Розглянуто статистичні закономірності наукових комунікацій, що описують явища і процеси самоорганізації в бібліотечній справі, наукознавстві та лінгвістиці. Методологічною основою роботи обрано синергетику.

Метою дослідження визначено розробку синергетичної концепції виникнення статистичних закономірностей інформаційних процесів і явищ у наукових комунікаціях для їх узагальнення та подання у вигляді одного закону.

Розвинено уявлення щодо синергетики наукових комунікацій як вияву об'єктивно існуючих, але теоретично не обґрунтованих кількісних відношень між суб'єктами й об'єктами цих комунікацій (вченими, публікаціями, термінами). Відзначено необхідність використання для опису масштабно інваріантних явищ і процесів стійких законів розподілу теорії ймовірностей. У математичному сенсі стійкість закону розподілу – властивість зберігати його тип для будь-якої суми випадкових величин, що мають цей розподіл. Математична абстракція «випадкова величина» в наукових комунікаціях набуває чіткої конкретики. Для закономірності Бредфорда випадковою величиною є кількість статей з певної теми в журналі, для закономірності Лотки – число публікацій вченого, для закономірності Ципфа – частота використання слова в тексті.

Встановлено характеристичний показник стійкого закону розподілу процесів і явищ у наукових комунікаціях, що дорівнює константі золотого перетину.

Сформульовано синергетичну концепцію наукових комунікацій: масштабно-інваріантні процеси і явища самоорганізації – вияв стійкого закону розподілу теорії ймовірностей з характеристичним показником, рівним константі золотого перетину

Ключові слова: бібліотечна справа, статистичні закономірності, масштабна інваріантність, стійкий розподіл

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A STUDY OF SELF-ORGANIZATION OF SCIENTIFIC COMMUNICATIONS: FROM STATISTICAL PATTERNS TO LAW

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1. Introduction

In the system of scientific communications, there are a number of statistical laws that describe the phenomena and processes of self-organization in the library science, the science of science, and linguistics [1–3]. Patterns were established in the first half of the 20th century, bear the names of discoverers, and are usually referred to as laws. However, given the empirical nature of their identification, it seems more correct to use the term "regularity" in relation to them, since a law is part of a sound scientific theory. These statistical laws are approximated by power or hyperbolic dependencies. At present, there is no generally accepted point of view on the mechanism of establishing the mentioned statistical laws or their generalization and presentation in the form of a single law. The solution to such a problem, which is relevant not only for scientific communications, requires the development of a mathematical model of the considered patterns and the identification of its parameters.

2. Literature review and problem statement

The results of studies of the distribution of scientists by publication activity were first presented in [1]. The established statistical regularity was formulated as follows: the number of authors who published n articles is about $1/n^2$ of those who published one article; the proportion of all authors who published one article is about 60 %. More recent studies have shown that the $1/n^2$ ratio requires clarification [4]. In [5], the results of studies of this pattern are presented by analysing articles on ecology in the Scopus database for the period of 2013–2017. The approximate nature of the pattern and the need for its approximation are noted.

J. Zipf's linguistic-statistical regularity approximately describes the distribution of the frequency of using words in any language [2]. The pattern has the following wording: if all words of a sufficiently long text are arranged by decreasing the frequency of their use, then the frequency of using a particular word in such a list will be inversely proportional to its serial number. For example, the second most applicable word is found about two times less than the first, the third is recovered three times less, and so on. Zipf's pattern is confirmed for all languages, scientific and literary texts, Internet resources, etc. [6].

It should be clarified that this pattern was discovered in 1908 in the process of developing a rational shorthand system. There should be a correlation between the frequency of use of the word and the corresponding shorthand sign. This sign should be the simpler the more common the word it represents. From the point of view of the modern theory of information, this was an attempt to solve the problem of optimal coding, taking into account the bandwidth of the telecommunication data channel. Zipf's pattern was repeatedly specified. In particular, in [7] the regularity was considered in the aspect of accounting for co-authorship.

Bradford's pattern characterizes the distribution of articles on a specific topic in an array of periodicals [3]. Its primary formulation is as follows. If the journals are placed in a descending order of the number of articles on the selected topic and the resulting list is divided into three zones with the same number of articles on this topic, then the number of journals in each group will be proportional to $1{:}n{:}n^2$. Today, Bradford's regularity is considered in terms of assessing the quantitative growth of literature [8], in identifying new approaches to determining the impact factors of journals [9], as well as in refining the parameters of concentration and dispersion of literature [10]. In [11], it was shown that the pattern of concentration and dissemination of information should be considered as a social phenomenon and the possibility of using it to solve many practical problems. One of them is to determine the preferred volume of journals in the collection of library depositories [12]. The approaches to the study of the considered patterns in digital resources are described in [13], where it is supposed to identify latent patterns on webpages, in particular on wikis.

The considered patterns are manifested in various fields of scientific communications (library science, linguistics, scientometrics, infometry, etc.). In the second half of the 20th century, it was noted that such patterns differed only in the areas of use, and the question should be raised about a single type of such patterns. The identification of this type was given considerable attention by a number of scientists [10–14]. A variety of works testifies, on the one hand, to the existence of a phenomenon of self-organization of scientific and communication phenomena and processes, and on the other hand, to the absence of their generally accepted mathematical model. Thus, in [14], to describe these processes, the concept of invariants and multiple relations of parts of documentary information flows was introduced, in [6] – "optimal coding", and in [15] – "the principle of asymmetry". However, the aforementioned fuzzy concepts and terms did not explain the emergence of patterns of self-organization of communications and did not contribute to the development of a methodology for their study. A general approach to the study of these laws was proposed in [16] as the methodology of applied informatics, which is based on 'power distributions described by the laws of Lotka, Zipf or Bradford'.

Particularly, it should be noted that in work [17] the models of self-similarity and fractality of the information space were analysed. The use of the synergetic concept of self-organization of this space seems to be the most promising direction for conducting analytical studies of scientific and communication processes and phenomena.

The number of published materials on the problems of the considered statistical laws reaches several dozens of thousands. For example, Google Scholar gives links to more than 640,000 papers to the request 'Law Bradford', and 40,000 and 30,000 papers to the requests "Law Zipf" and "Law Lotka", respectively. Therefore, we can state the existence of a sufficient source base for the study of the mentioned patterns. Each subsequent publication clarified the description of the laws that bear the names of their discoverers.

In [18], empirical tests of the laws of A. Lotka for computer science and library science were carried out. The authors present this regularity by a discrete probability distribution function, which describes the publication activity of the authors in this field as follows:

$$f(x)=\frac{C}{x^{\alpha}}, \tag{1}$$

where $f(x)$ is the number of authors with x publications, and α and C are the parameters that are determined from empirical data.

In [1], the productivity of scientists in the field of physical sciences was studied, where the value of α turned out to be close to 2. In article [18], which appeared 90 years after publication [1], the indicator α (for computer science and library science), determined using the method of least squares is equal to 2.3758. The authors state the need for similar studies in other sciences. It seems more appropriate to find a single analytical dependence of the distribution of authors on publication activity for all areas of knowledge.

The most significant development of Zipf's idea was carried out in [6], where its expression was rethought and corrected using the methods of information theory and probability theory to study the distribution of word frequencies. Words were considered as space-separated letter sequences that demonstrated a specific order of comparison of the written language and codes using an analogue or digital expression format. In [6], it is stated that all symbols have a certain meaning and can provide a priority opportunity for the dictionary to determine the minimum total average value, while the amount of information remains unchanged. One of the patterns in the interpretation of [6] has the following form:

$$f(p)=\frac{A}{p^{\alpha}}, \quad p=1,2,\ldots,n, \tag{2}$$

where $f(p)$ is the function of the relative frequency of occurrence of components (different words) in a list arranged by the frequency of their use), p is the relative frequency of occurrence of the word, and A and α are constants.

The initial formulation of Bradford's law suggested the division of the totality of journals, sorted by the number of articles on a particular topic, into three zones. In [14], this distribution is called the pattern of concentration and dispersion of information. Subsequently, the authors of [19–21] proved that the collection of journals could be divided into a larger number of zones with a power-law distribution of the number of articles in them. A significant contribution to the development of the Bradford concept was made in [22], where the possibility of applying this concept to the distribution of various components is substantiated: articles – journals, authors – articles, publications – queries, or lexical units – texts. The presented Fig. 1 shows the distribution of the number of Ukrainian scientists by the values of their Hirsch indices in the Scopus system (the values of this index were taken into account in the range from 1 to 20). Fig. 1 was generated by the analytical information system "Bibliometrics of Ukrainian Science" [23], created with the participation of the authors of the present article.

In the review of the family of statistical distributions, a wide range of phenomena in the information sciences and the main forms that take these patterns are considered. Moreover, it is repeatedly suggested that, despite the differences in their appearance, these distributions are variants of the same distribution. The fact that a single distribution should describe a wide range of phenomena, often outside the information sphere, is surprising. In [24], it is said that this phenomenon should be sought for an explanation based not on the models of a specific subject area but on the properties of a single statistical distribution. In [25], it is noted that it is necessary to determine the set of properties that subject domains should possess in order to identify a single statistical distribution, which in this case can be called the law.

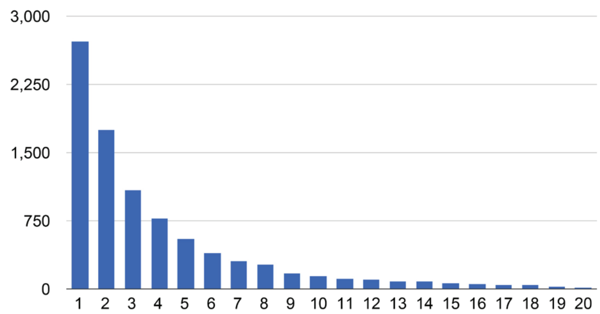

Fig. 1. The distribution of Ukrainian scientists by the Hirsch index in the Scopus system: across – the values of Hirsch indices from 1 to 20; down – the number of scientists with the corresponding index

Further development of these conceptual provisions can be considered as the publications of the authors of this article, where the phenomenon of large-scale invariance of information phenomena and processes in the system of scientific communications is taken as such a property [26, 27]. In these publications, the first attempt was made to justify the necessity and sufficiency of this property to describe a single analytical dependence of all the considered distributions in the system of scientific communications.

The methodological basis of the study is synergetics, which is an interdisciplinary direction whose task is to study phenomena and processes of various natures based on the principles of self-organization. The foundations of synergetics were laid in [28].

The history of synergetics is associated with the names of many prominent scientists of the twentieth century, who laid the foundations of nonlinear dynamics and a qualitative theory of differential equations. Probability theory methods of statistical physics should also be considered as sources of synergetics, namely, methods of averaging and obtaining finite equations for macrocharacteristics in systems with a large number of particles. Nonlinear statistical methods and computer simulation have become the basis of mathematical methods of synergetics.

In the 1960s and 1970s, the creation of new generations of powerful computers facilitated the development of fractal geometry and the geometry of self-similar objects.

The boundaries of applying synergetics is a subject of discussion, including philosophical, but only the practice of its use can reliably establish these boundaries. At the same time, it seems that in the coming years synergetics will become not only the basis for solving a wide range of interdisciplinary problems but also a supplier of new high humanitarian and intellectual technologies of the future [29].

The prerequisites for self-organization are the openness of the system and the entry of energy, matter or information into it from the external environment (according to classical thermodynamics, the entropy of a closed environment increases irreversibly and its 'thermal death' occurs). From these assumptions it follows that the synergetic concept of the system of scientific communications involves the receipt of new information into it and the readiness for the transformation processes caused by this information.

However, the mechanism of occurrence of such transformation processes in the above works has not been determined. It seems that the reason for this is the study of statistical laws separately for each subject area. All this enables us to argue that it is advisable to determine a single mechanism for the emergence of a family of laws and a mathematical apparatus for representing it in the form of a single law.

3. The aim and objectives of the study

The aim of the study is to develop a single concept for developing statistical patterns of information processes and phenomena in the environment of scientific communications.

To achieve the aim, the following objectives were set and done:

– to substantiate the fundamental concept of building a unified mathematical model of scientific and communication phenomena and processes;

– to determine the mathematical apparatus for generalizing the family of empirical laws of scientific communications and their presentation in the form of one law.

4. A synergetic concept of the emergence of patterns of information phenomena and processes in the environment of scientific communications

The idea underlying the study is as follows. The statistical laws of Bradford, Lotka, and Zipf are a manifestation of objectively existing but theoretically unsubstantiated quantitative relations between subjects and objects of scientific communications. The latter are scientists, publications, terms, etc. As one example of the manifestation of such a latent attitude, we present the obtained distribution of Ukrainian scientists, cited by the Scopus system, by city [23]. The distribution is shown in Fig. 2, which was generated by the already mentioned system "Bibliometrics of Ukrainian Science".

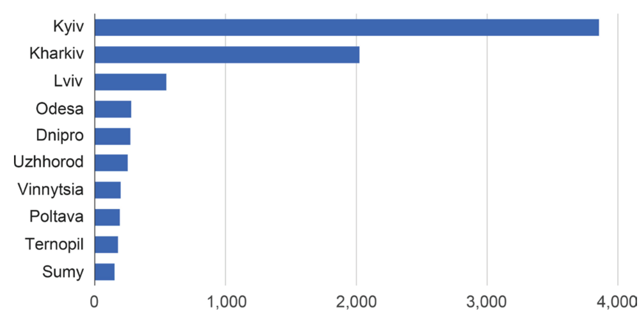

Fig. 2. The distribution of Ukrainian scientists whose publications are cited in the Scopus system by city: across – the number of scientists; down – cities

Further development of the theoretical base of scientific communications requires the use of a mathematical apparatus to accurately describe the family of the mentioned statistical laws. In determining this apparatus, we will proceed from the fact that the considered laws are characterized by large-scale invariance (self-similarity) of information processes and phenomena, that is, the ability to preserve the form of equations with arbitrary changes in scales (temporal, spatial, etc.). Initially, the concept of scale invariance was developed within the framework of physical theories and implied the property of invariance of equations describing a theory or process when all distances and time intervals changed by the same number of times. Such changes form a group of scale transformations (also called similarity transformations), determined by the following law of change in the coordinates of space and time:

$$x \to \rho x, \quad y \to \rho y, \quad z \to \rho z, \quad t \to \rho t, \tag{3}$$

where $\rho>0$ is the numerical parameter of the transformation, which for $\rho>1$ corresponds to the uniform tension, and for $\rho<1$, to the uniform compression of space-time by r times [30].

Of great importance is the geometric aspect of scale invariance – fractal geometry. As applied to the field of scientific communications, issues of scale invariance are described in [31], where it was stated that the self-similarity of information flows and processes manifests itself in any quantitative changes. Zipf's regularity is observed for both thin and thick books; Bradford's regularity holds for an arbitrary set of analysed periodicals. The distribution of scientists by publication activity (the Lotka regularity) does not depend on the size of their sample of fields of activity and geographical place of work.

A mathematical description of scale invariant laws requires the use of stable distribution laws of probability theory. In the mathematical sense, the stability of the distribution law is the property of preserving its type for any sum of random variables having this distribution [32]. The mathematical abstraction of a "random variable" in scientific communications takes on a clear specificity. For Bradford's regularity, the random variable is the number of articles on a specific topic in the journal; for Lotka's regularity, it is the number of publications of a particular scientist; and for Zipf's regularity, it is the frequency of using the word in a rather long text. From this interpretation of random variables it follows that the laws of Bradford, Lotka and Zipf, which approximately describe information phenomena and processes in various fields of scientific communications, should be considered as a manifestation of a stable probability distribution law.

5. A generalization of the family of empirical laws of scientific communications in the form of a single law

The distribution function $F(x)$ is called stable if for any real numbers $a_1>0$, $a_2>0$, and b_1, b_2 there are $a>0$ and b such that the equality holds:

$$F(a_1x + b_1) * F(a_2x + b_2) = F(ax + b), \tag{4}$$

where * is the convolution operation [32].

The study of stable distribution laws is carried out using their characteristic functions, which represent one of the ways to set the distribution. The characteristic function of a stable distribution is described by the equation:

$$\varphi(t) = \exp\left\{ idt + c|t|^{\alpha}\left[1 + i\beta\frac{t}{|t|}\omega(t,\alpha)\right]\right\}, \tag{5}$$

where $0<\alpha\leq 2$, $-1\leq\beta\leq 1$, and $c\geq 0$, d represent any real number, and

$$\omega(t,\alpha) = \begin{cases} \mathrm{tg}\dfrac{\pi\alpha}{2}, & \text{if } \alpha \neq 1, \\ \dfrac{2}{\pi}\ln|t|, & \text{if } \alpha = 1. \end{cases}$$

The key parameter of stable distribution laws α is called the stability parameter or characteristic indicator.

The considered distributions in the field of scientific communications are investigated using methods of mathematical statistics and computer technology. We present two computational experiments to identify the above key parameter.

One of the approaches to determining its quantitative value for the considered patterns is given in [33] by the example of analysing the Zipf pattern. The authors of this work conducted a computational experiment in order to identify the probability of the appearance of certain lexical units in the text. It is established that this probability is equal to some basis in the degree k, where k is an integer, its own for each dictionary unit. The best approximation of the distribution of text components (vocabulary and letter units) depending on their rank k is achieved with a base equal to the golden division constant – 0.618…. The values of the probabilities, which are equal to this constant in the degree k, form the basis in which the probabilities of the remaining vocabulary units are determined.

A similar result was obtained in [14], where the results of analysing documentary information flows are presented and the principle of multiple relations is formulated, the essence of which is the constancy of relations between parts of the information space.

It is known from the probability theory that stable distribution laws in the general case are not described by elementary functions. Exceptions are the normal distribution law (its characteristic indicator is 2), the Cauchy distribution (characteristic indicator is 1), and the distribution with the characteristic indicator is equal to 0.5 [32]. Therefore, numerous attempts to obtain an accurate model of the studied statistical laws based on power or hyperbolic functions could not be successful.

Thus, the proposed synergistic concept of the emergence of statistical laws of large-scale invariant information flows and processes in the environment of scientific communications made it possible to generalize these laws as a manifestation of a stable distribution law.

6. Discussion of the results of researching self-organization of scientific communications

The result of the study was achieved thanks to a methodologically sound approach to the study of scientific communications – synergetics, which studies the problems of self-organization of models and structures in open systems that are far from thermodynamic equilibrium. This approach provided a representation of objectively existing but theoretically unsubstantiated relationships between subjects and objects of scientific communications in the form of a stable law of probability distribution.

The prerequisites for self-organization in scientific communications are large-scale invariance of the phenomena and processes existing in them, that is, the absence of a distinguished characteristic and spatial scale. Self-organization processes develop due to openness, the influx of information from the outside, and the non-linearity of internal processes. Self-organization of scientific communications is a local manifestation of a more general law that applies to a wide range of phenomena of a natural scientific and social nature.

The existing alternative solutions were initially approximating in nature and were aimed at finding a solution in one of the areas of scientific communications (scientometrics, linguistics, and library science). The lack of an integrative principle prevented us from obtaining a positive result. An advantage of the proposed approach is its focus on identifying a single mechanism for the emergence of self-organization of scientific communications and the mathematical apparatus for its presentation. Thus, a theoretical basis is suggested for the transition from approximation to analytical methods for the study of the self-organization of scientific communications based on the stable laws of the distribution of random variables.

A probabilistic theoretical model of scale invariant phenomena and processes in the general case cannot be represented by elementary functions. Numerous attempts to use fuzzy concepts and terms "extremely hyperbolic functions", "coenoses", and "principle of asymmetry" instead of the concept of scale invariance of the processes did not lead to success. Apparently, this is due to the large number of publications on the laws of Bradford, Lotka, and Zipf, which are descriptive.

The manifestation of large-scale invariance in scientific communications is not a unique phenomenon. Invariance is present in biology (distribution of the biodiversity of organisms in a certain territory), geography (distribution of settlements by the number of inhabitants), economics (distribution of material wealth in society), architecture (geometric proportions of structures), etc. Large-scale invariance is considered one of the symmetries that form the Universe and affect its development. Therefore, the self-organization of scientific communications is a local manifestation of a more general law that applies to a wide range of phenomena of a natural scientific and social nature.

It is advisable to direct the further development of this study to the search for the optimal approximation of the aforementioned stable probability distribution law. In the applied aspect, the practical use of a generalized mathematical model of the laws of scientific communications should be ensured by creating a specialized computer program or tabular forms of reflection of these laws.

7. Conclusion

1. As a fundamental concept for constructing a generalized mathematical model of scientific and communication phenomena and processes in various fields of scientific communications, it is proposed to use large-scale invariance. In mathematics, the concept of scale invariance refers to the invariance of individual functions, in particular the probability distributions of random variables and processes, with respect to the similarity transformation. In scientific communications, the mathematical abstraction 'random variable' is an attribute of the subjects and objects of these communications (scientists, publications, and terms).

2. The mathematical apparatus for generalizing the family of empirical laws of scientific communications and their presentation in the form of one law are stable laws of distribution of random variables. In general, stable laws are not described by elementary functions and require the use of characteristic functions to operate with them. Its analytical study requires researchers to have a high level of mathematical training, in particular, the ability to use the characteristic functions of random variables.

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