Modeling Language Competition with Political Aspects

Alexander Medvedev, Oleg Kuzenkov

***Abstract*— The purpose of this study is to identify the prestige function of languages based on statistical data and to predict language dynamics. Methods. A mathematical model of a bilingual community is constructed, which takes into account the effect of language acquisition by children at an early age, the different prestige of languages for their speakers, and the effect of lexical similarity of competing languages. The model is studied using classical methods of the qualitative theory of dynamic systems with an unlimited increase in the time of dynamics. A study of the dependence of language parameters on time is conducted. For this purpose, a non-autonomous model is applied to natural data at different time periods. The prestige functions of the two most widespread languages of Ukraine are determined: Ukrainian, Russian. A forecast is made for language dynamics. Results. The dependence of the prestige of languages on time in the form of a logistic function is determined. Real statistical data on the Ukrainian-Russian language pair are used to model the language dynamics. An explanation is offered for the reasons for the rapid change in the number of native speakers. A forecast of language dynamics for the future is constructed. Conclusion. The dependence of the pres-tige of languages on time has been determined. A forecast of changes in the number of speakers of the languages under consideration has been made.**

***Keywords*— language extinction, lexical similarity, language volatility, bilingualism, language competition, language dynamics, language preservation, mathematical model, ordinary differential equations.**

I. Introduction

The methods of nonlinear dynamics theory are used in many branches of science. The only observation where it is applicable is the study of the dynamics of language use in society [1]–[7]. The information accumulated to date on the quantitative characteristics of the process of change in the number of language speakers in society allows us to describe and predict language dynamics quite accurately. Abrams and Strogatti [1] were among the first to mathematically model language dynamics. Their model assumes that any member of the community in question, regardless of which languages he or she speaks, currently prefers only one of the two. It also assumes that children born learn and use the language that their parents prefer, so that generational change does not affect the proportion of language speakers in society. Abrams and Strogatti introduced the concepts of language prestige and language volatility as the willingness of language speakers to change it. The number of community members was assumed to be constant. The Abrams and Strogatti (AS) model showed that one language, under the assumptions made, is always displaced by another over time. In 2005, the Mira and Peredes model appeared [2]. A new concept was introduced – similarity of languages (lexical similarity). This model showed that if languages are very similar, they can coexist together for a long time. In 2006, the Castello model [3] appeared. Its author introduced a new group of bilingual individuals – bilinguals, and showed the possibilities of stable coexistence of two languages in a community. Baggs and Friedman's model of interaction between monolingual and bilingual populations [4, 5] demonstrated the possibilities for the development of dynamics in which language groups can coexist or displace each other. Whyburn and Hayward demonstrated in their model the importance of a stable bilingual group for the coexistence of two languages [6]. Diaz and Schwidke introduced a new concept – language status [7]. In [8], it was demonstrated that language parameters are functions of time and can change significantly depending on the political situation. In [9], it was shown that the acquisition of two languages by children at an early age occurs sequentially and that this effect [10-13] is important in modeling language competition. The work [14] reveals the effect of mutual assistance within groups of native speakers of one language, which directly influences the attractiveness of mastering a second language.

Taking into account new effects allowed us to construct models describing situations in which: stable bilingualism exists or only one of the two languages is preserved. In the present study, we combine known effects in a new model and determine how some of them change over time.

The aim of this study is to construct and investigate a new model of a bilingual community that takes into account: the effect of language acquisition by children of bilingual parents at an early age; the different prestige of the second language for adults; different linguistic volatility for languages and the effect of lexical similarity of the languages under consideration. Determination of the dependence of the prestige of languages as a function of time. Construction of a forecast of further changes in the number of language speakers.

II. Methodology

A. Bilingual Community Model

For model language competition, we adopt the following hypotheses:

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- community members can speak one of two languages, conventionally called "first" and "second", or both at once; z_1 is the proportion of community members who speak only the first language, z_2 is the proportion of community members who speak only the second language, z_12 is the proportion of community members who speak two languages (bilinguals);
- the proportion of individuals who do not speak any language is negligible;
- the number of any language group is non-negative: $0 \le z_1, z_2, z_3 \le 1$;
- the size of the community is constant over time (the number of births is equal to the number of deaths), $z_1 + z_2 + z_{12} = 1$;
- the coefficient r simultaneously characterizes both the birth rate and the death rate;
- the probability of a child simultaneously (spontaneously) acquiring two languages is negligibly small;
- bilingual children initially acquire their first or second language with probabilities c_1 *and* c_2 respectively; $c_1 + c_2 = 1$ [10, 12];
- the prestige of languages is determined by coefficients c_1 *and* c_2 for the first and second languages respectively [1].
- it is assumed that the prestige of languages changes over time according to the law of the logistic function: $c_1(t) = p_1 \frac{e^{(t-p3)*p4}}{e^{(t-p3)*p4}+1} + p_2$, and its change is determined by the change in the socio-political situation in society [x].
- α and β – parameters of language volatility according to the hypotheses of Abrams and Strogatti [1];
- when speakers of different languages meet (the frequency of which is directly proportional to the product of the shares of their numbers), a change of language is possible with coefficients b_1 *and* b_2 for the first and second languages respectively;
- it is assumed that it will be possible for bilinguals to teach monolingual members of the community a second language [3];
- Russian and Ukrainian languages have lexical similarities, which, according to various sources, amount to 62%-86% [21-22], therefore, the lexical similarity parameter for our model is chosen as the average value *k=0.74* [2];

The parameter k is taken as a fairly constant argument over time, undergoing significant changes only over a time period significantly exceeding the period of the natural data of this work. Parameters of language volatility α, β and parameters $b_{1,2}$ are also quite inert, so we neglect their changes over time and consider them as constants.

The dynamics of language speakers in society will be characterized by the following system:

$$\begin{cases} \dot{z}_1 = (1-k)c_1(\tau)rz_{12} - b_1 z_1 (z_2 + z_{12})^{\alpha}; \\ \dot{z}_2 = (1-k)(1-c_1(\tau))rz_{12} - b_2 z_2 (z_1 + z_{12})^{\beta}; \\ \dot{z}_{12} = b_1 z_1 (z_2 + z_{12})^{\alpha} + b_2 z_2 (z_1 + z_{12})^{\beta} - (1-k)rz_{12}; \\ \dot{\tau} = \mathrm{T}. \end{cases} \quad (1)$$

The initial values of the proportions of the number of languages cannot be negative, based on the understanding of the meaning of these values. System (1) satisfies the conditions of quasi-positivity [16], and the sum of all equations of the system is identically equal to zero: $\dot{z_1} + \dot{z_2} + \dot{z_{12}} = 0$, therefore equality $z_1 + z_2 + z_{12} = 1$ will be preserved at all subsequent points in time. In the work [1], by studying statistical data, approximate values of the parameters were established: α,=1,31±0,25. Based on this, the present study is conducted for the following realistic limits of change of the specified parameters: α,=1,5±0,5.

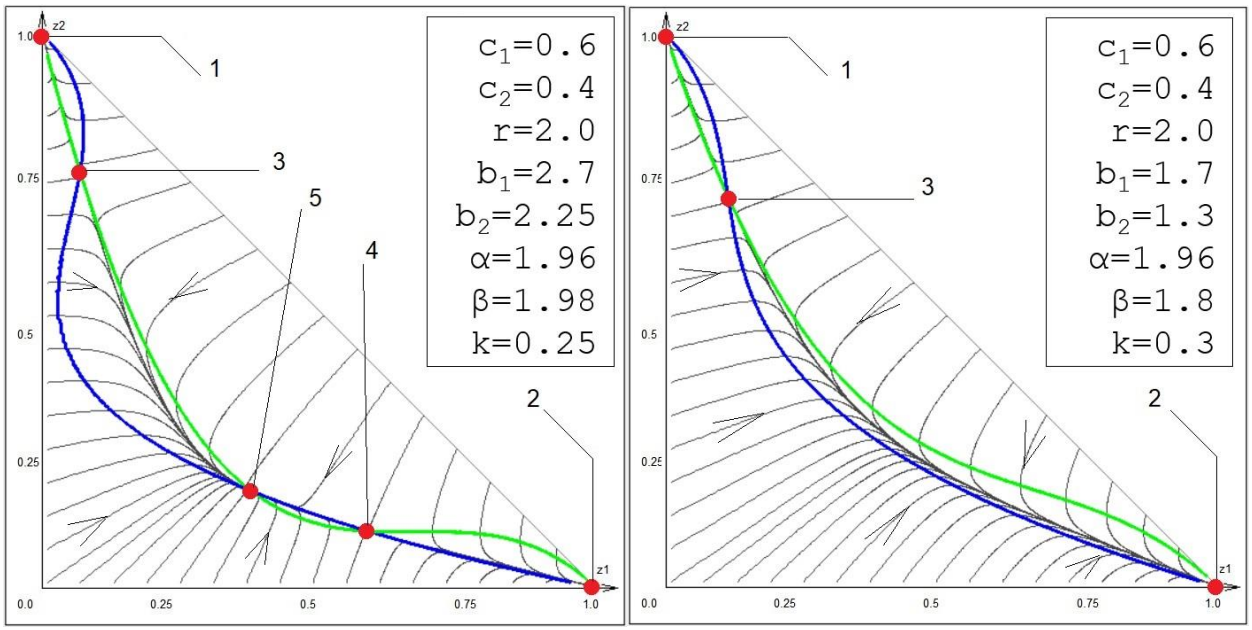
III. Results

A. Model Study

In this study, it is assumed that over short time intervals, the prestige of languages changes insignificantly and these changes can be neglected. Therefore, to determine the parameters of the prestige function, we consider gluing the dynamics of model (1) considered over short time periods, during which prestige is considered as a constant. The phase space of system (1), provided that the prestige does not change, is the three-dimensional standard simplex [16]. By replacing $z_{12} = 1 - z_1 - z_2$, system (1) is reduced to a system on a plane:

$$\begin{cases} \dot{z_1} = (1-k)c_1 r(1 - z_1 - z_2) - b_1 z_1 (1 - z_1)^{\alpha}; \\ \dot{z_2} = (1-k)(1-c_1)r(1 - z_1 - z_2) - b_2 z_2 (1 - z_2)^{\beta}. \end{cases} \quad (2)$$

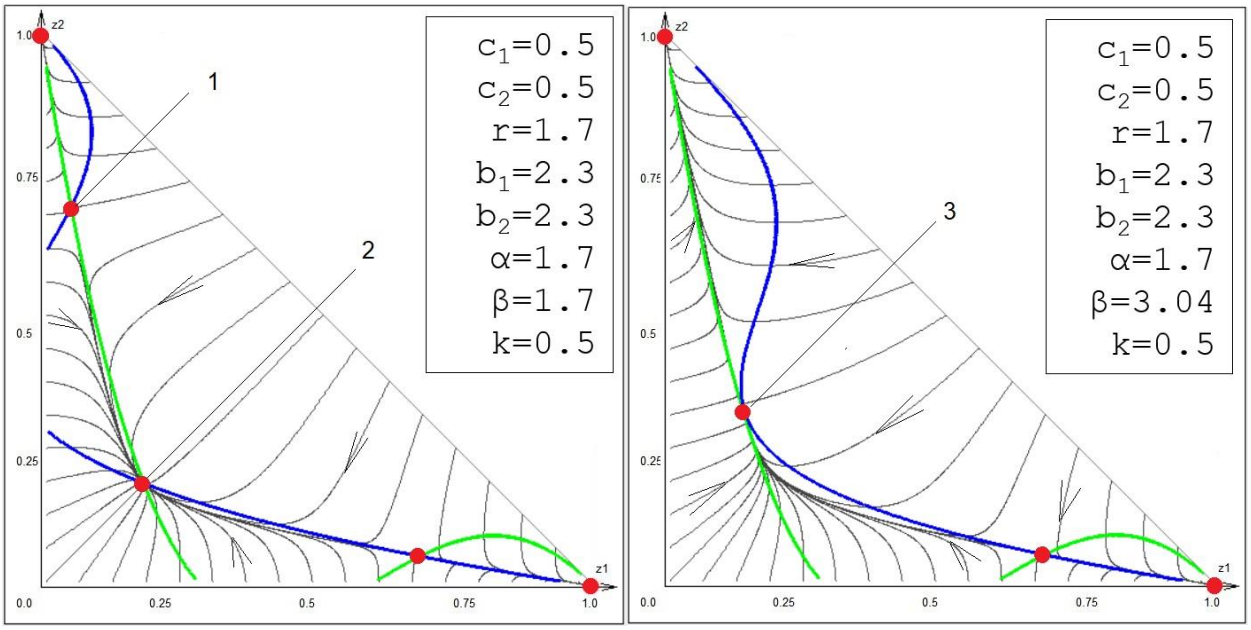
For model (2) c_1 is a constant, the quasi-positivity condition is satisfied, and the inequality is also true $z_1 + z_2 \le 1$. This model was investigated by standard qualitative methods. Phase portraits of the system (2) for different language parameters are shown in (Fig. 1). The red dots mark the equilibrium states. The blue and green curves represent the isoclines of horizontal and vertical slopes, respectively. The number of intersections of the isoclines with each other determines the number and nature of equilibrium points, as well as possible bifurcations. States No. 1 and No. 2 are always stable nodes and are always located on the boundary of the phase space at points (0, 1) and (1, 0) (Fig. 1).



а) б)

Fig. 1: Phase portraits of the model (2): a – coexistence of two languages and bilinguals; b – displacement of one language by another

The stability of these states was determined by the Lyapunov method, by determining the eigenvalues. The remaining equilibrium states are within the region defined by the following restrictions: $z_1+ z_2\leq 1$; $0\leq z_{1,2}\leq 1$. Their coordinates were determined by searching for the intersection points of vertical and horizontal slope isoclines. This problem was solved using the WolframAlpha software package. Calculations showed that system (2) can have 2-5 equilibrium states. The equilibrium character of the remaining states was determined by numerically constructing a phase portrait: No. 3 and No. 4 are unstable by the saddle type, and states No. 1, No. 2 and No. 5) are stable by the node type (Fig. 1). A qualitative study of the system (2) shows two possible dynamics: the survival of only one language or the coexistence of two languages with bilinguals.



а) б)

Fig. 2: Phase portraits of the model (2): a - before bifurcation; b - at the moment of saddle-node bifurcation

In this model, bifurcations are possible (Fig. 2). State No. 1 of the "saddle" type merges with state No. 2 of the "stable node" type. As a result of the saddle-node bifurcation, a new state No. 3 of the "saddle-node" type is formed. The isoclines of the vertical and horizontal slopes will touch each other. This situation is not rough and when the parameter β passes through the bifurcation value, state No. 3 will disappear. The absence of stable states inside the region $\{ {}_1+ z_2<1$; $0<z_{1,2}<1\}$ will lead to the fact that the coexistence of languages will be impossible.

B. Identification of the prestige function of languages

The works [17, 18] provide statistics on the proportion of people in Ukraine who identify themselves as Ukrainian-speaking or Russian-speaking for 1994–2012. The sources [19, 20] provide similar statistics for 2001–2023. The dynamics values for missing years were supplemented with average values over the interval. The curves reflecting the dynamics of language use are not monot-onous; areas of inflection in 1995, 2002, 2004, 2010, 2018, 2022 are clearly visible, which indirectly indicates the inconstancy of the prestige parameter of the languages in question (Fig. 3).

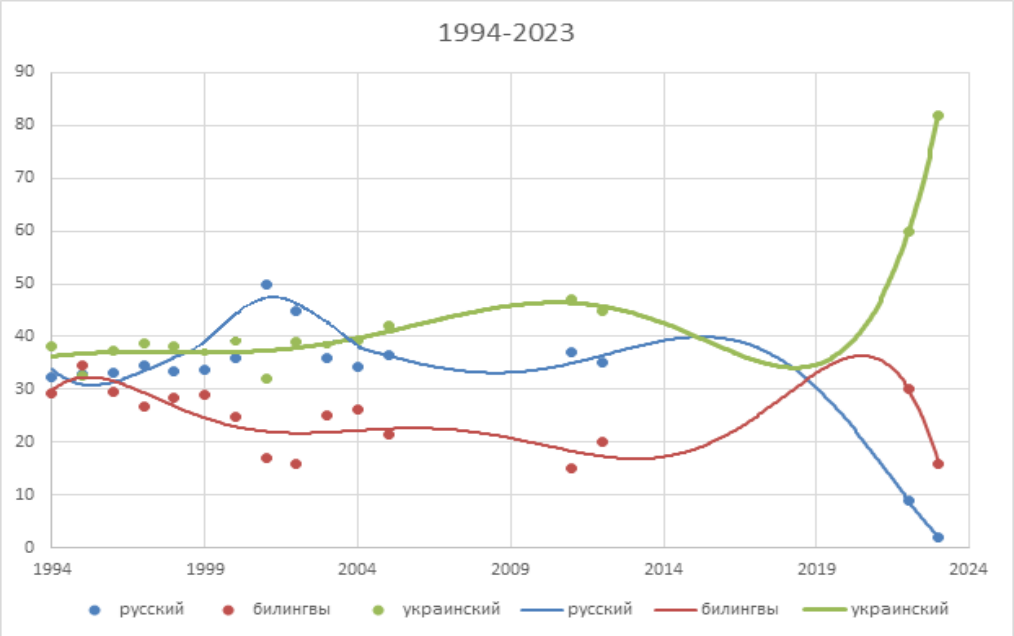


Fig. 3: Percentage of native speakers: dots indicate statistical data, curves are their approximation

In 2012, the Research & Branding Group conducted a study of public opinion on the language problem in Ukraine [17]. The press release of the project "Languages of Ukrainian Communication" presents dynamic data for 2004-2012, which show that over 8 years, Ukrainians changed their opinion 4 times on whether Russian should be the state language or not. This also indicates the inconsistency of the parameters of language prestige.

The parameters of model (2) were determined using the least squares method. Their values are given in Table 1.

Table 1

Model (2) coefficients

diff_old	***c1***	***c2***	***b1***	***b2***	α	β	***r***
0,316	0,9	0,1	1,0	1,0	1,1	1,1	1,0

Russian and Ukrainian languages are distinguished by their prestige $c_1=0,9$, $c_2=0,1$, and the parameters α, β, $b_{1,2}$ turned out to be equal for the two languages. The accuracy of the modeling turned out to be quite low *diff_old=0,316*, which gives reason to study the dynamics of languages separately for shorter time periods. Taking into account the inertia of the parameters α, β, $b_{1,2}$ and considering them as constants, the parameters of the prestige of the languages of model (2) were determined on shorter time intervals. Their values are given in the table 2.

Table 2

Model (2) coefficients

	1994-1998	***1999-2002***	***2002-2005***	***2005-2012***	***2011-2015***	***2015-2022***	***2020-2023***
c_1	0,5	0,3	0,4	0,9	0,6	0,9	0,95
c_2	0,5	0,7	0,6	0,1	0,4	0,1	0,05
diff	0,006	0,01	0,005	0,006	0,001	0,022	0,018

The accuracy of modeling on short time intervals has increased. According to the obtained values of the prestige parameter, the dependence of the prestige of the Ukrainian language on time was restored in the form of a logistic function (3). The unit of time measurement is one year.

$$c_1(t) = 0.35 + 0.65\frac{e^{(t-16)*0.3}}{e^{(t-16)*0.3}+1}. \quad (3)$$

The graph of the prestige values of the Ukrainian language obtained during the modeling, as well as the graph of the function approximating them, is shown in (Fig. 4).

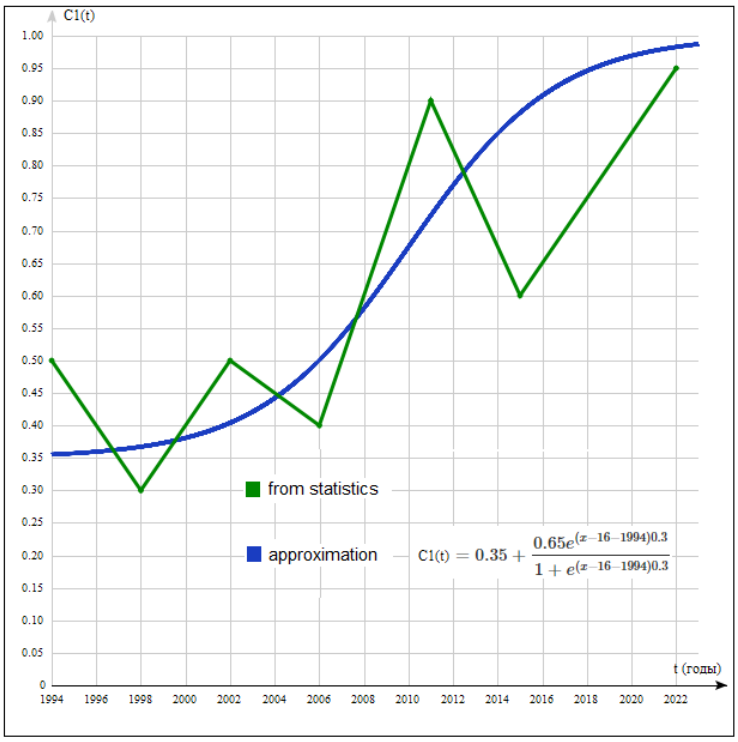


Fig. 4: Percentage of change in the prestige of the Ukrainian language over time: green – values obtained in modeling; blue – graph of the approximating function $c_1(t)$

The obtained expression of the language prestige function (3) was added to the model (1). The parameters of the model (1) were determined on the full time period of natural data: 1994-2022. Their values are given in Table 3.

Table 3

Model coefficients (1)

diff_new	***p1***	***p2***	***p3***	***p4***	***a***	***b***	***r***
0,185	0,65	0,35	16,0	0,3	2,15	1,0	4,9

The accuracy of the result of modeling the language dynamics using the new model, on the full range of natural data, significantly exceeds the accuracy of the result of modeling on old models: diff_new=0.185, diff_old=0.316. The results of modeling the dynamics are presented in Figure 5. The dots mark the data from the statistics, and the curves mark the data obtained as a result of modeling on model (1), taking into account the prestige function (3).

The rapid changes in the numbers of groups that speak Russian and Ukrainian give rise to some thoughts. Surzhyk is widespread among the population of Ukraine - a spoken language that includes elements of Ukrainian and Russian [23]. Surzhyk differs from both Ukrainian proper and spoken Russian, although it does not have clear boundaries with them. It is assumed that with changes in social tension between the Russian-speaking and Ukrainian-speaking parts of society, the use of surzhyk may increase or decrease, and citizens who speak surzhyk may identify themselves as either Ukrainian-speaking or Russian-speaking, depending on the social mood in society.

Paying attention to the parameter of lexical similarity of languages, we note the following - a low value of the parameter k affects the dynamics in such a way that one of the languages is usually displaced, and with high similarity, the languages coexist [2]. In the case of the Ukrainian and Russian languages, lexical similarity is considered high ($0.62 \leq k \leq 0.86$), which should contribute to the coexistence of languages, but in reality we see the opposite situation. We note that in Ukraine in the period 2015-2023 there is a factor of external influence on language dynamics. Therefore,

taking this parameter into account can be considered appropriate only under other equal conditions for languages. The situation is exactly the same with other "inert" language parameters: α, β, $b_{1,2}$, the values of which have a significant influence on language dynamics only in the absence of external influence on it.

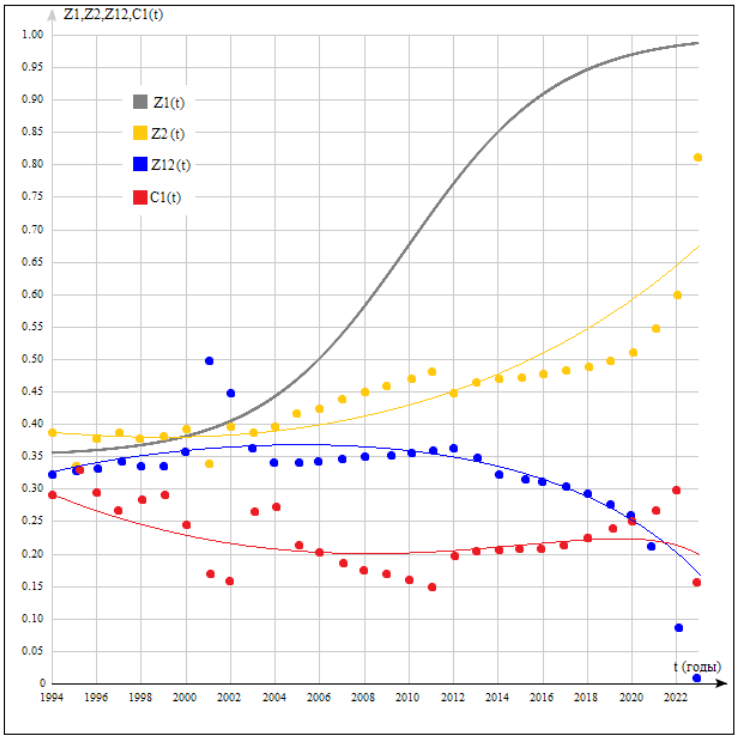


Fig. 5: Changes in the shares of the Russian-speaking and Ukrainian-speaking groups in 1994-2023 on the territory of Ukraine: dots - data from statistics; lines - data from modeling (1).
Color identification: gray - graph of the prestige function of the Ukrainian language $c_1(t)$; blue - size of the Russian-speaking group; yellow - size of the Ukrainian-speaking group; red - size of the bilingual group.

The values of the prestige function of the Ukrainian language tend to increase. In the event that the current situation in Ukrainian society continues, we predict the complete disappearance of the Russian language. The justification for this is the extremely low prestige of the Russian language (c2=0.05) and the rapidly declining number of its speakers: -37% for the period 2013-2023; while the prestige of the Ukrainian language is high (c1=0.95), and the change in the number of speakers is +36% for the period 2013-2023.

IV. Discussions

The effect of linguistic similarity is an important discovery in linguistic dynamics, studied by D. Mira and A. Perede in their model [2]. They considered the manifestation of this effect in dialects of the Spanish language (Galician, Castilian), the dynamics of which are relatively monotonous and do not experience significant external influence. In our work, we considered a language pair (Russian and Ukrainian) that exists in an environment that has a direct impact on its dynamics in the form of a social and political agenda. The study showed that most of the parameters taken into account in our model, under conditions of external influence on languages, lose their significance and do not affect the dynamics of the system due to their inertia. They simply do not have time to change in accordance with the trends occurring in the country and society. The only parameter of languages that reacts quickly enough to the change of the "situation" is its prestige.

In the work [14] it was noted that when considering language pairs of the “international–national” type, mutual assistance for the “international” language is close to a value of 0, and for the “national” language it is close to the maximum value, and for language prestige the situation is the opposite: for the “international” language the prestige is close to a value of 1, and for the “national” language it is close to a value of 0. In the example of the Russian-Ukrainian language pair, we can talk about the process of changing the classification of languages, because during the process of existence their parameters change symmetrically.

In addition to the main study, the model of this work was examined on short time intervals with non-fixed parameters for languages. The result showed that there is a strong correlation between the parameters c1 and α, β, b1,2 (Fig. 6), which was not noticed when examining a similar model on relatively “monotonous” natural data [8, 9, 14]. On this basis, we can conclude that the parameters of the model depend not only on time, but also on the prestige of languages, as a result of which they lose their significance under external influence on the dynamics. The model considered in the work can be applied to model the dynamics of languages whose development occurs naturally and is not regulated from outside. When applying this model to languages that have external control and conditional “management”, model (1) is simplified to model [8] due to the predetermination of its parameters.

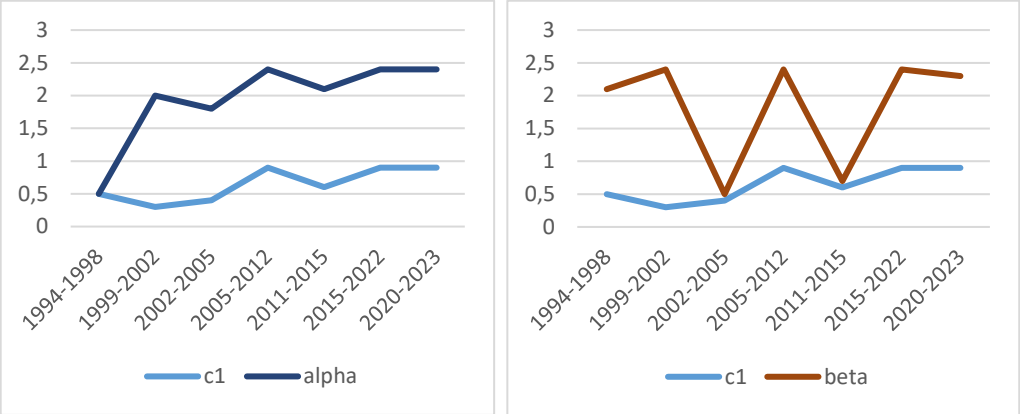


Fig. 6: Correlation of the values of the model parameters (2)

V. Conclusion

The paper constructs and studies a new model of language dynamics for a bilingual community that takes into account: various parameters of volatility of the languages in question, various coefficients of second language acquisition, as well as lexical similarity of the languages in question. The effect of sequential acquisition of languages by children at an early age is taken into account. The paper examines language dynamics based on real statistical data on the main languages of Ukraine: Russian, Ukrainian. A function describing the change in the prestige of languages is obtained. For this purpose, the initial model was simplified by replacing the function of language prestige with parameters. The simplified model was examined on short time intervals of natural data. For these intervals, the values of the prestige parameters were determined and approximated by a logistic function. The resulting function of language prestige was used to model language dynamics on a new model. The results of modeling on a new model showed higher accuracy values compared to the results obtained on old models. It is noted that under external influence on language dynamics, the parameters of language prestige are decisive. A forecast of further development of the dynamics of these languages is constructed.

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Моделирование конкуренции языков с учётом политических аспектов

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***Аннотация*— Цель настоящего исследования: идентификация функции престижности языков на основе статистических данных, а также прогнозирование языковой динамики. Методы. Строится математическая модель двуязычного сообщества, которая учитывает эффект освоения языков детьми в раннем возрасте, различную престижность языков для их носителей, а также эффект лексической схожести конкурирующих языков. Модель исследуется классическими методами качественной теории динамических систем при неограниченном увеличении времени динамики. Проводится исследование зависимости параметров языков от времени. Для этого неавтономная модель применяется к натурным данным на различных временных периодах. Определяются функции престижности двух самых распространённых языков Украины: украинский, русский. Строится прогноз по языковой динамике. Результаты. Определена зависимость престижности языков от времени в виде логистической функции. Для моделирования языковой динамики, использованы реальные статистические данные по украинско-русской языковой паре. Предложено объяснение причин стремительной смены численности носителей языков. Построен прогноз языковой динамики на будущее. Заключение. Определена зависимость престижности языков от времени. Составлен прогноз изменения численности носителей рассматриваемых языков.**

***Ключевые слова*— исчезновение языков, лексическое сходство, языковая волатильность, билингвизм, языковая конкуренция, языковая динамика, сохранение языка, математическая модель, обыкновенные дифференциальные уравнения.**

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