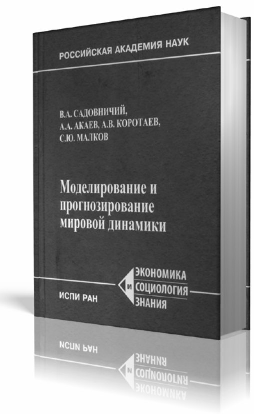
Methology of Modeling and Forecasting of the World Dynamics



Extant Methods of the World System Modeling: Capabilities and Limitations

Askar Akaev —
Dr.Sc. (Engineering), Professor, RAS foreign member
V.A. Sadovnichy —
Dr.Sc. (Physics and Mathematics), Professor, RAS Academician

Mathematical modeling of the world dynamics goes back to the papers of a prominent American scientist Jay Forrester to the famous Club of Rome in the late 1960s and early 1970s, devoted to the application of system dynamics models for long-term ecological and economic forecasting (Forrester, 1978). The main question that interested the Club of Rome that time was to determine the sustainability of economic model that prevailed in the West after World War II. This model assumed the dynamic growth and unlimited expansion with the use of resource-intensive technologies. Forrester's reports showed that the continuation of resource-intensive growth strategy in the face of unprecedented population growth occurred in this period would inevitably lead either to an acute shortage of resources in the world, or to a catastrophic environmental pollution, which could cause a global environmental crisis.

FORRESTER'S MODEL

Jay Forrester, a professor at Massachusetts Institute of Technology, is the founder of system dynamics models. He developed an apparatus of "system dynamics" which allows computer modeling of different scenarios of development in the dynamics of complex systems. The apparatus was based on the achievements of systems theory and computer modeling using the language of ordinary differential equations (ODE). J. Forrester, on the request of the Club of Rome which was established in 1968 on the initiative of the largest Italian public figure and businessman Aurelio Peccei, created first mathematical models of the world dynamics "World1" and "World2" (1971–1972) which put the beginning of global processes modeling. In 1971, J. Forrester published the first results of computer modeling of the world dynamics in the book "World Dynamics" (Moscow, Nauka 1978) which has become popular and in which he for the first time an attempt to describe the basic processes of economy, demographics, growth, environmental pollution, their interaction and conditionality on a planetary scale was made.

First of all, J. Forrester identified the most significant global processes. That time they were the following: 1) rapid increase in population; 2) industrialization and industrial growth associated with it which caused the environmental pollution; 3) food shortage; 4) increase in waste of production; 5) shortage of natural resources. Thus, the World-System, by Forrester, consists of the following main subsystems: population, capital assets (capital), agricultural funds, non-renewable natural resources, pollution of the environment.

Consequently, the world dynamics can be described by five major global variables as time-dependent functions: 1) N — world population; 2) K — fixed assets (capital); 3) X — share of assets in agriculture; 4) R — amount of non-renewable natural resources 5) Z — number of environmental pollution. J. Forrester believed that the influence of key variables N, K, R, X and Z to each other affects mainly through natural processes of interaction and supporting factors, such as, for example, increasing the difficulty of extraction of non-renewable resources as their depletion. In addition to these variables, J. Forrester introduced another concept — the quality of life which is in the nature of the indicator of system functioning. Quality of life Q is defined a priori as a product of four unitary factors:

$$Q = Q_C\, Q_F\, Q_N\, Q_Z \quad (1.1)$$

where $Q_C\, Q_F$ is dependence of life quality accordingly with material standard of living *(C)* and food *(F)*; $Q_N\, Q_Z$ reflect the influence of factors N and Z on quality of life as correspondent functional dependencies.

For the construction of simulation models that describe the dynamics of World-system there are used ordinary differential equations of the same type of the first order in the following form:

$$\frac{dy_i}{dt} = f_i^+ - f_i^-, \qquad i = \overline{1,n} \quad (1.2)$$

where, f_i^+ is a right side of equation which includes all the factors that cause the growth of the variable y_i, and f_i^- includes all of the factors that cause the decrease of the variable. It is also assumed that the summands on the right side could be represented as a product of functions that depend only on factors F_j which, in their turn, are functions of the main variables y_i. For example,

$$f^+ = \phi^+(F_1, F_2, \ldots F_m) = \phi^+(F_1)\, \phi^+(F_2) \ldots \phi^+(F_m), \quad (1.3)$$

where $F_j = \Psi_j(y_{j1}, y_{j2}, \ldots y_{jl})$, $j = \overline{1,m}$, and $m<n$, $l<n$. It follows that the number of factors must be less than the basic variables, and

each factor does not depend on all major variables, but only a part on them. These restrictions were necessary in order to simplify the task of modeling.

Thus, there is a system of ordinary differential equations ODE (1.2) with right sides of the form (1.3). In order to solve this system of ordinary differential equations of the first order it is necessary to specify initial conditions at a particular time.

$$t = T_0 \,;\, y_{i|t=T_0} = y_{i0} \qquad (1.4)$$

These conditions together with the ODE (1.2) define the Cauchy problem. Under certain conditions, there exists a unique solution to this problem. Consequently, the task of the initial conditions (1.4) determines definitely the World-system dynamics. In connection with this the model of Forrester had been criticized as "mechanistic", referring to the lack of flexibility and controllability.

J. Forrester's model of the world dynamics has, correspondingly, five ordinary differential equations describing five global variables. In general, they are five non-linear ordinary differential equations. J. Forrester conducted calculations on this mathematical model for the time interval from 1900 to 2100. 1970 was taken for reference, since the data were compared with available statistics on the time interval of 1900–1970. This made it possible, first, to debug and verify the model itself, and second, to pull up poorly known model parameters. And from the 1970 calculations are purely prognostic. Of course, the chosen forecasting horizon up to 2100 does not allow speaking about an acceptable reliability and accuracy of the forecast beyond XX-th century, because this model does not directly take into account technical progress which plays the key role for long-term development. And for 130 years, the technological structure has changed three times (Glazyev, 1993), that has a significant impact on the age-old path of environmental and economic development. However, for such a model, J. Forrester did not set the problem of accurate prediction; the purpose of modeling was to identify trends in the development of system and its qualitative characteristics. In the essence, this is a model of industrial economy dynamics. In whole a scenario analysis of the model revealed threat of a crisis in the relationship between humanity and nature in the XXI century and showed the existence of "global balance" on the assumption of self-restriction and resource problems solving. J. Forrester considered that the only way to avoid a crisis connected with exponential growth is the transition to a global balance, where the system variables are located on the stationary values and do not change. In principle, it is impossible to complete full stabilization in the framework of Forester's model, since resources can only decrease over time. However, for other variables an output to stationary values may be reached, albeit for limited time periods.

MODIFICATIONS OF THE FORRESTER'S MODEL. A MODEL "WORLD 3"

The Club of Rome has supported a number of further projects on global modeling and study of the interdependence of various processes of the world dynamics. Direct continuation of Forrester's model was a model "World[3]" developed by his talented disciple Dennis Meadows and international research group. In the "World³" model there was held a disaggregation of variables while saving five major subsystems (like J. Forrester did). The truth is that in the latest version of model "World³" there has been added sixth subsystem — "Management". In addition, D. Meadows introduced into this model a large number of interconnections, about 3 times exceeding the number of them used by J. Forrester. As a result, the system was constructed from 12 non-linear ordinary differential equations for the basic variables. Calculations on the model "World³" showed that, despite the great detailization, its predictions were qualitatively and quantitatively very similar to the results obtained by the model "World 2". In the model "World 3" there have failed attempts to overcome any of the major drawbacks of the base Forrester's model. The fact is that the unnecessary complication of the model without its drastic improvement has only led to the fact that the identification of system parameters has become even more difficult, because they trebled while the amount of objective statistical data remained extremely low.

However, the results obtained by using the "World 3" model and published in 1972 in the book "Limits to Growth", which was the first official report of the Club of Rome, had a noticeable response in the world and had a significant impact on the universal understanding of world development. In this book there were firstly expressed warnings about serious threats that may arise on the way to sustainable human development due to reduced supplies of energy and other natural resources, and also as a result of intense environmental pollution. These findings had great resonance in the world; the results of them increased the attention to environmental issues and widespread introduction of energy- and resourse-saving technologies of production. Responsible political leaders realized the danger of saving the old economic model and attempted to move to a new economy based on knowledge.

However, there was also strong criticism from different points of view. According to experts' opinions, the model of the world dynamics by Forrester-Meadows was too mechanical, it did not take into account regional structure of the World-system, there occured discrepancies with the theories of economic growth, the impact of social and technological innovation was not considered. Indeed, Forrester-Meadows model allows only searching for the scenario that would prevent the crisis cituation, by computer modeling of a number of successive scenarios with increasing restrictions on the intensity of resource consumption and environmental pollution. This model does not solve the problem of management the processes affecting the development of the global dynamics.

D. Meadows and his colleagues for nearly forty years continuously studied physical limits to growth imposed by the depletion of natural resources and limited ability of Earth's biosphere to absorb industrial and agricultural pollution. The results accumulated during this time are published in the book (Meadows, Randers, Meadows, 2008) which again confirms its science-based conclusion that the trends of modern economic and industrial development are the way leading to global ecological crisis. However, they also convincingly show the possibilities for humanity to shift to sustainable development of mankind without stopping of economic development and reducing the standard of living in developed countries.

MESAROVIC-PESTEL MODEL

In the project “Strategy for Survival” M. Mesarovic and E. Pestel (Mesarovic, Pestel 1974) formulated a problem of constructing a model of the world dynamics based on the theory of multi-level hierarchical systems and reflecting the process of human interaction with the environment, as well as a complex of economic, social and political relationships in society. This model supposed to be manageable and had to include decision-making process conducted by a person. And most importantly, the world was proposed to be viewed not as a homogenous whole, but as a system of interacting regions with different levels of development and socio-economic structure.

In the Mesarovic-Pestel model, all countries were divided into 10 regions according to their socio-economic structure and level of development. Each region was described by a system of special sub-models with the same structure. Communication between regions was realized through import, export and migration. The main submodels were submodels economy, demography and energetics. Feedbacks between individual submodels were usually absent. This led to a rigid version of definition of endogenous variables for sub-models that use the calculations of other submodels as input information. In these submodels a number of parameters remained uncertain. Management was implemented through a choice of scenario by assigning values to uncertain parameters. The scenario was chosen by decision maker (DM) — a person who conducts computer modeling.

Models of Forrester-Meadows and Mesarovic-Pestel were among the major global models of the first wave. The main characteristics of these models are presented in the *Table 1.*

As a result of forecast calculations according to Mesarovic-Pestel model, it was shown that the world is facing not a global catastrophe (about the middle of XXI century as it follows fron the results of the model “World 3”), but a series of regional disasters which will begin much earlier and for many different reasons for different regions. Thus, they see the future of mankind in various protracted regional crises — environmental, energy, food, raw materials, and demographic ones. The effects of regional disasters will be felt around the world, and avoidance of global catastrophe can only be achieved by agreed efforts of international community — that was the conclusion of Mesarovic-Pestel. They argued that such crises can gradually cover the entire planet, if the international community will not take efforts to achieve a balanced development of all parts of the World-system. So Mesarovic and Pestel called their concept of world development as “organic growth”. Therefore, the undoubted advantage of this model is the division of the World-system by interacting regions, as well as specialization and focus of sub-models on the solution of specific problems.

THE DEVELOPMENT OF GLOBAL MODELING IN THE USSR

Soviet scientists from the very beginning took an active part in the work of the Club of Rome, joined the research on global modeling and became essentially the leaders of the second wave of research on global modeling. The work was carried

Table 1.1 Mathematical models for Global Development (1970s, the first wave)

Authors Organization, institution	Levels of World-system The basic variables	Theory and Principles	The final models	Publications
Forrester, J., the founder of the construction of the system dynamics mathematical models. Massachusetts Institute of Technology (MIT), USA	WORLD-SYSTEM N — number of population K — physical capital X — share of capital in agriculture R — amount of non-renewable resources Z — amount of environmental pollutions	Theory and principles of the modern dynamics Mathematical models of the global dynamics $\begin{cases} \frac{dy_i}{dt} = f_i^+ - f_i^-, i=1,n; \\ y_i(t=T_0) = y_{i0}; n=5 \end{cases}$	World 1 (1971) World 2 (1972) On the instructions of the Club of Rome	The World dynamics. Moscow, Nauka, 1978 (English version — 1971)
Meadows D., Randers J. MIT, USA The Club of Rome	WORLD-SYSTEM Subsystem "Management" was added Disaggregation of variables was held	Detalization and specification of Forrester's model Mathematical model: a system of 12 nonlinear ODE	World 3 The official report of the Club of Rome	Limits to Growth, 30 Year Update. Moscow, Akademkniga, 2008 (English version — 1972)
Mesarovich M. (USA) **Pestel E.** (West Germany) The Club of Rome	WORLD-SYSTEM Division into 10 interacting regions Each region is described by a system of submodels	The theory of multi-level hierarchical systems Management and decision-making theory	Submodels of economy, demography and energetics based on structural differential equations	Mankind at the Turning Point. — Second report to the Club of Rome. 1974

out widely by Scientific Research Institute for System Studies of the RAS under the leadership of D.M. Gvishiani and by Computing Centre of the Russian Academy of Sciences under the leadership of academician N.N. Moiseev. The key innovation in these researches was the introduction of control parameters and studying of the possibilities of global processes management. There was proved the existence of controls that allow moving, lessening or even avoidance of the negative effects of global development *(Gelovani, Egorov et al, 1975)*. However, a high sensitivity of global models to the null hypothesis, the basic statistical information *(Gelovani, Britkov, 1979)* was also shown. Hence the conclusion that the possibility of application of mathematical methods of management and optimization has limited practical use for this kind of macro models. Therefore, further development of global modeling in the USSR went on the path of improvement of tools of computer support for decision-making processes and information management in the framework of modified Forrester-Meadows model. The concrete results of these studies culminated in well-known "Nuclear winter" model created under the direction of N.N. Moiseev

(Moiseev, Alexandrov, Tarko, 1985) and the report "On the threshold of the third millennium (global problems and processes of the USSR)" prepared under the direction of V.A. Gelovani. More detailed information of all this can be found in the article *(Dubovsky, 2010).*

First, the model of the world dynamics with management was proposed by V.A. Egorov *(Egorov, 1980).* His idea was to create new industries for recycling and recovery of resources to clean up the environment from pollution and re-cultivation of lands. Then it was possible to manage the processes of natural resources use, pollution, food production areas by the direction of required amount of capital in these industries. Naturally, this requires a redistribution of capital which can be optimized by a certain criteria. In mathematical model, the idea of managing a variable is implemented by adding to the right side of a proper ODE (2) an additional term containing as a factor a share of capital that is submitted to a new industry, serving subsystem. The latter serves as a control parameter. If we set all control parameters as a function of time, they will define a certain scenario of the World-system development. Next, we solve the problem of optimal management for a given criterion.

The group of V.M. Matrosov created a detailed and modified model of Forrester and Meadows with management of V.A. Egorov *(Matrosov, Izmodenova-Matrosova, 2005).* The distinctive feature of this model consisted in the fact that it did not set a problem of optimization according to some criterion. Moreover, the laws of variation of control parameters were rigidly defined and, in addition, the functional connections between the control parameters and the main variables of the model were introduced. Modification of Forrester's model was, in particular, in the use of more accurate equations describing system variables. For example, the economy sector was described by the neoclassical production function which expresses the dynamics of GDP and consideres the movement of capital, demographic dynamics and scientific and technical progress. Within the framework of derived model stationary solutions were found and their stability was proved. The disadvantages of this model include the complication of modification, making its identification problematic.

The main characteristics of global models of the second wave developed in the USSR are presented in the *Table 2.*

THE MAIN DIRECTIONS OF GLOBAL MODELING IMPROVEMENT

The next wave of interest to the issues of forecasting the future was born in the 1990 in connection with the approach of the third millennium and natural desire to look into a new century, a new millennium. During this period, a number of studies in which the authors tried to make sense of the results of rapid XX century, with its two world wars, the unprecedented development of scientific and technological progress and the demographic explosion, as well as to imagine world development in the XXI century were performed. As a result, a number of futurological prediction and science fiction occured, which had no direct relation to the global modeling.

By the way, the global modeling itself in the 90's of the last century has sharply decelerated, although for the studying of various aspects of the global dynam-

Table 2. *Global modeling and sustainable development with management (USSR — Russian Federation)*

Authors and writing teams Organization, institution	Theory and Principles	Models	Publications
Academician Gvishiani D.M., Gepovani V.A., Britkov V.B., Dubovsky S.V. et al. All-Union Research Institute for Systems Studies	The key innovation is the introduction of management and exploring of global processes management possibilities	1. Improvement of Forrester's model and the instruments of computer supporting 2. World-system and 9 regions	Report: On the threshold of the third millennium (global problems and processes of development in the USSR) — 1984
Academician Moiseev N.N., Alexandrov V.V., Tarko A.M. Computing Centre of the Russian Academy of Sciences	The noosphere doctrine System analysis Mathematical models of climate and global biogeochemical cycles	1. Global model of biosphere 2. Model of "Nuclear winter"	Man and the Biosphere. — Moscow, Nauka, 1985.
Prof. Egorov V.A. and a group of colleagues Keldysh Institute of Applied Mathematics RAS	The applying of optimal management theory to the global dynamics processes was first proposed	Mathematical model of the global dynamics with control parameters	Mathematical models of the global development. — L: Gidrometeoizdat, 1980.
Academician Matrosov V.M. and a group of colleagues RAS SB	Sustainable development Replacement of individual standard DE on the structural DE	Modified Forrester-Meadows model with Egorov's management	The noosphere doctrine, global modeling and sustainable development. — Moscow: Academia, 2005.

ics all around the world there were many research institutions and laboratories. A huge number of people were engaged in this work. However, the gradual complication of models led to the fact that they ceased to express the true cause-and-effect patterns. The majority of experts agree that sophisticated models developed in the 1980's did not justify their expectations, because they didn't make it possible to predict the actual development of economic processes. S. Kapitza *(Kapitza, 2008, p. 24)* cited in this context one remark of an American economist and Nobel Prize winner Herbert Simon that "forty years of experience in modeling complex systems on computers that are getting more and more rapid taught us that the brute force does not lead to the royal path of understanding of such systems… thus, modeling requires appeal to the basic principles that will lead us to the resolution of this paradox".

In recent years, the world has witnessed a new upsurge of activity in the field of geo-physical, ecological and socio-economic forecasting of the future. This is due to the aggravation of environmental and energy problems of mankind. Food problem also can significantly worsen together with considerable population growth. Unfortunately, the environmental load of humanity continues to grow, despite the advances in technology and the efforts of non-governmental organizations. The situation is complicated by the fact that humanity has gone beyond reasonable limits and finds itself in the area of unsustainable development.

Thus, at the turn of the centuries an extremely important and urgent task of ensuring sustainable development throughout all mankind has clearly shaped *(Meadows, Randers, Meadows, 2008).* Achieving sustainable economic growth makes the development of long-term forecasts, allowing forming the long-term goals and strategies to achieve them not only possible, but postulate it as a necessary condition. It should be noted that socio-economic forecasts are carried out in different time frames — from short-term (one year), medium-term (from one to five years) to long-term (from five to 30–50 years).

If the purpose of short-term models is forecasting aimed at opportunistic activity, and medium-term models are to select a development policy in the near future, the long-term models are designed to investigate the conditions of sustained economic growth. Long-term models are primarily models of growth theory in the sense that they are an instrument for the study of future state of society according to its development strategy.

In recent years we have witnessed the emergence of serious scientific forecasts designed for three decades, and even for a half-century perspective, for example, forecasts of "PricewaterhouseCoopers" Corporation — *"The World in 2050" (The world in 2050, 2006*) and "Goldman Sachs" — *"Dreaming with BRICs: the path to 2050" (Wilson, Purushothaman, 2003).* However, as a rule, such forecasts are within the powers of only large interdisciplinary research teams. In many countries of the world forecast for decades, and even for 30–50 years are now developed. In such prognostic and similar projects of recent time very simplified models were used, which are unlikely to meet the modern requirements. For example, in the construction of mathematical models describing the dynamics of the socio-economic development the neoclassical model of growth by Solow, based on the traditional production function of Cobb-Douglas is used:

$$Y = AK^{\alpha}L^{1-\alpha}, \quad (1.5)$$

where K is physical capital, L — labour force, A — technical progress or total productivity of factors, α — share of income that results from the growth of capital expenditures. Under the technical progress Solow understands not only new technologies, but also a new level of knowledge and skills of the labor force, new materials, and new forms of organization of production. However, the development of human capital is better taken into account in models of endogenous economic growth, a simplified version of which was used in the model of "PricewaterhouseCoopers" corporation. It should be noted that most of the global models of the first and second generations used different versions of neoclassical growth model of Solow to describe a block of economic dynamics.

The main drawback of described model is that it is based on supply-side economics. Consequently, the model ignores a factor of solvent demand and comes only from the expected dynamics of production factors. However, the era of supply-side economics has passed for long time together with neoclassical economic theory. An era of economic demand, the Keynesian era, is coming again. It follows that the new dynamic macro models of the economy are to be built with the account of a joint action of long-term equilibrium growth and cyclical fluctuations around it determined by supply and demand. This is the main direction for the improvement of currently used mathematical macro models of socio-economic development dynamics.

The interaction of cyclical fluctuations and growth trend are the very things that reveal a bifurcation point, where the economic system becomes unstable and could plunge into a crisis recession *(Akayev, 2008).* Thus, considering the joint interaction of cyclical fluctuations and growth allows predicting the timing of the crisis, whereas the traditional model only described trend trajectory and could not predict the crisis and recession. The latter was regarded by critics as the main shortcoming of global models of the first and second generations.

As for the deep cyclical crises repeated every 30–40 years and associated with the change of technological structure, the change of great Kondratieff cycles, for their forecasting it is necessary to synchronize long-term models with real Kondratieff cycles either globally or within the national economy. This allows safe and relatively accurate setting of forecasting horizon which is determined by the duration of the next great Kondratieff cycle and measured in 30–40 years. It is also important that in this period of time one and the same technological system is operating; this guarantees the stability of characteristics of technological progress and, therefore, the constancy of production function parameters (1.5). The fact is that the parameters of production function, first, are different even for countries at similar levels of economic development, and secondly, they are different at different stages of development in the same country. So the synchronization of economic growth model with great Kondratieff cycle simplifies the problem of identifying the parameters. In the models of Forrester-Meadows and Mesarovic-Pestel, the hypothesis of the constancy of these parameters on the long time period of about 1000 years were taken; this certainly does not hold, because two technological structures are laid in this period of time, and each of them has its own parameter values. This in many respects explains the low accuracy of these models which becomes unacceptable for high horizons of modeling — forecasting.

One of the main drawbacks of first generation global models was the description of selected global processes by differential equations of the same type and standard form (1.2), they did not take into account the internal properties and mechanisms of processes development. J. Forrester, D. Meadows and their followers described the right sides of equations (1.3) as it was appropriate in econometrics — on the base of existing statistical data rows processing, which in most cases were very scant. This explains the low accuracy of global modeling results of the first wave. In this regard, in the development of global models of second generation a special emphasis was laid on structural models describng the internal mechanisms of the impact of factors that determine the development dynamics of key global processes and the World-system as a whole.

Structural models of global processes are based on appropriate scientific theories revealing the nature of these processes, the causal relationships within them. Obvious examples are global models of interaction between mankind and biosphere of the Earth, developed under the direction of Academician N.N. Moiseev *(Moiseev, Alexandrova, Tarko, 1985)*. An integral part of these models is climate model based on the achievements of classical science: fluid dynamics, thermo-dynamics and calculus mathematics. It is important that climate model allowed identifying changes in climatic characteristics arising due to anthropogenic factors. Thanks to this the model for the first time in 1983 provided an analysis of climatic consequences of a hypothetical nuclear war and to see how climatic parameters change a year after the nuclear disaster, how nuclear night gradually occurs and gets clarified. Of course, drawing Forrester's equations of the form (1.2) wouldn't make it possible to achieve something like this.

Therefore, one of the most important areas of improvement models of global processes is the usage of structural models as the most reliable and accurate. Structural models are already widely used in demographic and economic forecasting; it will be shown in this paper. It should be noted that structural models of socio-economic processes are fundamentally different from the structural models of physical phenomena. In contrast to physical phenomena, socio-economic processes are usually self-organizing, self-developing, i.e. they are themselves involved in the programming of their behavior. For such systems modeling it is not enough to describe the internal structure of its elements interaction, we should still provide for the emergence of new properties of self-organization and self-development, which can not be derived from the properties of the individual parts of the system *(Golanskiy, 1983)*.

True, this specific of socio-economic processes is not always taken into account when modeling. For example, the model of Forrester — Meadows, created in the form of interaction between subsystems feedback contour, ignored the integral characteristics of social system reducing them to a simple sum of the properties of subsystems components. The authors of the second forecasting model prepared for the Club of Rome — M. Mesarovich and E. Pestel — pointed at this drawback of Forester — Meadows model. The realization of sub-systems principle, proceeding from the interests of the whole, requires the construction of a multi-level hierarchical model, and this is precisely what the named authors did not succeed in.

2. Hierarchical dynamic modeling of the world dynamics

The undertaken above analysis of existing models and approaches to the modeling and forecasting of global development indicates the presence of hitherto unsolved problems and urgency of creating a hierarchical system of mathematical models to describe the macro trends and cycles of global and regional dynamics. In this system of modeling it is appropriate to allocate three interconnected hierarchical levels:

- modeling of the general trends of the world as a whole system;
- modeling of regional dynamics peculiarities; and the global dynamics is the result of regional cooperation and contradictions;
- modeling of socio-economic dynamics of individual countries in the context of world and regional development.

Accordingly, the composition of models should be formed:

• At the first level of modeling there is dynamic model of the World-system as a whole, intended for analysis of trends in the world development.

• At the second level of modeling there are models of regional dynamics intended for a more detailed description of global socio-economic changes with the uneven development of individual countries and regions.

• The results of the study of macro processes on the first and second levels of modeling set the external conditions and restraints for modeling at the third level which is the level of individual countries.

• At the third level of modeling there are models of particular countries intended for the analysis and prediction of their development in the context of the existing limitations and scenarios formed on the first and second levels of modeling.

Models of each level should be designed in order to enable concretization and expansion of their capabilities for solving particular problems. Thus, the models should have a "core" which describes the most important, basic processes related to each level of modeling and also to allow completing the "core" with individual blocks for more detailed description of particular phenomena and processes.

Three most important directions of improvement of global modeling were identified and formulated above. All of them are summarized in the *Table 3* for illustrative purposes.

Separately, it should be said about the importance of taking into account the cyclical processes in the global dynamics associated with uneven development of technology and innovation.

The world economic crisis that began in 2008 and was caused by the problems that have arisen in the U. S. financial sector, has led to a slowdown in many developed and developing economies of the world. The U.S. economy entered into a phase of prolonged instability and experienced a deep recession. A real threat of a new wave of economic recession remains. This situation portends new crises and long-term depression in the world economy in the coming decade.

All this has once again reminded the politicians, economists and businessmen about the uneven, cyclical nature of market economy development and the need to take drastic measures to identify a new

Table 3. *Basic directions of improvement of mathematical modeling of global processes.*

Directions of improvement	What is achieved
Use of socio-economic and geopolitical development patterns arising from the theory of great Kondratieff cycles	Reliable forecasting horizon about 30–40 years
Consideration of the impact of short-term cyclical fluctuations (self-oscillations) on the trend path of long-term development for the identification of critical phenomena	This allows determination of the bifurcation point and the point of failure into the crisis economic recession
Using of structural differential equations to describe the global processes by their deducing from the laws and mechanisms of relevant processes passing	This provides high accuracy and reliability, simplifies mathematical models

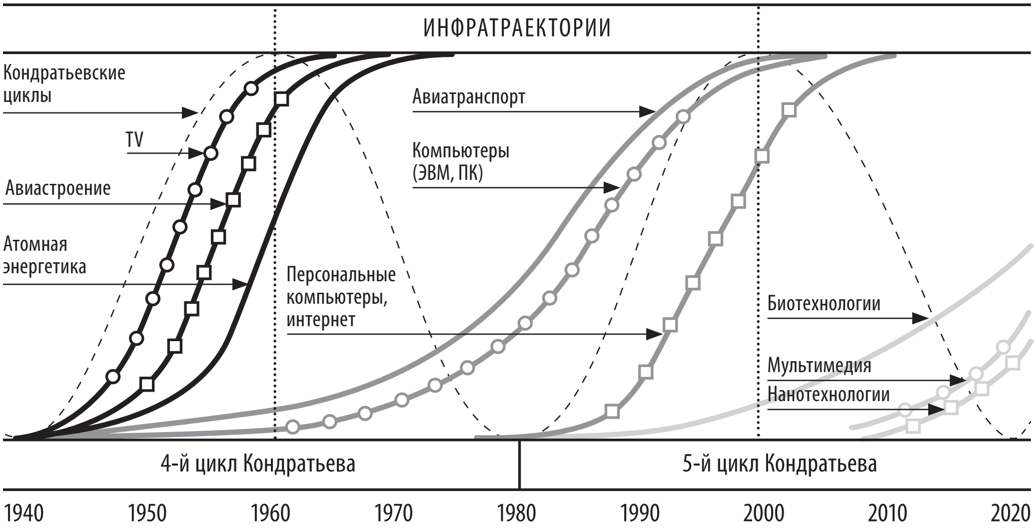
generation of basic technologies and the introduction of various innovations based on them, in order to overcome, painlessly as possible, the impending crisis and depression. In this regard, many researchers *(Glazyev, 2010; Klinov, 2010)* turned their eyes to the coming great Kondratieff cycle, uprising of which will probably be held in the 2020–2040, and they already make forecasts about its parameters and key basic technologies.

In 1912, the great economist of the twentieth century, Joseph Schumpeter, pointed out that the main driving forces of economic development are scientific and technical innovations. He wrote *(Schumpeter, 1982)* that when the innovation that is being introduced into the economy, we have the so-called "vortex of creative destruction" that undermines the balance of old economic system, causing retirement of old technologies, obsolete organizational structures and the emergence of new industries, new institutional capabilities, resulting in an unprecedented dynamism of economic development. Innovations are increasingly acting as a locomotive of economic development, determining its effectiveness and productivity of labour force. Innovations as a process are supported by the investments and related institutions, without which the mechanism to implement them does not work. Investments without innovations are meaningless and sometimes even harmful, because they mean investing in the reproduction of obsolete goods, products and technologies.

Scientific and technological progress in general, and the process of innovation, as it is now widely recognized, develops unevenly over time, namely — cyclically. This results in cyclical fluctuations of economic activity. Long-wave oscillations opened by the prominent Russian economist Nikolay Kondratieff *(Kondratieff, 2002)* were in the focus of researchers in the XXth century. Studying in the 1920s laws of the world economy phenomena, he discovered long cycles of economic conditions around a half-century duration which become called "great Kondratieff cycles". He fully justified the natural connection between "upward" stages of these cycles and waves of technical invention and their practical application in the form of innovation.

J. Shumpeter developed Kondratieff's doctrine of great cycles of conjuncture and elaborated an innovative theory of long waves, integrating it into the overall innovative theory of economic development *(Schumpeter, 1939).* Schumpeter considered cyclical movement of production as a form of deviation from the equilibrium which the economic system always seeks for. Spontaneous clots of innovation cause radical changes in the economy that lead it away from the primordial equilibrium path. The system never returns to its previous equilibrium. A new cycle begins during the next depression on a new level of equilibrium. According to Schumpeter, the change of equilibrium levels determines the long-term trajectory of economic development in which the economic system stays in dynamic equilibrium. Since the theory of great Kondratieff cycles plays a key role in Schumpeter's innovation theory of economic development, as well as the fact that Schumpeter considered it as a cornerstone of his theory, it would be fair to call the latter in the future the "innovative-cyclical theory of economic development by Schumpeter-Kondratieff".

Figure 1. *The diffusion of innovations along the cycle raise of Kondratieff's economic activity*



Most recently, M. Hirooka *(Hirooka, 2006)* showed on the base of processing and analysis of a large array of empirical data the close correlation of innovations and great Kondratieff cycles, and first confirmed that the diffusion of innovations is strictly synchronized with the upward wave of Kondratieff cycle and reaches its maturity in the highest cycle peak, as it is shown in the *Figure 1.* And different basic innovations, thanks to the action of self-organization, form a cluster and appear as a group on the stage of depression. This phenomenon was discovered by Gerhard Mensch *(Mensch, 1979)* who called it "a triggering effect of depression". In other words, depression forces companies to seek opportunities for survival, and the process of innovation can provide them, that is, depression starts the process of innovation. Clusters of basic technologies lead to emergence of new industries and, in turn, launch the next great Kondratieff cycle. Due to synergetic effect of innovations interaction within the cluster, they produce a powerful cumulative growth of economy; that is why they are the main driver of economic development.

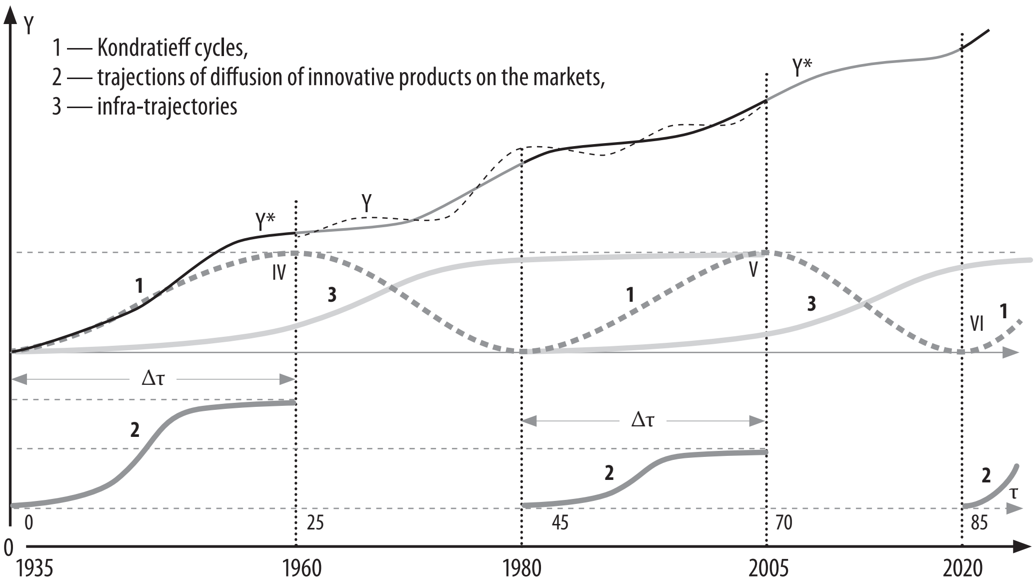
Certain innovations extend beyond one Kondratieff cycle to the next one *(see Figure 1)*, contributing to the emergence of new infrastructures and networks, creating a longer trajectory of development which M. Hirooka called an infra-trajectory (for example, computers, aviation, biotechnology, etc.). Those innovations are called main (stem); they first spread in order to create new markets, but then their potential expand to form a new infrastructure in the economy. Infra-trajectories also form a sharply defined clusters, each of such clusters has a backbone main innovation. For example, in the current fifth Kondratieff cycle computer technologies act in this capacity.

Proceeding from the new innovative paradigm established by M. Hirooka, knowing of current infra-trajectories which are defined by main innovations of previous Kondratieff cycle, as well as the trajectories of basic innovations of the current Kondratieff cycle, we can build a predictive trajectory of dynamics of innovation and economic development, as it is shown graphically in the *Figure 1.2.* This is achieved by the summation of total value added generated by the basic innovation in the current Kondratieff cycle, and the value added created by institutional changes and a restoration phenomenon caused by infra-trajectories. The GDP trajectory has a characteristic stepped form, and, as Schumpeter argued, each step is best described by logistic curve which is a consequence of changes in economic conjuncture in accordance with the phases of great Kondratieff cycle. *Figure1.2.* presents the period of time that includes the fourth (IV) and fifth (V) Kondratieff cycles. Reliable forecasting could be extended at least until 2040, that is — the top of the sixth (VI) Kondratieff cycle peak.

The described above process of innovation and cyclical development of market economics has been formalized and described in the paper *(Akayev, Hirooka, 2009).*

In the 80s of the last century, after a global economic crisis, a heightened attention was given to the study of theory and practical applications of great Kondratieff cycles and there was a great number of works on this subject, including the development of mathematical models. However, mathematical models of that time were aimed at a qualitative analysis of cyclical fluctuations, at the definition of their key parameters such as cycle duration, the characteristic points, etc. One of the first mathematical models of Kondratieff's long wave was

Figure 1.2 *Graphical scheme of the construction of the trajectory of total output Y (GDP)*



proposed in the work of S.M. Menshikov and L.A. Klimenko *(Menshikov, Klimenko, 1984)*. It was a system of first order differential equations with delays. The model naturally generates oscillations similar to those of the economic conjuncture in Kondratieff cycles. It also allows very rough estimation of cycle duration and the turning points of the long waves. Dubovsky S.V. developed a more sophisticated model *(Dubovsky, 1995)* in which the cyclical development is embedded in the model of economic growth. In this model, GDP dynamics is described by the differential equation derived from the neoclassical growth model of Solow, and is completed with the investment model, respective to the technological cycles generating Kondratieff cycles. Dubovsky model also allows carrying out a qualitative analysis of differential equations solution and more precise identifying the periods of long waves corresponding to great Kondratieff cycles, as well as characteristic point related to the rise and fall of Kondratieff cycle.

An important task is to continue these studies in order to describe quantitatively the mechanism of innovation and cycle economic development by Kondratieff-Schumpeter, as well as, apart from the qualitative analysis of the impact of cyclical fluctuations on the long-term growth, to be able to calculate the trajectory of GDP, to evaluate the cycle duration and to predict the times of crisis recession in the economy.

The main objects in the emerging system of hierarchical modeling — forecasting are economy, demography, scientific and technological progress, natural resources and ecology. They determine the order parameters — those slow variables under the behavior of which the rest will adjust. The key parameters of order in the world history were and remain the number of population (N), available resources (R), the level of technology (A) and education (E), as well as national income (Y) depending on them. The following chapters there will provide specific implementation of described in this section program of the improvement of global mathematical modeling.