Fractal model of “breakthrough” innovation in nanotechnology

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Abstract. The fractal modeling approach is applied to the distribution process of breakthrough innovation in nanotechnology. For modeling, a diffusion-limited aggregation fractal is used. This model takes into account the change in the probability of adhesion (the ability to perceive innovations) and viscosity (the rate of propagation of innovations). Evaluation of the fractal dimension of the simulated structures allows us to identify trends and predict their further development. The model system reaches a breakthrough jump with a fractal dimension greater than 1.6. The unstable nature of the further development of the system will be observed with a sharp increase in fractal dimension, if the parameters of the ability to perceive innovations and the speed of innovation spread to level 1. Favorable conditions for the technological leap are realized in the case with a slightly lower fractal dimension when the rate of innovation spread is 1. The stable nature of the development of the system is observed at medium rates and above. With general trends below the average, the leap will be difficult to achieve.

1. Introduction

Today, the main component necessary to obtain a leading position in high-tech industries, such as nanotechnology, which allows creating breakthroughs, is innovation. In the difficult conditions of our time, especially for Russia, it becomes possible to achieve leadership only through economic leap [1], which can be realized as a result of applying the scientific approach to the strategic management of the innovative development of Russian nanotechnologies in individual regions and in the country as a whole.

It is obvious that the restructuring of the economy on an innovative character as a whole, and especially in nanotechnology, will require at least optimization of resources and mobilization of the country's innovative potential, and in general, a systemic transformation of the institutional structure of the economy [2].

An innovative economic leap is possible when using an effective distribution system of both new technologies and scientific knowledge and approaches in the country's economy [3].

An effective system for the dissemination of innovative technologies, with the presence of a sustainable effect of adaptive synergies, can be successfully implemented using cluster and fractal approaches, as well as within the framework of the principles of institutional evolutionary theory [4, 5].

In resonance processes, especially in the case of the presence of high-quality transitions [6] that describe jumps, the key condition is the correct typological configuration of the system and the
architecture of the effect on it. So, for example, small, properly organized resonant effects lead to a synergistic effect. The pace of development of the system is determined by the quality and effectiveness of process control: mainly, the choice of areas of "breakthrough" and "growth points".

Analysis of studies of the mechanisms of development of public, social, socioeconomic and sociotechnical systems allows us to generalize that the process of development, application of innovative approaches and the transition to new technologies in the fields of high-tech industrial organizations developing the field of nanotechnology passes through a cascade of self-similar small, medium and large cycles of innovative changes [7].

All this allows us to assert that the processes of technological development are fractal in nature and, therefore, can be represented as fractal systems.

Thus, the presence of fractality in the development of high-tech industrial systems allows us to argue that the development of the industry requires innovation that changes the fractal system.

A fractal of an industrial organization is defined by the initial conditions from the elements and limitations of the system and the functioning rule that describes the interaction of its elements [8].

Thus, if an innovation arises in the system that changes the initial conditions and the rule of interaction of its elements, then its impact leads to the development of the system at a new qualitative level, which is evidence of a jump.

Moreover, the fractal as well as the multifractal nature of the development of an industrial organization allows, in particular, to predict the process of innovation distribution based on the principles of multifractal.

Modeling the process of emergence or penetration with the subsequent spread of innovations within the framework of the fractal approach allows us to visualize its mechanisms and predict development directions, i.e. identify the prospects for the formation of regional high-tech clusters based on innovatively active territories with the aim of their "inclusion" in the future in the overall macroeconomic dynamics.

2. Methods

The diffusion of innovative ideas is diffuse, which, to a first approximation, can be described by the diffusion equation [9-11].

To visually simulate the development of innovation from idea fluctuations to the multifractal of a new industry (Fig. 1), fractals with a diffusion type of organization, such as diffusion-limited aggregation (DLA), were chosen [12, 13].

The process of embracing an innovative idea with the subsequent dissemination and development within the framework of fractal geometry was simulated in relation to the production system of high-strength parts for mechanical engineering industries, in which an innovative method of hardening by spraying and nanomodification of the surface was applied [14-16].

The industrial system was described as a two-dimensional region, divided into cells of the same size, describing homogeneous production elements - laboratories for the deposition of nanocoatings and heat hardening.

Laboratories interacted among themselves, exchanging innovations, forming an innovative fractal cluster. In the proposed model, the propagation velocity of the innovative method of deposition of nanocoatings and heat hardening was described by the parameter v [17] and the ability to perceive the new method was p. These parameters describe the innovativeness of the system and can be evaluated by various methods [18-24].

The proposed model is a simulation, therefore, the above parameters for our calculations, in a first approximation, take values from (0; 1).

Within the framework of the model under consideration, an innovative method is described as a particle originating within an industry in one or more laboratories, presented as a nucleus structure (Fig. 1a [25]). At each time step, an innovative idea is generated as a particle moving randomly in the computational domain and interacting with other particles according to the rules of the von Neumann neighborhood [26].
The algorithm for the formation of such a fractal-cluster consists of steps (Fig. 1):
1) a nucleus structure is defined on a square two-dimensional lattice;
2) far from the cluster (from the nucleus), a new particle is generated in the nucleation region of the calculated region $R_p$;
3) a new idea particle wanders randomly, the step size is determined in accordance with the velocity parameter $v$;
4) if an idea particle approaches a busy cell, in accordance with von Neumann's neighborhood, then it joins it with a given probability $p$;
5) if the particle-idea goes far enough away from the cluster, outside the external sphere $R_e$ it is destroyed;
6) a repeat, starting from step 3 until the particle joins the cluster with a given probability, after which a new particle is launched [27].

![Diagram of DLA fractal formation scheme](image)

**Figure 1.** DLA fractal formation scheme for the case of the emergence of innovation within the system (a), the scheme of formation of a DLA fractal in the case of innovation from outside (b).

For the simulated structures, the fractal dimension was estimated, which made it possible to evaluate their geometric characteristics (area, perimeter). The proposed approach allows us to assess the trends in the spread of innovation. In our opinion, the system will reach a jump with a fractal dimension greater than 1.6. Under this condition, the computational domain will be significantly filled (75-95%) with elements that have accepted innovation, which will lead to favorable conditions for a jump to a higher technological level. The fractal dimension was estimated using the concentric neighborhood method [28, 29].

For the case of penetration of innovative ideas from outside the industry, for example, the purchase of technology, the DLA model is applicable when the embryo structure is located at the lower boundary of the computational domain (Fig. 1b) [30].

3. **Results and discussion**

The fractal describing the process of the spread of innovation was modeled on a rectangular computational domain of 100 rel. units ($R_p = R_e = 50$ rel. units), the number of particles was set as $N = v * S$, where $S$ is the area of the computational domain.

When varying the probability of perceiving innovation at a fixed speed ($v = 1$ in the case of the maximum speed of innovation propagation) from 0.1 to 1, the fractal dimension of the constructed fractals varied in the range from 1.5 to 1.87. In this case, a favorable mode for innovations occurs at a value of $p$ starting from 0.15, when the value of the fractal dimension becomes greater than 1.6.

Similarly, by varying the velocity $v$ from 0.1 to 1 with a fixed $p = 1$, the fractal dimension varied from 1.8919 to 1.8980. A small range of fluctuations in the fractal dimension near the value of 1.89 demonstrates the presence of a regime favorable for innovation with the presence of saturation.
Figures 2-3 present model images of fractals for one center of innovation aggregation located randomly, in extreme cases, when parameters are set to 1 and the probability of perceiving innovation (p) or speed (v) is varied. The case v = 1 describes the situation when the maximum speed of innovation propagation is observed in the system, the susceptibility p in can vary (Fig. 2). Obviously, as the parameter p increases, structures with smoother boundaries and a homogeneous structure are generated, moreover, the fractal object more and more encompasses the computational domain (the number of particle ideas depends on the susceptibility).

An analysis of the calculations in the limiting cases (Fig. 2-3) allowed us to conclude that a technological leap is possible with a sharp increase in fractal dimension, if the parameters p and v go to level 1, but in this mode the innovative coverage is uneven, trends may be unstable in the future, due to the fact that the structures are unevenly sparse in nature. On the other hand, a good start for a technological leap will be the situation when only parameter p reaches value 1, when uniform, well-filled structures arise, but with a slightly smaller fractal dimension. In this case, in our opinion, a leap with subsequent stable development can be achieved.

Fig. 4 shows images of fractals of the maximum, average and minimum rates of innovative development, with a single center of aggregation in the middle of the computational domain. From fig. 4 we can conclude that at rates above the average and average, a jump can be achieved due to the large coverage of the computational domain with innovation, on the other hand, with general trends below the average, the jump will be difficult to achieve (Fig. 4g, h).
Fig. 5 shows fractals simulating the nature of the spread of innovations in the case of an aggregation center at the border, i.e. penetration of innovation from outside. In this case, favorable regimes for the jump are observed in the case of 5 c, d. The jump will be difficult in case 5 a, b.

![Figure 5](image)

**Figure 5.** The case of innovation penetration from outside a) \( p = 0.01, v = 0.1 \); b) \( p = 0.1, v = 0.5 \); c) \( p = 0.5, v = 1 \); d) \( p = 0.8, v = 1 \).

The cases of the existence of several aggregation centers in the system were also considered. Fig. 6 depicts a system with two centers of innovation aggregation. Fig. 6 a-d show fractals in the limiting case according to one of the parameters. Comparing 6 a and 6 c, we can conclude that the parameter \( p \) has a stronger effect on the resulting fractal. In fig. 6 e-h show the system in the case of varying the parameters from the level above average to low. In the case of sufficiently high \( p \) and \( v \) indices, the fractals formed around single aggregation centers are combined into one (Fig. 6 a, b, d, e, f, g). If the parameters \( p \) and \( v \) are close to zero at the same time, then the fractals remain isolated from each other (Fig. 6 c, h).

![Figure 6](image)

**Figure 6.** A system with two centers of aggregation: a) \( p = 1, v = 0.1 \); b) \( p = 1, v = 0.5 \); c) \( p = 0.1, v = 1 \); d) \( p = 0.5, v = 1 \); e) \( p = 0.75, v = 0.75 \); f) \( p = 0.5, v = 0.5 \); g) \( p = 0.25, v = 0.25 \); h) \( p = 0.1, v = 0.1 \).

Fig. 7a shows the corresponding fractal dimensions from fig. 4: 1 - fig. 4a, 2 - fig. 4b, 3 - fig. 4c, 4 - fig. 4d, 5 - fig. 4e, 6 - fig. 4f, 7 - fig. 4g, 8 - fig. 4h.

The fractal dimension of fractals at average rates of development higher than 1.6 (Fig. 7a: 1-6), which indicates good conditions for the implementation of the jump. On the other hand, in the case of development rates below the average, the fractal dimension does not exceed 1.6 (Fig7a: : 7-8), which indicates unfavorable conditions for the implementation of the technological leap.

Fig. 7b shows the values of the fractal dimensions of the figures from Fig. 6: 1 - fig. 6a, 2 - fig. 6b, 3 - Fig. 6c, 4 - fig. 6d, 5 - fig. 6e, 6 - fig. 6f, 7 - fig. 6g, 8 - fig. 6h.

Based on fractal dimensions, an unfavorable situation is observed in cases 3 and 8, when the fractal dimension is 1.47 and 1.53, respectively. In case 7, with \( D = 1.64 \), a slow spread of innovations will be observed, while in cases 1 and 2, the highest rates of spread of innovation are achieved when \( D = 1.92 \) and 1.9, respectively. Also, a good stable pace of development is achieved in cases 4-6.
Thus, the performed calculations allow us to conclude that if there are several aggregation centers, the computational domain will fill up faster and a favorable situation for the jump will be realized at lower values of the parameters \( p \) and \( v \).

4. Conclusions
Analyzing the simulation results, we can conclude that when the jump is realized at a fractal dimension greater than 1.6. Assessing the simulated trends, we can conclude that favorable conditions for the technological leap can be realized in the case of a smaller fractal dimension when the speed of the spread of innovation tends to 1. In addition, the stable nature of the development of the system is observed at medium rates and above. Thus, the proposed approach makes it possible, as a first approximation, to assess the conditions and trends for achieving a “breakthrough” innovation jump in nanotechnology.

References
[1] Gohber L M and Kuznetsova T E 2012 Bulletin of international organizations: education, science, new economy 37 2 101-117
[2] Novikova N B 2011 Bulletin of YURGTU (NPI) 2 162-169
[3] Ochkovskaya M S 2007 Creative Economics 1 1 80-86
[4] Afonasova M A 2009 Basic research 3 111-112
[5] Vasilenko L A 2019 WISDOM 12(1) 62-72
[6] Knazyeva E N and Kurdyumov S P 1994 The laws of evolution and self-organization of complex systems (Moscow: Nauka)
[7] Skharupeta E V and Smyshlyaev V A 2012 Bulletin of the Voronezh State Technical University 7 14-17
[8] Golov R S and Mylnik A V 2018 Innovative-synergetic development of industrial organizations (theory and methodology) (Moscow: Dashkov and Co)
[9] Mejia J, Britto R and Buitrago O 2015 Ciência e Técnica Vitivinícola 30
[10] Moya J 2016 Energies 9 6
[11] Batty M and Longle P 1989 Environment and Planning A 21
[12] Bunde A and Havlin S 1991 Fractals and Disordered Systems (Berlin, Heidelberg: Springer-Verlag)
[13] Meakin P 2011 Fractals, Scaling and Growth Far from Equilibrium (NY: Cambridge University Press)
[14] Evstunin G A, Abrahin S I, Golubev A S and Arakelian S M 2016 Modern high technology 5
[15] Arakelian S M, Evstunin G A, Scryabin I O, Abrahin S I and Novikova O A 2016 Modern high technology 5
[16] Arakelian S M, Evstunin G A, Juravel V M and Abramov D V 2016 Sciences of Europe 8 1
[17] Shinohara K and Okuda H 2010 Comput Econ 35 51
[18] Wang W et al 2006 Applied Mathematical Modelling 30
[19] Al'gina M V and Bodnar V A 2011 Modern Management Technology 1 1
[20] Usov N, Trofimov O, Frolov V, Makusheva U and Kovilkin D 2018 *Russian Journal of Entrepreneurship* **19** 2921 10.18334/rp.19.10.39487
[21] Burlankov S P and Kuzmin S A 2018 *Bulletin of the Plekhanov Russian University of Economics* **6**
[22] Samokhin S V 2017 *Young Scientist* **28** 64-67
[23] Goraeva T U and Shamina L K 2015 *St. Petersburg State Polytechnical University Journal. Economics* **221**
[24] Mityakova O I 2004 *Finance and Credit* **13**
[25] Maignan L and Yunes J B 2013 Proceedings - 2013 1st International Symposium on Computing and Networking, CANDAR 2013 (Washington: IEEE Computer Society)
[26] Bukharov D N et al 2020 *J. Phys.: Conf. Ser.* **1439** 012050
[27] Mroczka J, Woźniak M and Onofri F R A 2012 *Metrol. Meas. Syst.* **19** 3
[28] Wang C Y and Yihan L X 2019 *Chaos, Solitons & Fractals* **126**
[29] Gushchina E S and Smogunov V V 2016 *Modern scientific research and innovation* **2**
[30] Feder J 1988 *Fractals (Physics of Solids and Liquids)* (New York: Springer)