A cognitive approach to modeling sustainable development of complex technogenic systems in the innovation economy*

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Abstract
Sustainable development of ecological, economic and socio-humanitarian systems is a crucial challenge in the modern world of instability and crises. To address this challenge, integrated models based on mathematical methods, models and innovative technologies are needed to manage and predict the nonlinear dynamics of these systems. Moreover, these models should incorporate humanitarian and cognitive variables that affect the behavior and decision-making of the system agents. In this paper, we present and develop a cognitive approach to modeling sustainable development of complex technogenic production systems in the innovation economy. We propose an integration model of sustainable development as a family of models for creating integrated information systems of ecological, economic and socio-humanitarian management of various social and organizational systems, especially economic objects of anthropogenic nature. We also present a cognitive model of nonlinear system dynamics that takes into account the dynamics of the humanitarian component with management in general. Furthermore, we introduce a model of innovation capital dynamics for the eco-economic and socio-humanitarian system (EESHS), as innovation capital is broader than intellectual capital by its nature and content. We derive an extended integral model of nonlinear stochastic dynamics of EESHS in the innovation space. The theoretical foundations and paradigms of our research are based on: systems of type "X", integral models and the problem of sustainable development, models such as "NMSSD" and systems such as "SEEHS", convergent technologies "NBIC" and "NBIC⊕SG".

Keywords
sustainable development, complex technogenic system, cognitive factor, innovation economy, knowledge-intensive enterprise, Industry 4.0, convergence, stochastic, human capital

1. Introduction

Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. It is a multidimen-

M3E2-MLPEED 2022: The 10th International Conference on Monitoring, Modeling & Management of Emergent Economy, November 17-18, 2022, Virtual, Online
* Extended and revised version of paper [1] presented at the 10th International Conference on Monitoring, Modeling & Management of Emergent Economy.
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sional concept that encompasses ecological [3], economic [4] and socio-humanitarian aspects [5, 6]. Sustainable development aims to achieve a balance between environmental protection, social equity and economic growth [7]. It is also a global challenge that requires collective action and cooperation among all stakeholders.

The United Nations has adopted 17 Sustainable Development Goals (SDGs) as part of the 2030 Agenda for Sustainable Development, which sets out a 15-year plan to achieve them [7]. The SDGs cover various areas such as poverty eradication, health and well-being, education, gender equality, clean energy, climate action, peace and justice. The SDGs are interrelated and interdependent, meaning that progress in one area affects and depends on progress in other areas. The SDGs also reflect the complexity and diversity of the world's problems and solutions. Currently, there is some progress in many areas, but in general, actions to implement the goals have not yet reached the necessary pace and scale. These goals have also been adapted and accepted for implementation in Ukraine [8].

One of the key challenges for achieving sustainable development is to understand and manage the complex dynamics of ecological, economic and socio-humanitarian systems in the modern conditions of instability and crises. These systems are characterized by nonlinearity, uncertainty, feedback loops, emergent properties, self-organization and adaptation [9]. They are also influenced by various factors such as technological innovations, human behavior, social norms, cultural values, political decisions and environmental changes [10]. Therefore, to effectively address the problems and opportunities related to sustainable development, integrated models based on mathematical methods, models and innovative technologies are needed.

Moreover, these models should take into account not only the physical and material aspects of the systems, but also the humanitarian and cognitive aspects that affect the behavior and decision-making of the system agents. Humanitarian factors include ethical, moral, legal, social and psychological dimensions that shape the attitudes, values and preferences of individuals and groups [11]. Cognitive factors include mental processes such as perception, memory, learning, reasoning, problem-solving and creativity that enable individuals and groups to acquire, process and apply information [12]. These factors play an important role in determining the outcomes and impacts of sustainable development initiatives.

In this paper, we present and develop a cognitive approach to modeling sustainable development of complex technogenic production systems in the innovation economy. A technogenic production system is a system that consists of human-made elements such as machines, tools, materials, products and processes that interact with natural elements such as resources, energy and environment to produce goods or services. An innovation economy is an economy that is driven by technological innovations that create new products or services or improve existing ones [13]. A cognitive approach is an approach that focuses on understanding how human cognition influences or is influenced by system dynamics [14].

The main contributions of this paper are extension of the results presented earlier in [15, 16]:

- We propose an integration model of sustainable development as a family of models for creating integrated information systems of ecological, economic and socio-humanitarian management of various social and organizational systems.
- We present a cognitive model of nonlinear system dynamics that takes into account the dynamics of the humanitarian component with management in general.

- We introduce a model of innovation capital dynamics for the eco-economic and socio-humanitarian system (EESHS), as innovation capital is broader than intellectual capital by its nature and content.
- We derive an extended integral model of nonlinear stochastic dynamics of EESHS in the innovation space.

2. Results

Currently, the determining factors of a knowledge-intensive enterprise (KE) are not so much production capacity, but rather knowledge, know-how, research and development.

The theory of production factors (PF) by the beginning of the 21st century became one of the actual research directions, covering the methodology of economic analysis and management of economic subjects. The main postulate of the theory of production factors is that the ratio of external factors of production and the internal state of the economic entity determines its strategic position in a complex and multidimensional market space, i.e. its organizational, economic and structural sustainability [17, 18, 19, 20].

The main provisions of the modern theory of PF can be formulated as follows: organizational and economic sustainability of the economic entity is determined by the ratio of available factors of production and their effective management; competitive advantages of the economic entity depend on the availability (including ownership) of strategic resources; effective management of available factors of production is provided by organizational capabilities of KE; taking into account cognitive, stochastic, humanitarian and "NOT-" factors.

A logical question arises: what properties should the factors of production have, so that the innovative development of the KE could be effective, intensive and adaptive?

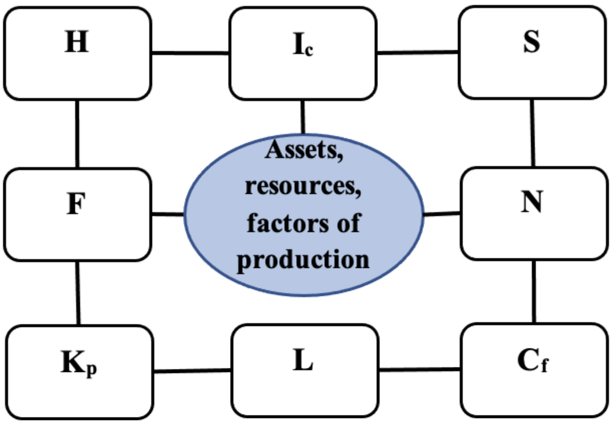
To answer this question, it is necessary to clarify the list of PF, which play a key role for the sustainable functioning and development of KEs, to introduce the concept and give a definition of cognitive factors of production; to develop a classification of cognitive factors of production, etc.

To implement this task, we will use the system paradigm, analyze the known concepts of PF and identify the main characteristics of cognitive production factors, which determine the organizational and economic sustainability of KE[1] (figure 1) [15].

Cognitive production factors (CPF). The analysis of the development of the theory of production factors and the emergence of their new types shows that the composition and role of production factors are most closely connected both with changes in production itself, and with the development of economic science, identifying and explaining the emergence and purpose of certain production factors by increasing opportunities for economic growth of knowledge-intensive enterprise.

Thus, according to the theory of human capital (the term was introduced by G. Becker [21, 22, 23]), the stock of knowledge, abilities and motivation embodied in a person contributes to the growth of human productive power. Human resources are to a certain extent similar to natural resources and physical capital, but in this interpretation they are divided into two parts.

[1]KE – knowledge-intensive enterprises of the high-tech sector of the economy. Knowledge-intensive enterprises (in other words, high-tech enterprises – HE) are technological leaders in the national innovation economy.



S	*Social capital*
F	*Financial capital*
N	*Natural capital (land, water, etc.)*
K_p	*Physical capital (main production assets)*
L	*Labor resources (manpower)*
H	*Human / intellectual capital*
C_f	*Cognitive factors of production*
I_c	*Innovative capital*

Figure 1: "Octagon" of basic assets/resources that support the sustainability and safety of the system.

The unit of "human capital" is not the worker himself, but his knowledge. However, this capital does not exist outside of its bearer. And this is the fundamental difference between human capital and physical capital – machines and equipment.

By its economic essence, human capital is closer to the intangible fixed assets of an enterprise. According to the theory of human capital, investments in human beings are regarded as a source of economic development, no less important than "ordinary" capital investments. This means that an economic dimension is applied to a person.

The modern stage of KE development is characterized by qualitative changes in the types of socially significant human activity: labor characteristic of an industrial society is replaced by creativity in a post-industrial society. Machine technology gives way to "intellectual technology". As a result, knowledge and information become the leading factors of production, which leads to a decrease in the role of material factors of production. Radical changes in production relations have led to special requirements for the quality of human resources, highlighting their intellectual component and making them an independent factor of production.

Let us introduce the concept of cognitive production factor (CPF) – it is an embodied in an economic entity totality of knowledge, abilities, skills, which contribute to the growth of human productive power in the creation of an intellectual product demanded by the market.

The convergence of intellectual resources and information technology as a productive force causes the emergence of new types of factors of production – cognitive production factors (CPF, C_f) – which means specific, difficult to imitate resources of an industrial enterprise to create a product and added value, demanded by the market.

CPF are considered as a productive force arising from the convergence of human cognitive abilities and information technology.

Cognition as a scientific-cognitive action, is moving to a new quality, providing relevant knowledge for complex research. Artificial intelligence, neurocomputers, technologies of various interfaces based on the use of the properties of the human brain [24, 25] – a fundamentally new environment of human productive activity. The use of cognitive principles in economics allows to bring the main production processes to an intellectually new level.

CPF provide internal (endogenous) opportunities for the development of industrial enterprises and, in fact, become one of the sources of endogenous economic growth [18, 19]. The management of CPF means the emergence in the practice of industrial enterprises of a specific type of organizational and economic activity associated with their identification, ranking, analysis, evaluation and monitoring at all stages of the reproduction cycle to achieve the goals of long-term economic growth.

The allocation of CPF as a new type of productive force necessitates the development of appropriate methods and models of their management, the practical implementation of which is possible due to the mechanism of integration into the overall management circuit of the industrial enterprise.

The effectiveness of methods used in the management of traditional factors of production is becoming less effective, since it does not take into account the dynamics of modern changes, the need to process a large amount of data, the structural complexity of management tasks, the need to use coordination mechanisms.

The study of theoretical and practical results of production factor management allowed us to conclude that CPF management should be integrated into the overall management circuit of a high-tech enterprise and be supported primarily by end-to-end activities implemented through appropriate business processes.

The increasing intellectualization of industrial production contributes to the fact that the distinctive features of enterprises become:

- significant individualization of products in conditions of high flexibility of high-volume production;
- the modern vector of civilizational development of society is represented by the intensive spread of global technologies: nano-, bio-, information and communication technologies. Cognitive technologies refer to the technologies of the global level, the transformative effect of which gives a new quality of interacting elements and leads to the formation of a fundamentally new technological platform for economic development;
- integration of consumers and manufacturers in end-to-end processes of the entire product lifecycle and value chain;
- integration of information and data within production networks, reflecting all aspects of requirements, design, development, production, logistics, operation, service, etc., i.e.

creation of “production intelligence”;
- globalization of product/goods development teams, as the complexity of products requires a variety of competencies;
- formation of a networked production “ecosystem” through cooperation and reduction of barriers between enterprises and customers;
- development of cloud technologies as a way to implement customized production on demand; use the production capabilities of virtual production networks based on united production sites, and support them with special software;
- isolation and accumulation of intangible functions, such as research and forecasting of the market and demand, formation of the product concept, formation of technical requirements, etc.; since intangible components take an increasing share in the cost and price of the finished product;
- formation of the market value of enterprises due to the knowledge of employees, know-how, knowledge-intensive technologies, inventions, industrial designs and other intangible assets. The qualitative change of production factors puts forward a set of interrelated tasks for industrial enterprises [19, 20];
- the integration into Industry 4.0, increasing the continuity and flexibility of production, the transition to flexible production systems that ensure the adaptation of the production infrastructure to innovative activities, changes in market requirements demand different approaches to the composition and configuration of key factors of production [26];
- increased consistency in the duration and productivity of all interrelated subdivisions of industrial enterprises causes the accounting of results not only at the place of application of production factors, but also in related units from the perspective of their impact on the economic performance of enterprises;
- rational increase in the growth of R&D costs, which ensures the implementation of scientific and technological policy directly in the process of scientific and production activities, determines the assessment of their relationship with the share of revenues from new types of products;
- the uncertainty of the economic environment, high risks in the development of innovative products create the preconditions for the development of economic-mathematical models that are adequate to the object of research and improve the quality of the effectiveness of industrial enterprises.

Thus, sustainable economic growth and development of modern industrial enterprises determines not so much the number of personnel, but the presence of workers who are able to conduct scientific and technological development at the modern level, to create competitive products and services on their basis, to propose new ways of organizing production, to determine the process of forming new trends in technological development in the market environment. In this regard, we need a different system of productive forces, surpassing the capabilities of industrial type of production and other ways of combining human and material labor.

The convergence of intellectual resources and information technologies as a productive force causes the emergence of new types of production factors – cognitive factors of production – which are understood as specific, difficult to imitate resources of an industrial enterprise that allow creating a product that is in demand by the market.

Cognitiveness, as a scientific and cognitive action, is moving into a new quality, providing appropriate knowledge for comprehensive research. Artificial intelligence, neurocomputers, technologies of various interfaces based on the use of the properties of the human brain are a fundamentally new environment for human production activities. The use of cognitive principles in the economy allows you to bring the main production processes to an intellectually new level.

Cognitive production factors provide internal opportunities for the development of industrial enterprises and, in fact, become one of the sources of endogenous economic growth [18, 19, 20]. Cognitive production factors management means the emergence in the practice of industrial enterprises of a specific type of organizational and economic activity related to their identification, ranking, analysis, evaluation, monitoring at all stages of the reproduction cycle in order to achieve the goals of long-term economic growth.

The identification of cognitive factors of production as a new type of productive force necessitates the development of appropriate methods and models of their management, the practical implementation of which is possible due to the mechanism of integration into the overall control loop of an industrial enterprise [15, 16, 27, 28].

So, cognitive production factors (CPF, C_f) – are the result of the convergence of intellectual resources / intellectual capital and information technology:

$$\text{“IR/IC” \& “IT”},$$

where & – here is a conditional symbol of convergence.

Cognitive basis of high-tech activity, which includes the unity of knowledge, experience, creativity and information technology. Structural elements of CPF are: knowledge, experience, creativity and skills in the use of information technology, i.e. *CPF – is a tuple <knowledge, experience, creativity, level of use of IT, ...>.*

One of the variants of correlations of cognitive production factors (CPF), human capital (HC) and intellectual capital (IC) by three comparison parameters.

1. Structural elements:
   - CPF: Knowledge, experience, creativity, skills, in the use of information systems and technology.
   - HC: Level of education, health status.
   - IC: Market assets, human assets, intellectual property, infrastructure assets.
2. Methods of evaluation and measurement:
   - CPF: Indicator based on up-to-date financial and accounting statements.
   - HC: Aggregated indices, the calculation of which requires an extensive information base.
   - IC: Ratio of market value to book value; Intellectual coefficient of value added.
3. Correlation with performance results:
   - CPF: Production function.
   - HC: The balanced scorecard system.

- IC: Aggregate of IC and capital involved.

Note that the presented list of CPF is not exhaustive, it can and should be supplemented and improved.

So, CPF is a set of both active and intensional, as well as tangible and intangible factors of production:

- tangible-active can include those CPF, which are embodied and directly used in the economic turnover. These include local computer networks for information exchange, flexible manufacturing systems (FMS), simple/complex robots, automated information storage and retrieval systems, planning systems (ERPI, ERPII), design systems (CFD, CAE, PLM), electronic document management systems, vision systems;
- intangible assets include objects of intellectual property: know-how, technical solutions, licenses, patents, databases, information about customers and suppliers, etc;
- material-intentional cognitive factors include the potential use of advanced technologies, such as augmented reality technologies, artificial intelligence technologies: Internet of Things technologies, big data, cloud computing, deep learning, 5G, etc;
- intangible-intentional include personal characteristics of employees, experience, culture of thinking, ability to learn, creativity, insight, intuition, level of education, level of digital literacy, ability to cognitive activity, analysis, reflection, self-regulation, communication abilities, compliance with ethical and social norms.

Let us also note now that innovation capital is one of the most important and specific forms of capital, reflecting the ability of industrial enterprises as participants in the innovation cluster to generate income due to the development of innovative activity and acquisition of a special status due to the dynamics of innovation potential as an institution capable of transformation into capital as a result of the synergistic effect of interaction between economic entities in the process of innovation development. Innovation capital from the point of view of classical economic theory is characterized by three essential features, namely, it is a product of past labor, the role of which is played by innovation potential; it is a production or product stock in the form of innovations produced and ready for implementation, as well as innovations requiring further improvement and innovations that can be accumulated in the form of innovation potential; it is a source of income based on the effective commercialization of innovation [29, 30].

By its nature and content, innovation capital is wider than intellectual capital, which according to the concept presented in the works of Milner [29, 23], consists of three elements: 1) human capital; 2) organizational (structural) capital; 3) consumer capital. Machlup [22] in 1966, analyzing the processes of knowledge production and dissemination in the United States, without downplaying the role and importance of material production, reasonably proved that the economic development of the “new age” is determined not so much by the availability and productivity of material resources as by the availability and speed of information distribution in society and the amount of intellectual capital [17, 18, 20].

Let us present a cognitive model of the nonlinear dynamics of the system, taking into account the dynamics of the humanitarian component with control (as an extension of the integral model [15, 16]), in general terms it can be represented as stochastic differential equations:

$$\frac{dH_{\mathcal{U}}(t)}{dt} = \chi_{+}H_{\mathcal{U}}^{+}(t) - \chi_{-}H_{\mathcal{U}}^{-}(t) + \sigma_{H_{\mathcal{U}}}(H_{\mathcal{U}}, t)dW_{H_{\mathcal{U}}}(t) + b_{H_{\mathcal{U}}}U_{H_{\mathcal{U}}}(t). \tag{1}$$

$$\frac{dC_f(t)}{dt} = \vartheta_{+}C_f^{+}(t) - \vartheta_{-}C_f^{-}(t) + \sigma_{C_f}(C_f, t)dW_{C_f}(t) + \vartheta_{C_f}U_{C_f}(t). \tag{2}$$

The model of the dynamics of innovativeness of the eco-economic and socio-humanitarian system (EESHS) can also be represented in the form of an equation of dynamics:

$$\frac{dI_c(t)}{dt} = \varsigma_{+}I_c^{+}(t) - \varsigma_{-}I_c^{-}(t) + \sigma_{I_c}(I_c, t)dW_{I_c}(t) + \vartheta_{I_c}U_{I_c}(t). \tag{3}$$

In equations (1)-(3) the variable $H_{\mathcal{U}}(t)$ is a humanitarian variable, $C_f(t)$ – cognitive variable, $I_c(t)$ – variable (level) of innovativeness in the integral model EESHS [16]; $\chi_{+}, \chi_{-}, \vartheta_{+}, \vartheta_{-}, \varsigma_{+}, \varsigma_{-}$ – parameters, and other designations are given in the same work.

So, supplementing the system of equations of the integral model [15, 16, 31] with equations (1) – (3) we obtain an extended (generalized) integral model of nonlinear stochastic dynamics of EESHS in the innovation space.

The generalized production and technological function (PTF) can now be represented as:

$$Y(t) = F[K(t, L(t), H(t), N(t), \Phi(t), S(t), I_c(t), C_f(t); \vec{c}]. \tag{4}$$

It can be used to study sustainable development.

In the general case, the integral level of sustainable development can be represented as a nonlinear function:

$$Y_{sdl}(t) = F_{sdl}[K(t), L(t), H(t), N(t), \Phi(t), S(t), I_c(t), C_f(t), \vec{c}]. \tag{5}$$

Private versions of the PTF model:

a) Mankiw-Romer-Weil model. Option of accounting for human capital H in the production function (PF), along with physical capital (K), labor (L) and natural (N) resources:

$$Y(t) = K^{\alpha}(t) \cdot H^{\beta}(t) \cdot [A(t) \cdot L(t)]^{1-\alpha-\beta}, \tag{6}$$

where $\alpha, \beta > 0$, $\alpha + \beta < 1$; H; $A(t)$ – function of scientific and technological progress. Note that α – is a part of capital provided by investment growth (capital costs); β is similar.

b) Model of accounting for all fixed assets:

$$Y(t) = A(t)K^{\alpha}(t) \cdot L^{\beta}(t) \cdot H^{\gamma}(t) \cdot S^{\rho}(t) \cdot \Phi^{q}(t) \cdot N^{\tau}(t) \cdot I^{\nu}(t), \tag{7}$$

where $\alpha, \beta, \gamma, \rho, q, \tau, \nu > 0$ and $\alpha + \beta + \gamma + \rho + q + \tau + \nu = 1$.

The following notations are also used here: K – physical capital, L – labor (labor), H – human capital, S – social capital, Φ – financial capital, N – natural resources (land, water, etc.), $A(t)$ is a function of the level of scientific, technical and technological development, for example, $A(t) = aT^{S}(t)$, where $T(t)$ – volume of innovative technologies (resources).

In [16], the equation of the dynamics of the potential of the R&D sector in the integral model is presented as:

$$\frac{d}{dt}[\dot{\varphi}(t)] - \delta_\varphi \varphi(t) = G[\varphi(t)]^{\gamma_1} \cdot [\alpha_{L_1}^1(t) L_1(t)]^{\gamma_2} \cdot [\alpha_K^1(t) K(t)]^{\gamma_3} \cdot [s(t)]^{\gamma_4} + \sigma_\varphi(\varphi, t) e_\varphi(t), \quad (8)$$

where $\varphi(t)$ – stock of knowledge and technologies in the economy – the number of inventions that have not lost their relevance by the year t; $\dot{\varphi}(t)$ – increase in the stock of knowledge per unit of time – the number of new inventions per year t minus obsolete; $L_1(t)$ – the volume of skilled (more precisely – highly skilled) labor (skilled labor force with qualifications, i.e. the product of the number of skilled workers $L_1(t)$ and the level of qualification of the average employee $h(t)$, i.e. $h(t)L_1(t)$); s(t) – social index; δ_φ – the rate of knowledge attrition due to its obsolescence $\delta_\varphi > 0$; $\alpha_{L_1}^1(t)$ – share of skilled labour employed in the R&D sector $0 \leq \alpha_{L_1}^1(t) \leq 1$; $\gamma_1, \gamma_2, \gamma_3$ – static parameters $0 \leq \gamma_1 \leq 1$, $0 \leq \gamma_2 \leq 1$, $0 \leq \gamma_3 \leq 1$; G – scale parameter: $G > 0$. Here $\{e_\varphi(t), t \in T\}$ – white noise with continuous time; $\sigma_\varphi(\varphi, t)$ – volatility coefficient.

From [15, 16] we have a more general equation of dynamics, i.e. the equation of the STP index (STP weight), which shows the growth and efficiency of the use of labor, capital and technology in production, i.e. $\tau(t)$:

$$\frac{d}{dt}[\dot{\tau}(t)] + \delta_\tau \tau(t) = B[\dot{\varphi}(t) + \delta_\varphi \varphi(t)]^{\beta_1} \cdot [\dot{\sigma}(t) + \delta_\sigma \sigma(t)]^{\beta_2} [\dot{s}(t) + \delta_s s(t)]^{\beta_3} [\dot{z}(t) + \delta_z z(t)]^{\beta_4} \quad (9)$$

where $\dot{\tau}(t)$ is the increase of the STP index caused by the change in the number of advanced production technologies used in production per unit of time, δ_τ – the rate of decrease of the STP index due to the obsolescence of advanced production technologies, $\delta_\tau > 0$; $\beta_1, \beta_2, \beta_3, \beta_4$ – static parameters, $0 \leq \beta_1 \leq 1, 0 \leq \beta_2 \leq 1, 0 \leq \beta_3 \leq 1, 0 \leq \beta_4 \leq 1$; B – scale parameter; $B > 0$.

Note that $\tau(t)$ – STP index, dependent on the number of advanced production technologies $w(t)$ and used in production, for example, $\tau(t) = [w(t)]^d$, where $d - const$.

Now in this generalized and integral variant we can use the conditions of development stability from [15, 16, 32].

This construction of the indicator will reflect the importance of each of the considered components: eco-economic and socio-humanitarian subsystems (spheres) in the performance of the objective function. A change in any of the private indicators leads to a change in the value of the aggregate indicator and captures a change in the steady state of the region. In the general case, all indicators change over time, i.e. have a certain dynamic.

Simple conditions for sustainable development (SD) are defined as follows.

1) Condition of weak stability:

$$\frac{dF[\cdot]}{dt} \geq 0 \quad or \quad F_{t+1}[\cdot] \geq F_t[\cdot], \quad (10)$$

where

$$F_t[\cdot] = F[K(t), L(t), H(t), N(t), \Phi(t), S(t), I_c(t), C_f(t), \vec{c}] \quad (11)$$

2) Condition of strong stability:

$$\frac{dF[\cdot]}{dt} \geq 0 \quad , N = N^C + N^S \quad and \quad \frac{dN^C}{dt} \geq 0, or \quad N_{t+1}^C \geq N_t^C, \quad N = 1...4 \quad (12)$$

where N^C – critical part of natural capital, and N^S – natural capital, which can be replaced by artificial.

For example, given critical natural capital N^C, sustainable development can be supplemented by a time limit on depletion of this value. For a time-decreasing production function, the arguments of which are aggregated variables: labor – L, capital – K and natural – resource N, we will have the ratio:

$$F_t(K, L, N) \leq F_{t+1}(K, L, N) \tag{13}$$

or, in the general case:

$$F(K(t), L(t), H(t), N(t), \Phi(t), S(t), I_c(t), C_f(t), \vec{c}) \leq$$

$$\leq F(K(t+1), L(t+1), H(t+1), N(t+1), \Phi(t+1), S(t+1), I_c(t+1), C_f(t+1), \vec{c}) \tag{14}$$

And it also requires compliance with the condition of not decreasing in time the value of N^C, i.e. $N_t = N_t^C + N_t^S$, as well as the condition of partial replacement of natural capital N by artificial N^S (or non-renewable resource for renewable resource): $N_t = N_t^C + N_t^S$.

The integrated level of sustainable development for all capital (resources) can be defined, for example, in the case of linear dependence as:

$$Y_{sdl}(t) = c_1K(t) + c_2L(t) + c_3H(t) + c_4N(t) + c_5\Phi(t) + c_6S(t) + c_7I_c(t) + c_8C_f(t), \tag{15}$$

where $c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8$ are weight (normalizing and scaling) coefficients.

3. Conclusion

This paper presents and develops a cognitive approach to modeling sustainable development of complex technogenic production systems in the innovation economy. We propose an integration model of sustainable development as a family of models for creating integrated information systems of ecological, economic and socio-humanitarian management of various social and organizational systems, especially economic objects of anthropogenic nature. We also present a cognitive model of nonlinear system dynamics that takes into account the dynamics of the humanitarian component with management in general. Furthermore, we introduce a model of innovation capital dynamics for the eco-economic and socio-humanitarian system (EESHS), as innovation capital is broader than intellectual capital by its nature and content. We derive an extended integral model of nonlinear stochastic dynamics of EESHS in the innovation space.

Our approach is based on the theoretical foundations and paradigms of systems of type “X”, integral models and the problem of sustainable development, models such as “NMSSD” and systems such as “SEEHS”, convergent technologies “NBIC” and “NBIC$\oplus$SG”. We show how these concepts can be applied to understand and manage the complex dynamics of technogenic production systems in the context of innovation economy.

We also demonstrate how our approach can address the challenges posed by the transition to an information society, which leads to a change in the structure of total capital in favor of human capital, an increase in intangible flows, knowledge flows, intellectual and innovative capital. We investigate the problem of sustainable development based on 8 important assets that support the sustainability and viability of EESHS.

We claim that our approach can increase the efficiency of solutions in the management of technogenic production systems, enhance the utilization of innovations and identify areas of innovation strategies for the regions.

The presented result requires further research, generalizations and computer experiments on real data. We plan to extend our approach to other types of complex systems and domains, as well as to incorporate more cognitive factors and methods into our models. We also aim to develop practical applications and tools based on our approach that can support decision-makers and stakeholders in achieving sustainable development goals.

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