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STUDY OF THE INNOVATIONS DIFFUSION ON THE BASE OF NAMING GAME MATHEMATICAL MODEL

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Abstract: The innovation diffusion is the research issue being a subject of multiple research works in the recent years. The goal of the innovation diffusion theory is to explain the way, new ideas and practices are spread among the social system's members. The major part of the existing models is based on parameters determining the process of innovation adoption and simple mathematical functions focused on the observation and description of diffusion models. These models allow researching the process of diffusion more accurately, but its use foresees the evaluation of diffusion coefficients obtained as a rule from the empirical data of chronological rows. This may cause some trouble, for example, when the data is insufficient or missing. The paper considers the process of innovations distribution in the social community based on the Naming Game Model. Numerous experiments have been conducted and main scenarios of the innovation diffusion in the social system are identified. There is a suggestion to apply an alternative approach to modeling the innovation diffusion in order to overcome some issues typical of the existing models.

Keywords: innovation dynamics; innovation diffusion; spread of ideas in social groups; the Naming Game mathematical model.

I. INTRODUCTION

A. Innovation Process Parameters

The innovation process is the preparation and implementation of innovative changes. It consists of interconnected phases forming a single, integrated complex. As a result of this process, a realized, comprehensive change appears the innovation. The innovation process is cyclic in nature. Modern innovative processes are quite complex and require an analysis of the laws of their development.

B. Diffusion of Innovations in Social Structures

For the implementation of the innovation process, diffusion is of great importance (the spread in time of already once mastered and used innovation in new conditions or places of application). Diffusion of innovations is a characteristic not only for scientific research in the field of communication, but also for practical use in almost all other spheres, including information systems and the economy [1–4]. Diffusion is a process in which innovation over time spreads through certain channels among members of the social system. Innovation is an idea, practice or object whose novelty is felt by an individual or group [5]. A social network is understood as a social structure consisting of many agents (subjects – individual or collective, for example, individuals, families, groups, organizations) and a certain set of relations defined on it (a set of relations between agents, for example, dating, friendship, cooperation, communication).

The author of the monograph "Diffusion of innovations" Rogers, having studied a huge number of scientific works in the field of diffusion of innovations, found such a pattern where all the studied works included the following components [6]:

- any innovation;
- transfer of information from agent to agent;
- community or social environment;
- time factor.

In real innovation processes, the rate of diffusion of innovations is determined by various factors:

- the form of decision making;
- the method of transmitting information;
- the properties of the social system, as well as the properties of the innovation process itself.

C. Innovation Features

Properties of innovations are: relative advantages in comparison with traditional solutions; compatibility with established practice and technological structure, complexity, accumulated experience of implementation, etc.

One of the important factors in the spread of any innovation is its interaction with the corresponding socio-economic environment, an essential element of which are competing technologies. According to Schumpeter's theory of innovations, diffusion of innovations is a process of cumulative increase in the number of agents introducing innovations after the innovator [7–12].

II. METHODOLOGY

A. Dynamic Parameters of the Innovation Spread

The dynamics of the process of innovation diffusion (the proportion of the population that has accepted innovation) is usually modeled by a logistic *S*-shaped curve and differs into the following stages:

- innovators (innovators who begin to accept and apply innovation);
- early followers (early adopters who begin to accept and apply innovation shortly after its appearance);
- early majority (early majority, perceiving innovation after innovators and early followers, but earlier than most other agents);
- later majority (late majority, perceiving innovation after its distribution);
- late followers (late adopters, perceive the latter).

All listed groups are shown in fig. 1, which shows the so-called stage curve, which is a derivative of the logistic curve [13−16].

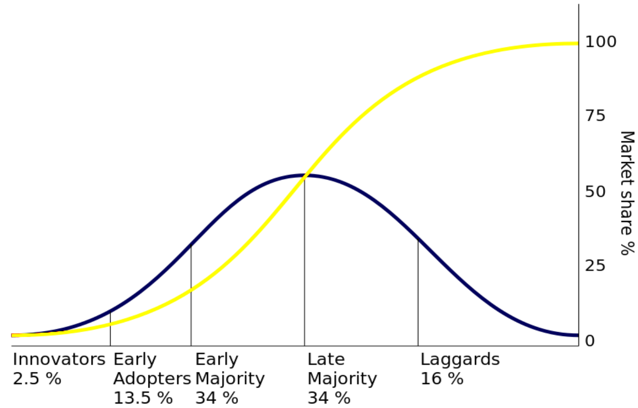


Figure 1. Dynamics of Innovations Spread

B. Diffusion of Innovation Limits

The process of diffusion of innovation has the limits of possible changes due to limited resources, which is also characteristic of many other processes in nature and society. This is due to limitations in the capabilities and capacity of the social system. The S-shaped function consists of three levels of development: the first is slow growth, where the development base is formed, the second is sharp growth, and the third is slow growth, saturation. The speed of diffusion processes is determined by the factor of interpersonal communication between supporters of this innovation and those who still hesitate or have not heard anything about the innovation.

C. The Innovation Spread Theory

This theory is known to consider the diffusion of innovations in the social system. Scientists in this field are researching how fast innovation spreads in the social system and what factors increase or decrease the likelihood of innovation being accepted by members of the social system. Innovation is introduced into the social system by innovators, and then gradually adopted by many agents who transmit information about innovation to each other, in this regard; the nature of the social system plays an important role. The spread of innovation is influenced by many factors: characterizing the relationship of innovative parameters and the nature of the social system. The study of diffusion in its simplest form is the study of the interaction of these and other factors affecting. The Naming Game model is applied in the paper for research of innovation spread [17].

D. Main Characteristics of the Diffusion of Innovation Mechanism

Let us consider the main characteristics of innovation and the diffusion mechanism. Each member of the social system is faced with the need to make a decision (if it is not collective, that is, undertaken by all members of the system, or imperious, that is, undertaken for all by the few with power) on the adoption and use of innovation. The process of accepting innovation by an agent goes through the following stages:

- knowledge (the agent is familiar with the innovation, but does not have complete information about it);
- conviction (the agent is interested, forms a favorable or unfavorable attitude to innovation, searches for additional information);
- decision (the agent analyzes the advantages and disadvantages of adoption of the innovation, makes a decision);
- testing/implementation (the agent uses innovation);
- confirmation (the agent evaluates the results and makes a decision on further use).

Based on cost-benefit analysis, a decision is made to adopt innovation.

III. SOLUTION OF THE PROBLEM

A. Formulation of the Problem

In this paper, to study the spread of innovation, the Naming Game model is used. The concept of Naming Game was introduced by the philosopher Ludwig Wittgenstein. It gives a definition of what most fully characterizes the considered concept of Naming Game as a game, which can be represented in the form of construction. “Let's imagine the language as scaffolding. The language is intended for communication between builder A and bricklayer works with building materials; there are blocks, columns, slabs and beams and more. In must supply building materials in the exact order in which they are needed and precisely in those parts of the walls and floors that are being built at the moment. To do this, they use scaffolding, through which materials get to the place of their laying” [15, 18–20].

Similarly, the concept of Naming Game in the innovation environment consists of “words-blocks”, which are key aspects of innovation in this area. Further around these blocks’ “scaffolds” are grouped, that is, specifying characteristics of one or another innovative activity. That is, the Naming Game in this case works in the “duplex mode”, firstly, it forms the “innovation core” in the form of various specific terminologies that characterizes this or that innovation and gives a clear idea about it. And, secondly, it allows revealing the essence of this innovation as widely as possible, making it accessible to members of the social network due to the commonality of their language and, as a result, the absence of a communication barrier between innovators and followers.

However, when describing the phenomenon of diffusion of innovations using the Naming Game concept, uncertainty often arises when making a decision. One of the main causes of uncertainty is the uneven distribution of innovators within a social group, which, in turn, affects the speed of innovation.

B. Mathematical Model and Main Dependencies

Let’s consider *N* communities. The Naming Game model assumes community members can exchange information between themselves. Each member of the community has an opinion that he exchanges with his neighbors according to certain rules. In the Naming Game model [1, 9, 14, 21, 22], it is assumed that each member of the community (innovator or agent) can communicate with everyone, community members interact in pairs to reach agreement. The basic algorithmic rules of the Naming Game: a pair of neighboring nodes is selected, i.e., the innovator and the agent. The innovator voices his opinion, if the agent agrees with the opinion of the innovator, then both participants adhere to this opinion, otherwise the agent ignores the opinion of the innovator and remains at his own opinions. In the following, for simplicity, we will use the words “term” to denote opinions. The above rules are presented in fig. 2.

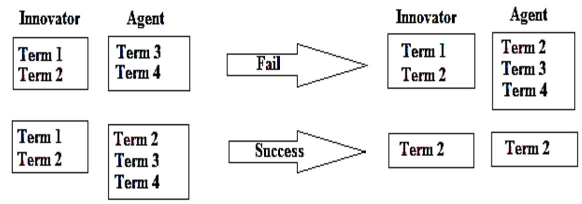


Figure 2. Graph dependences of the Naming Game model

At the beginning, the “dictionary” for all members of the community can conditionally be “empty”. At each turn, an innovator is chosen who will say the “term” from his list. If the agent has this term in the "dictionary", then he removes the remaining terms, otherwise he adds this term to the dictionary. If at least one agent in the list had this term, then the innovator leaves only it in his list. Thus, the dictionaries of all agents begin to expand. Over time, the disagreement will go away, as more and more community members will use the same words.

Consider the dynamics of the spread of innovation in the Naming Game model. At first, we will suppose that all terms are the same and the innovator can be heard by each agent with probability k (generally speaking, inversely proportional to the distance between them). Then we can write the following balance relations [8, 23, 24, 25] for the density of agents f_a with an innovative idea:

$$\begin{cases} 1 = f_a + f_{null} \\ \frac{df_a}{dt} = k * f_a * f_{null} \end{cases}, \tag{1}$$

where f_a– community density with a non-empty dictionary, f_{null} – community density with an empty dictionary, k – term distribution coefficient.

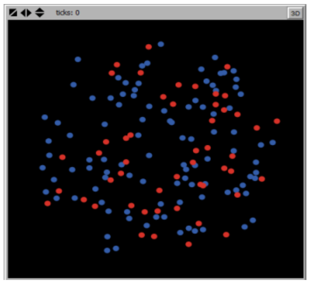
Express f_{null} through f_a and substitute in the second equation:

$$\frac{df_a}{dt} = k \times f_a \times (1 - f_a), \tag{2}$$

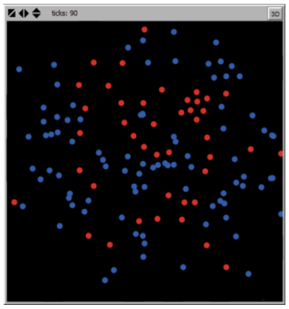
The resulting equation has the form of the Verhulst equation (2) [22, 23, 24−28], which we use to describe the “diffusion of innovations”. Adding to the model the condition that with probability g the agent can forget the word from his dictionary, we obtain an equation similar to (2) for the density of agents with a non-empty dictionary:

$$\frac{df_a}{dt} = k * f_a * (1 - f_a) - g * f_a, \tag{3}$$

Figure 3 shows the results of numerical modeling of these processes on flat times at different points in time (red dots – innovators, blue – agents), from which it can be seen that over time, the community breaks up into some groups of agents of approximately constant numbers that co-migrate along the plane.



a



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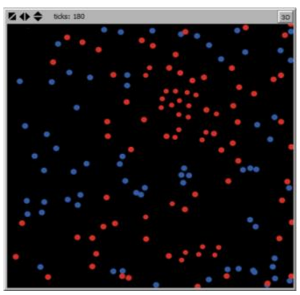

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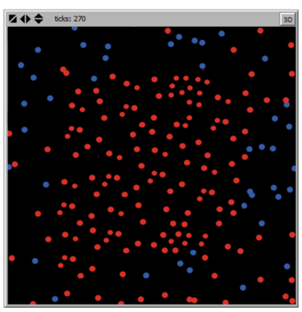

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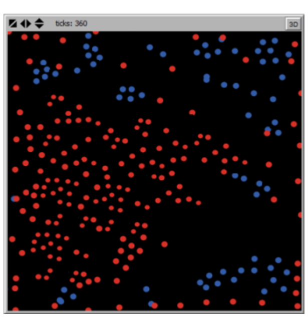

e

Figure 3. The Results of Modeling on a Plane:
(a) the original picture; (b)90 time steps; (c) 180 time steps;
(d) 270 time steps; (e) steady state picture

IV. RESULTS AND DISCUSSION

The analysis given in fig. 3 data indicates that the increase in the number of innovators and, accordingly, the reduction in the number of agents occurs evenly and in stages. This is especially clearly seen when comparing fig. 3 a and fig. 3 b. Initially, the number of innovators is small. However, then in the process of diffusion, innovations begin to penetrate through the communication channels into the environment of agents, using the concept of Naming Game. It should be emphasized that each innovator can be considered as a “core” around which primary agents are grouped. And the wider the circle of contacts of the innovator, the more primary agents are subject to diffusion of innovations. Initially, there are few primary agents, and the diffusion of innovations in their environment spreads according to the law of arithmetic progression.

Even more significant processes are presented in fig. 3 c. In this case, the primary agents themselves become innovators. Moreover, their social circle is broader than that of innovators at the beginning. The range of secondary agents is expanding significantly, which may be subject to diffusion of innovations not only by primary agents, but also by innovators themselves. Therefore, in accordance with the Naming Game concept, the expansion of the communicative activity of primary agents is in direct proportion to the diffusion of innovations. Therefore, the diffusion of innovation is much faster, obeying the law of geometric progression.

In fig. 3 d already shows data indicating that the processes of diffusion of innovations in the community under consideration have already entered the saturation phase. A sharp increase in the number of secondary agents continues. Mathematically, an increase in their number can be described by an exponential law, or even using the Huygens wave law. In this case, the remaining members of the community, not covered by the diffusion of innovations, are practically isolated from each other. In their immediate circle of communication, both primary and secondary agents are present, and therefore the diffusion process occurs as if by inertia and is already self-regulating. Around the same innovators, who were the initiators of the diffusion of innovations in this community, a clear barrier has already been built from primary and even secondary agents. In fact, innovators themselves may not even interact with the rest of the community, and the diffusion process itself is carried out through secondary and to a lesser extent primary agent. The community structure acquires a pronounced network-centric structure with a core of innovators and periphery of agents not yet covered by the diffusion process.

The picture of the diffusion process shown in fig. 3 e indicates that the diffusion process, having passed the saturation phase, entered the stabilization phase and began to decay. The overwhelming majority of the members of the community in question perceived the innovative ideas put forward by innovators at the beginning of the process, and already perceive them as an established reality. The remaining members of the community for some reason (most likely of a personal nature) are not covered by the diffusion process of innovations. Their transformation into secondary agents is stochastic and is not an indicator of the further spread of innovation to the periphery of the community. And the number of increases in secondary agents is not large and does not exceed the error of the proposed mathematical model based on the concept of Naming Game.

V. CONCLUSION

Based on numerical calculations using the Naming Game model, the process of innovation distribution in the social system is investigated. Mathematical modeling using the Ferhulstap dependency showed that when a new idea arises, society does not perceive it evenly, but can fall into groups perceiving a new idea and not perceiving. Therefore, a refined mathematical model of the diffusion of innovations was proposed.

As the results of a numerical experiment shows, the proportion of community members who accept an innovative idea increases sharply as soon as they reach a certain level and, accordingly, the dynamics of the spread of innovation changes stepwise. Initially, an increase in the number of primary agents occurs according to the law of arithmetic progression. Later, when secondary agents appear, the diffusion of innovation is accelerated according to the law of geometric progression. And finally, at the saturation stage, there is a sharp jump in the growth of the number of innovators and their agents according to the exponential law.

The results of numerical modeling can be used later in the study of more complex processes in various social groups, as well as the processes of interaction of different groups within a single society. In this case, the developed mathematical model will be an integral part of the numerical algorithm for solving the applied problems.

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