System Challenges to Sustainable Humanity Development

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Abstract

The purpose of the research is to analyze the challenges to sustainable world development, associated with the evolution of humanity as a system, considering the interrelated processes of demographic transition, growth of knowledge and GDP dynamics. It is shown that the mathematical model of human population during demographic transition, based on the women's choice between having many children and employment, is in good agreement with the average population projection according to the UN. It was determined that the demographic dynamics begin to deviate from a hyperbolic growth after the value of the world GDP per capita achieves $(G/N)_{\mathbf{dem}}$≈5070 USD per person in international dollars of 2017.An analysis of the growth over time of the amount of explicit knowledge (Z) accumulated in the largest libraries of the world showed that their dynamics are well described by the dependence $Z \approx 30 \cdot (N(T-25)/N_0)^{1.25}$. It is shown that the global GDP growth is proportional to the number of people and the amount of explicit knowledge: $G = k \cdot N(T-25)^{2.25}$. As a result of the existence of the maximum number of people $N_{max} \approx 11$ billion, the amount of human knowledge, as well as the average GDP per capita have a value limit, with Z_{max} = 60 million CB, G_{max} = 54,500 international dollars of 2017. The transition to the specified limit values in less than a century will lead to a drastic change in the world dynamics compared to the current dynamics. These changes can cause destabilization of world relations, thus threatening with international conflicts.

Keywords: sustainable development, systematic approach, world dynamics, demographic transition, GDP, forecast, knowledge, limits of growth

1 INTRODUCTION

What are the most important challenges that expect us in the future? In order to understand it, we need to pay attention to the development of humanity as a system. First, it grows in number, and until 1960, this growth followed the hyperbolic dependence $N = C/(T_1 - T)$, where T is time and $T_1 \approx 2025$ is the date of demographic singularity [1], [2]. But after 1960, as a result of the birth rate reduction to mere reproduction, the process of “demographic transition” started. The population of the Earth began to follow the logistic (S-shaped) dependence with the expected achievement of a stable population of about 11 billion people [3]. Is this transition one of the main challenges to sustainable development? Until now, there is no agreement among researchers regarding the main cause of demographic transition and a sharp decline in the birth rate in most countries. And since the reasons are not clear, one cannot be confident in further forecasts of the demographic dynamics and possible methods for mitigating negative consequences. But this is only the first batch of problems, the real situation is much more complicated. It is important that the change in the birth rate essentially means that humanity as a system has passed into a new state and such transitions for exceptionally complex systems occur only in extreme cases. The change that has occurred means that many other important characteristics will also be changing, and, above all, the dynamics of the knowledge system and economic development will. Humanity is the only known system of reason known to us and it has been constantly developing and growing over three million years. In connection with the demographic transition, there is a threat of stagnation of its rational activity, as the number of the reason carriers is stabilizing [4]. That is a challenge. But on the other hand, an alternative threat is posed by artificial intelligence, which has the potential to replace the first system of reason. It should be noted here that we touched upon the issue of analyzing the knowledge of humanity. The knowledge exists in two basic forms: codified (explicit) and non-codified, whose carriers are people. Both types of knowledge are very important for the development of humanity as a system. But at present, the theory of knowledge management is at the beginning of its development [5] and does not set an enough ground to develop reasonable programs of state and international politics. The lack of understanding of the role of knowledge for global development contributes to the creation of an environment favorable for various demographic myths. For example, Thomas Malthus [6] popularized the idea of the need to control the population growth rate to make it consistent with the slowly growing food production capacity. As shown by further studies, the population of the planet grows much faster than expected by T. Malthus (not exponentially, but as a hyperbolic dependence, which tends to infinity) and means of subsistence fail to significantly limit the population growth in real life. But the ideas of T. Malthus continue to influence public consciousness.

More than 50 years ago, one of the progenitors of the systems approach, Jay Forrester [7], attempted to calculate the World Dynamics. But he did not consider the factor of scientific and technological progress as a resource for the humanity development and made the same mistake as Malthus had made 200 years before. His apocalyptic predictions unwittingly generated projects to reduce the burden on nature at the expense of the least developed peoples. Another threat is associated with the cyclical development of the world economy based on the growth of knowledge and technological innovations [32]. The resulting technological revolutions in conjunction with demographic changes lead to a situation when the leaders of economic development give way to other countries. Each of such changes leads to international conflicts that have already caused several world wars, both “hot” and “cold” ones. The current level of technical development of humanity makes it possible for such conflicts to end up in a global catastrophe. This is one of the most critical threats to sustainable development. But without a proper understanding of the development processes taking place in the world, the institutions of society and top-level decision-makers cannot make the right decisions. Therefore, the analysis of these processes is a very relevant problem.

This paper considers challenges to the sustainable development of humanity as a single system that is in a transitional state, from the accelerating growth to constant global characteristics of the population, knowledge, and world wealth.

2 METHODOLOGY

To study the challenges of sustainability of humanity, we used systems analysis as the main methodology [8], [9], [10]. At the same time, we used the system diagram of the knowledge-based development of humanity, presented in Fig. 1 [4].

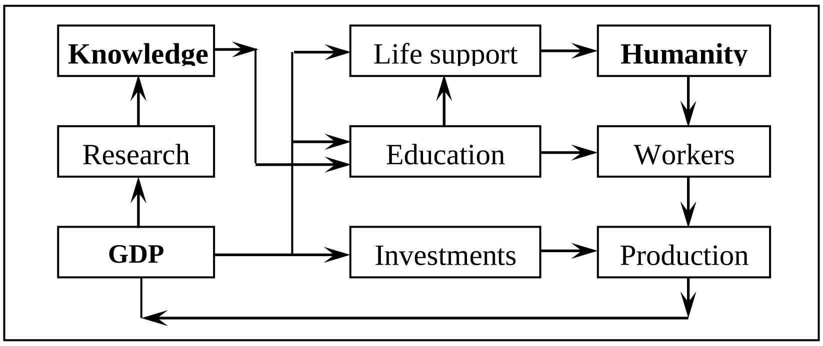

Fig. 1. Diagram of the humanity development with account of knowledge

According to this model, the growth of population results from the growth of well-being, characterized by the GDP value. The growing humanity creates more knowledge that directly accelerates the growth of production and, accordingly, the GDP. To calculate the demographic dynamics, we used a mathematical model reflecting the system diagram presented in Fig. 1. The task was to find an analytical solution to this problem in order to identify the causes of the changes and the main influencing factors, disregarding any situational and minor factors. The obtained analytical dependencies were compared with the current forecast of the world demographic dynamics [3].

The growth of the human knowledge volume was analyzed using S.P. Kapitsa’s hypothesis [2], which assumes that the system properties of humanity are caused by the information interaction, as well as the hypothesis if this interaction is fulfilled through an explicit knowledge exchange. The amount of knowledge (Z) was determined based on the data on the storage volume in the largest libraries of the world in various periods. For this purpose, we introduced the concept of Conventional Book (CB), a book that takes 1 MB of memory when digitized. The data on the amount of knowledge in different periods were approximated by a power dependence. The global GDP growth was analyzed based on the previously obtained results on the ratio of GDP at PPP and the amount of the human knowledge Z

[4], using current data and updated PwC forecasts of the GDP value. Based on the results obtained, we derived a formula for the maximum global GDP at PPP.

3 LITERATURE REVIEW

The most important publications for this research are the studies analyzing humanity as a system and demographic dynamics.

3.1 Humanity as a single system

In [1], it is shown that the population (N) of the planet Earth has been changing over a long period in accordance with a hyperbolic dependence (1) on time (T), where $C \approx 18 \cdot 10^{10}$ ppl.•years, and $T_1 \approx$ year 2025.

$$N \approx C/(T_1 - T) \tag{1}$$

P. Kapitsa drew attention [2] to the fact that the population growth rate during this period was proportional to the number of people squared (2):

$$dN/dT = N2/C \tag{2}$$

Usually, the growth rate of an unrestricted system of unreasonable living organisms is proportional to its population in accordance with the following formula (3):

$$dN/dT = N/C \tag{3}$$

In this case (3), the size of the colony grows exponentially, that is, very quickly. At the same time, dependence (2) is characterized by the fact that with a small population (N), it grows slower than the exponent, and with a large population, it grows much faster, tending to infinity for time $T \approx T_1$. This happened in the 20th century, when the number of people almost doubled. This gave rise to concerns about the critical overpopulation of our planet. It should be noted that equation (2) shows that humanity, unlike the system of unreasonable living organisms (3), grows as a single system. If we divide humanity into two equal parts isolated from each other, the growth rate of each of them, according to equation (2), will decrease by 75%, and their combined growth will reduce by half. What is the reason for the quadratic dependence of the population growth rates? S.P. Kapitsa analyzed the behavior of humanity as a single system and summarized as follows: “According to the obtained results, we can state the unity of the humanity development as a single whole and consider it as a certain global structure, a global *superorganism* embraced by a common information interaction” [2]. Despite the rapid population growth in the 20th century, the number of people could not reach infinity, as, according to the systems approach, there will be many limiting factors (feedbacks). At least one of them would certainly manifest itself. S.P. Kapitsa proposed an equation for describing the population growth in such a case (4) and its solution (5), which well reflects the real dynamics of the population in the process of demographic transition [12].

$$dN/dT = C/((T1 - T)2 - \tau 2) \tag{4}$$

$$N = (C/\tau) \cdot \mathrm{Arcth}\,((T1 - T)/\tau) \tag{5}$$

However, it was noted in publication [13] that this solution “does not reveal the essence of the existing laws and remains a phenomenological statement of the discovered empirical regularity.” If the limiting factor were exhaustion of the planet’s resources, including self-healing capabilities, humanity would face an irreversible situation, which was generally described by Dennis L. Meadows et al. [14], [15]. In this case, the extinction of the civilization would be highly likely. But some time before the exhaustion of the Earth’s resources, another feedback factor manifested itself and began to inhibit the hyperbolic growth of population since 1960. According to M. Kremer, it was the *unwillingness* of wealthy families to have many children [16]. Accordingly, M. Kremer proposed an empirical dependence of the relative growth rate of the population ΔN/N (birth rate minus mortality) on the gross product per capita (G/N). His calculations also are in good agreement with the real dependence of the number of people in the demographic transition period. However, it is not clear to what extent this agreement is provided with a significant number of empirical parameters used in the study, as noted in the publication [13]. In addition, a decline in the standard of living, for example in Russia after 1992, did not lead to an increase in fertility, which means that the ΔN/N function does not depends only on G/N and can allow hysteresis, that is, a behavior depending on the history of the phenomenon (while the progress of the direct and reverse processes can vary). Another version of the demographic transition causes was proposed by A.V. Podlazov [17], who believed that as technologies develop, their life-saving efficiency, i.e. their ability to reduce mortality, decreases. However, publication [13] indicates that this hypothesis is not consistent with the reality, since demographic transition is not associated with the impossibility of reducing mortality, but with a decline in the birth rate.

Finally, publication [13] substantiates the fact that the demographic transition cause is the increase in female literacy in the course of modernization (technological progress), which is to a certain extent confirmed by statistical data [18]. Thus, at least four mathematical models were developed, which differently interpret the causes of the demographic transition of humanity as a system and are consistent with the data on the growth of the world's population.

There are also many studies, in which the process of demographic transition is considered as the total of demographic characteristics in various countries, forecasts of the Population Division of the UN Department of Economic and Social Affairs [3], [20]. Such studies are much more extensive and complex, as they require considering the age distribution of the population of all countries, the dynamics of fertility, migration, and welfare growth, as well as other demographic factors. As a result, it is difficult to identify a limited number of parameters defining the phenomenon in them. As a rule, they also do not sufficiently consider the system characteristics of the demographic transition, which are very important, since humanity develops as an interacting system.

4 RESULTS

Below are the results of our analysis of the conducted studies analyzing the challenges of sustainable world development associated with the evolution of humanity as a system.

4.1 Human population growth model

Above, we have considered several system models of demographic transition. The last of them, which considers the results of previous authors' studies, was presented in the publication of A.V. Korotaeva et al. She proceeded from the fact that the cause of demographic transition was the increasing literacy among women. However, an analysis of the impact of the growth of literacy (in tens of percent) and GDP (PPP) per capita in the world (in tens of thousands of international dollars of 2017) in the period 1950–2010 (Fig. 1) on total fertility rate (TFR) shows that the birth rate began to decline despite the monotonously changing literacy and GDP after 1965, for no apparent reason [21].

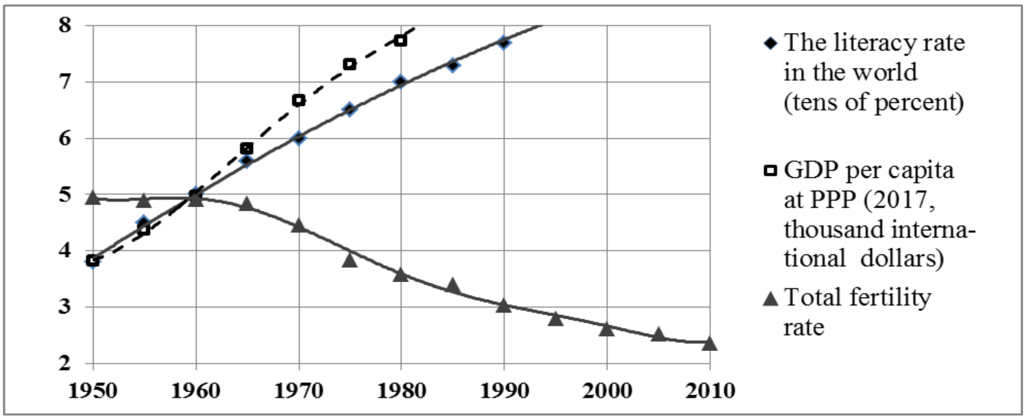

Fig. 2. Ratio of TFR, literacy and GDP (PPP) per capita

Up to this point, the impact of literacy and GDP per capita on the birth rate (the number of children born per woman) was unnoticeable, although the literacy rate reached a significant level of 55%. Although women's literacy somewhat lagged the average [22], it was quite high and its rapid growth would have manifested itself in the TFR dynamics, if the main cause were women's literacy. This figure shows that the change patterns of the dynamics of literacy and GDP per capita do not affect the birth rate. It seems that in the process of industrialization, which occurred at about the same time in many countries, the involvement of women in production activities and their literacy growth were closely related. It became difficult to work as an employed person and raise children, which led to a decrease in the birth rate to a level that allowed combining work with raising children. Thus, the growth of literacy is not a cause, but a consequence of the economically important process of involving women in production activities. It seems logical to assume that the cause of the demographic transition was not just the desire of wealthy families not to have many children, as M. Kremer believed, but rather their economical reasoning. Families chose between two alternative behaviors for women: work for hire or have many children. The more a woman can earn, the more attractive the option of employment is for her. Such a hypothesis allows us to form a mathematical model of demographic dynamics. It is since the population growth **dN** during time **dT** is proportional to the following factors:

Population **N**;

The value of excess GDP per capita **(G/N–m)**.

The limiting factor, whose profile corresponds to the choice of alternative cost described above, including an increase in the birth rate at low **G/N** values and its decline at large **G/N** values.

In order to make the model more convenient for analysis, we could take the value of the limiting factor like the well-known equation of the logistic growth of unreasonable organisms. However, here we chose GDP per capita as the limiting factor, as its growth contributes to women's choice of employment rather than having many children. As a result, this system has the following form: **1 – k•G/N**. In this case, the differential equation for the growth of the number of people has the following form (6):

$$dN/ dT = A \cdot N \cdot (G/N - m) \cdot (1 - k \cdot G/N) \qquad (6)$$

To express G/N in an analytical form, we used expression (7) proposed in [13]:

$$G = N \cdot (m + \gamma N) \qquad (7)$$

Constants γ and m have the following values: $\gamma = 1.57 \cdot 10^{-6}$ dollars/person^2•year; m = 333 dollars/person•year in international dollars of 2017. Using expression (7), we transformed equation (6) to the form (8) or to the simpler one (9) [2].

$$dN/ dT = A \cdot \gamma \cdot (1 - k \cdot m) \cdot N2 \cdot (1 - k \cdot \gamma \cdot N/(1 - k \cdot m)) \qquad (8)$$

$$dN/ dT =(1/C) \cdot N2 \cdot (1 - N/N_{max}) \qquad (9)$$

To determine the constants in equations (8, 9), we used two passages to the limit. With $N/N_{max} \rightarrow 0$, equation (9) should be converted to (1), and with $N/N_{max} \rightarrow 1$, the condition dN/dT = 0 and $N = N_{max}$ should be fulfilled. As a result, we found the connection between the constants A, k and C, N_{max} (10, 11)

$$A \cdot \gamma \cdot (1 - k \cdot m) = 1/C \qquad (10)$$

$$k \cdot \gamma/(1 - k \cdot m) = 1/N_{max} \qquad (11)$$

The resulting equation for the growth of the human population can be tested for adequacy. For example, with a known value of the derivative dN/dT, it allows finding the maximum population of humanity (12) and compare it with the known solutions, e.g. with the UN forecast.

$$N_{max} = N/ (1 - C(dN/dT)/N2) \qquad (12)$$

For example, in 2015, the growth rate of the Earth's population was dN/dT = 84.6 million people per year, N = 7.383 billion people. [3]**.** Taking C = 180 billion people•years, we obtained the value of N_{max} = 10.25 billion people, which is less than the average forecast of the UN and the model of S.P. Kapitsa by approx. 10%. It should be noted that according to the UN forecast, there is a 20% probability that the population of the Earth will be by 10% less than the average forecast by 2100 [3], which characterizes the accuracy of the estimate (12).By introducing the dimensionless variable $X = N/N_{max}$, we can convert equation (9) to the form (13), the solution of which has the form (14), and when returning to the variable N, the solution has the form (15).

$$(1 / (X2 \cdot (1 - X)) \cdot dX = (N_{max}/C) \cdot Dt \qquad (13)$$

$$1/X - Ln (X/(1 - X)) = (N_{max}/C) \cdot (T1 - T) \qquad (14)$$

$$T = T1 - C/N + (C/N_{max}) \cdot Ln(N/(N_{max} - N)) \qquad (15)$$

Fig. 2 shows a comparison of solution (15) with C = 160 billion, N_{max} = 10.5 billion, T_1 = 2022 with the average forecast of the demographic dynamics of the UN made in 2015 [3]. The data for the period of 1900–2050 correspond to publication [23].

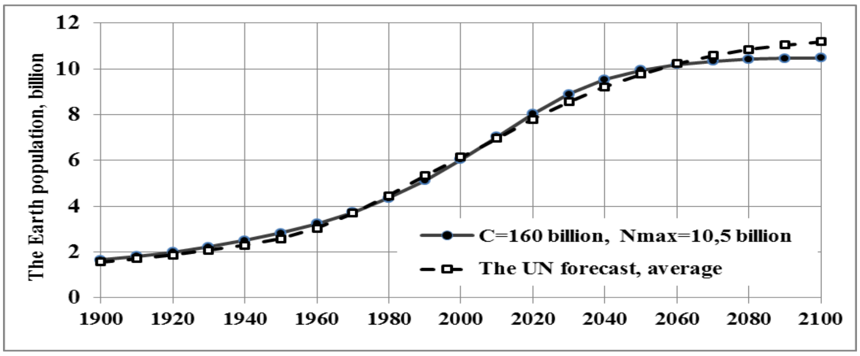

Fig. 3. Comparison of the obtained solution of demographic dynamics (15) with the average world population forecast of the UN in billions of people

It is evident that, in general, these two dependences are fairly consistent (note that the parameter C, according to the data during the hyperbolic growth [2], is about 180 billion, but for calculating the demographic transition, the value C = 160 billion provides a better agreement with the previous values). The highest deviation of the solution (15) from the UN data covers the period of 1940–1960 and reaches 9% of the current population (with no more than 6.3% in 2100). This is since the theoretical model does not consider the factor of population declines during the Second World War, as mentioned by S.P. Kapitsa [2], as well as after the war. An analysis of the UN data [3] on the annual increase in the world's population in millions of people shows that the demographic crises caused by wars later manifested themselves several times, as shown in Fig. 3 (the trend line is a cubic polynomial in this case).

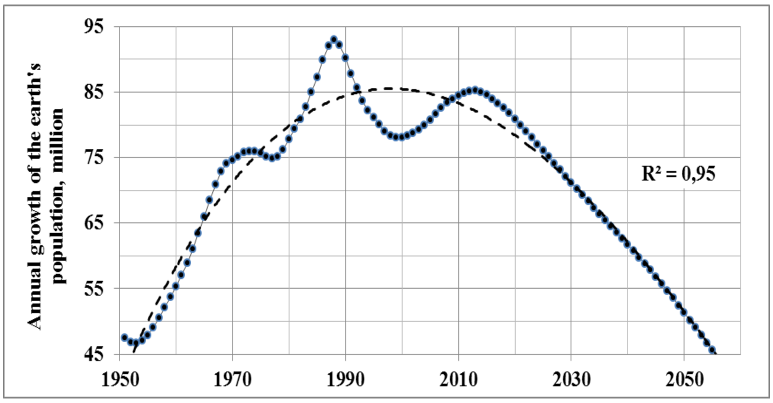

Fig. 4. Fluctuations in annual population growth (in millions of people)

It is necessary to bear in mind the presence of such fluctuations, since they reflect the high vulnerability of demographic processes to wars. In particular, the demographic processes in China, Russia, and Japan had a high impact on the fluctuations in the rate of the world population growth, as shown in Figure 4 according to the results of the UN data analysis [3]. In Fig. 4, charts are given in millions of people, being quintupled for Russia and Japan.

As can be seen from Fig. 4, the largest fluctuations in population growth took place in China and Russia, with three noticeable population increment regressions, reaching more than 50% of the maximum value. In Russia, the first regression took place during the Second World War, and in China, it happened after the war. Although the detailed projections, such as the UN forecast, are more detailed and consider diverse demographic realities, the proposed analytical solution embodies additional system information about the process of demographic transition, which is analysed below. The role of the factors A, k (10), (11) is considered in equation (8). The value k determines what value of G/N causes women to prefer employment instead of raising children. This is precisely the economic meaning of demographic transition. The dimension of k is [people•year/dollars]. From the above expression (11) for the factor k, it is equal to $k = 1/\gamma \cdot N_{max} \cdot (1 + m/\gamma \cdot N_{max})$. Since $m/\gamma \cdot N_{max} \approx 0.015$, then $k = 1/\gamma \cdot N_{max}$ with an accuracy of 2%. For N_{max} = 11 billion people, the value $1/k \approx$ 16,900 dollars/person•year (in international dollars of 2017). A decline in fertility, despite an increase in welfare, becomes significant when the value of the limiting factor in equation (8) is $k \cdot G/N \sim 0.3$. At the same time $(G/N)_{\mathbf{dem}} \approx 0{,}3/k \approx 5070$ dollars/person in international dollars of 2017. As can be seen from Fig. 1, this value reached this level in 1960, which marked the beginning of the global decline in the birth rate. Equation (15) shows that the determining parameter of the process of demographic transition is the ratio C/N_{max}. The greater its value, the faster the demographic transition proceeds. With the typical of humanity values of C = 160–180 billion, $N_{max} \approx 11$ billion, the ratio is $C/N_{max} \sim 15$ years, and this period characterizes the demographic transition rate. There will be about five of such periods from 1965, when the effect of demographic transition began to manifest itself (Fig. 1), until 2040, when it will be mostly completed. On the other hand, expressions (10) (11), considering the small value of $m/\gamma \cdot N_{max}$, can show that $A \approx k/C \cdot N_{max}$. This determines the value of A as a characteristic of the rate of achievement of a GDP per capita value, at which the birth rate will decrease in the course of demographic transition. However, instead of the parameter A, it is more convenient to use the product C/N_{max}, which offers a convenient visual interpretation.

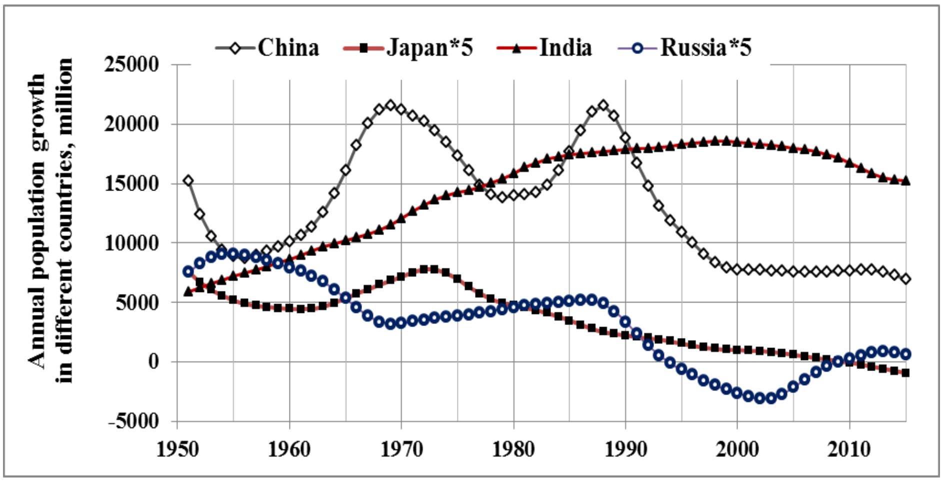

Fig. 5. Annual population growth in China, India, Russia, and Japan in 1950–2015

An analysis of the constants of the equations of population dynamics (9), (15) shows, which parameters of humanity as a system determine its growth and the process of demographic transition:

– at the stage of hyperbolic growth, the factor C is governing;

– near the demographic transition, of importance are: the value of GDP per capita, at which the demographic transition begins: $(G/N)_{dem} \approx 0.3/k \approx 5070$ dollars/person, and also the characteristic time scale of the transition: $T_{dem} = C/N_{max} \approx 15$ years.

An analysis of the equation of the dynamics of human population showed that all its characteristics had been established long before the process of demographic transition, and the transition itself occurs within the lifetime of a person (~75 years). The transition rate is what represents the main problem, since it does not allow time for people to adapt to new system conditions. And although the demographic transition has not yet been fully completed, there is very little time left until its end and it is necessary to foresee what kind of new problems it will bring.

4.2 Accumulation of human knowledge and its correlation with the GDP growth

Above, we considered the correlation between the human population and the GDP per capita, as well as paid attention to the significant manifestation of the system characteristics of humanity and to the fact that the system properties are associated with the information interaction of people [2]. It is important to identify the nature of this interaction. It can be assumed that it is associated with explicit knowledge, which is distributed primarily in the form of books and contributes to the development of the GDP production. As a source of information on the amount of knowledge, we used the data on the amount of books and brochures stored in the world's largest library, the Library of Congress [24]–[27], which retained ~14.5 million books and brochures in 1960, 30 million in 2000, 35.8 million in 2012, and 39.3 million in 2017. Of course, there are duplicates among those publications, but this is offset by the fact that the library does not have all the knowledge-containing materials published in the world. It is important that we used a unified approach to determine the dynamics of the amount of knowledge over time. Thus, we determined the amount of knowledge with an accuracy of an approximately constant coefficient. To measure the amount of knowledge, in contrast to the amount of information or data, we used the concept of Conditional Book (CB), which, when digitized, has 1 MB of information. The amount of knowledge in the Library of Congress in this unit is provided in Table 1.

One of the largest libraries of antiquity was the Library of Alexandria, which was established in 300 BC approximately and stored between 100 to 770 thousand scrolls [28]. The amount of knowledge in each of the scrolls is estimated at 20% of a CB. Accordingly, the amount of knowledge in the Library of Alexandria is estimated at 80,000 CB.

Table 1. - The amount of explicit knowledge of humanity in the largest libraries

#	Library	Year AD	Population of the Earth (millions)	Relative number of people	The amount of knowledge in thousands CB	Knowledge in CB per thousand people	Relative amount of knowledge
		T	N	N/N0	Z	Z/N	$Z/(N/N0)^{1.25}$
1.	Library of Congress	2017	7,550	75,500	23,600	3.15	18.9
2.		2012	7,128	71,280	21,500	3.07	18.5
3.		2000	6,145	61,450	18,000	3.00	18.6
4.		1960	3,033	30,330	8,700	2.83	21.7
5	Library of Alexandria	–300	86	860	80	0.93	17.2

Obviously, the estimates of the knowledge amount through the number of books are not sufficiently accurate, but this approach may provide an answer to the question of the impact of knowledge on the development of humanity as a system. As can be seen from the table, the amount of knowledge per thousand people changes relatively slowly over time. This allows if it varies in proportion to the population in degree *n* close to unity. The last column of Table 1 shows the ratio of the amount of knowledge to the relative number of people (N/N_0, where N_0 = 100,000, being the conditional initial human population [1]). As can be seen, this parameter varies little over time. The relative standard deviation is 8.8%. Changing the exponent of *n*, we achieved the minimum value of the relative standard deviation of 8.0% for n=1.23, but in practice it is more convenient to use n=1.25. As a result, the global amount of knowledge can be approximated with formula (16) [29].

$$\mathbf{Z \approx Z_0 \cdot (N/N_0)1.25 = 20 \cdot (N/N_0)1.25} \quad (16)$$

Formula (1) can be also used to obtain an equation for the dependence of the global amount of explicit knowledge on time during the period of the hyperbolic growth of population (17).

$$\mathbf{Z \approx 1.5 \cdot 109/(T1-T)1.25} \quad (17)$$

Near the date of conditional singularity $T_1 \approx 2025$, formula (17) becomes untrue. However, knowledge is not created by all human beings, but only by educated people. Therefore, it is more accurate to use data on the population of the Earth about 25 years before the time T. If we accordingly adjust constant coefficients, formulas (16), (17) will be converted to (18), (19).

$$\mathbf{Z \approx 30 \cdot (N(T-25)/N_0)1.25} \quad (18)$$

$$\mathbf{Z \approx 2.25 \cdot 109/(2050-T)1.25} \quad (19)$$

In Fig. 5, curves (16), (18) with different time shifts and reference points from Table 1 are shown for comparison.

It is seen that the reference points are better approximated by equation (18), which is characterized by a more rapid growth of the amount of knowledge in the future, compared to formula (16) featuring no time shift. Thus, we have shown that due to the short duration of the demographic transition, one should consider a 25-year time delay needed for the labour resources to grow up. Also, we showed above that the knowledge of humanity grows somewhat more rapidly than the population of the Earth, at an exponent of about 1.25. Above, we used the expression for GDP at PPP (7) with a quadratic dependence on the number of people. However, over the recent period, it has become evident that this formula is not sufficiently accurate and should be refined for the purposes of predicting future development. In publication [2], it was shown that the value of GDP at PPP is proportional to the product of the population by the amount of human knowledge. Therefore, it is more efficient to approximate GDP at PPP with equation (20). The coefficient *m* after 2000 can be neglected as an insignificant value.

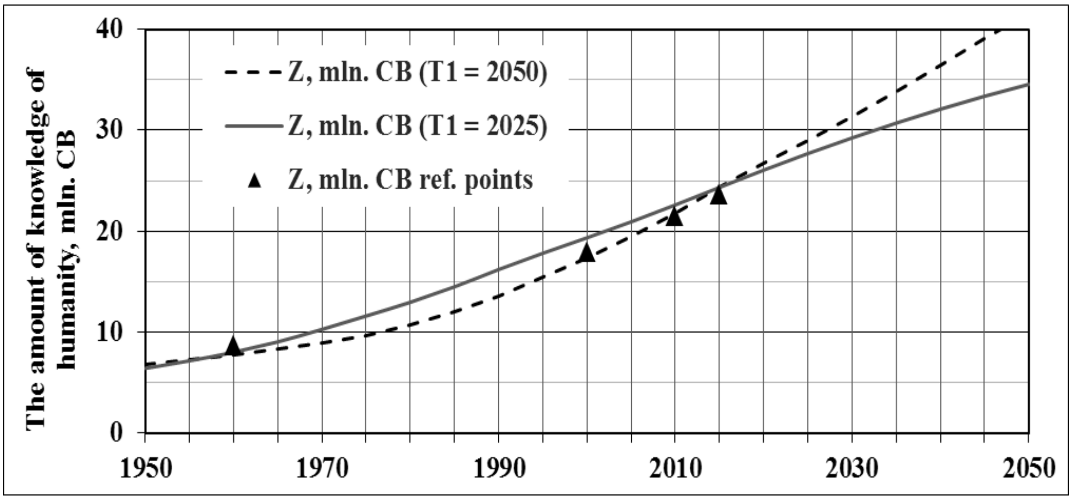

Fig. 6. Comparison of the knowledge growth formulas with different time shifts

$$G=k\cdot N(T-25)2.25 \tag{20}$$

Fig. 6 shows a comparison of the dependence (20) for k = 2.72 with available statistical data: A. Maddison [23] until 2008, and the World Bank data [30] for the later periods, in hundreds of trillions of international dollars of 2017 at PPP. It also includes the data on the world GDP at PPP forecast of the PwC company [31]. The dashed line shows the annual growth rate of the GDP at PPP in percent according to the formula of equation (20).It is obvious that the dependence of the GDP at PPP on time has a logistic form, which corresponds to the nature of the Earth's population growth. The statistical data for the period near the year 2000 are in good agreement with the dependence in equation (20), although they slightly exceed it in the earlier period. The PwC forecast for 2030 is in good agreement with dependence (20) but is somewhat lower for 2050. However, the PwC forecast for 2050 was revised in 2016 and reduced by about 7% compared to their forecast of two years before [32], so the agreement of these data with curve (20) can be considered quite acceptable, especially given the usual accuracy of long-term forecasts.

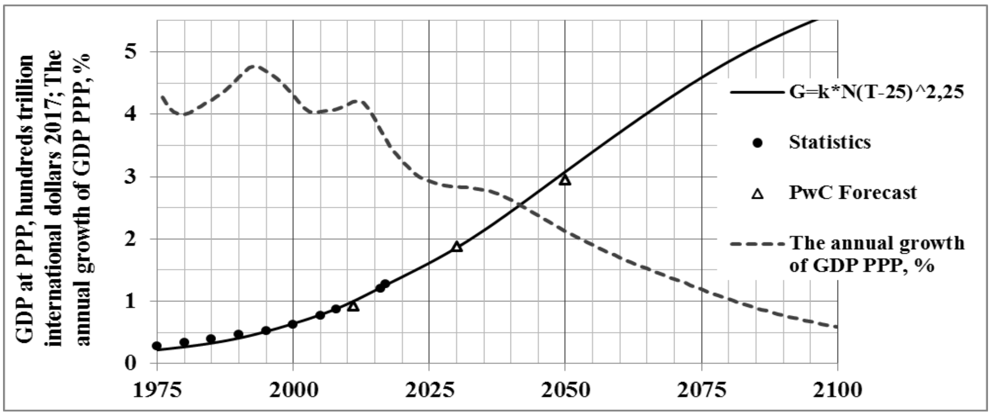

Fig. 7. Global GDP forecast according to the dependence $\mathbf{G = k\cdot N(T-25)^{2.25}}$

Annual GDP growth rate is rapidly decreasing from around 4% per year to 0.6% in 2100. Since this is the average growth rate for all countries, many countries will have an even lower or negative growth. Also, characteristic are fluctuations in the growth rates in the period 1975–2030, which mirror the fluctuations in the global population growth, as shown in Fig. 3.

An important result of the efficient use of the findings obtained from the analysis of human knowledge growth for predicting GDP growth is the understanding of the systemic consistency of important aspects of human activity, such as knowledge growth and economic dynamics. Both characteristics are also closely related to the growth of world population. In addition, we identified quantitative adjustments to formula (7) for the dependence of the world GDP on population in the form of equation (20), which will be important for obtaining subsequent results. It is extremely important that formula (7) used in the study and the limitation of the maximum population (N_{max}) imply that there is a limit to the GDP per capita growth, which can be obtained from formula (20) in the form of formula (21).

$$(G/N)_{ma}=k\cdot N_{max}1.25 \quad (21)$$

For N_{max} = 11 billion, $(G/N)_{max}$ = 54,500 international dollars of 2017. Currently, G/N = 16,940 dollars, so the average world GDP per capita can grow 3.2 times at most. For comparison, the world GDP increased by the same factor from 2001 to 2018. This limitation arises from demographic transition and from the fact that the population of the Earth ceases growing. Seemingly, the fact that the level of well-being of the population will not increase more than 3.2 times does not raise any concerns. But this means that the development of humanity will slow down dramatically. Economists in developed countries are already concerned by the slowing down growth of their economies, especially compared to the developing countries. But the same situation will gradually occur in the currently developing countries, too. It follows from the analysis that the steady decline in the economic growth rate is a systemically determined pattern of the humanity development. If we do not recognize this fact, world events, including economic crises and the commitment of developing countries to fighting for their rights, will lead to tensions between countries and conflicts, including armed ones. This seems to be one of the most fundamental causes of instability in the world for the next hundred years. At the same time, awareness of this threat can give rise to positive changes that can mitigate the risk of worldwide stagnation. In this study, we analyzed only the dynamics of explicit knowledge, but of no less importance is the pattern of changes of implicit knowledge that is contained in the minds of people. A more detailed analysis of the knowledge dynamics can provide us with approaches to overcoming the knowledge growth limit while stabilizing the Earth's population. There are resources, such as people who have not received any education and, accordingly, do not participate in the production of world knowledge. This and several other resources can be used to overcome the systemic threat to sustainable world development, considered in this study.

5 DISCUSSION

We formulated the differential equation of demographic dynamics using the linear dependence of GDP per capita on the population size, as proposed in previous studies. However, we later revisited this dependence and showed that it is more accurate to use the exponent of 1.25. But, with a fractional indicator, the equation has no analytical solutions; therefore, the system characteristics of the solution are not so obvious. At the same time, the solution obtained is in good agreement with the statistical data. In the future, a more complex parameterization of the equation of demographic dynamics can be considered, although the main errors are not made by this assumption, but by the influence of world wars and other cataclysms. The paradox consists in the fact that fears have traditionally [6], [14], [15] been caused by the growth of the Earth's population, leading to overloading the natural environment, depleting its resources and ability to self-recover. This study shows the possibility of the opposite threat of the humanity development stagnation in the nearest future. Further efforts should be focused on understanding, which one of these threats is more critical.

6 CONCLUSION

We developed mathematical models describing the system of world dynamics with account of the interrelated processes of demographic transition, knowledge growth, and GDP dynamics. The conducted analysis of the challenges to sustainable world development associated with the evolution of humanity showed that a dramatic slowdown of the global GDP growth as a result of demographic transition and the limitation of the maximum population of the Earth at N_{max} = 11 billion people poses a serious threat. The maximum value of GDP per capita at purchasing power parity will be able to increase 3.2 times at most, compared to the current level, and will not exceed 54.5 thousand international dollars of 2017 at PP. The second risk is a dramatic slowdown in the knowledge growth, also associated with demographic transition and the limited nature of N_{max}. This phenomenon can lead to a radical change in the cognitive and innovative activities of humanity. Against the background of these processes, conflicts between various countries may ramp up, aggravated by economic crises, posing a serious global threat in the conditions of rapidly increasing countries' level of armaments.

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