamma_n$ are the degrees of smoothing of the time series, trend and seasonality/cyclicity, respectively, which can take values from 0 to 1, $m_1, m_2, \dots, m_n$ – duration of seasonality periods.

To account for cycles, we need to adjust the value of *n* by the resulting composite seasonal component s_t and trend component b_t:

$$n = b_t s_t\left[(r_b - r_d)\left(1 - \frac{P}{K_e}\right) + \frac{(a-b)P}{K_e}\right]. \quad (13)$$

Similarly, we modify the Solow [7-9], Ramsey-Cass-Koopmans [10-12], and Mankiw-Romer-Weil models [13].

The prerequisites of Solow's model [7-9] are capital intensity, k = *K/L* is not a constant, as in Keynesian models, but varies depending on the macroeconomic situation in the country, the price of goods, services and resources is set by the market mechanism, the growth rate of labor resources is equal to the average growth rate of the population, but the dynamism of wages is not taken into account; there is a hypothesis that population growth and technical progress are absent at the initial stage; the rates of saving, depreciation, technical progress, capital and labor elasticities, and population growth are constants, although they change over time. Finally, the Solow equation [7-9] takes the form:

$$k^{\bullet} = sAk^{\alpha} - (d+n)k, \quad k_0 = k(t_0). \quad (14)$$

The Ramsey-Cass-Koopmans model [10-12] has similar preconditions and production function to the Solow model, except for the exogeneity of the rate of accumulation. Then the equation of the Solow model takes the form:

$$k^{\bullet} = Ak^{\alpha} - c - (d+n)k, \quad k_0 = k(t_0). \quad (15)$$

The Mankiw-Romer-Weil model [13] is a modification of the Solow model with the addition of human capital (H) to the model, and the basic equation becomes a two-dimensional system and is modified to look like:

$$k^{\bullet} = s_k Ak^{\alpha}h^{\beta} - (d+n)k, \quad k_0 = k(t_0),$$
$$h^{\bullet} = s_h Ak^{\alpha}h^{\beta} - (d+n)h, \quad h_0 = h(t_0), \quad (16)$$

where s_k – rate of accumulation of physical capital, a s_h- rate of human capital accumulation.

Modeling results and discussion. Thus, with the theoretical basis and methodology in place, we turn to an empirical analysis of the impact of demographic change on economic growth. Using economic growth models, we will assess how changes in fertility, mortality, and population structure correlate with the dynamics of capital in the economy. To do this, we will conduct an analysis based on real data, compare the accuracy of different model specifications, and determine which factors play a key role in explaining economic development.

The modeling was based on World Bank statistics [14]. The total sample covered 150 countries out of 217 available (see Fig. 1), and the analysis excluded observations that contained incomplete or missing data necessary for modeling. The study period was chosen to be as long as possible, which allowed us to assess the impact of demographic changes on economic growth in different time intervals and to investigate how the length of the observation period affects the modeling results.

To assess the accuracy of the modeling, a wide range of metrics were used, including the coefficient of determination (R^2), mean absolute error (MAE), mean square error (MSE), root mean square error (RMSE),

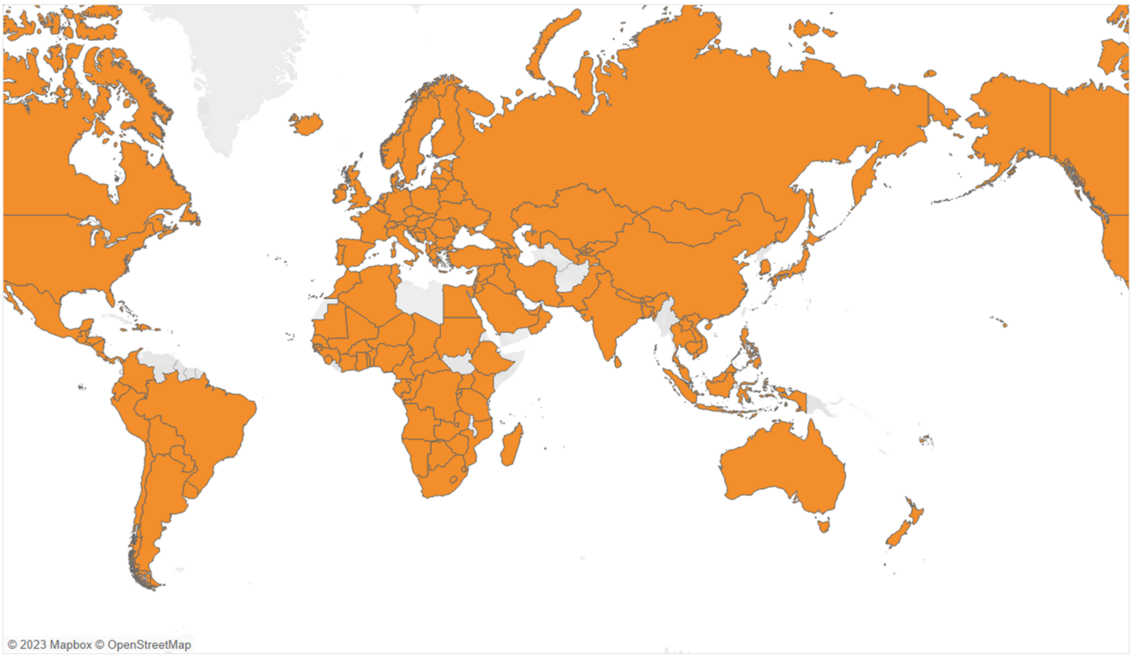

Fig. 1. Countries used in the study

mean relative error (MRE), mean square logarithmic error (MSLE) and its root (RMSLE). This approach provides a comprehensive evaluation of models:

- The coefficient of determination (R^2) allows you to determine how much of the variation in the dependent variable is explained by the model.
- MAE and MSE provide an indication of the average error, but MSE penalizes large deviations more.
- RMSE simplifies the interpretation of MSE because it preserves the units of the variable.
- MRE provides a scale-independent comparison of errors between different models and samples.
- MSLE and RMSLE are especially useful when modeling exponentially varying data because they reduce the impact of large values and emphasize relative errors.

The use of such a diverse set of metrics allows for a more balanced assessment of model quality, taking into account both absolute and relative errors, and ensures that the analysis is robust to different data scales.

First, we will analyze general trends and consider how the statistical quality of the models varies depending on the choice of variables, the observation period, and the estimation method. This will allow us to identify the main patterns and assess the stability of the results. After that, we will move on to a more detailed analysis of individual cases, compare model predictions for different groups of countries, and assess possible reasons for deviations in the results.

At the first stage, we analyze the dynamics of model quality metrics to assess how their accuracy varies depending on the sample, observation period, and modeling parameters. In particular, we consider the trends in the coefficient of determination (R^2) to determine the explanatory power of the models, as well as the estimates of MAE, MSE, RMSE, MRE, MSLE, and RMSLE errors (Fig. 2).

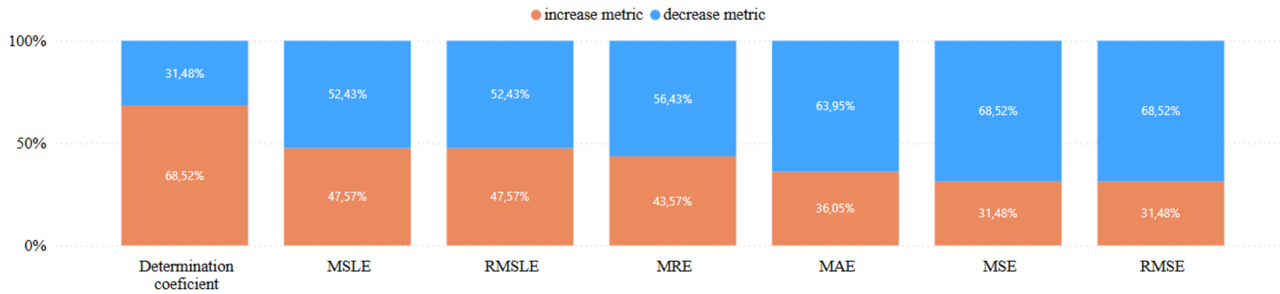

Fig. 2. Dynamics of quality metrics of economic growth models

The analysis has shown that the use of dynamic indicators of demographic development, in particular variables that take into account changes in the structure of the population and its growth, significantly improves the quality of the models. In particular, the coefficient of determination (R^2) increased in 68% of cases compared to models that used a static population growth rate, which indicates an increase in the explanatory power of the models (Fig. 2).

In addition, other accuracy metrics decreased in 52% to 68% of cases (Fig. 2). This indicates that in most cases, models with dynamic demographic variables demonstrate not only better explanatory power, but also reduce average forecast errors. This trend confirms the importance of taking into account changes in demographic characteristics over time to build more accurate models.

Next, let us consider the results in terms of economic growth models (Fig. 3).

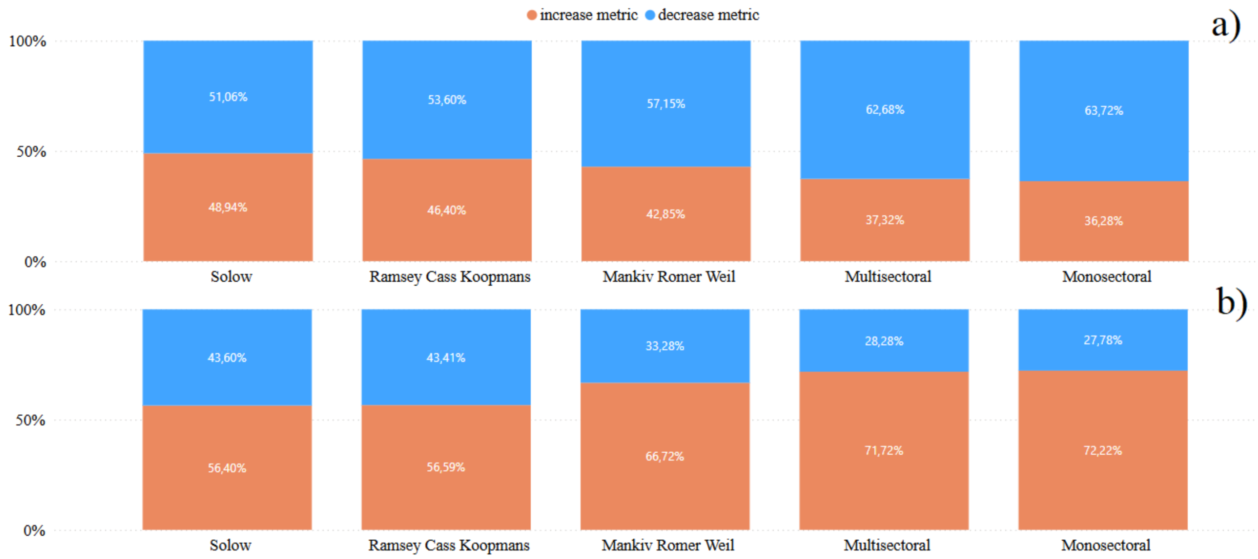

Fig. 3. Dynamics of metrics based on the average error (a) and coefficient of determination (b) in the context of economic growth models

The analysis showed that taking into account dynamic changes in population growth significantly improves the quality of economic growth models. In particular, the accuracy of classical one-dimensional models, such as the Solow model and the Ramsey-Cass-Koopmans model, increased in 52% of cases (Fig. 3), which indicates a certain improvement in their explanatory power even in the simplest version.

The more complex two-dimensional Mankiw-Romer-Weil model, which takes into account human capital as an additional factor along with physical capital, demonstrated an even higher increase in quality – in 57% of cases (Fig. 3). This confirms the hypothesis that supplementing traditional models with new factors contributes to a better reflection of economic reality.

The greatest improvement was observed in the case of multivariate models that include additional demographic, social, and economic variables. Their quality increased in 63% of cases (Fig. 3) after replacing the static population growth rate with a dynamic formula.

The improvement in the quality of economic growth models is most significant in the short term, particularly over the last 10-20 years, where in 73% of cases models with a dynamic population growth rate demonstrate higher accuracy than the traditional static approach (Fig. 4a). This may be due to the fact that in the short term, demographic changes have a more predictable and direct impact on economic processes, as structural transformations, such as urbanization, educational reforms, or migration flows, manifest themselves more quickly.

However, with the increase of the period duration to 60 years, the positive effect of taking into account the dynamic growth rate gradually decreases, and the improvement of the quality of the models is observed in 64% of cases (Fig. 4a). This can be explained by the fact that in the long run, economic growth is influenced by a greater number of factors, such as technological changes, political transformations, wars, crises, and structural shifts in the global economy. These factors can offset the impact of demographic dynamics or make it less pronounced.

The improvement in the quality of economic growth models as a result of replacing the static population growth rate with a dynamic one is most pronounced for underdeveloped countries – in 73% of cases (Fig. 4b, 4c). This may be due to the fact that demographic changes in such countries play a key role in shaping economic dynamics. High fertility rates, young age of the population, and rapid changes in the structure of the labor force have a significant impact on consumption, investment, and human capital formation. As these economies are less diversified and more dependent on basic macroeconomic factors, their inclusion in a dynamic format can significantly improve the accuracy of the models.

For developed countries, the quality of models has also improved, but to a lesser extent – in 67% of cases (Fig. 4b, 4c). This is because the economies of highly developed countries are more stable and less dependent on demographic changes in the short and medium term. In these countries, population growth is often low or even negative, and economic growth is largely determined by factors of innovation, technological

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progress, institutional quality, and global economic integration. Accordingly, the impact of demographic change is less significant, which explains the lower increase in model accuracy compared to underdeveloped countries.

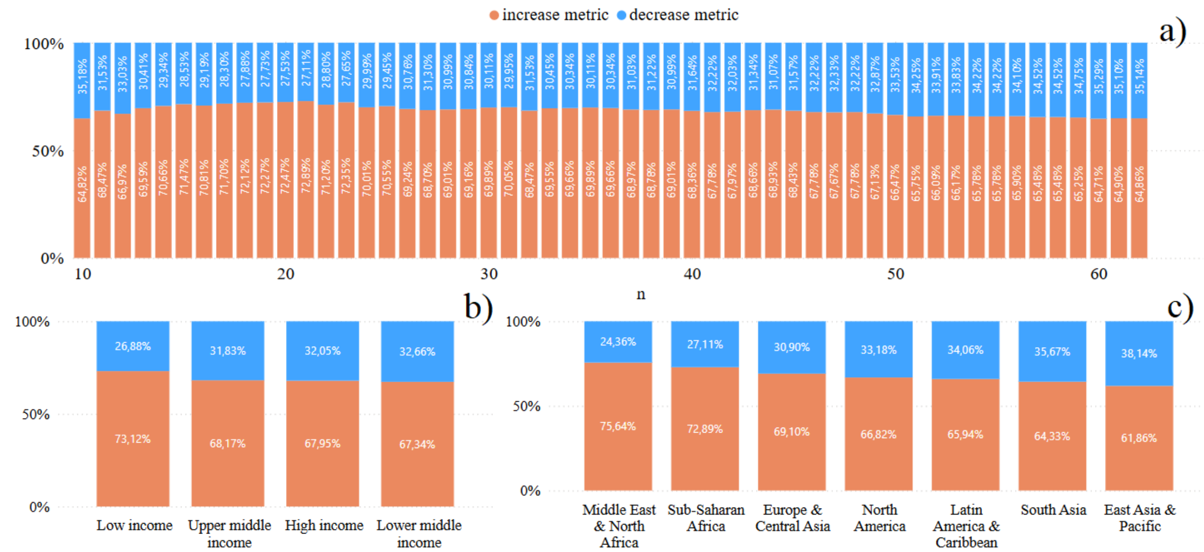

Fig. 4. Dynamics of the coefficient of determination by the length of the modeling period (a), groups of countries by income level (b), and geographical location (c)

The dynamics of RMSLE fully confirms the conclusions drawn earlier about the impact of the dynamic population growth rate on the quality of models (Fig. 5). According to RMSLE, models that use the dynamic population growth rate become more accurate in 55% of cases. This improvement is particularly noticeable in the short and medium term modeling periods, where demographic changes have a more pronounced impact on economic growth, and thus the dynamic coefficient is able to more accurately reflect these changes.

In highly developed countries, this effect is even more pronounced: the accuracy of models with a dynamic coefficient increases in 59% of cases (Fig. 5b, 5c). This is because in such countries, demographic changes may be smaller, but they are still important for economic forecasting, especially in conditions of stable growth or slowing population growth. In these countries, changes in population size and age structure can have a major impact on labor needs, consumer demand, and investment flows, making dynamic models more effective for forecasting.

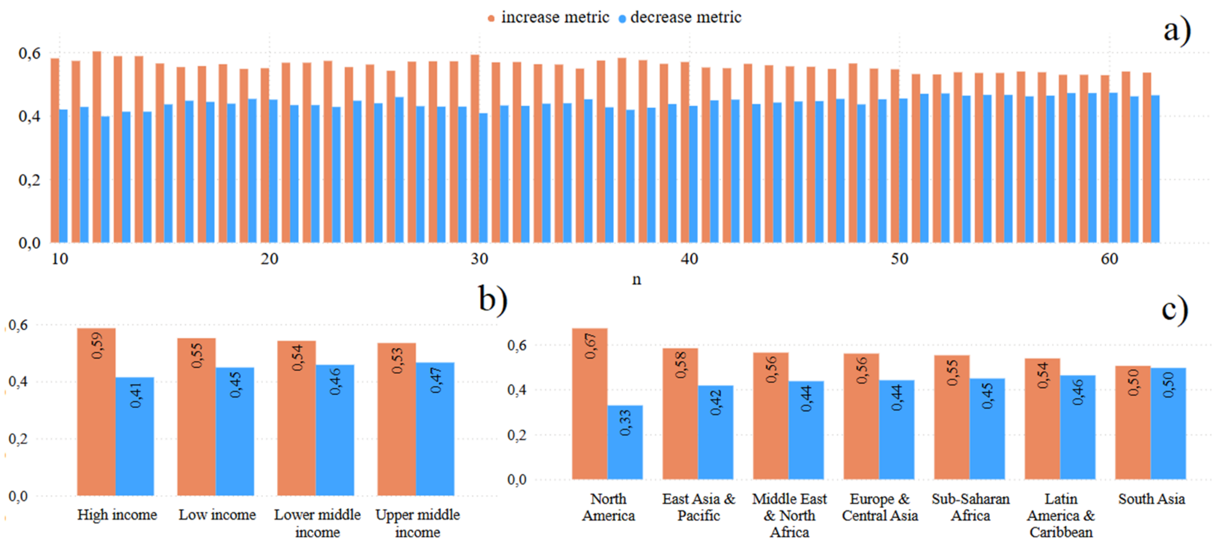

Fig. 5. Dynamics of the RMSLE metric by the length of the modeling period (a), country groups by income level (b), and geographic location (c)

Despite the fact that in underdeveloped countries demographic changes are often more significant and can have a greater impact on economic development, the improvement in model accuracy by using the dynamic coefficient is observed in 55% of cases (Fig. 5b, 5c), which is also a significant result. This confirms that although dynamic factors play an important role in such countries, other economic and social factors, such as political conditions, investment levels, and infrastructure development, also have a major impact on the predictive accuracy of the models..

Next, let's compare the absolute values of the model quality metrics, in particular, using RMSLE (Fig. 6).

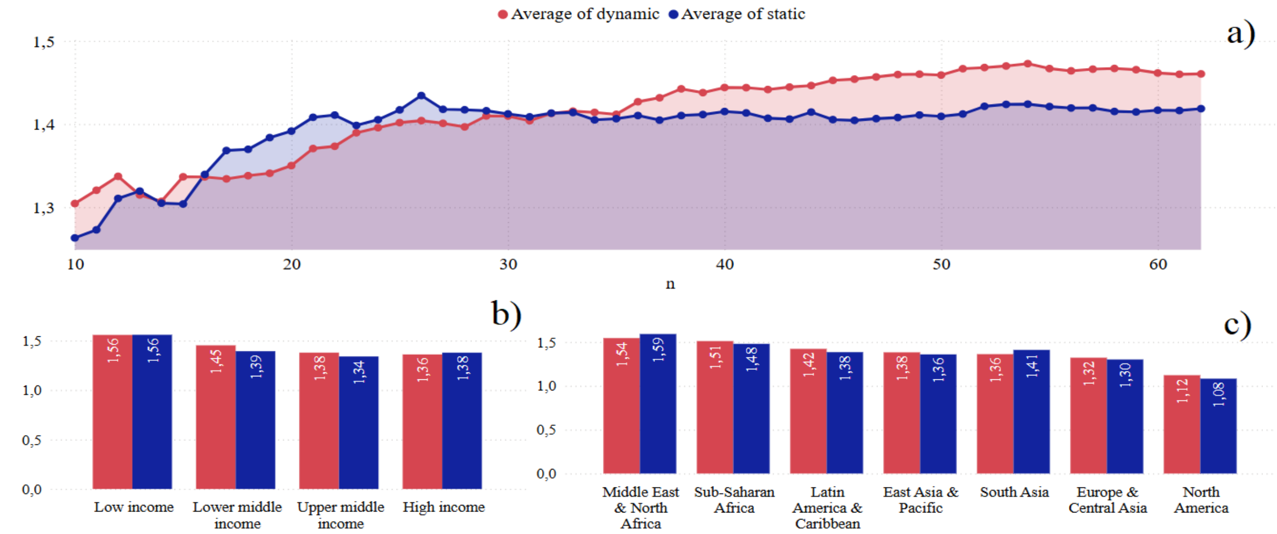

Fig. 6. RMSLE by the length of the modeling period (a), country groups by income level (b), and geographic location (c) for one-dimensional/ two-dimensional models.

For the period from 20 to 40 years, when using a static coefficient for the Solow, Ramsey-Cass-Koopmans, and Mankiw-Romer-Weil models, the RMSLE decreases (Fig. 6a) compared to periods longer than 40 years, where the situation is reversed. This may indicate, on the one hand, that in this period dynamic changes in fertility or mortality are less pronounced, and models with a constant coefficient are better at predicting economic trends in stable demographic conditions, and complicating the model with additional calculations makes it less stable. And on the other hand, that the size of the error is more influenced by unrealistic model limitations that become critical in the long run.

At the same time, for multivariate models that take into account not only demographic but also economic and other factors, the use of a dynamic coefficient leads to a consistently lower error at any time interval (Fig. 7).

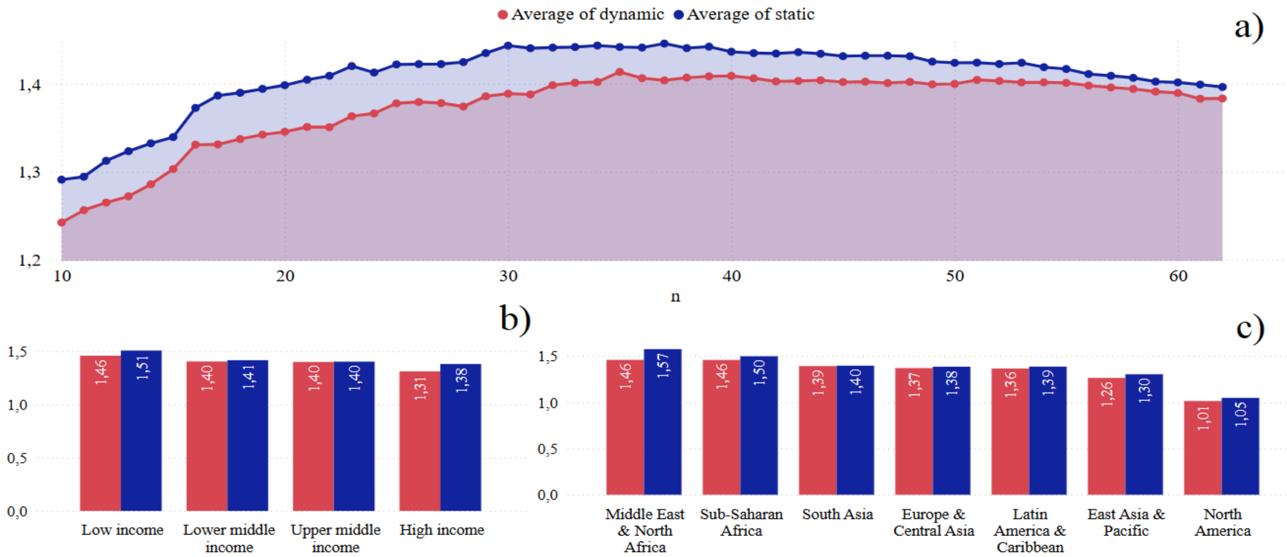

Fig. 7. RMSLE by the length of the modeling period (a), country groups by income level (b), and geographic location (c) for multivariate models

This is because multivariate models are able to more accurately capture the complex relationships between different variables and their impact on economic growth. Dynamic coefficients in such models allow for a better reflection of real changes in the structure of the population and economic processes, which leads to a reduction in forecast errors over different time horizons. Therefore, it can be concluded that the main problem with Fig. 6 is precisely the limitations of the models that were studied.

For multivariate models, the particular increase in quality after the introduction of the dynamic population growth rate, which is reflected in the metrics as the coefficient of determination, MSE, MAE, and RMSE (Fig. 8, 9), is largely due to the improvement in accuracy due to the inclusion of the components of total savings and human capital. This can be explained by several factors related to the importance of these components for overall economic development and the impact of dynamic changes on economic processes.

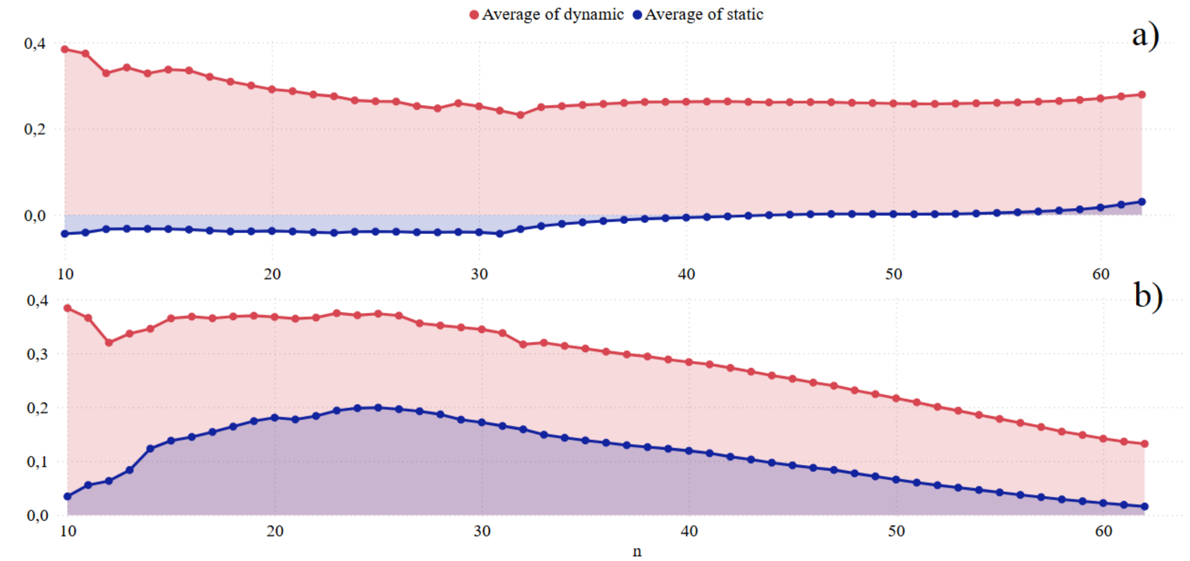

Fig. 8. The coefficient of determination by the length of the modeling period for the human capital equation (a) and total savings (b)

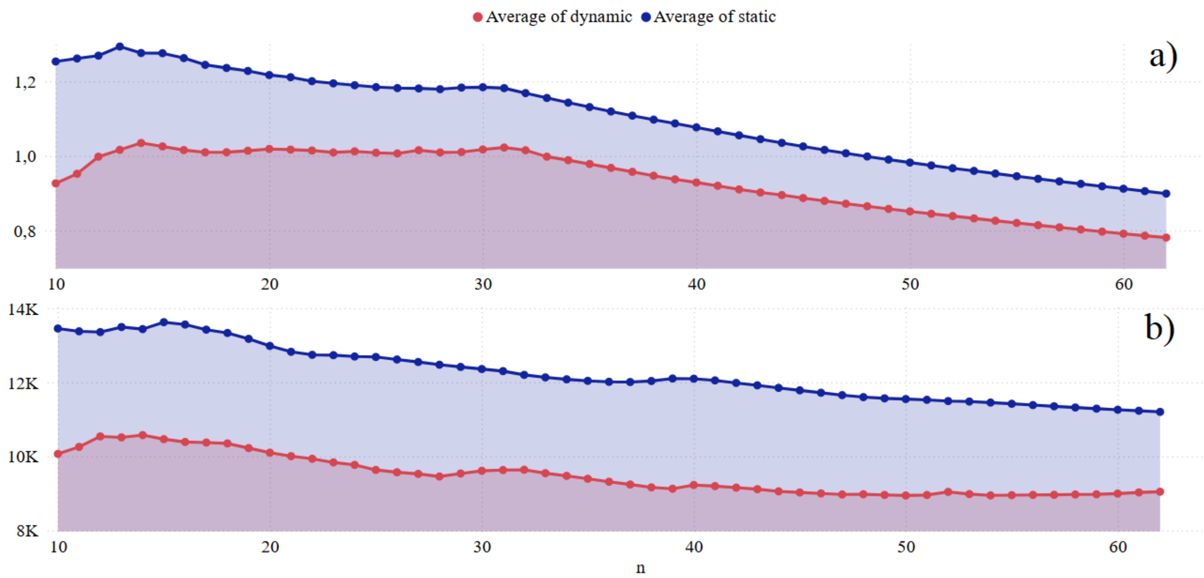

Fig. 9. RMSE by the length of the modeling period for the human capital equation (a), total savings (b)

Next, let's compare models with static and dynamic population growth rates (n) on the example of Ukraine's economy for the period from 1991 to 2021 (Fig. 10, 11). This period is particularly important for the analysis, as it covers significant transformations in the country's economic and demographic development, including the transition from a planned to a market economy, as well as major economic, social, and political changes associated with the collapse of the USSR, the crises of the 1990s, reforms, and globalization processes.

Statistical analysis of the Solow models using static and dynamic population growth rates shows that both approaches have similar results, but with some differences in error and accuracy characteristics (Fig. 10). The model with the dynamic coefficient demonstrated a lower average absolute error, which indicates better accuracy of predictions in the context of real economic conditions, in particular, changes in demographic factors over time. This model has the

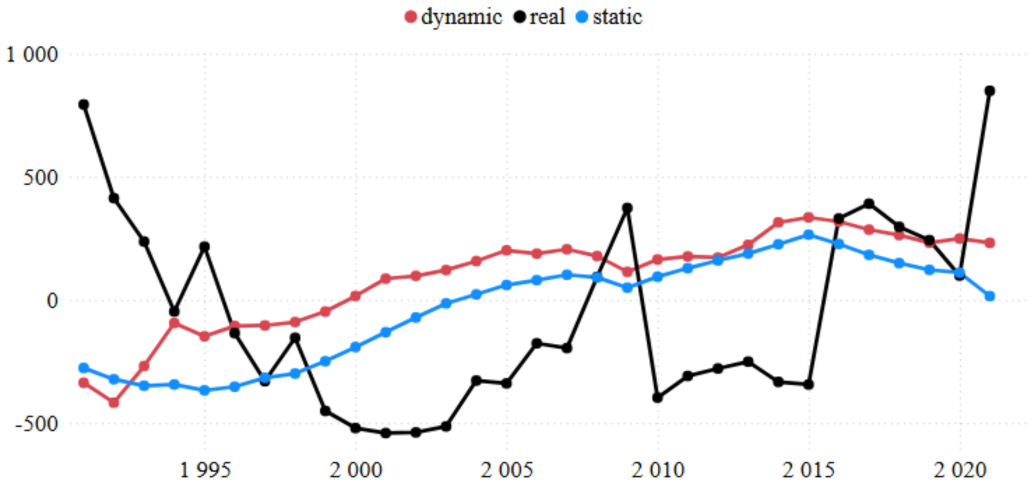

Fig. 10. Growth of capital intensity for the Ukrainian economy according to the Solow model

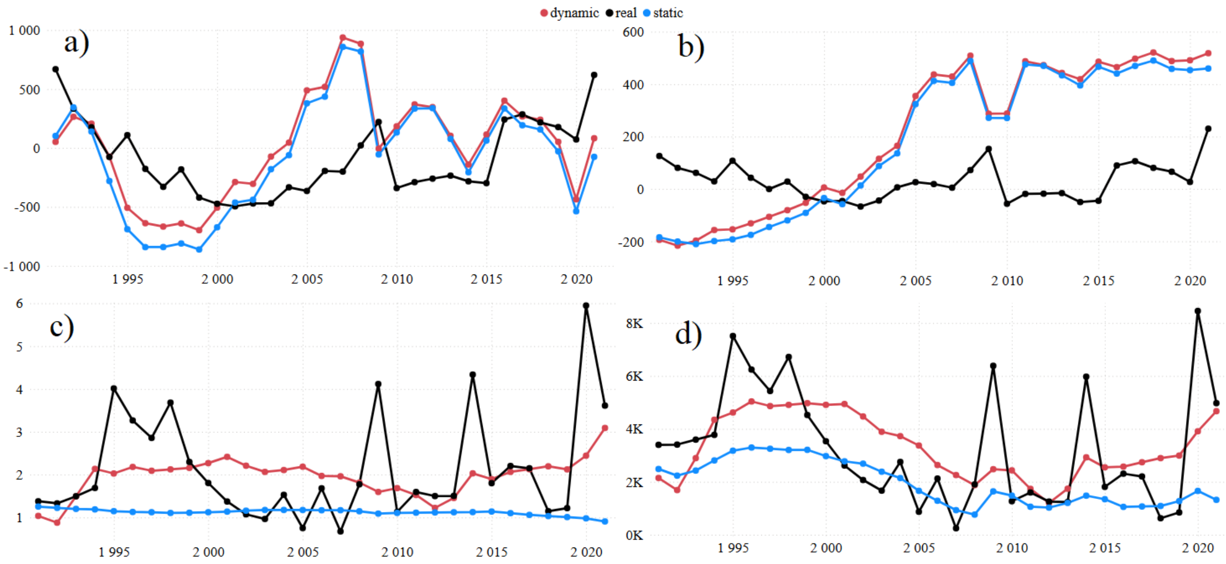

Fig. 11. Growth of the capital intensity of the private sector (a), public sector (b), human capital (c), and total savings (d) for the Ukrainian economy according to a single-sector multidimensional model

ability to adapt to changes in population growth rates, taking into account changes in its structure, which makes forecasts more consistent with real-world scenarios.

Looking at the multidimensional model, in the context of analyzing the capital intensity of the public and private sectors, the models for both sectors are almost identical in their basic structure. The dynamic population model becomes more adapted to the actual development trajectory for human capital and aggregate savings (Fig. 11), as it is able to integrate changes in demographic indicators that have a direct impact on these economic components. One of the main aspects that makes such a model more flexible is its ability to take into account not a constant population growth, but migration, fertility and mortality rates that change over time.

Conclusions. As a result of the study, several important conclusions can be drawn about the impact of demographic factors on economic growth using computer models that include a static or dynamic population growth rate.

First, the use of a dynamic coefficient instead of a static one significantly improves the accuracy of economic growth models, in particular, this is most evident for human capital and aggregate savings in multivariate models. This allows for a better reflection of real changes in the size and structure of the population, which directly affect labor productivity, investment potential, and overall economic development of the country.

Second, multidimensional models that include not only capital but also other factors show a more significant increase in quality, in particular due to adaptation to dynamic changes in population. This is confirmed by better indicators of quality metrics, and as a result, allow for more accurate forecasting of economic growth in a changing demographic situation.

Third, a study using real data showed that the greatest improvements in model quality occur for low-development countries, where demographic change has the greatest impact on economic growth.

Thus, the use of dynamic models that take into account demographic changes is a promising approach for more accurate analysis and forecasting of economic growth, especially in the context of countries where demographic factors can significantly affect economic processes.

References

1. Kolyada, Yu., Poznyak, S. et al. (2024). Adaptation Applying of Economic Growth Theoretical Models. *Digital Economy Concepts and Technologies Workshop*, 3665. pp. 22-35. Retrieved from https://ceur-ws.org/Vol-3665/paper3.pdf.

2. Kolyada, Yu., Poznyak, S. (2024). Adaptyvna model ekonomichnoho zrostannia dlia vidkrytoi ekonomiky [Adaptive Model of Economic Growth for an Open Economy]. *Natsionalni interesy Ukrainy – National interests of Ukraine*, 2(2), pp. 267-286. DOI: https://doi.org/10.52058/3041-1793-2024-2(2)-267-286 [in Ukrainian].

3. Poznyak, S., Kolyada, Yu. (2024). Adaptyvna model zrostannia vidkrytoi ekonomiky [Adaptive growth model of an open economy]. *Teoriia modernizatsii v konteksti suchasnoi svitovoi nauky* [*The Theory of Modernization in the Context of Modern World Science*]. Proceedings of the III International Scientific Conference. (pp. 87-92). Kryvyi Rih. DOI: https://doi.org/10.62731/mcnd-02.08.2024.001 [in Ukrainian].

4. Kingsland, S. (1982). The Refractory Model: The Logistic Curve and the History of Population Ecology. *The Quarterly Review of Biology*, Vol. 57, no. 1, pp. 29–52. DOI: https://doi.org/10.1086/412574.

5. Theil, H., Wage S. (1964). Some Observations on Adaptive Forecasting. *Management Science*, Vol. 10, no. 2, pp. 198–206. DOI: https://doi.org/10.1287/mnsc.10.2.198.

6. Winters, P. R. (1960). Forecasting Sales by Exponentially Weighted Moving Averages. *Management Science*, Vol. 6, no. 3, pp. 324–342. DOI: https://doi.org/10.1287/mnsc.6.3.324.

7. Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics,* Vol. 70, no. 1, pp. 65. DOI: https://doi.org/10.2307/1884513.

8. Solow, R. M. (1957). Technical Change and the Aggregate Production Function. *The Review of Economics and Statistics*, Vol. 39, no. 3, pp. 312. DOI: https://doi.org/10.2307/1926047.

9. Swan, T. W. (1956). Economic growth and capital accumulation. *Economic Record*, Vol. 32, no. 2, pp. 334–361. DOI: https://doi.org/10.1111/j.1475-4932.1956.tb00434.x.

10. Ramsey, F. P. (1928). A Mathematical Theory of Saving. *The Economic Journal*, Vol. 38, no. 152, pp. 543. DOI: https://doi.org/10.2307/2224098.

11. Cass, D. (1965). Optimum Growth in an Aggregative Model of Capital Accumulation. *The Review of Economic Studies*, Vol. 32, no. 3, pp. 233. DOI: https://doi.org/10.2307/2295827.

12. Koopmans, T. C. (1963). On the Concept of Optimal Economic Growth. Cowles Foundation for Research in Economics. *Yale University, Discussion Paper,* No. 163. Retrieved from https://elischolar.library.yale.edu/cowles-discussion-paper-series/392.

13. Mankiw, N. G., Romer, D., Weil, D. N. (1962). A Contribution to the Empirics of Economic Growth. *The Quarterly Journal of Economics*, Vol. 107, no. 2, pp. 407–437. DOI: https://doi.org/10.2307/2118477.

14. World Bank. Retrieved from https://data.worldbank.org/.

Коляда Ю., Позняк С. Віртуальні сценарії демографічного впливу на економічне зростання

На підставі різноманітних комп’ютерних моделей (класичних одновимірних та авторських багатовимірних – систем рівнянь) нелінійної економічної динаміки досліджується демографічний вплив на сценарії зросту економіки, але за наявності динамічної модифікації статичного, як правило, коефіцієнта приросту населення суспільства. Основною ціллю статті є трансформація демографічного впливу з використання статичного коефіцієнта зростання населення в динамічний, для досягнення якої було застосовано модель Ферхюльста, котра дозволяє більш точно врахувати зміни в чисельності та структурі населення протягом певного часу. Дослідження проводилось на реальних даних 150 країн світу, охоплюючи різні етапи економічного розвитку, соціально-економічні умови та демографічні характеристики. Використано ряд метрик для оцінки точності моделей, зокрема коефіцієнт детермінації, MAE, MRE, MSE, RMSE, MSLE та RMSLE. Результати порівняння цих метрик дозволяють зробити висновки про ефективність застосування динамічного коефіцієнта зростання населення, моделюючи економічне зростання суспільства. Стаття наочно демонструє, що згадуваний вище динамічний підхід дозволяє значно підвищити точність прогнозів і краще відображає реальну траєкторію розвитку економік різних країн, зокрема в умовах змінюваного демографічного фону.

Ключові слова: економічне зростання, моделі економічного зростання, демографія, міграція, природний приріст населення.

Kolyada Yu., Poznyak S. Virtual Scenarios of Demographic Impact on Economic Growth

On the basis of various computer models (classical one-dimensional and author's multidimensional – systems of equations) of nonlinear economic dynamics, the demographic impact on economic growth scenarios is studied, but in the presence of a dynamic modification of the static, as a rule, population growth rate of society. The main objective of the article is to transform the demographic impact from the use of a static population growth rate to a dynamic one, for which purpose the author used the Verhulst model, which allows for a more accurate accounting of changes in the size and structure of the population over time. The study was conducted on real data from 150 countries, covering different stages of economic development, socioeconomic conditions and demographic characteristics. A number of metrics were used to evaluate the accuracy of the models, including the coefficient of determination, MAE, MRE, MSE, RMSE, MSLE, and RMSLE. The results of comparing these metrics allow us to draw conclusions about the effectiveness of using the dynamic population growth rate in modeling the economic growth of society. The article clearly demonstrates that the aforementioned dynamic approach can significantly improve the accuracy of forecasts and better reflects the real trajectory of the economies of different countries, in particular in the context of a changing demographic background.

Keywords: economic growth, models of economic growth, demography, migration, natural population growth.

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