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Information and Communication Technology for Developing the National Innovation System

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***Abstract*—The article reveals new theoretical and methodological aspects of information and communication technology implementation into the national innovation system. Analysis of the role of information and communication technologies for developing the national innovation system is based on the structural-functional approach implemented in a mathematical model. The mathematical model reflects the target sequence of stages of the economic and mathematical modeling cycle which shows functions of logical interrelationships of model elements in a numerical form. To determine priorities of development of the national innovation system, interdependent elements (technical and communication tools, organizational and methodological support) were identified. The efficiency indicator for information and communication technologies reflects the state and prospects of technical and communication tools forming the environment for the effective use of limited resources and reproduction of the innovative product by the national innovation system, as well as organizational and methodological support creating conditions for the adequate use of information and communication technologies. The mechanism, sequence and procedures for implementation of information and communication technologies are presented. They allow to follow acceptable practical recommendations and proposals when applying level segmentation which determines the rationality of hierarchical structuring of innovative processes and their organizational and target development. The article analyzes a management system for the national innovation system and describes its operation principle. The need for forming a constant set of parameters and regular assessment of integral indicators of the efficiency of the national innovation system and its attractiveness for innovators and investors (monitoring of the dynamics of innovative, economic, social and other processes) based on the mathematical model for evaluating the efficiency of information and communication technologies was substantiated. For adjusting management procedures and development of optimal management decisions, a rational scheme for evaluating the efficiency of the management system of the national innovation system was developed. It involves comprehensive assessment of prospects and risks.**

Keywords*—information and communication technologies; mathematical model; mechanism; national innovation system; organizational and methodological support; management system

I. INTRODUCTION

Analysis of the theoretical and methodological aspects of information and communication technologies (ICT) used for development of the national innovation system (NIS) is an important task for creating conditions of the expanded reproduction process determining the development and explaining the nature of economic phenomena.

ICT are methods for applying computer equipment when collecting, storing, processing, transmitting and using data. The NIS is a system based on innovations, constant technological improvement, production and export of high-tech products with very high added value and technologies.

It is difficult to define the effective innovation policy in developing countries [1, 2, 3]. The assessment of the modern national innovation system shows the propensity of the Russian state to preserve the traditional system. The results of current policies speak for further degradation of the national innovation system [4]. At the same time, over the past three decades, the

NIS has acquired great intellectual and practical importance [5, 6].

When studying the role of ICT for NIS development, it is appropriate to apply the structural-functional approach to display ICT elements interacting in an order established through federal and regional legal acts taking into account the priority of tasks and determined by the NIS status. The NIS as an object of management should be considered as a multi-component economic space developing due to activities of public authorities aimed at achieving one goal and solving specific tasks.

II. Mathematical Model

Modern conditions for NIS development impose restrictions on methods for introducing ICT due to transformation of economic ties and more “tough” competition for limited resources. The unsustainable state of the NIS caused by these restrictions dictates the need for correct assessment of causes, factors and incentives for ICT implementation.

When developing a mathematical model for evaluating the ICT efficiency, it is necessary to take into account the “classical postulates” of innovative systems. First, the innovation system is influenced by external and internal factors determining the NIS. Secondly, the NIS is a complex (large) system having diverse constituent subsystems (a wide range of volatile and invariant external and internal links) and self-organization elements. Thirdly, in various innovation systems, there are different interrelations, motivations, needs and goals, priorities and degrees of importance.

At the same time, one should expand the NIS analysis using the image of complementary symbiosis of its subsystems. The NIS is a symbiosis of complex probabilistic dynamic subsystems encompassing processes of interaction between economic agents and managerial relations in the innovation reproduction cycle.

The main method for studying the morphogenesis of ICT efficiency is a modeling method, a method of theoretical analysis and practical action aimed at developing and using optimal models. In the mathematical model developed for evaluating ICT efficiency, it is advisable to adhere to the target sequence of stages of the economic and mathematical modeling cycle.

It is necessary to numerically express the functionality of logical interrelationships of ICT elements affecting the NIS structure caused by exogenous and endogenous factors. For correct reasoning, we will define the system to reveal its utilitarian image.

The system image is characterized by elements, links between these elements, as well as by the holistic combination of these elements. Emphasizing the system criteria, one can define the system research as a set of scientific problems interpreting the objects as a set of interrelated elements acting as a whole. On the one hand, a system is a physical reality with respect to which decisions are made; on the other hand, the system analysis creates an abstract and conceptual system described by symbols or other means which is a definite structural-logical tool for understanding, describing and optimizing the behavior and relationships of the elements of a real physical system.

The NIS is a targeted system used for achieving high values: the index of economic freedom, the education and science development level, the technological structure of the economy [7], living standards, cost and quality of intellectual capital [8], competitiveness of the economy, the share of innovative enterprises and innovative products [9], competition and demand for innovations, redundancy of innovations, developed industry of knowledge and knowledge export.

When developing a mathematical model for evaluating the ICT efficiency and choosing effective methods for influencing ICT implementation, it is necessary to determine a priority direction (strategy). Setting priorities in innovation development, it is necessary to determine the structure of indicators, restrictions, an executive function, a performance criterion and a solution. When developing a mathematical model, the basic principles should be applied to define the NIS as an innovative system: systematic, complex, long-term, conjugacy, continuous variability, counterintuitive behavior of complex Forrester systems, stable imbalance, sufficiency, conformity, optimality, emergence, formalization.

In order to systematize the process of ICT efficiency assessment, it is necessary to single out interdependent elements: technical and communication tools (TCT); organizational and methodological support (OMS) which fits into the classical canons of theoretical innovation.

The TCTs form the environment for effective ICT, the OMS is conditions for development.

By structuring the TCTs and the OMS, one should take into account the systemic principle of interdependent elements, according to which it is impossible to determine the most significant element (priority is objectively untenable). The results of the ICT efficiency assessment should reflect the state and prospects of the use of TCTs forming the environment for the efficient use of limited resources and reproduction of the total innovative NIS product and the OMS creating conditions for proper use of ICT.

When evaluating the ICT efficiency, a number of indicators can move into the category of parameters. It is necessary to have cognitive intuition and logical reasoning to choose a parameter so that the nature of the change in a function is universal.

Let us present the imperatives of the ICT efficiency assessment. First, the parameters determining behavior of the system can be characterized by two values: the value of the parameter at a given time and its hodograph (direction and variation trends). All parameters are numerical and vector values. They depend on other parameters which are vector values as well. When describing the NIS, it is necessary to use vector values. If we take into account that each vector depends on other vectors, we get a vector field described by matrices.

Secondly, the system is a set of interrelated elements which form a certain unity. The combination of elements is a system when there are certain connections between them.

The mathematical model for assessing the ICT efficiency is based on the analysis of dependencies of significant "vector-function" indicators:

$$F(t) = F(\tilde{o}_1(t), x_2(t), x_3(t),..., x_n(t), y_1(t), y_2(t), y_3(t),..., y_n(t), z_1(t), z_2(t), z_3(t),..., z_n(t)) = F_{TCT}(t) \times F_{OMS}(t) \quad (1)$$

$$F_{TCT}(t) = F_{TCT}\left(\left|\frac{X(t)}{X(t)+Y(t)}\right|\right) \quad (2)$$

$$F_{OMS}(t) = F_{OMS}\left(\left|\frac{Y(t)}{X(t)+Y(t)}\right|\right) \quad (3)$$

$$X(t) = \prod_{n=1}^{N} f_{x_n}(Z(t)_n) \quad (4)$$

$$Y(t) = \prod_{n=1}^{N} f_{y_n}(Z(t)_n) \quad (5)$$

$$Z^*(t) = \coprod_{n=1}^{N} f_{z_{nn}}(x_n, y_n) \equiv Z^*(t) = \prod_{n=1}^{N} f_{x_n}(Z(t)_n) \times \prod_{n=1}^{N} f_{y_n}(Z(t)_n), \quad (6)$$

where $F(t)$ is the ICT efficiency surface; $F_{TCT}(t)$ is the TCT development efficiency; $F_{OMS}(t)$ is the OMS efficiency development; $Z(t)$ is the first factor variable - the ICT indicator at certain t; $X(t)$ is the second factor variable - the logical dependence of the significant TCT indicator on $Z(t)$; $Y(t)$ is the third factor variable - the logical dependence of the significant OMS indicator on $Z(t)$; $Z^*(t)$ is the NIS indicator at certain t.

The process of mathematical ICT assessment model implementation is presented as a two-dimensional array (matrix).

The first stage is regression analysis.

$$f_x(z) = f_x(i) = a \times i + b. \quad (7)$$

Regression equation is

$$x(i) = a \times i + b, \quad i = 0,1...100. \quad (8)$$

$$f_y(z) = f_y(j) = c \times j + d. \quad (9)$$

Regression equation is

$$y(j) = c \times j + d, \quad j = 0,1...100 \quad (10)$$

The second stage is performance evaluation.

$$Z_{ij} = f_{ij}(x(i), y(j)). \quad (11)$$

TCT is determined by formula

$$F_{i_{ij}} = \left\{\left|\frac{x(i)}{x(i)+y(j)}\right|\right\}. \quad (12)$$

$$\text{OMS} - F_{j_{ij}} = \left\{\left|\frac{y(j)}{x(i)+y(j)}\right|\right\}. \quad (13)$$

$$\text{NIS} - Z_{ij}^* = \left\{\left|\frac{x(i)}{x(i)+y(j)}\right| \times \left|\frac{y(j)}{x(i)+y(j)}\right|\right\}. \quad (14)$$

Selection of indicators depends on goals and individual abilities of the researcher. A mathematical ICT efficiency assessment model allows choosing a system-forming and aggregated TCT and OMS indicator which is dominant in the ICT. Using this indicator, the assessment can be a reliable representation of the NIS morphogenesis.

III. ICT Implementation Mechanism

One of the logical research-related tasks is development of an ICT implementation mechanism. In order to substantiate the choice of a rational and optimal method for solving this problem, as well as a set of management decisions for ensuring the ICT efficiency, let us consider the sequence of interrelated elements of the ICT implementation mechanism:

1. The mathematical ICT efficiency assessment model (see above) will reveal significant factors affecting the NIS.

2. Recommendations on formation of a regional innovation system (RIS) [10, 11, 12]: effective use of regional resources and infrastructure, elimination of restrictions; improvement of competitiveness of high-tech industries by regulating production mobility and creating conditions for innovative activity; growth of economic, social, institutional, legal quality of regional innovation policies; development of regional self-sufficiency factors due to effective interaction on regional markets, reduction of administrative barriers and restrictions, formation of zones of innovative activities.

3. Projects aimed at controlling economic agents of the Russian regions: formation of the legal environment of innovation activities; coordination of regional innovation policies aimed at reducing regional contradictions; organization of effective use of financial, economic and institutional resources.

4. Intraregional tools for implementation of innovation measures: regional funds to promote implementation of federal innovation programs based on the principles of public-private and cooperative-state partnerships; regional monitoring system [13]; use of regional financial resources for development and implementation of federal innovation policies and programs promoting their implementation.

5. Tools for implementing innovation policies at the federal level: Federal Target Program for Innovative Development; government monitoring of innovative development of regions; use of federal funds for development and implementation of

federal innovation policies and programs promoting their implementation in regions; use of federal funds for innovation development; federal financial assistance regions and municipalities.

ICT implementation procedures involve clarification and formalization of organizational and target development of the NIS by determining the quality of internal communications and relationships with other systems and the external environment. Procedures have a closed cycle and consist of three processes (analysis, organization and control) divided into seven steps: Step 1 - analysis of modern mathematical models for evaluation and ICT implementation mechanisms in order to determine limits of invariance of the typological image of developed methodological tools; Step 2 - development of the mathematical model for evaluating the ICT efficiency on the basis of system principles establishing the direction of processes and taking into account specific conditions for localization of elements; Step 3 - formation of the ICT implementation mechanism based on the laws and postulates of systemology taking into account specific features of the process of diffusion of structural elements and optimization of interrelations (functions) of elements; Step 4 – application of the level segmentation of ICT implementation and identification of priority directions for NIS development; Step 5 - development of practical recommendations and proposals for ICT implementation for determining the harmonious form of control actions, ensuring a steady NIS development trend; Step 6 - making management decisions; Step 7 - formation of a system of indicators through systematization of the results of implementation of management decisions in the form of the “appropriateness” of ICT implementation.

The sequence of ICT implementation procedures is formed within the postulated statement: to establish priority NIS development directions and develop practical recommendations and proposals, level segmentation should be used. It determines the rationality of the hierarchical structuring of innovation processes in the context of organizational and target development. Organizational-target NIS development is achievement of mutual and cumulative conditionality of TCT and OMS elements which can create conditions for ICT implementation by expanding the range of synergistic relationships. The ICT implementation process is a complex mechanism of interaction between structures, regulators, organizational and economic factors of the NIS which ensure the functioning of the innovation system in the form of laws (self-development, transformation, integration, relativity, priorities, harmonization, system) and principles (hierarchy, adaptability of all phenomena and processes in nature and society, openness of all systems, self-sufficiency, compliance of the functional space of law, information, management and economics, differences of concepts, focusing, analysis, resource self-sufficiency of the system) of systemology.

The process-oriented interaction of the TCTs and the OMS is a mechanism as a set of horizontal-vertical economic and managerial relations aimed at effective ICT implementation. In terms of the structural-functional approach, the mechanism can be represented as a conceptual model in the form of interpenetrating levels of ICT implementation. The criteria for differentiating ICT by levels are degrees of interdependence of TCT and OMS elements of each level, the ability of NIS to preserve an innovative architecture. The decisive condition for choosing TCT and OMS indicators is their specific ability at each level to meet ICT needs, use the whole range of limited resources, and achieve maximum utility.

It is possible to structure ICT implementation levels. Analyzing the NIS elements, the hierarchical structure displays directions towards NIS development and integrity of the ICT implementation process.

The first level (technology parks and business incubators) consists of independent enterprises which need ICT. In accordance with the cumulative causation and taxonomy, enterprises move to the most concentrated innovation space, setting boundaries for NIS development. The first level aims 1) to ensure optimal NIS development through an effective management system and an effective set of managerial influences; 2) to determine optimal parameters for ICT implementation and highlight the individual range of exogenous and endogenous factors; 3) to increase the efficiency of cost management for ICT implementation and create conditions for development of the TCTs and the OMS; 4) to divide management functions into external and internal, eliminating duplication and focusing on their optimization in the context of harmonious TCT and OMS operation and NIS development.

The second level (the initiators are innovative technology centers and technology transfer centers) forms systems of enterprises structured by industries taking into account the developing NIS and a new level of TCTs and OMS. In contrast to the first level, the TCTs and the OMS are structured taking into account the optimal use of resources, contributing to their effective development for NIS development. Formation of the second TCT structure level is a result of integration of goals and objectives of the organizations. When organizations are grouped, a criterion with respect to which it is possible to establish the ability of an individual organization to apply ICT in a group with industry specific goals is determined. To increase the ICT implementation efficiency, it is necessary to fulfill the condition of compliance with goals of an organization and a leading industry which can be achieved by adjusting the possibility of using new TCTs.

The third level (innovation-industrial systems, clusters, sectoral innovation systems, RIS) is determined by integration of goals and objectives of the group of propulsion organizations (“growth poles” are mechanisms which attract and create specialized factors) which are combined in partnerships for achieving mutually satisfactory results. The aggregated range of OMS elements expands, incorporating the more progressive intellectual level of a person. To give the OMS a focus on the TCTs, it is necessary to highlight priority areas and determine relevant factors. This kind of regulation will determine the specificity of the third level of ICT implementation for NIS development.

The third TCT level is presented by various types of ICT systems and government measures to develop the intellectual level of the Russian population. It is necessary to take into account the growing potential of the global TCTs and the OMS which allows NIS development.

The third level criterion is growing innovation activities (innovation activities of organizations) contributing to a targeted change in the ICT level when high living standards depend on knowledge production without increasing the volume of consumed natural resources. This type of development implies a constantly growing demand for knowledge among consumers and producers.

Third level development is a global integration cycle which includes elements of the first and second levels. In accordance with the laws and principles of systemology, there are two directions: 1) third-level optimization of organizational behavior of leading organizations taking into account measures for innovative potential development stimulation; 2) stimulation of integration processes of the tiered system in order to minimize the cost of ICT implementation. The third level is associated with the first and second levels, incorporating and connecting them according to the laws of systemic development.

The fourth level (the national innovation system) can be considered as a federal structure of or a regional confederation. The federal structure aims to preserve the integrity of the national innovation economy. At the fourth level, ICT is implemented initiating an innovative interregional innovation space preserving the NIS integrity and developing the NIS. The NIS integrity is largely determined by the "strength" of the innovative interregional space which is able to set and maintain the pace of innovation development, which is seen as a required condition for preservation of the Russian state.

The regional confederation has to be considered as a possibility of formation of regions fully preserving their independence, having their own government bodies. The declining efficiency of federal regulation of regional development dramatically increases the cost of ICT implementation.

The level system of ICT implementation is formed by combining all elements into the system through direct and inverse connections: from the bottom to top - embedding local processes into more complex processes of the upper levels and from top to bottom - creating conditions and prerequisites for normal development of the process at lower, local levels. To implement ICT, it is necessary to take into account the cyclical nature of development of the innovation system as a reflection of the law of system time. In order to increase the efficiency of ICT implementation, this cycling should be as stable as possible.

Stability is an integral property of complex systems. It can be structural or functional. Structural sustainability should be considered as a system interdependence of structural relations, a form of general objectification based on the physical and constructive idea of the system. Functional stability shows the ability of the system to maintain and / or restore logical relationships when affecting its elements.

The described level system of ICT implementation has to obey the laws and principles of systemology, possess properties of the innovation system: cyclicity, self-development, transformation, integration, harmonization, hierarchy, manufacturability, openness, self-sufficiency. It has to have sufficient cyclic stability.

IV. NIS Management System

The NIS management system (MS) scheme as a stylized, easily recognizable typological image simplified by a graphic image of connections between its elements [14, 15] reflecting the constructive directionality is presented in Fig. 1.

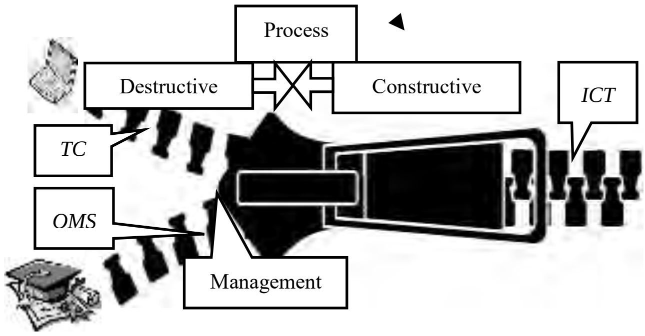

Fig. 1. NIS MS schema

The physics of NIS MS can be reflected using the principle of the Clasp Locker fastener (zipper fastener). The rationality and optimality of NIS MS is determined by its ability to provide high-quality "coupling" and "uncoupling" of TCT and OMS elements when forming and implementing the ICT. Depending on goals and consistency of federal and regional management decisions, it ensures the quality of the constructive or destructive process. The constructive process organizes optimal "cohesion" of TCT and OMS elements: optimal ICT and the corresponding form and content of economic and managerial relations in the NIS, as well as in the interregional innovation space are formed. The destructive process is aimed at "uncoupling" - in order to determine a new variant of the possible "coupling" of TCT and OMS elements under changing conditions (environment).

NIS MS materializes within the proposed ICT implementation mechanism which makes it possible to limit the possibility of making conflicting management decisions and impacts on the innovation process. The NIS MS assumes the availability of a methodological toolkit used for assessment and official reporting of indicators. For NIS MS, it is necessary to form a constant set of parameters and regularly assess integral indicators of ICT efficiency and its attractiveness for innovators and investors - monitoring of the dynamics of innovative, economic, social and other processes. NIS MS analysis should be performed using a mathematical model for ICT efficiency assessment.

In order to adjust management procedures and formulate a set of optimal management decisions (impacts), the most rational NIS MS performance evaluation scheme should be followed. It involves the comprehensive assessment of prospects and risks.

The main elements of NIS potential assessment are as follows: resources and raw materials: theoretical substantiation of the doctrine of sustainable socio-ecological and economic development, the study of possibilities and specifics of innovative market environmental management mechanism formation, verification of analytical tools designed to optimize management of recreational processes; production: identification of production costs, optimization of industry rates and development proportions determining the model of innovation policies; consumers: analysis of the level of income of the population; infrastructure: enterprises and organizations engaged in production and sale of telecommunication devices, computers, providing information, telecommunication and consulting services; the level of educational and cultural development; an institutional element is the role of administrative and constitutional laws determining formal rules of innovation.

The main elements of NIS risk assessment are as follows: economic: the probability of a decrease in economic performance, depending on the management decision; political: possible losses or reduction in profit margins resulting from government policies; social: dangers to the human or the society; environmental: adverse environmental consequences of anthropogenic changes in natural objects and factors, environmental degradation or an unstable state as a result of current or planned economic activities, possible loss of control over environmental events, likelihood of civil liability for environmental damage (life and health of third parties).

V. CONCLUSION

To determine conditions for ICT implementation into the NIS, a mathematical ICT efficiency assessment model and a mechanism for ICT and MS implementation were developed. ICT resources for NIS development were defined as a consecutive variation of TCT and OMS states according to relationships, needs and goals expressed in interrelationships of elements forming the NIS structure.

The mathematical ICT efficiency assessment model analyzes logical dependencies of significant and optimal indicators. The model identifies optimal TCT and OMS development directions, logical dependence of the significant TCT and OMS indicator on the NIS state. At the same time, it is possible to choose sufficient system-forming TCT and OMS indicators which allow full ICT implementation. The assessment using this indicator will direct the configuration of the ICT implementation mechanism to the natural implementation process. The objectivity and relevance of the assessment of indicators used for development and implementation of the ICT implementation mechanism can be improved. It is also possible to determine optimal parameters of impacts on TCT and OMS development.

The ICT implementation mechanism is a logical-structural relationship of TCT and OMS showing their optimal interaction, allowing harmoniously modifying the structural relationship depending on changing external and internal conditions. Implementation involves identification of significant factors, formation of recommendations and proposals. It involves clarification and formalization of NIS goals by solving the following tasks: to determine limits of invariance of management tools; to establish directions of innovation processes; to take into account features of innovation diffusion; to reveal the multidimensionality of the innovation process; to determine harmonious control forms; to establish the order of purposeful impact on TCT and OMS determinants; to show the possibility of focusing on previously developed practical recommendations and suggestions, etc.

The implementation of the ICT implementation mechanism ensures optimal interaction of TCT and OMS in the tiered system. The efficiency criterion is ability of the NIS to maintain a self-sufficient architecture. Within the tier system, it is possible to assess the efficiency of federal and regional authorities taking into account regional interests in innovation development. This can eliminate regional monopolism which has a negative impact on stable development of the NIS and preserve stability of the government. The level system is designed to maintain the stability of innovation reproduction.

The typological NIS MS scheme is presented as links between NIS elements showing the constructive focus of innovative processes through systematization of the structure of indicators; reflection of relationships of elements in the level system; criterion evaluation of management decision efficiency; coverage of environmental factors of direct and indirect impacts; analysis of the system; identification of the best methods for influencing deviations; selection of rational and / or optimal impact options; baseline correction; making decisions on selection and correction of parameters; making recommendations. The efficiency of the MS is assessed depending on the degree of utilization of the potential and compensation of risks due to TCT and OMS interaction.

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