UDC 331.101.262
JEL: A13; O10; O49
DOI: https://doi.org/10.32983/2222-4459-2023-11-133-141

THE LIFE CYCLE OF INNOVATIONS AND KONDRATIEV WAVES IN THE CONTEXT OF THE CONCEPTION OF INDUSTRY 4.0

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The nature of long Kondratiev waves, reflecting the cyclical nature of economic development, has attracted the attention of scholars for more than a hundred years. This problem becomes especially relevant in times of global crises. And although this theory do not belong to the mainstream of economic thought, the great theorists of the twentieth century have tried to either prove or disprove the reality of the very existence of long waves. The very idea of the non-linearity of the development of a system of any nature was impossible within the framework of the science of the nineteenth century, therefore, in order to understand the revolutionary nature of Kondratiev?s ideas and his contribution to changing the paradigm of economic science, the work compares the epistemological principles that were inherent in the science of the nineteenth century and at the beginning of the twentieth century. In particular, the main attention is paid to consideration of the fundamentals of thermodynamics of non-equilibrium processes, which examines the processes of self-organization in open systems, and synergetics, one of the cornerstones of which is the axiom of the non-additivity of the properties of the whole as an aggregate of the properties of its parts. The paper demonstrates the application of such a system of scientific views to determine the features of the life cycle of innovations. This approach makes it possible to apply the mathematical apparatus of non-linear dynamics to study the evolution of non-equilibrium economic systems and to determine the final state of the system by studying its possible trajectories in phase space. The respective analysis of the development of endogenous theories of long cycles made it possible to investigate how views on the place of innovations in determining the nature of Kondratiev waves changed. It is shown that it is not the presence of innovations that is essential, but the formation of an innovation cluster. Such a cluster consists of the so-called improving innovations, the use of which contributes only to the quantitative growth of economic indicators, and the catalyst is the basic (or systemic) innovations, the implementation of which determines the transition of the economic system to a new industrial type. In further research, it is expedient to use such an approach to the analysis of the ways of evolution of the economy in the context of sustainable development.
Keywords: *thermodynamics of non-equilibrium processes, bifurcation, dissipative structures, synergism, order from chaos, innovation, sustainable development.*
Fig.: *2.* ***Bibl.:*** *30.*

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УДК 331.101.262
JEL: A13; O10; O49

Маляреть Л. М., Лебедєв С. С. Життєвий цикл інновацій і хвилі Кондратьєва в контексті концепції «Індустрія 4.0»

Природа довгих хвиль Кондратьєва, що відображають циклічність розвитку економіки, вже понад сто років привертає увагу вчених. Особливо актуальною ця проблема стає в період глобальних криз. І хоча ця теорія не є мейнстримом економічної думки, видатні теоретики XX століття намагалися або довести, або спростувати реальність самого існування довгих хвиль. Саме уявлення про нелінійність розвитку системи будь-якої природи було неможливим у рамках науки XIX століття, тому, щоб зрозуміти революційність ідей Кондратьєва і його внесок у зміну парадигми економічної науки, у роботі проведено порівняння гносеологічних принципів, що були притаманні науці XIX – початку XX ст. Зокрема, основна увага приділена розгляду основ термодинаміки нерівноважних процесів, яка досліджує процеси самоорганізації у відкритих системах, та синергетики, одним із наріжним каменів якої є аксіома про неадитивність властивостей цілого як сукупності властивостей його частин. У роботі продемонстровано застосування такої системи наукових поглядів для визначення особливостей життєвого циклу інновацій. Такий підхід дозволяє застосовувати математичний апарат нелінійної динаміки для вивчення еволюції нерівноважних економічних системи і визначати кінцевий стан системи за дослідженням її можливих траєкторій у фазовому просторі. Проведений аналіз розвитку ендогенних теорій довгих циклів дозволив дослідити, як змінювалися погляди на місце інновацій у визначенні природи хвиль Кондратьєва. Показано, що суттєвим є не сама наявність інновацій, а формування інноваційного кластера. Такий кластер складається з так званих поліпшуючих інновацій, застосування яких сприяє лише кількісному зростанню економічних показників, а каталізатором служать базисні (або системні) інновації, впровадження яких визначає перехід економічної системи до нового промислового типу. У подальших дослідження доцільно використовувати такий підхід до аналізу шляхів еволюції економіки в умовах сталого розвитку.
Ключові слова: *термодинаміка нерівноважних процесів, біфуркація, дисипативні структури, синергізм, порядок із хаосу, інновації, сталий розвиток.*
Рис.: *2.* ***Бібл.:*** *30.*

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At the present time, the assertion that economic development as a process is far from the linear one cannot be questioned. Although economic indicators are growing in general, this growth is irregular. Even under conditions of social stability, periods of slow development and even stagnation, during which there is a slight increase in labor productivity (due to qualitative rather than quantitative improvement of tools and industrial technologies), are replaced by periods of abrupt rapid growth. That is, longer periods of gradual evolutionary change are separated by the respective short periods of revolutionary transformations.

Back in the 20s of the last century, Mykola Kondratiev generalized the study of the dynamics of some economic indicators, in particular the interest rate, the volumes of production and consumption of coal, cast iron, lead, as well as the prices for raw materials, agricultural and industrial goods, and identified the presence of cycles whose duration ranged from 45 to 60 years. In 1927, together with Dmytro Oparin, he presented the report «Large Conjuncture Cycles», and this work marked the beginning of the development of the theory of long waves [1], which were later called Kondratiev cycles. At the time of the emergence of the theory of long waves, the very existence of such cycles was doubted by many scholars. In particular, opponents criticized Kondratiev on the basis of his theory being actually a mechanical extension of the theory of 7–11 year cycles, which were introduced into discourse by Mykhailo Tuhan-Baranovskyi (who in turn borrowed the idea from Clément Juglar), over a longer period of time. In particular, it was pointed out to Kondratiev that his results may be essentially artifacts of the moving average method that he chose to process statistical data. It is further related to the Slutzky – Yule effect [2–4]. This effect occurs when application of the moving average method to determine the trend of series of random numbers (for instance, the so-called «white noise») creates false wave-like patterns that do not reflect any underlying tendency apropos of the data in question. Such scientists as Finn Erling Kydland, Edward Prescott, and Ragnar Frisch considered cyclical fluctuations to be the result of the impact on the economic system of random shocks that would lead to a violation of economic equilibrium. Nevertheless, Kondratiev's theory found supporters who in their works examined the nature of such long-term cycles. This theory has aroused interest and still is of particular importance to those researchers who are engaged in forecasting. Thus, it can be considered that the influence of the theory of long waves on the development of world economic science is significant, although it has not become mainstream.

The *purpose* of the presented work is to study the historical background against which the theory of long waves by Kondratiev was created and formed, also to identify and systematize views on the theory of long waves in connection with the paradigm of innovative development in general and the conception of Industry 4.0 in particular.

Kondratiev considered the economic indicators of the most developed countries of his time, namely England, France, Germany and the United States. In the pertinent conclusions, he relied on an analysis of economic indicators from 1780 to 1920. During the period under study, Kondratiev discovered the existence of two complete cycles and the beginning of the third cycle. Various researchers have different estimates of the boundaries of these cycles. According to Kondratiev, the boundaries of the two complete cycles were considered in the range from 1789–1803 to 1841–1843 and from 1844–1851 to 1890–1896. In his early works, Kondratiev adhered to the views of Juglar and Tuhan-Baranovskyi, that is, he put the crisis in the center of the cycle, therefore, the sequence was as follows: «rise, crisis, depression». Later, in accordance with his views on the nature of cyclicity, he moved on to a model where the crisis became the final part of the cycle. The same principle is adhered to by modern researchers. Subsequently, Kondratiev's followers expanded the time limits of research, also included such countries as China, Japan, Singapore, Canada, Australia, South Korea and other countries that are currently considered as countries with developed economies [5]. As a result of these studies, the third long cycle from 1891–1896 to 1945–1947, the beginning of which was described by Kondratiev, was supplemented, and 2 more cycles were identified, namely from 1945–1947 to 1981–1983 and from 1981–1983 until 2025, according to the forecast [6]. It can be argued that the study of the nature of the cyclical nature of economic phenomena has never been left behind the attention of scientists, and the financial crisis of 2008–2010 contributed to an increase in interest in this issue.

The conception of long waves of economic development, which originates in Kondratiev′s works, is a reflection of the general trends of changing the paradigm of scientific views of that time. Kondratiev was far from theoretical physics, however, from the standpoint of epistemology, the theory of technogenic cycles, which considers the nature of Kondratiev long cycles, can in turn be considered as an extension of the provisions of Prigogine′s non-equilibrium thermodynamics to macroeconomic processes and phenomena. The above is another example of how the paradigms of theoretical physics become philosophical views in other branches of science. Ilia Prigogine himself subsequently applied the same approach to the study of chemical processes and received the Nobel Prize «For his work on the thermodynamics of irreversible processes, especially for the theory of dissipative structures» in 1977.

To understand the essence of that upheaval in the philosophy of science, which became the distinguishing mark of the twentieth century, it is necessary to characterize the specifics of the scientific views of the eighteenth and nineteenth centuries. Regardless of the scientific field, they had one thing in common: these views were a reflection of mechanistic ideas about evolution. In the process of research, the object was divided into parts, and this division was carried out until the functioning of each individual part became clear. Then the sum of the properties of these parts, reunited into a single object, was considered as a property of the whole. That is, additivity was taken as an axiom determining the relationship between the whole and its parts. Also, any system, including economic systems, was seen as a closed one, and its possible deviations from the state of equilibrium as small. That is, the processes in the system take place in a direction that ensures the system returns to a state of equilibrium, and the relevant processes are of a linear kind. The basis of such a system of scientific views is classical thermodynamics as a branch of physics that studies the processes of energy exchange and transformation in the systems isolated from external influences. Besides, such a fairly simple system of views can be successfully used in modern research provided that certain restrictions are met. A reflection of the mechanistic view of the evolution of any system is the well-known statement of the outstanding mathematician and astronomer Pierre-Simon Laplace (who, by the way, in his works proved the stability of the equilibrium state of the solar system) that a creature capable of covering the entire amount of data on the state of the universe at any moment of time could not only accurately predict the future, but also restore the past to the smallest detail.

In contrast to classical thermodynamics, thermodynamics of non-equilibrium processes considers the behavior of an open system, or a system that generally exchanges energy, mass, and information with the external environment (*Fig. 1*).

The behavior of an open system is determined by the Prigogine – Onsager principle [7; 8]. According to this principle, with significant deviations from the state of equilibrium, the system, having crossed the limit of stability, falls into a critical state. This state is defined as the bifurcation point when the system becomes unstable with respect to fluctuations. At this point, even a small fluctuation can randomly determine the direction of the system′s development and dramatically change its structure and properties. Accordingly, there is uncertainty about the transformations that can take place in the system, since the system can move either to a chaotic state, or as a result of the processes of self-organization, a new, higher level of orderliness is formed. In the second case, the consequence of external influence is the development of relaxation processes in the system, which is defined as self-organization, and the result of these processes is the formation of dissipative structures. Due to the dissipation (scattering) of energy coming from the outside, such structures ensure the stability of an open system in a state far from the initial state of equilibrium. Accordingly, the open system moves to a new state of equilibrium, in spite of constant external influence. As reflected by Prigogine in the title of one of his books, order is formed from chaos.

The state the system will move to as a result of a fluctuation perturbation at the bifurcation point depends on the direction of the connections between the elements within the system. By the way, the term «bifurcation» is derived from the Latin word *bifurcus*, which means *ambivalent*. If positive feedback prevails in the system, then in response to a perturbation, they amplify this perturbation, and the strength of the influence of such a pertur-

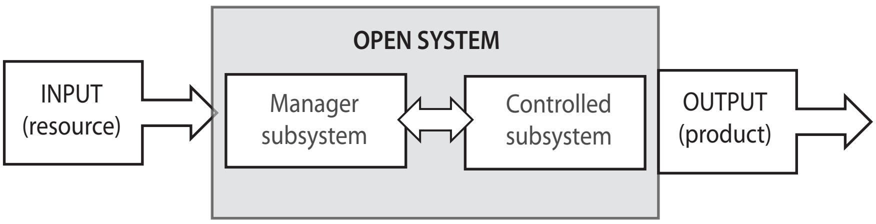

Fig. 1. General scheme of an open system

Source: summarized by the authors on the basis of [7; 8, and others].

bation increases exponentially. Thus, positive feedback accelerates the response of the system to changes in the input signal, so the development of processes in such a system is far from linear. Conversely, if negative feedback prevails in the system, then the system resists external influences. Negative feedback makes the system more resistant to random parameter changes. Therefore, if the behavior of a closed system is determined and symmetrical in time, then for an open system this symmetry between past and future is broken. According to Prigogine, crossing the bifurcation point has the same random consequences as a coin toss.

Prigogine's ideas as to that self-organization processes can develop in an open system when crossing the bifurcation point gave impetus to the formation of a new interdisciplinary direction in epistemology, which was called «synergetics». As noted above, in the eighteenth and nineteenth centuries, the basis of the methods of scientific research was the idea that the properties of the whole (system) are the sum of the properties of its parts. In the twentieth century, the axiom of additivity of properties was replaced by the idea of their multiplicativeness, that is, the properties of the whole can differ significantly from the sum of the properties of the parts that comprise this whole. In the 60[s] of the twentieth century, self-organization in non-equilibrium open systems was considered within the framework of various natural sciences, until the interdisciplinarity of this conception was realized by Hermann Haken, who introduced the term «synergetics» [9]. Studying optical systems, he came to the conclusion that self-organization in systems of different nature has many common features, and to characterize phase transitions in open systems, one generalized variable, or the order parameter, will suffice (for example, for a system in a state of chaos, the order parameter equals zero). At this, when nonlinear dynamical systems are combined, the properties of the new formation will be not equal to the sum of the properties of the parts, so that this new system has a different organization with its own properties. The non-additivity of properties provision is one of the cornerstones of synergetics.

Thus, even a brief analysis of the historical background against which the formation of Kondratiev's conception of long waves took place indicates that the twentieth century was an era of change in the very philosophy of science, the worldview of the researcher. These changes were reflected in all fields of knowledge, and one of the examples of the application of synergetics in economic theories is the theory of catastrophes, studying the processes of self-organization of non-equilibrium systems in such terms as bifurcation, attractor (i. e., an aggregate of points in the space of states of the system, to which phase trajectories, or trajectories of system development, are «attracted»), instability, qualitative analysis by phase trajectories [10–13, etc.]. It is worth noting that the application of the mathematical apparatus used in the construction of models of theoretical physics to research in the field of economics drew attention of philosophers. This was even reflected in the question of whether economics can be considered an extension of physics [14]. This resulted is such a new term as econophysics. So the international consulting firm McKinsey and Co is sponsoring a new annual award – the Young Scientists in the Field of Socio- and Econophysics Award. Now let's review the theory of long waves, based on the provisions of non-equilibrium thermodynamics and synergetics.

In general, the modern economic theory allocates several types of cycles [15; 16]. Short cycles (lasting 3–4 years) are called Kitchin cycles. While in the 20[s] of the twentieth century Joseph Kitchin associated their existence with fluctuations in world gold reserves, in modern economic theory the nature of these cycles is explained by a time lag in the transmission of information that affects managerial decision-making. The existence of average Juglar cycles (lasting 7–11 years), also called investment cycles, is associated with the time lag of investments in fixed assets, that is, with the gap in time between the investment decision and the implementation of investments. There is another type of medium cycles (lasting 15–25 years), or *Kuznets swing cycles*, which the author of this theory, Simon Kuznets, called demographic and associated them with the influx of immigrants. Other researchers consider changes in real estate prices as well as land prices to be the main cause of such cycles, that is why these are also called construction cycles. Long Kondratiev cycles, or man-made cycles, have a longer duration (40–60 years). We can also mention longer cycles, namely the Forrester cycles (200–400 years), when the discovery of new sources of energy or materials becomes a source of long-term economic growth, as well as the Toffler cycles (1000–2000 years), associated with the birth and disappearance of civilizations. The first two types of cycles are quite clear to be comprehended, while the last two appear rather hypothetical and are mostly of scientific interest.

Theories that reveal the essence of periodic processes in the economy are usually combined into two groups. These are internal theories, which link the cyclical nature of economic indicators with the influence of internal socioeconomic factors, and external theories, which consider external factors as the causes of cyclicity. According to Arthur Schlesinger [17], who was a proponent of the internal theory, the causes of cyclicity should be sought in its intrinsic nature. He believed that the true cycle is self-reproducing, it cannot be determined by external phenomena unless they are associated with wars and revolutions, i. e., with social catastrophes. On the contrary, adherents of external theories explain the presence of long cycles by the influence of a number of exogenous factors, and such factors are considered not only global shifts at the level of society as a whole, resulting in global shifts in the economy, but also, first and foremost, changes in production technologies. The theory of long cycles, proposed by Kondratiev, belongs to the group of external theories. Kondratiev himself associated the cyclical nature of economic processes primarily with changes in technology, but he also took into account such factors as wars and revolutions, the emergence of new countries on the world map and fluctuations in gold production. However, Kondratiev considered the main «empirical correctness» of his theory to be the coincidence of the growth of economic indicators, which he defined as the beginning of a new long wave, with qualitative changes in economic conditions. Thus, he associated the first long cycle with the invention of the steam engine and the growth of textile production. The second cycle, in his opinion, was caused by the birth of the steel industry, and the development of rail transport contributed to the mass transportation of people and goods, leading to rapid economic growth. Still, such interpretation of the nature of long waves is questionable. For instance, some researchers believe that the period 1789–1814, which Kondratiev considered as the period of growth of the first long cycle, cannot be included in the industrial age. The increase in prices during this period was of a military-inflationary nature, and industrial production was still at the stage of formation.

Kondratiev's external ideas about the nature of long waves were further developed in the works of Joseph Schumpeter [18; 19]. Schumpeter proposed a theory that simultaneously describes the features of three types of cycles: Kitchin cycles, Juglar cycles, and Kondratiev long waves. According to this theory, the superposition of the waves of the Kitchin, Juglar and Kondratiev cycles determines the level of conjuncture at each point in time, with one Kondratiev cycle including 6 Juglar cycles, and one Juglar cycle containing 3 Kitchin cycles. Schumpeter himself called this superposition of waves of different periodicity a «grand unification». In particular, his explanation of the Great Depression was that the hidden negative trends of all three cycles coincided in time. Comparing cyclic processes of different durations, Schumpeter noted the fundamental difference between Kondratiev waves and the short-term cycles. From his point of view, this difference lies in the consideration that the beginning of a long wave is associated with the accumulation of technological innovations.

Schumpeter contemplated the nature of innovation as creative destruction. This means that although the introduction of innovations gives impetus to the development of certain industries, ensuring a rapid increase in labor productivity, this process destroys existing technologies, as they become obsolete. The process of «creation–destruction» stimulates transformations in the economic system, determines the specific form of their implementation and, accordingly, the progress of society as a whole.

At present, the innovative conception should be considered the main theoretical basis of Kondratiev cycles, although it was severely criticized in its day. Thus, analyzing the Schumpeter – Kondratiev innovation theory, Simon Kuznets pointed out the following key issues [20]. Firstly, for the emergence of a long wave, it is necessary either that innovations change production processes very significantly, or there must be a large concentration of them in a limited period of time, that is, a cluster of innovations must be formed. Secondly, within the framework of Schumpeter's theory, it remained unclear why the duration of the impact of significant and important innovations (their significance followed from the first remark) is determined in decades, not years. And these questions were constructive ones. In addition, the reasons for the cyclical nature of depression were ignored by the innovative theory. It should be mentioned that Kuznets was a supporter of wave theories in economics, his name is associated with the discovery of the «construction cycle», the duration of which is considered to be about 15–25 years.

The next impetus for a return to the theory of longer waves was the work of Gerhard Mensch [21], in which he presented new facts that confirmed the innovative nature of long waves. He analyzed the features of those innovative technologies that influenced the development of industry, and divided them into the basic (or systemic) ones, that is, those that lead to qualitative changes in production, and the improving ones, that is, those that contribute only to a slight quantitative increase in labor productivity. In fact, all technological revolutions were the result of the embodiment of innovations that were simultaneously basic for several industries. Mensch showed that innovative development is cyclical and the end result of the accumulation of innovations is the formation of a powerful cluster of basic innovations. This occurs during periods of depression, when the economic situation is most susceptible to the diffusion of innovation. Based on a careful analysis of technological innovation, Mensch proposed a theory that quite fully responds to all criticisms as to the innovative nature of long waves. *Fig. 2* shows a diagram corresponding to one period of the Kondratiev wave.

Following the basic thought by Kondratiev, modern economic theory considers depression to be the beginning of a long wave. In the period of decline in production, there is a need for a significant improvement in production processes, that means, for the basic innovations. This was interpreted by Mensch as the trigger mechanism of economic depression. But what preceded the depression? According to Mensch, in a market economy (unless the situation is a crisis), the improving innovations always have an advantage, since they do not require large costs, and therefore are less risky. As a rule, the implementation of basic innovations requires the company to get involved in processes that go beyond the company's boundaries, and, accordingly, provide for cooperation and coordination of actions with other market participants, while in

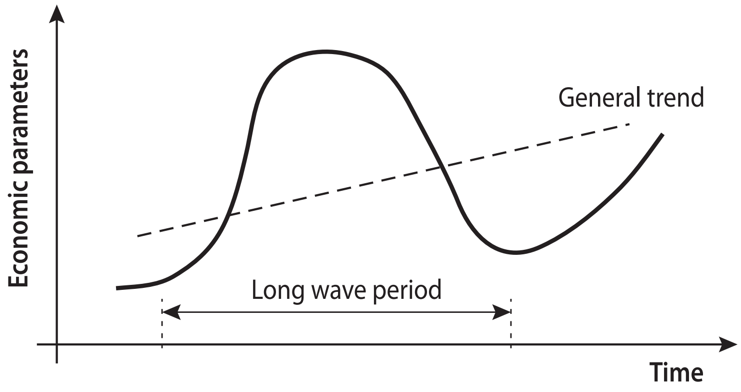

Fig. 2. One period of the long Kondratiev wave

Source: summarized by the authors on the basis of [1; 20; 21, and others].

the implementation of improving innovations, efforts are concentrated within the company as such [22].

Their implementation causes an economic boom, that is, an ascending phase of a long cycle. However, the series of improvements associated with the introduction of improving innovations eventually hits the limit on both the supply and demand side. This boundary defines the highest point (the top of the wave) and the turning point of the cycle. The economic situation begins to deteriorate gradually and finally becomes crucial. Consequently, the possibilities of improving innovations have been exhausted, and there is a need to introduce the basic innovations. The situation when old technologies no longer allow to maintain high rates of development, and the new ones have not yet become a source of economic growth, Mensch calls a «technological stalemate», which necessarily leads to an economic crisis. It is depression that triggers innovative processes that will later form the upward phase of the long wave. Since the formation of an innovation cluster requires a significant amount of time, this process covers the phases of depression and revival, and partially the phase of growth. In the future, the diffusion of innovations ensures a long-term rise in economic indicators – a new long wave begins. Consequently, Mensch's research made it possible to obtain answers to Kuznets' criticisms about the innovative nature of the long Kondratiev waves.

The next contribution to substantiating the innovative nature of the long waves was made by Jacob van Duijn. In fact, the theory of the life cycle of innovation, proposed by van Duijn, can be considered an inversion of Kondratiev's theory of long waves, when cause and effect change places. The synthesis of these two directions of economic theory, proposed by L. Punzo [23], allows us to consider innovation as the main exogenous factor that determines the cyclical nature of changes in economic parameters at the macro-, mesa- and micro-levels. This approach is the basis of the endogenous model of economic growth, according to which fluctuations in economic variables that characterize the state of the system are associated with profound transformations that occur at the level of structural shifts in the economy. Therefore, relying on the provisions of thermodynamics of non-equilibrium processes and synergetics as paradigm of the modern philosophy of scientific knowledge, there is an open system in which the processes of self-organization take place. To study the evolution of such a system, it is expedient to use the mathematical apparatus of nonlinear dynamics. The «bifurcation point», passing through which transfers the system to a new ordered state, is the stage of depression. However, simultaneously, the stage of depression can be considered an attractor to which the economic system is headed, choosing any of its own phase trajectories. The process of self-organization in such a system is the formation of an innovation cluster, which further determines the achievement of a new level of economic growth. Such an approach is consonant with the one proposed by Masaaki Hirooka [24].

Based on a thorough study of the innovations of the industrial age, Hirooka identifies the presence of a cascade of three interconnected non-linear trajectories: technological development as such, creation and development of innovative products, and the diffusion of these products into markets. He proves that all these trajectories are described by a logistic curve and lag behind each other for a constant period of time, that is, they form a rigid cascade structure.

Although the innovative nature of long waves can be considered proven, there's another important issue – to not only define the boundaries of each of the waves, but to find an answer which systemic innovations led to their occurrence. Having no answer, it is impossible to ensure the reliability of the forecast. The present-day scholars believe that economic development has five long waves, and now we are at the beginning of the sixth wave. The boundaries of the first two cycles, the nature of their occurrence and the beginning of the third cycle were determined by Kondratiev in his time. The third long wave was the first of the waves caused by the practical application of scientific knowledge. It is associated with the rise of the electric power industry, during which innovations in the chemical industry made it possible to establish mass production of goods. The development of the fourth long wave was fostered by the growth of the petrochemical industry, which in turn stimulated the development of the automotive market. However, this growth ended when the Organization of the Petroleum Exporting Countries (OPEC) raised the price of crude oil in the 1970s. The fifth long wave is associated with the advent of computers and the development of information and communication technologies. In social terms, this means the transition to an information society, and in economics, this period is considered the third industrial revolution, which is called the digital revolution and is defined as the transition to the automation of production processes [25]. Also, the fifth long wave marked the transition from an industrial to a post-industrial society and the formation of a knowledge economy.

The spread of information and communication technologies, the rejection of an analogue in favor of a digital method of data transmission, that took place at the end of the twentieth and the beginning of the twenty-first century, was the beginning of the sixth long wave and the fourth industrial revolution, called Industry 4.0 [26]. Conventionally, the boundaries of the sixth long wave are determined in the range of 2018–2042. Thanks to digitalization, it has become possible to implement the conception of the Smart Enterprise, when machines, production systems and logistics systems interact with each other almost autonomously and independently carry out the production process almost in full. At this, men do not interfere in the production process, only limit themselves to observations and, if necessary, exert a controlling influence. Under such conditions, the study of the features of the life cycle of innovations at the level of system dynamics becomes relevant [27]. From the point of view of system dynamics, the digitalization of society should be considered as a bifurcation, since it does not just affect the development of technology, but leads to the system going beyond the limits of stability, followed by the formation of a new order. It should be noted that in the EU countries, digitalization is considered as a key factor that ensures the success of transformations of the economy and society as a whole, therefore, significant funds are allocated to support the digital transformation of the EU countries.

Owing to the fact that digitalization is the center of crystallization of a cluster of innovative technologies, the most important is human capital, specialists who have the appropriate competencies for the implementation and use (operation) of solutions based on these technologies. Therefore, the process of gaining knowledge about these technologies and their use becomes crucial. In this regard, the conception of open innovation has been formed [28; 29], which provides for the open implementation of digitalization in all spheres of life.

The modern wave of the long Kondratiev cycle has another peculiarity. The process of globalization has led to that humanity has begun to realize the limitations of natural resources. People have understood the need to determine the balance between meeting modern needs and protecting the interests of future generations. This was reflected in the formation of the conception of sustainable development [30]. Sustainable development does not mean that there will be no fluctuations in economic indicators in the future. No, the economic system remains open, and the number of direct connections in this system increases significantly due to globalization. Consequently, such a system is approaching the bifurcation point even faster, and about the new structure that will be formed as a result of self-organization, there are many forecasts, both pessimistic and optimistic.

CONCLUSIONS

The analysis of the development of Kondratiev's theory of long waves, carried out in this study, allows us to draw conclusions related to various aspects of the economy. The innovation theory of the nature of long waves asserts that the basis of economic recovery is the introduction of basic innovations, and the gradual transition to the use of innovations, which are improving in their impact on the efficiency of technology and on labor productivity, leads first to a slowdown in the rate of economic growth, and then to an economic recession and depression. Taking into account the cyclical nature of this process, it is advisable to pursue an active government policy to stimulate the essential use of basic innovations in various industries, since their implementation is costly in financial terms and is associated with risks. The transition to sustainable development and a circular economy implies respect for natural resources, and it is such basic innovative technologies as, for example, green energy, that make it possible to achieve the sustainable development goals as formulated by the United Nations.

Since economic development is a process being far from linearity, and the economic system itself remains an open one, it is advisable to use the mathematical apparatus of nonlinear dynamics to build long-term forecasts, allowing for a qualitative analysis of the evolution of the system (along phase trajectories). In the current conditions, as a result of the development of globalization processes, not only the economy, but also society as a whole can be considered as an open system with positive feedbacks. In such a system, any fluctuations advance the point of bifurcation, the transition through which leads either to chaos or, as a result of self-organization, to the formation of an ordered structure with new properties. And the task of system dynamics is to study the future ways of development of such a system.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest in connection with the current research, including financial, personal, authorial, or any other aspect that could affect the research and the results presented in this article. ■

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