WORLD NUMBER OF SCIENTISTS IN DYNAMIC SIMULATION FOR THE PAST AND THE FUTURE

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ABSTRACT

The purpose of this article is to model a semi-structured correlation of the economic growth with the change in the number of scientists in the world in the past and in the future based on the empirical study of its determinants. We used the method of studying both quantitative and qualitative correlation of the economic growth sources and the number of scientists. As a result of this work, we established the evolutionary dependence of the growth of the number of scientists in the world within the path of the stable development of the knowledge economy. An analysis of the empirical base showed that the correlation of the number of scientists with the human knowledge volume before the demographic transition is expressed as a quadratic hyperbolic dependence over time $N_S = 16 \cdot 10^9/(2050 - T)^2$. *We established the periods of application of the logistic and other dependences for the approximation of the number of scientists in the world, which allows estimating the prospects of the knowledge economy development for the period until 2080.*

The obtained results can be used to forecast the pace of the economic growth and science development. The novelty of this work consists in revising the existing idea, according to which the number of scientists in the world in the past was growing exponentially, and finding out that their number largely depends on the GDP after the transition to the knowledge economy. The main conclusion of the article is that the evolutionary (before and after the demographic transition) dependence, built using various mathematical models on the macro level, allows predicting the growth of the number of scientists based on the economic growth.

Keywords: *prediction, number of scientists, knowledge economy, human capital, knowledge of mankind, R & D experts, future*

1. INTRODUCTION

The modern world is aspiring to the "Knowledge economy", and the role of intellectual activity is growing rapidly. One of the indicators of such changes is that by the beginning of the 21st century, in most countries of the world, the share of human capital (HC) in the national wealth has reached 80% and it is growing continuously[1] [2] (Fig. 1).

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[1] Koritsky, A.V. (2013). *The Impact of Human Capital on Economic Growth*. Novosibirsk.

[2] Korchagin, Yu.A. (2005). *Russian Human Capital: A Factor of Development or Degradation? Monograph*. Voronezh.

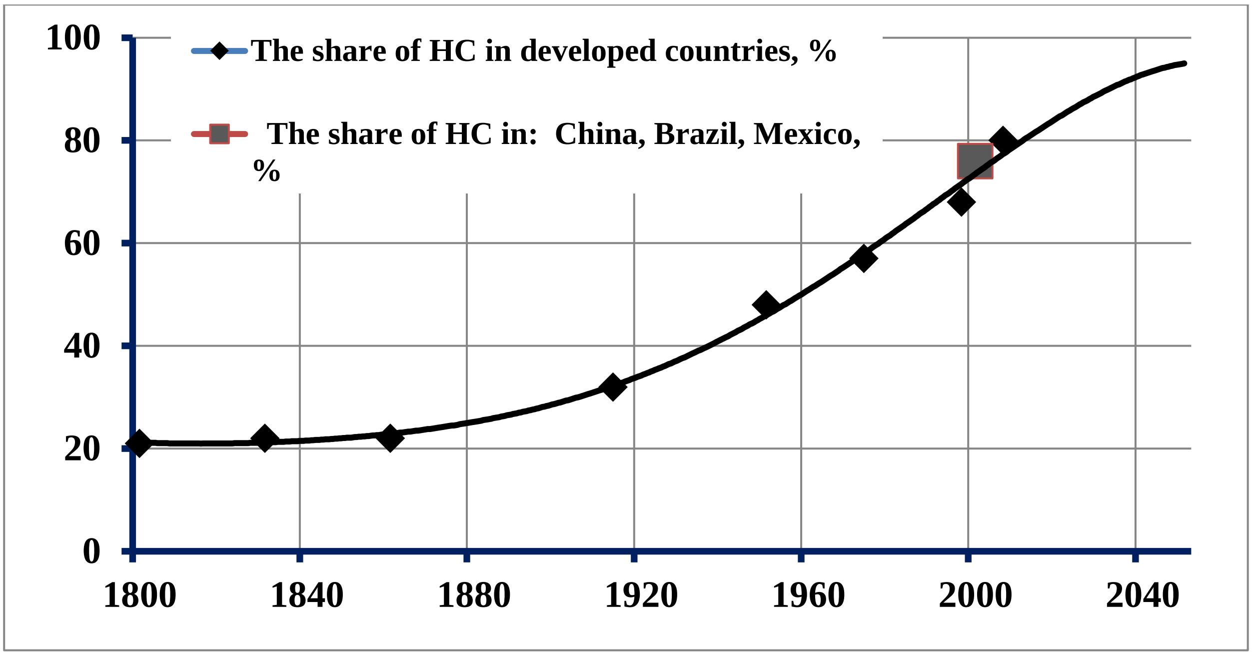

Fig. 1. The share of HC in the national wealth of the countries

What is the reason? First, in the past half-century, the number of higher education students has grown **10** times in the world[3 4 5 6], and this growth is about twice as fast as the GDP growth[7 8]. However, in the world leading economies, the share of the employees with higher education has already reached 30% and the resource of intellectual and human capital growth due to higher education is already approaching the point of exhaustion[9 10 11 12 13].

Another important and major in terms of volume resource for improvement of the specific human capital of the countries is the growing number of scientists. It is this resource that determines the growth of the explicit knowledge in the world, directly affecting the growth of world gross product per capita and keeping it in an active state.

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[3] *The Number of Students in Different Countries of the World*. (n.d.). The Federal PortalProton.ru. Retrieved August 19, 2017, from http://www.protown.ru/information/hide/3542.html

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[5] *Today There Are 153 Million Students in the World*. (2009, July 6). Innovative Educational Network "Eureka". Retrieved August 19, 2017, from http://www.eurekanet.ru/ewww/promo/10407.html

[6] *Education at a Glance 2013: OECD Indicators*. (2013). Retrieved August 19, 2017, from http://www.oecd.org/edu/eag2013%20(eng)--FINAL%2020%20June%202013.pdf

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[8] Orekhov, V.D. (2015). *Forecasting the Development of Mankind, Taking into Account the Factor of Knowledge: Monograph*. Zhukovsky: MIM LINK. (p. 210).

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[10] Hall, R.E., & Jones, C.I. (1999). Why Do Some Countries Produce so Much Output per Worker than Others? *The Quarterly Journal of Economics, 114*(1), 83-116; Caselli, F. (2005). *Accounting for Cross-Country Income Differences*. CEP Discussion Paper No. 667. Centre for Economic Performance.

[11] Shultz, T. (1968). Human Capital. In *International Encyclopedia of the Social Sciences* (Vol. 6). New York.

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The dependence of the growth of the number of scientists over time is also of great interest for the purpose of understanding the laws governing the development of civilization in terms of knowledge.

2. AVAILABLE DATA ON THE NUMBER OF SCIENTISTS

Let us consider how the number of scientists changed in different epochs of human development. According to the SED[14], in the 17th century the number of scientists began to double every 10-15 years. The information on the number of scientists in the world is presented in Table 1 and in Fig. 2, which also shows the diagram of the exponent with the tenfold growth rate over 50 years (doubling over 15 years).

$$\mathbf{N_S = 10^{(T-1650)/50}} \qquad (1)$$

Table 1. The number of scientists in the world

Time	Scientists, thd.	Time, year	Scientists, thd.
At the turn of the 18th-19th centuries [15]	~ 1	1975[16]	4,900
In the middle of the 19th century	10	2002	5,800
In 1900	100	2007	7,100

It can be seen that the information about the number of scientists, represented in Table 1, is fairly well approximated by the exponent before 1970. But this dependence means that by the time of the establishment of the French Academy of Sciences in 1666 there had been only two scientists in the world. Such a small number of scientists in the past also does not agree with the existence of the ancient science and the scientists of the Renaissance. Apparently, this disagreement lies in whom to consider as scientists. Whereas the scientists are the people engaged in research and development (R & D), i.e. in creation of knowledge and in development of new products and technologies based on them, then their number should be logically correlated with the volume of knowledge of mankind and the complexity of the products created.

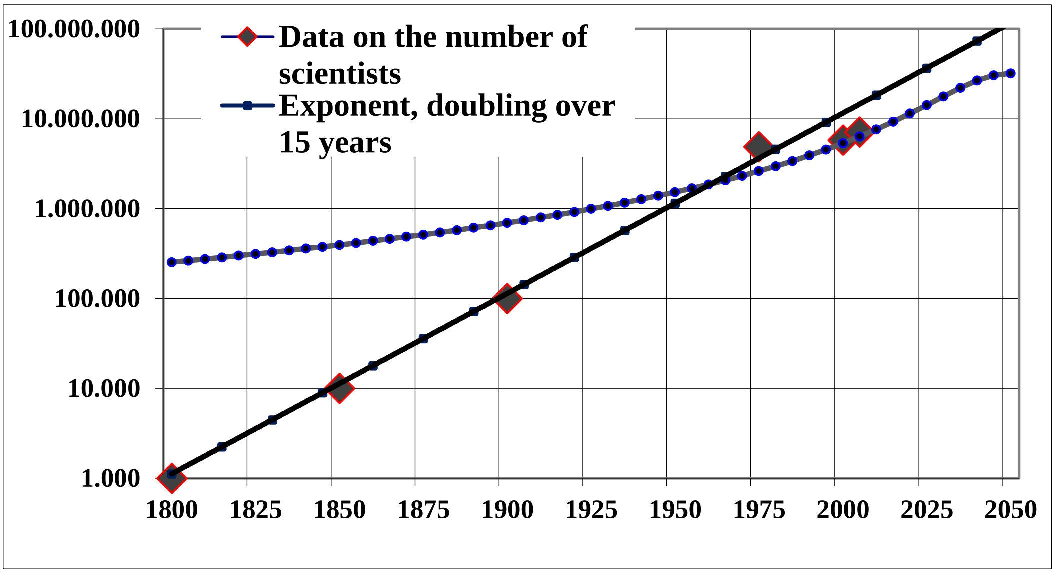

Fig. 2. Models of the number of scientists in the world

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[14] *Soviet Encyclopedic Dictionary*. (1987). Moscow.
[15] *Features of Modern Science*. (n.d.). Scientific-Informational Journal "Biofile". Retrieved August 19, 2017, from http://biofile.ru/his/2038.html
[16] *The USSR in Figures in 1975*. (1976). Moscow.

3. THE CONNECTION BETWEEN THE GROWTH IN THE NUMBER OF SCIENTISTS AND THE VOLUME OF KNOWLEDGE OF PEOPLE

According to S.P. Kapitsa, the development of mankind "is determined by the mechanism of reproduction and dissemination of the generalized information on a scale of humanity"[17]. In this paper, we will proceed from the hypothesis that the most fundamental factor affecting the growth and development of the mankind is the volume of accumulated knowledge, especially the obvious ones.

Since people are the creators and the carriers of knowledge, there seems to be a dependence of the amount of knowledge on the number of people in the world, the number of which till 1960 (the beginning of the demographic transition) can be expressed by hyperbole (2)[18]:

$$\mathbf{N = C/(T_1 – T)} \tag{2}$$

In the formula (2) T is the time, measured in years, C ≈ 180 bln. is a constant with the dimension of [pers.•year], and $T_1 \approx 2025$ is the date of singularity.

Since, approximately until 1960, most part of the codified information was stored on paper carriers, it is natural that the amount of knowledge during this period is related to the volume of books published. To determine the volume of world knowledge as the reference points, the data on the volume of books, pamphlets and newspapers in the Library of Congress can be used, which in 1960 amounted to about 14.5 million books and brochures, in 2000 it was equal to 30 million, and in 2012 – to 35.8 [19, 20, 21]. Although not all the knowledge of the world is stored in the Library of Congress, currently, it is the largest repository in the world. Moreover, it contains the duplicates.

Therefore, with some approximation, the amount of storage in it can be taken as the knowledge of mankind. In order to emphasize the difference between the knowledge and the information for measuring the volume of knowledge, the concept of a "conditional book" (CB) which is equal in volume to a book that, when digitized, will have a volume of 1 MB, is used herein. In these units, the storage capacity of the Library of Congress will be: 18 million CB in 2000, two times less or 9 million CB in 1960, 21.5 million CB in 2012.

The Alexandrian Library, containing from 100,000 to 700,000 volumes in its repositories, which was created around 300 BC, is chosen as the fourth reference point[22]. Let us assume that the size of these volumes is equal to one fifth of the conditional book. Although the Alexandrian Library did not contain the knowledge of all mankind, it was close to it, so we will take the amount of knowledge stored in this library for all the knowledge of the world as of that time – 80 thousand CB.

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[17] Kapitsa, S.P. (2012). *Paradoxes of Growth: The Laws of the Global Development of Mankind* (p. 49). Moscow.
[18] Foerster, H. von, Mora, P., & Amiot, L. (1960). Doomsday: Friday, 13 November, A.D. 2026. *Science, 132*, 1291-1295.
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[20] *The Library of Congress*. (2012). Wikipedia. Retrieved August 19, 2017, from http://ru.wikipedia.org/wiki
[21] *General Information – About the Library (Library of Congress)*. (2012). Retrieved August 19, 2017, from http://www.loc.gov/about/general-information
[22] *Soviet Encyclopedic Dictionary*. (1987). Moscow.

As the last point, the time of beginning of origination of the mankind is taken – about 1.6 million years ago, when the number of people was equal to $\mathbf{N_0}$ **~** 100 thd.[23]. The volume of the neural memory of one individual, the degree of development of which exceeds the chimpanzee, but less than the degree of development of a modern man, ~ 20 CB[24] is taken as the volume of knowledge of the mankind at this time. The obtained estimates of the volume of knowledge and their relation to the growth of the mankind are presented in Table 2. As can be seen from this table, the volume of knowledge (Z) per person varies relatively slowly over time.

Table 2. The volume of knowledge of the mankind

No.	**Source**	**Year from the beginning of AD.**	**Population of the Earth, mln.**	**Volume of knowledge, thd. CB**	**Knowledge CB per thousand people**
1.	The Library of Congress	2012	7,000	21,500	3.07
2.	The Library of Congress	2000	6,000	18,000	3.00
3.	The Library of Congress	1960	3,077	9,000	2.92
4.	The Alexandrian Library	-300	86	80	0.93
5.	Origination of the mankind	-1600000	0.1	0.02	0.20

Thus, the main parameter influencing the volume of knowledge of the mankind **Z** is the number of people **Z ~ N**. Accordingly, to approximate the global volume of knowledge, the formula of the type of hyperbola can be used[25]:

$$\mathbf{Z \approx 1.5 \cdot 10^9/(T_1 - T)^{1.25}} \qquad (3)$$

The formula (4) is true in the period of hyperbolic growth of the mankind (before 1960). Using the formula (2), the expression for the volume of knowledge, which is also true for the period of the demographic transition, can be obtained[26]:

$$\mathbf{Z \approx Z_0 \cdot (N/N_0)^{1.25} = 20 \cdot (N/N_0)^{1.25}} \qquad (4)$$

The derived formulas for the volume of knowledge of the mankind (3), (4) are the estimates of the order of magnitude, but they show that the amount of knowledge depends mainly on the number of people and, respectively, on time in the period of hyperbolic growth. In addition, there is also an indicator linking the growth of the volume of knowledge with the improvement of the human brain, since it is clear from formulas (3), (4) that the amount of knowledge grows not in proportion to the number of people, but more rapidly – in the degree of 1.25.

Since the main factor determining the volume of knowledge is the number of people, and the periods between the technological revolutions in recent times are equal to 20-30 years, the delay for the time of growing-up of the people up to the working age should also be taken into account in the formulas (3, 4)

[23] Kapitsa, S.P. (2012). *Paradoxes of Growth: The Laws of the Global Development of Mankind* (p. 49). Moscow.
[24] Anisimov V.A. (2006). *On the Complexity Increase Law*. Retrieved August 19, 2017, from www.yugzone.ru/articles/438
[25] Orekhov, V.D. (2015). *Forecasting the Development of Mankind, Taking into Account the Factor of Knowledge: Monograph*. Zhukovsky: MIM LINK. (p. 210).
[26] Ibidem.

In the first approximation, this can be done using the value of the number of people 25 years earlier – N (T-25) in the formulas (3, 4) and, correspondingly, increasing the numerical coefficient by about 1.5 times. In this case, they acquire the following form, where $T_2 = 2050$:

$$\mathbf{Z \approx 2.25 \cdot 10^9/(T_2 - T)^{1.25}} \qquad (5)$$

$$\mathbf{Z \approx 30 \cdot (N(T-25)/N_0)^{1.25}} \qquad (6)$$

The comparison of the approximate formulas (3) and (5) for the volume of knowledge, as well as the reference points from Table 2 for the last century, are shown in Fig. 3. It can be seen that the formula (5) approximates the reference points much better than the formula (3) at the beginning of the demographic transition.

Assuming that there is an unambiguous connection between the creation of new knowledge and the number of scientists and developers, it is possible to estimate their number N_S. The annual increase in knowledge ΔZ can be estimated by the differentiating equation (3):

$$\mathbf{dZ(T)/dT = K/(T_2 - T)^{2.25}.} \qquad (7)$$

As noted above, the performance of knowledge creation increases more rapidly than the number of people (2), proportionally to the hyperbole in the degree of 0.25, therefore when determining the number of scientists, it is necessary to adjust the formula (7) for the labor performance growth and to obtain the expression for the growth of the number of R & D workers in time:

$$\mathbf{N_S = A/(T_2 - T)^2,} \qquad (8)$$

where A = **16•10⁹**[27].

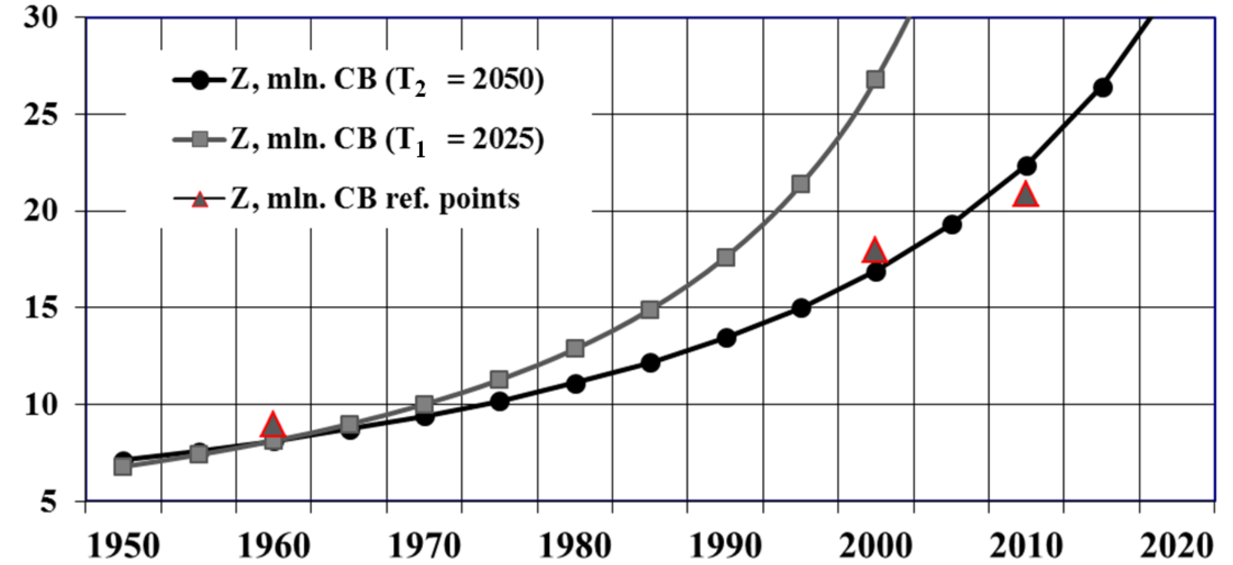

Fig. 3. The comparison of the approximate formulas (3) and (5)

According to this dependence, in the Renaissance there were 60 thousand experts in the sphere of R & D in the world, in the Antiquity – about 3,000, in the times of ancient Egypt – more than 600, in the megalithic era ~ 100, and the first R & D expert appeared about 120 thousand years ago. This number of R & D experts is better than the corresponding complexity of products and structures created in historical times, than according to the exponent.

[27] Orekhov, V.D. (2015). *Forecasting the Development of Mankind, Taking into Account the Factor of Knowledge: Monograph*. Zhukovsky: MIM LINK. (p. 210).

4. FORECASTING THE NUMBER OF SCIENTISTS AFTER 1960

In order to prolong this dependence for a period after 1960, the approach for transformation of the exponential dependence into a logistic one is used. By differentiating the equation (8), the following can be obtained

$$\mathbf{dN_S/dT = -2\,A/(T_2 - T)^3 = -2N_S/(T_2 - T)} \qquad (9)$$

Hence, a differential equation for the number of scientists (10) in the period of hyperbolic growth of the number of people is obtained.

$$\mathbf{(1/N_S)\,dN_S = -\,2dT/(T_2 - T)} \qquad (10)$$

In order to eliminate the infinite growth of the hyperbola (8) and to bring this equation to a type analogous to the logistic one (with respect to the hyperbola), it is required to add a limiting factor of the type $\mathbf{(N_S/N_{max} - 1)}$ on the right-hand side of equation (10) and the following equation can be obtained (11):

$$\mathbf{(1/N_S)\,dN_S = -\,2(1 - N_S/N_{max})dT/(T_2 - T)} \qquad (11)$$

This equation can be transformed to the form (12), where $X = N_S/N_{max}$:

$$\mathbf{(1/X)\,dX + (1/(1 - X))\,dX = -\,2dT/(T_2 - T)} \qquad (12)$$

Let us integrate the equation (12) and reduce it to the form (13):

$$\mathbf{N_S = N_{max}/(1 + (N_{max}/A)\cdot(T_2 - T)^2).} \qquad (13)$$

At $T \to -\infty$, the value $N_S \to A/(T_2 - T)^2 \to 0$, which corresponds to the data in Table 1, and at $T \to T_2 = 2050$, the value $N_S \to N_{max}$, that is, it is limited, as in the logistic curve.

In order for the theoretical curve to agree well with the data on the current number of scientists, the constant coefficients in the equation (3) should have approximately the following values $N_{max} = 32\cdot10^6$, $A = 16\cdot10^9$. The corresponding curve is shown in Fig. 2 (hereinafter referred to as the "quadratic logistic hyperbola"). Unlike the equation (8), the curve (13) does not tend to infinity and does not exceed $N_{max} = 32\cdot10^6$. The drawback of this curve (3) is that in 2050 it reaches a maximum and then decreases, which hardly reflects the growth in the number of scientists in the future.

5. OTHER OPTIONS FOR PREDICTING THE NUMBER OF SCIENTISTS

Let us consider other options for predicting the growth in the number of scientists in the future. Fig. 4 shows the diagrams of the growth in the number of R & D experts according to the quadratic logistic hyperbole (13) and the logistic dependence (14)[28] (T_0 = 1900, N_0 = 0.1 mln., N_{max} = 32 mln., C = 24 years), which is the solution to the differential equation (15).

$$\mathbf{N(T) = N_0\,exp(T/C)/(1 + (N_0/N_{max})\,(exp(T/C) - 1))} \qquad (14)$$
$$\mathbf{dN/dT = (N/C)\,(1 - N/N_{max})} \qquad (15)$$

The forecast of the number of R & D experts according to the scientific paper[29] (triangular points) taking into account the prevailing tendencies of their number growth in the largest economies of the world up to 2100, is also presented there.

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[28] *Logistic Equation*. (2016). Wikipedia. Retrieved August 19, 2017, from https://ru.wikipedia.org/wiki

[29] Orekhov, V.D. (2015). *Forecasting the Development of Mankind, Taking into Account the Factor of Knowledge: Monograph*. Zhukovsky: MIM LINK. (p. 210).

According to this forecast, the number of R & D experts is approximately expressed by the dependence:

$$\mathbf{N_S = 3.7 + 0.09\,(T - 1980) + 0.001(T - 1980)^2} \qquad (16)$$

It can be seen that the logistic curve (the initial exponent of which doubles in C ln2 = 24 ln2 ≈ 17 years) is the closest to the current data on the number of R & D experts and to the forecast values.

The logistical quadratic hyperbola (13) grows much faster after 2015 than forecasted (16). The point corresponding to 1975 should not be taken into account, primarily because it corresponds to the existence of the USSR and the CMEA, and in these countries the number scientists sharply decreased after 1990.

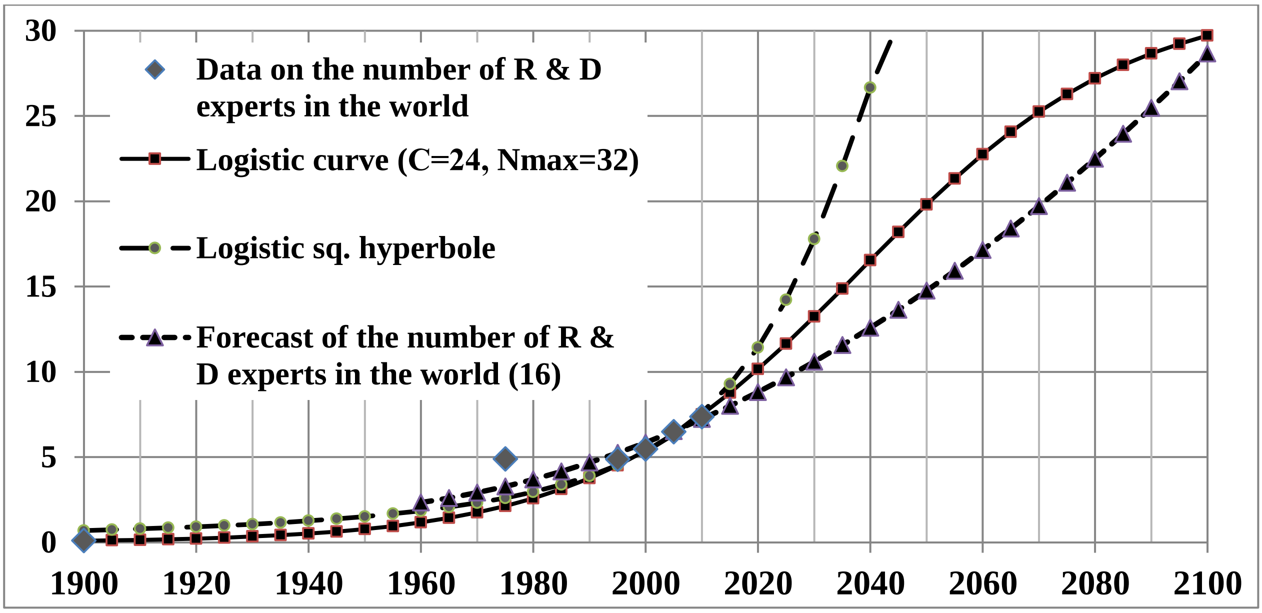

Fig. 4. Different models of the number of R & D experts in the world.

6. THE GROWTH IN THE NUMBER OF SCIENTISTS AND THE WORLD'S GROSS PRODUCT.

The problem is: why did the growth in the number of R & D experts seem to correspond to a quadratic hyperbola before the demographic transition, and is recently closer to logistic dependence?

Note that the growth of the world GDP for the last millennium according to A.V. Korotaev and D.A. Khalturina[30] corresponded approximately to the square of the number of the mankind, and taking into account the H. Foerster equation (2)[31] the value of GDP by PPP (in trillions USD as of 1990) is described by a quadratic hyperbola.

[30] Khalturina, D.A., & Korotaev, A.V. (Eds.). (2010). *System Monitoring: Global and Regional Development* (p. 50). Moscow: LIBROKOM.

[31] Foerster, H. von, Mora, P., & Amiot, L. (1960). Doomsday: Friday, 13 November, A.D. 2026. *Science, 132*, 1291-1295.

Fig. 5 represents a comparison of GDP by PPP values according to A. Maddison[32] in the period 1400-2000 with a quadratic hyperbola of the type (17), from which it can be seen that they are in good agreement.

$$\mathbf{G=0.12 + 28000/(2020 - T)^2} \qquad (17)$$

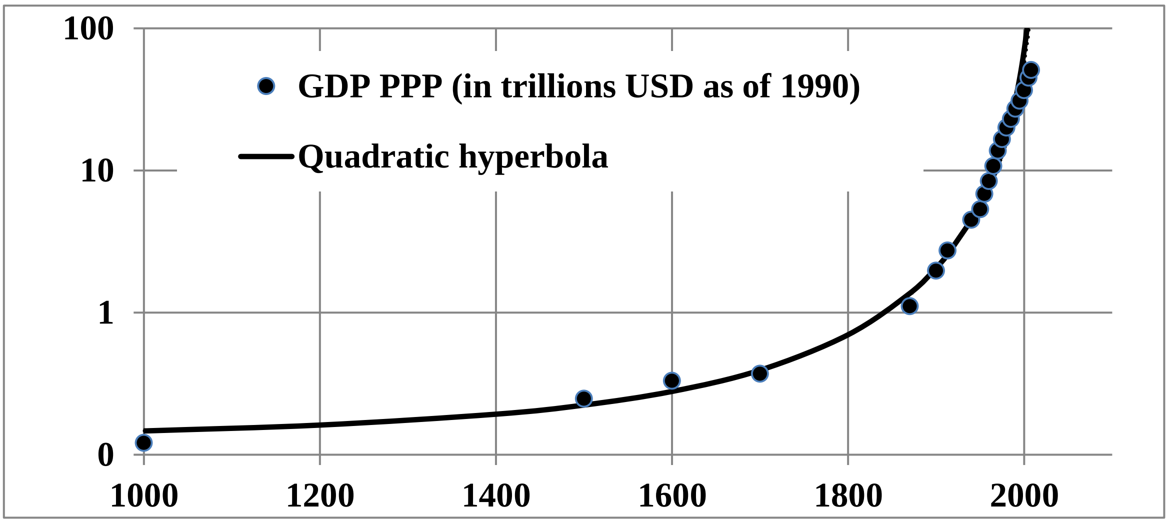

Fig. 5. Quadratic hyperbole as a model of world GDP growth

However, with the approach to 2000, the actual GDP growth begins to lag behind the quadratic hyperbola (17), which is natural, since it has a singularity in 2020. During this period, the dependence of the GDP growth on time becomes approximately exponential, as can be seen from Fig. 6. The forecast of GDP[33] by PPP in 2030 and 2050 is given here according to the article[34].

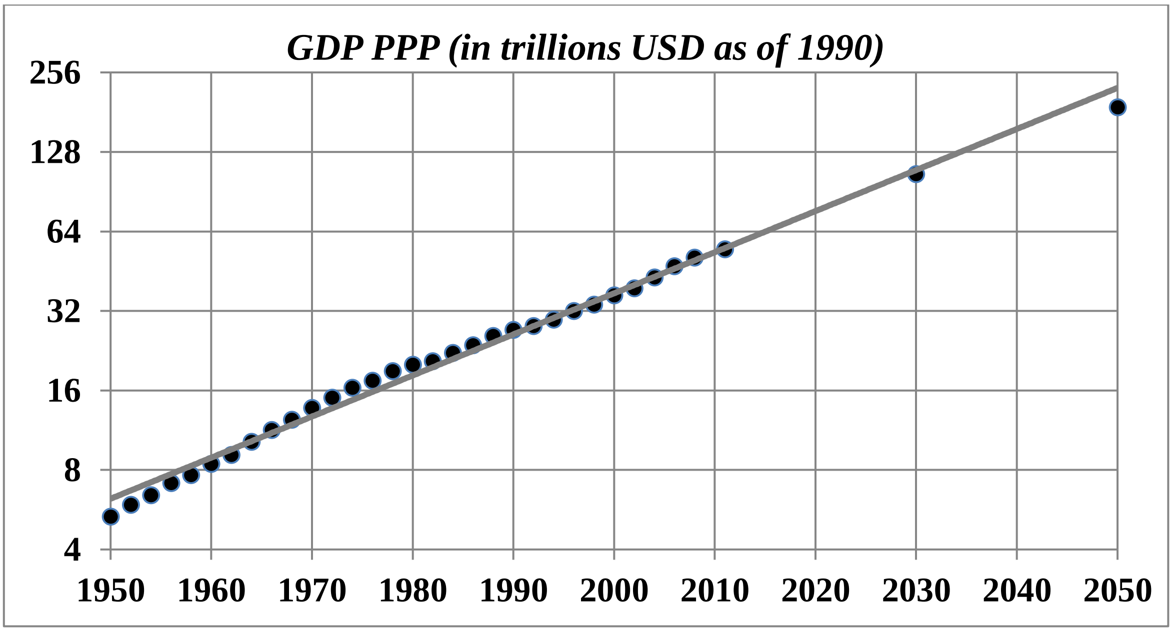

Fig. 6. Quadratic hyperbole as a model of world GDP growth

[32] Maddison, A. (2010). *Historical Statistics of the World Economy: 1-2008 AD*. GCDC.
[33] Ibidem.
[34] Hawksworth, J., & Chan, D. (2013). *World in 2050. The BRICs and Beyond: Prospects, Challenges and Opportunities*. PricewaterhouseCoopers.

Thus, it can be declared that the number of scientists (N_S) is approximately proportional to world GDP ($N_S \sim G$). This is quite logical, since it is clear that the number of R & D experts depends significantly on the possibilities of financial support of the scientific activity.
On the other hand, the increase in the number of R & D experts leads to the increase in knowledge and, accordingly, to the GDP growth, so these two values are interdependent. The ratio of the number of scientists in the world and the world GDP (N_S/G) in the period 1995-2010 is shown in Fig. 7, 8. It can be seen that they grow at about the same rate, but there is a tendency to reduction in the number of scientists per billion dollars of GDP, especially in the initial period, due to a sharp decrease in the number of scientists in the USSR and Eastern Europe.

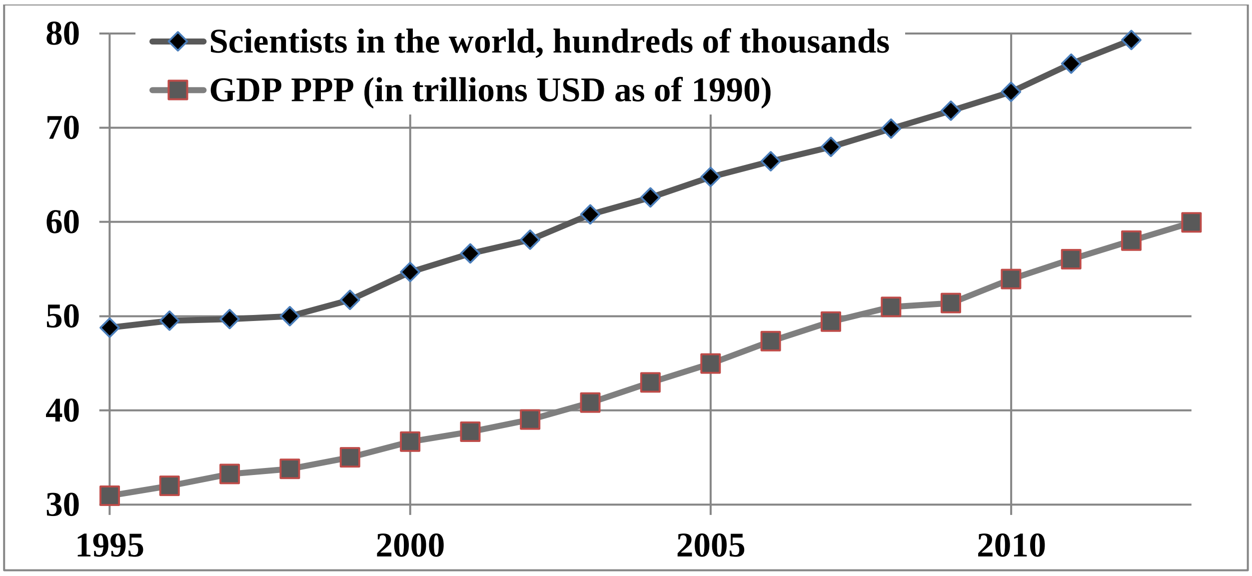

Fig.7. The growth in the number of scientists and GDP in the world

It is interesting that during this period the GDP per capita in the world grew rapidly. Having considered the information on the value of N_S/G versus GDP per capita (G/N), a rather paradoxical dependence can be observed (Fig. 9): the number of scientists decreases with the growth of GDP per capita, although, as a rule, the richer countries are able to pay more attention to science.

Probably, this is due to the fact that GDP grew very rapidly in this local period, and the growth in the number of scientists either lagged behind GDP growth in some countries (developing countries) or it had been high enough already in other (developed) countries.

The dynamics of the number of scientists were also affected by the competitive strategies for the development of the science in various countries. To assess these factors, Fig. 10 shows the ratio of NS/G in various countries, depending on GDP per capita (herein GDP PPP in USD as of 1990).

Figure following on the next page

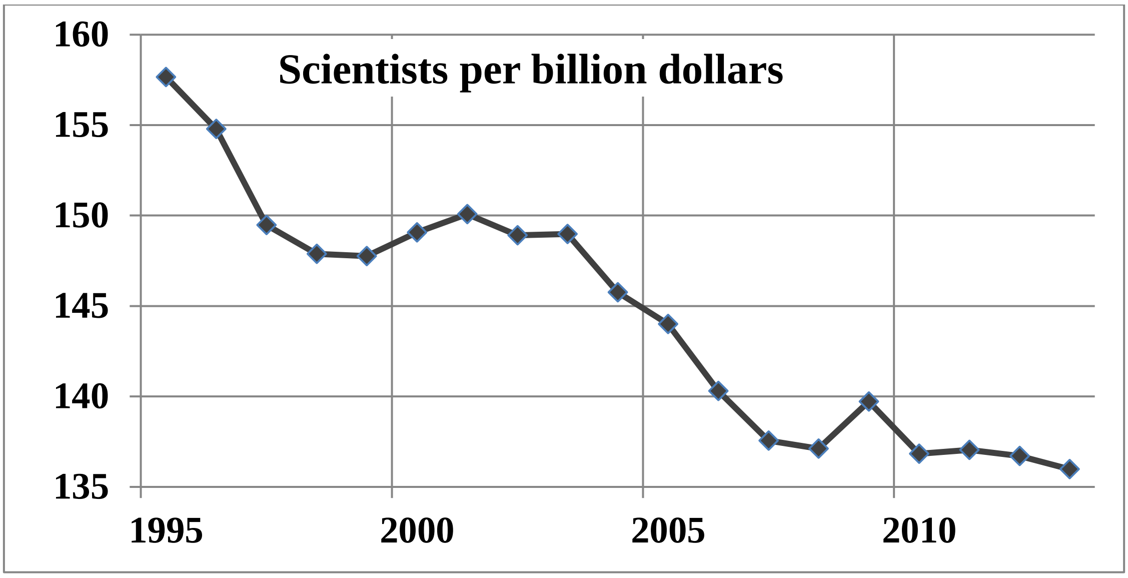

Fig. 8. The number of scientists per billion dollars (NS/G) in the world

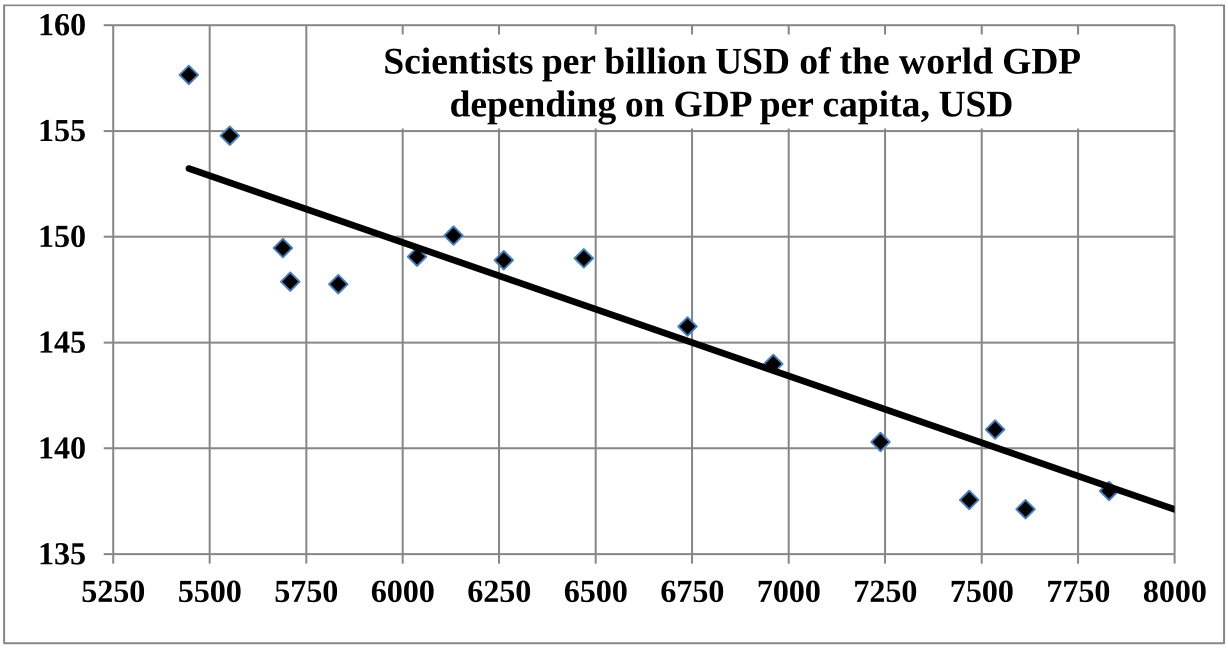

Fig. 9. N_S/G ratio depending on *G/N (USD as of 1990)*

It is evident that the NS/G number in the USA remains at a stable level of about 120 people per billion USD, which is enough to preserve the world scientific leadership. In China, the NS/G remains roughly constant at the level of 150-160. Germany, Britain and Canada maintain this ratio at the level of 170, despite a marked increase in GDP per capita.

The number of R & D experts in Russia has sharply decreased, but it is still much larger than in other countries. The NS/G number in India and Indonesia is decreasing, although the GDP per capita in these countries is the lowest. NS/G slightly decreased in Japan. Only South Korea shows a significant increase in this parameter, which already almost twice exceeds the level of the USA.

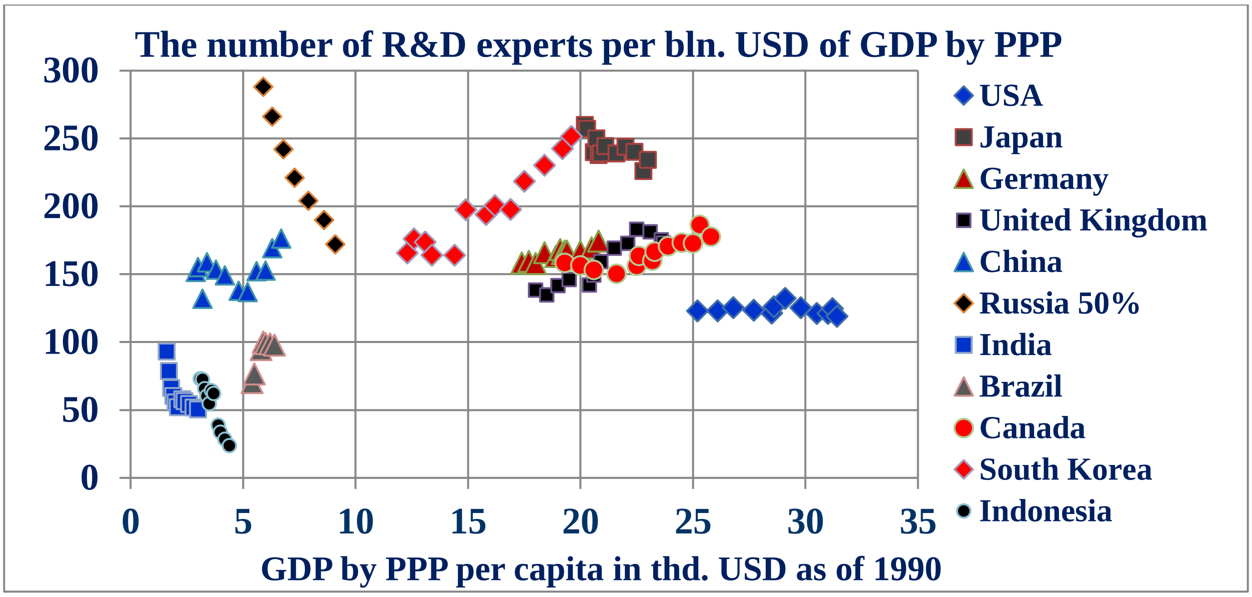

Fig. 10. Dependence of N_S/G on G/N in various countries

Thus, it is clear that the dynamics of the number of R & D experts in various countries is situational in nature and relatively little depends on GDP per capita. The dominant parameter is the GDP growth by PPP.

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