Digital Activation and Statistical Modeling of Effective Innovative Working of Industrial System

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Abstract: Against the background of digital activation, the analytics of the effective functioning of the industrial system in the information and intellectual environment is based on the statistical concept of V.A. Trapeznikov on the dependence of the effect of the functioning of the controlled complex on the amount of control information entered into it and the logistic equation (the Verhulst and Redenour models). The state and prospects of digital transformation and maturity of Russian enterprises are revealed. The conclusions of the analysis of the logistic model presented in the article expand the understanding of the patterns of the dynamics of the effect of the industrial system, its entropic features and limiting conditions of behavior. The results of the study obtained in the course of the symbiosis of views and methods of natural-scientific and economic teachings find application in the adaptive management of industrial systems in the space of increasing disturbances.

1 INTRODUCTION

Global challenges and threats, accelerated by the rapid development of knowledge-intensive production, give rise to extraordinary dynamic processes in the space of the world and national economies, prompting them to adapt their real sector to the stunning disturbances of their environment. At the time of the formation and rooting of a natural technological structure, the theoretical and applied value of research on the analysis and maintenance of the effective activity of Russian companies in the environment of an innovative and technological breakthrough obviously increases. In the context of industrial digitalization, according to the Industry 4.0 Market report, the size of the Industry 4.0 market is expected to grow from USD 94.42 billion in 2023 to USD 241.58 billion by 2028 at an average annual growth rate of 20.67% during the forecast period (2024-2029) and will reach USD 367.50 billion by 2030. According to the government inter-industry project "Smart Production", the digital maturity of the main production processes of industrial enterprises of the Russian Federation in 2023 was estimated at 50%, should increase every year by 5% and will already amount to 85% in 2030.

In general, the digital transformation of the country is gaining momentum as a national priority. In accordance with the Decree of the President of the Russian Federation "On the national development goals of the Russian Federation for the period up to 2030 and for the future up to 2036" dated 07.05.2024, these include a stable and dynamic economy, technological leadership and digital transformation of public and municipal administration, the economy and the social sphere. The task has been formulated to achieve digital maturity of public and municipal administration, key sectors of the economy and the social sphere by 2030 within the framework of unified industry digital platforms and a data-based management model, taking into account the accelerated implementation of big data processing technologies, machine learning and artificial intelligence.

According to the order of the Government of the Russian Federation "Strategic direction in the field of digital transformation of manufacturing industries related to the scope of activities of the Ministry of Industry and Trade of the Russian Federation" dated

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07.11.2023 for the period up to 2030, measures are provided to increase the digital maturity of the domestic industry by creating updated, effective business processes and management processes, ensuring the stable functioning of production and technological processes and the continuity of their management. In particular, the inter-industry project "Smart Production" provides for an increase in the digital maturity of the main production processes of industrial enterprises from 50% in 2023 to 85% in 2030., under the project "Digital Engineering" - reducing the cost of development and reducing the time it takes to bring high-tech products to market, primarily through the development of mathematical and computer models with a high degree of up to 50% of enterprises by 2030, under the project "Products of the Future" - the share of enterprises using industrial Internet of Things technologies, data collection and dispatch control to manage production processes in real time, from 50% in 2023 to 95% in 2030, the Intelligent State Support project - the share of enterprises using artificial intelligence technologies, from 9% in 2023 to 85.2% in 2030.

On this basis, the task of modeling the effective functioning of an industrial system in the information and intellectual environment of a digitalized economy, searching for and interpreting entropic patterns and limiting conditions for the dynamics of the effect of this system is updated.

2 MATERIALS AND METHODS

The solution to the research problem required the involvement of a wide range of natural science and economic teachings: thermodynamics, statistical mechanics, information theory, cybernetics, innovation and production management, mathematical modeling. The information base of the study was made up of official materials of government and management bodies, information from the Federal State Statistics Service, analytical reports.

3 RESULTS AND DISCUSSION

The development and promotion of the arsenal of capabilities of the technological structure of Industry 5.0 saturate the information and intellectual environment of modern industrial structures and their industrial systems with revolutionary innovations. In view of this, their successful adaptation to the rapidly changing environment brings to life the task of developing analytics for the efficient and stable behavior of the industrial system, sensitive to the influence of both geopolitical, global and national financial and economic shocks, as well as increased competition in the markets for innovative developments and high-tech products. Theoretical and applied significance is acquired by research on instrumental support of production management, equipped with economic and mathematical models of the evolution of industrial systems in the space of growing destructive and innovative disturbances.

A wide panorama of studies on theoretical and methodological problems of activation of the digitalized economy testifies to the attractiveness of the topic of the future of Russia in new technological and world economic structures (Glaz`ev, 2018), on the essence of digital transformation (Silakova, Andronik, Kiselyov, 2024), the formation of a digital economy in the implementation of human capital (Voronina, 2024), technological sovereignty of Russia (Chistyakova, 2024), analysis of trends in digital transformation of the industry in a non-stationary environment of geopolitical and innovative disturbances (Chuprov, 2024), etc.

The generation, transfer and development of knowledge-intensive technological and product innovations transform the information and intellectual environment of industrial systems, on the one hand, by integrating functionally and algorithmically promising management modules into it, and on the other hand, by loading the processes of developing management decisions into a non-stationary environment excited by cardinal and high-speed disturbances. The latter changes the established stereotypes of partner interactions and the rhythm of the measured flow of business life, catalyzing communications between counterparties and increasing the uncertainty of the economic situation in the country.

According to Rosstat, among the dominant trends in the development of advanced production technologies in 2015-2023 are ahead of the created technologies of production information systems and automation of production management with a growth of 3.92 times, which is preferable from the standpoint of adaptive production management of industrial systems. However, among the factors limiting production growth in the manufacturing industries, the uncertainty of the economic situation, according to respondents, is the leader and varies in flexible ranges: if in 2006 it was 20.0-24.0% of enterprises in the industry, then in 2022 the indicator reached the limits of 47.0-61.0%, although in 2023 it stabilized to 42.0-47.0%, and in the first half of 2024 it amounted

to 40.0%, while in second place is the factor of insufficient demand in the domestic market. (35.0-37.0%).

Meanwhile, activation and mastering the advantages of the new technological order gives rise to growing risks of innovation and investment support of modernized productions in conditions of incompleteness and disturbance of the available initial data, prompting the transfer of statistical regularities to the analysis of the effect of the functioning of the industrial system. Under the influence of many random factors, it obeys the rules of probabilistic behavior laid down by the doctrines of thermodynamics and statistical mechanics. Exposure to random influences results in a decrease in orderliness and chaos of macrosystems, which can be resisted only by supplying energy to it from the outside to reduce the entropy (a measure of irreversible energy dissipation) of an open thermodynamic system.

In this context, the fight against the disorder of the controlled complex is revealed by the theoretically proven and practically confirmed concept of V.A. Trapeznikov on the dependence of the effect E of the operation of such a complex on the amount of control information I received by it (Trapeznikov, 1983) and described by the equality:

$$E = E_{\max}\left(1 - B_0 e^{-\frac{I}{I_0}}\right), \qquad (1)$$

where $E_{\max}$ is the effect of an ideally operating complex (the maximum possible effect);

B_0 is the disorder of the complex in its initial state;

I_0 is the volume of information characteristic of a given complex.

Graphically, the model of V.A. Trapeznikov (1) can be represented by an exponential curve (Fig. 1), displaying the cause-and-effect relationship of the control information I in the complex (part of it i is entered by the human operator, and the other Ic by the control system) and the effect E of its functioning.

Based on the type of visualized dependence (1), we can state that its non-linearity means a disproportionate increase in the effect E of the controlled complex over time. The early growth rate is fairly uniform, but as the limit $E_{\max}$ is approached, the magnitude of the increment E decreases monotonically compared to the rate of control information I introduced into the complex. And in this limit transition $E \to E_{\max}$, the decreasing gap between the ideal $E_{\max}$ and current values E (exponentially decreasing gap) shows the size of the loss in the effect of the operation of the controlled complex due to the disorder of its functioning (resistance to entropy), despite the continuous flow and accumulation of control information in the complex.

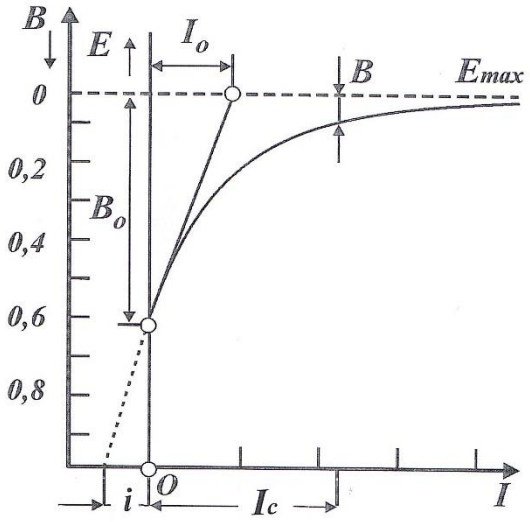

Figure 1: The effect of the controlled complex depending on the amount of control information (Trapeznikov, 1983, p. 8).

This is the very thing that recognizes as fundamentally irreparable the complete disorder of industrial systems, which reveals itself in anomalies and one or another chaotization of the behavior of excited systems - the lack of coordination of the actions of production personnel, the disruption of the movement of material, technical, financial, information flows, deviation from technological and executive discipline, failures and equipment breakdowns, etc.

Let us add to this that the French sociologist G. Tarde in his work “The Laws of Imitation” (Tarde, 2011) presented the dynamics of the spread of innovations in society as a process demonstrating a similar phenomenon. He believed that inventions bring social benefit as a result of imitation, and at the first stage the introduction of innovations “stalls” due to their unfamiliarity, after which innovations are overcome and then actively mastered by

entrepreneurs until the stage of limiting the growth of their use occurs.

The specific regularity of the exponential change in the effect of an industrial system as its response to the introduced control information (1) introduces an adjustment to the concept of innovation and investment support for the modernization of the system, since the idea of achieving the maximum possible effect of its functioning by intensively "pumping" control information runs into the entropically conditioned "restraint" of the process. In view of this, the increasing complexity of the modernized control systems with the latest algorithmic, software, hardware and other resources for improving the generation of control information cannot ignore a balanced approach to the selection of a modernization project with a comparison of the planned values of costs and the effect of the operation of these systems.

With an exorbitant increase in the amount of control information I according to the exponential of the trajectory graph (Fig. 1), the increment of the effect E (the upper branch of the curve) monotonically decreases and the payback period of investments in the control system increases sharply. According to the calculations of V.A. Trapeznikov, with the magnitude of the effect of the controlled complex equal to 0.8 of the maximum $E_{\max}$ (B_1 = 0.2), and the payback period of the control system of 1 year, bringing the effect of the complex E to the value of 0.98 (B_2 = 0.02) would result in a payback period of additional investments in the complex control system of 10 years (Trapeznikov, 1983, p. 9). Hence, the intention to increase the magnitude of the effect of the operation of the controlled complex by 1.23 times (0.98:0.8) looks economically questionable, since would require a tenfold increase in the payback period for investments made in the modernization of the complex (10:1).

Economic and mathematical modeling of the change in the effect E of the complex with the reproduction of a similar pattern of its dynamics suggests the possibility of using the Verhulst model and Redenour. A notable property of it is the modeling of a nonlinear process "with saturation", when its movement with a changing rate after the breaking point of the trajectory curve begins to reduce the rate of increase of the analyzed characteristic. Mathematically, this model is described by the logistic equation (Verhulst, 1838; Zhuravlev, Anikovsky, 2005) and is formalized in our notation by the expression:

$$\frac{dE}{dt} = KE\left(1 - \frac{E}{E_{\max}}\right), \qquad (2)$$

where the coefficient K (K >0) specifies the growth rate of the effect of the system's behavior.

This logistic model has attracted the attention of analysts in biology, social protests and economics in the problem of consumer behavior of a certain technology (Bezruchko, Koronovsky, Trubetskov, Khramov, 2015; Zhuravlev, Anikovsky, 2005). By the way, in the concept of V.A. Trapeznikov, the ratio (size L_C):

$$L_C = \frac{E}{E_{\max}} \qquad (3)$$

has a clear meaning and analytical significance, having received the name of the level of "management perfection" (Trapeznikov, 1983, p. 51).

Let us transform the differential equation (2), for which we first separate the variables:

$$dE = KE\left(1 - \frac{E}{E_{\max}}\right)dt,$$

then

$$dE = KE\left(1 - \frac{E}{E_{\max}}\right)dt = KE\frac{E_{\max} - E}{E_{\max}}dt$$

and finally arrive at the equality:

$$\frac{dE}{E\frac{E_{\max} - E}{E_{\max}}} = Kdt.$$

Now, by carrying out mathematical transformations and integration, we will find a logistic expression for the magnitude of the effect of the functioning of the industrial system:

$$E = \frac{E_{\max}}{1 + \left(\frac{E_{\max}}{E_0} - 1\right)e^{-Kt}}, \qquad (4)$$

where E_0 is the magnitude of the effect of the functioning of the industrial system in its initial state.

Next we comment on two boundary conditions.

The first boundary condition corresponds to the initial moment of time t = 0. In this case, the indicator of the effect of the industrial system activity:

$$E = \frac{E_{\max}}{1 + (\frac{E_{\max}}{E_0} - 1)e^{-K0}} = E_0$$

is expected to be equal to its value E_0 in the initial state.

The second boundary condition corresponds to the limit transition of the time parameter $t \to \infty$. When substituting it into expression (4), the magnitude of the effect E:

$$E = \frac{E_{\max}}{1 + (\frac{E_{\max}}{E_0} - 1)e^{-K\infty}} \to E_{\max}$$

tends to the maximum possible value of the effect $E_{\max}$.

The burdening of the procedures of adaptive management of industrial systems with risk and uncertainty factors logically moves towards an organic synthesis of "hard" and "soft" computational algorithms for finding management solutions provided by intelligent technologies. With their use, it becomes possible to bypass the difficulties in the face of which traditional template management schemes lose their constructiveness, and to use procedures for processing difficult-to-formalize initial data. As a result, the information and intellectual environment of managers partially compensates for the uncertainty of the economic situation by increasing valuable poorly structured information, creating the preconditions for stable activity through a verified model justification of management decisions and maximizing the effect of the functioning of industrial systems.

It is appropriate to return to the indicator of the level of management perfection L_C (3), for which we will use equality (4):

$$L_C = \frac{E}{E_{\max}} = \frac{1}{1 + (\frac{E_{\max}}{E_0} - 1)e^{-Kt}} \quad (5)$$

and similarly determine its boundary values.

It is clear that at the initial moment of time ($t = 0$) of the functioning of the industrial system, the level of management perfection L_C:

$$L_C = \frac{1}{1 + (\frac{E_{\max}}{E_0} - 1)e^{-K0}} = \frac{E_0}{E_{\max}}$$

has a minimum value equal to the ratio of the initial effect E_0 to the maximum $E_{\max}$. And with a monotonic increase in the time parameter $t \to \infty$, the value of the level of management perfection (5):

$$L_C = \frac{1}{1 + (\frac{E_{\max}}{E_0} - 1)e^{-K\infty}} \to 1$$

is maximized to the limit level of 1.

Such a limit transition assumes a step-by-step increase in the effect E of the functioning of the industrial system at a constant $E_{\max}$, or an increase in growth rates E by $E_{\max}$, if the radical modernization of the system provides for an increase in its economic potential and the threshold level of the effect $E_{\max}$. At the same time, a non-stationary environment abounding in destructive and innovative disturbances manifests itself as a "tendency" to trigger increased chaos in industrial systems and reduce the predictability of their business environment, as a result of which the cycles of making and implementing management decisions in an uncertain economic situation are shortened. In such a vortex space, the available array of statistical information on the activities of an industrial enterprise in the past loses its predictive value for developing risk solutions in future periods of time and dictates the need to focus on finding and maintaining a sufficient reserve of resources. On the one hand, to dampen the consequences of fluctuations in demand for manufactured products and maintain the stability of the enterprise, and on the other, to increase the upper limit of the effect $E_{\max}$ of its work.

In conclusion, we note that the dependence of the amount of control information I in an industrial system on the level of perfection of its management L_C is of analytical significance (Chuprov, 2021). Omitting the mathematical calculations, I will give the final form of the formula:

$$I = I_0 \ln(\frac{B_0}{1 - L_C}). \quad (6)$$

The resulting equality (6) is illustrated by the graph in Fig. 2, which displays the nonlinear relationship between the amount of control information in an industrial system and the level of perfection of its management. From the point of view

of the analysis of economic dynamics, it has been confirmed that the amount of control information I introduced into an industrial system is logarithmically related to its disorder B_0 and the level of perfection of this system's management Lc .

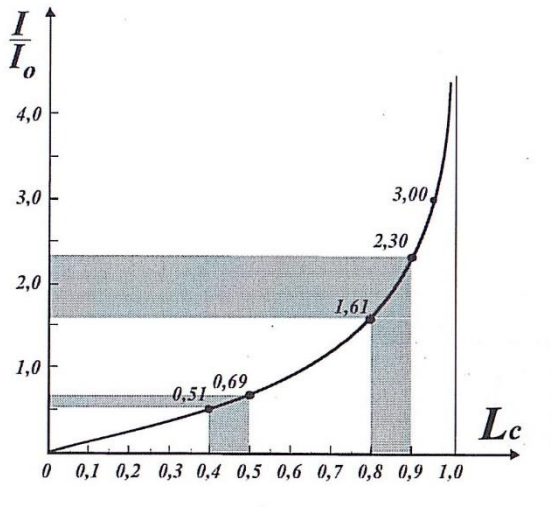

Figure 2: Dependence between the relative values of the amount of control information $\frac{I}{I_0}$ in an industrial system and the level of perfection Lc of this system's management.

In an effort to ensure an increase in the level Lc , it is easier to achieve an increase I if the disorder B_0 of the system is sufficiently low. And vice versa, when it is quite large B_0, it is more difficult to increase the level Lc , since to reduce entropy it is necessary to increase the amount of information I .

Point localization and neutralization of chaotic behavior of industrial systems is identical to the reduction of their entropy, reduced by the intellectualization of adaptive control by enriching its information support with expert assessments that compensate for the deficit of initial information and the absence of precise knowledge about the environment, and by embedding intelligent algorithms for processing non-numeric information and soft computing into control technologies (Piegat, 2001).

4 CONCLUSIONS

The main direction of innovative development of Russian industry, thanks to its digital activation, launches a mechanism of high-tech modernization of industrial systems in a stressful geopolitical and economic environment. The use of mathematical models, universal enough to describe a wide range of dynamic processes, enables in-depth analysis and understanding of non-trivial patterns of functioning of industrial systems. In a risky non-stationary space with turbulent flows of destructive and innovative disturbances, the information and intellectual environment of adaptive management of these systems undergoes an evolution with its inherent increasing uncertainty of the economic situation and intellectualization of technologies for finding management solutions.

The appeal to the statistical concept of V.A. Trapeznikov and the logistic model of Verhulst and Redenour in order to ensure the proper effect and stability of the activities of industrial systems reveals and objectifies the nature and boundary conditions of change of this effect, their features and entropic interpretation in the task of substantiating innovation and investment projects for the development of industrial enterprises.

The area of promising research on this issue forms a broad panorama of research on trends, threats and opportunities for innovative activity of Russian industry in the process of transition to a digital economy (Pasmurtseva, 2020), its challenges and opportunities for sustainable development (Cao, 2024), digitalization as a factor of sustainable development of the economy and economic security (Musostova, Berkaeva, Geraskin, 2023), etc. With an interdisciplinary coverage of complementary principles and methods of natural science and economic teachings, an understanding of the trends in the digitalization of the economy and the promotion of model tools for adaptive management of industrial systems in a disturbed space are achieved.

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