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Nonlinear Natural Scientific Thinking and Ecological Consciousness for Sustainability

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Abstract

The article investigates sustainable development from the holistic perspective, taking into account the complex nature of the world and the dynamism of the socio-economic systems. The study is interdisciplinary, as it addresses the issues of economics, mathematics and physics with the main focus on the modern perspective of sustainable development offered in the field of education. The article focuses on key questions concerning the expansion of the educational processes and deepening of ideas and knowledge about the dynamism and diversity of the planetary system. The holistic approach implies the interaction of various nonlinear features that have been used in the paper to build a mental model and a causal relationship schema. The understanding of the interaction of energy flows in socio-economic systems has been used by the authors to explain the underlying connection of various processes. The authors of the article propose a systemic dynamic model of sustainability, which can open up an understanding of some of the reasons for changes in the potential of the industrial sector. Modeling results have been obtained and interpreted using historical USA statistical data from 1949 to 2019. In the article, the authors reveal the relationship between nature, society and human from the point of view of promising and methodological approaches of the “new” and “old” world. The diversity of experiences makes it possible to question the dominant approaches of traditional teaching in education. This creates the need to look for new foundations that can promote the development of more sustainable learning for the future.

Keywords: Dynamic system, education for sustainable development, linear and non-linear development, power.

Introduction

The world's best minds are being deployed to solve the problem of unsustainable development. The highest importance of the problem is evidenced by the founding of the Nobel Sustainability Trust Foundation (NST) in 2007 in Zurich, Switzerland. The concept of sustainable development arose in the 1970–1980s against the backdrop of recognition by the world community of the problems of social and scientific development, limited natural resources and the environmental situation. Sustainable development was understood as development "in which current activities and meeting the needs of modern society do not cause harm to subsequent generations, but find a balance between them" (Brundtland, 1987). Nowadays, "sustainable development" is understood as economic growth that does not harm the environment, contributes to the resolution of social problems, finding a balance between economic, environmental and social development. We have to solve the problem of economic growth when this growth is no longer possible in principle and cannot be ensured (resource limits). And if we do not grow, then what? It means we are either slowing down or stagnating. However, it is not accepted to talk about slowing down the pace of scientific and technological progress, so as not to disturb the sensitive society. Therefore, the real problem of recession is publicly framed as the problem of achieving sustainable development. The complex meaning of the task entrusted to scientists is related to one thing – we are slowing down, but we need to speed up.

At the same time, it is desirable not to waste the entire world, so that future generations will have enough natural resources for their livelihood. Exactly in the second half of the 20th century – in the 1970s–1980s, the *two biggest changes* in human consciousness took place. As a result, humanity feels these processes after more than 50 years (Trusina & Jermolajeva, 2022).

The first change is the awareness of the limited resources of the earth, the threat of the environmental crisis and the need to change moral and value attitudes towards environmental awareness. *The second is the discovery and awareness of nonlinear behavior as the natural state* of most natural systems. The first shift in consciousness, rooted in the work of the Club of Rome on World Dynamics modeling, has been the driving force behind multi-million-dollar movements of green and environmental legislation movements in many countries around the world (Forrester, 2003; Meadows et al., 1972). The second shift is discussed mainly in special scientific audiences in relation to solution specific problems in natural science.

There is a deep connection between these two shifts in human consciousness. Overcoming the threat of an environmental crisis requires a fundamental change in public consciousness towards "ecological consciousness", based on other concepts of values. At this point, we cannot say for sure what these value ideas will be. However, it is already clear that if non-linear thinking succeeds in winning over the idea that has prevailed since the Renaissance, then humanity will be able to gain a truly ecological consciousness and get out of the linear tracks of uncontrolled and disastrous progress, which is leading us directly into a global economic crisis.

Many people believe that their lives have nothing to do with abstract mathematical theories and fundamental physical laws. This is a completely wrong idea. In fact, fundamental mathematical and physical ideas, dominant physical and mathematical paradigms leave their mark not only in the thinking of scientists, but also in the everyday thinking of all people without exception. They appear in language, logic, psychology and politics, moral ideas and value systems, ethics and aesthetics. Human

being tries to live and act according to their nature – this has always been the case, but we can understand and express the laws of nature in the terms offered by modern science.

The aim of the article is to holistically explain the main provisions of sustainable development within the framework of the concept of nonlinear systems and the modern understanding of the complex world based on the methodology of system dynamics and analysis of changes in energy flows and the power of socio-economic systems.

The authors consider that nonlinear science contrasts linear and unambiguous ideas about natural processes with much more complex and ambiguous ideas, which require careful research, doubt and reflection in each specific case. Despite the relativity of any general judgments, one has to come to terms with the obvious fact that the world is more complex than simple. The simple and clear postulates of linear thinking are contrasted with the "nonlinear" objections. The authors use economics, mathematics and physics with the main focus on the modern perspective offered in the field of education, which provides a more holistic understanding and explanation of sustainability phenomena.

The paper focuses on key questions concerning creation of the model of system sustainable development under various scenarios of changes in the useful power of the industrial sector based on two approaches: system dynamic modeling in combination with modeling changes of the socio-economic system energy flows. The results of the main positions of the system dynamic models and their interpretation are presented based on the historical statistical data of the United States of America in the period of 1949–2019. The authors also consider equations of sustainable development in the nature-society-human system, describing more broadly the so-called "old" and "new" worlds and trying to show the need for changes in the processes of learning and world perception.

Learning, Experience and Education

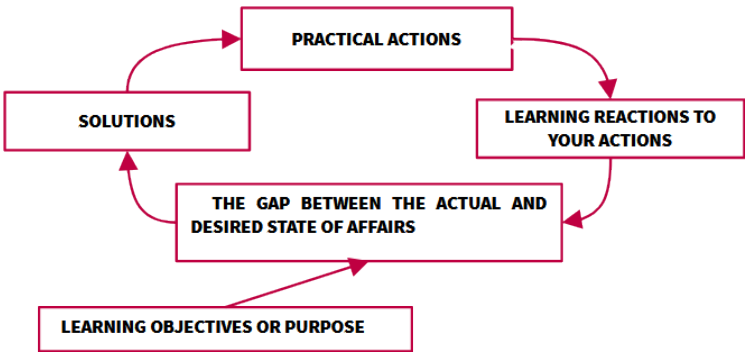
Learning as a System With a Feedback Loop

Sometimes people feel like the center of the world. Our influence spreads like the vibrations of water from a stone thrown into a pond. We do not know the far shore on which they will subside. We only know about the waves of feedback returning to us, although we do not always understand how we created them. This is self-learning – changing ourselves with the help of feedback activated by our actions (Figure 1). The concept of learning goes deeper than the idea of a formal apprenticeship because we are always our own teachers – everything we do teaches us. Learning is a process that involves action and change, but experience definitely affects us and changes us.

Therefore, the authors of the present article believe that education plays an essential role in the life of every person and especially in the understanding of sustainable development in its broadest sense. Education starts in the family, but at the same time we understand that parents cannot always provide the necessary knowledge and therefore educational institutions, from pre-school to higher education, have a crucial role to play in creating a comprehensive and complete understanding of what is happening around and the process for mutual relations. In this context, teachers, including their own education, are essential. Education for sustainability is a holistic

approach to education and learning that enables people to develop the knowledge, skills and values necessary for sustainable living (Blewit, 2018).

Figure 1
Learning as a System With a Feedback Loop



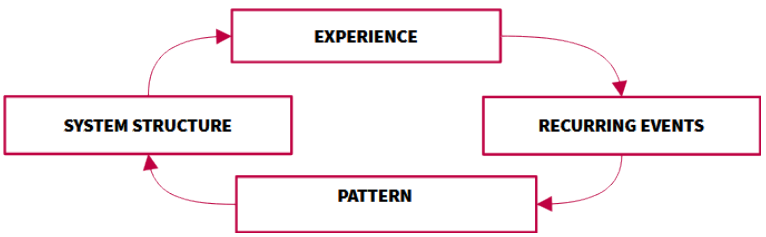
Source: Created by the authors based on O'Connor & McDermott (1997)

Experience and Pattern

People can use systems thinking to literally draw conclusions – a single event can mean anything. If there is a threefold repetition, then this is already a certain pattern, regularity (Figure 2).

At the level of a single event, the ability to influence the system may be small. However, if we discern the pattern, we have the opportunity to build a model of the system structure and find in it the point of application of the lever, which will make it possible to change the structure, and thanks to this, events.

Figure 2
Experience as a System With a Feedback Loop



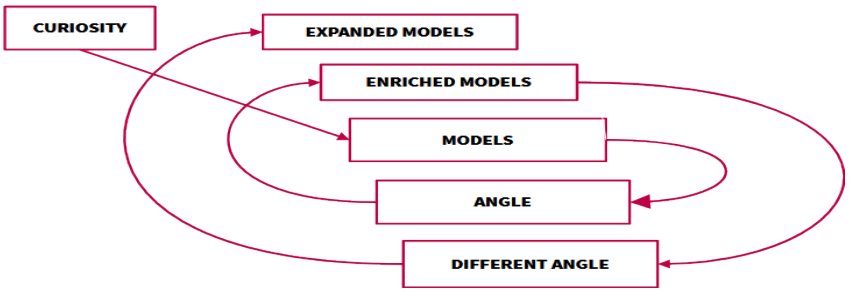
Source: Created by the authors based on O'Connor & McDermott (1997)

Expanding the Horizon

Systems thinking allows us to see the world from a different perspective. It draws attention to the interconnectedness of events, i.e., how the interaction of a part and a whole arises. At the same time, the fundamental principle of systems thinking is to see events from a variety of angles. The variety of perspectives expands the range and scope of our mental models (Figure 3).

Figure 3

Structure of the Way From Curiosity to an Expanded Model



Source: Created by the authors based on O'Connor & McDermott (1997)

Curiosity gives rise to a variety of aspects of consideration; a wealth of perspectives and usefulness is a personal, value judgment based on previous experience. The ability to be creative and different types of intelligence require the ability to see objects and phenomena from different angles and, accordingly, receive different types of feedback. Systems thinking considers the situation and our ideas about them as a whole. We will not see them in this way unless we look at them from the outside, i.e., it is necessary to step back to cover all the patterns.

The need for new competences is nowadays emphasized in various documents, studies and events related to education, e.g., Council Recommendation of 22 May 2018 on key competences for lifelong learning (The Council of the European Union, 2018), preparing our youth for an inclusive and sustainable world (OECD, 2018), global competence development at higher education institutions (Kjellgren & Richter, 2021) and many others.

Sustainability and Education

The Journal of Teacher Education for Sustainability (JTES) has many publications on teacher education issues in the context of sustainable development, especially in recent years, increasingly focusing on topics that include and broadly explain development processes and their influencing factors. Several editorial articles of the JTES emphasize such issues as a co-evolutionary perspective in the search for sustainable education, the creation of deeper personal meanings for sustainable education by JTES (Salīte, Fjodorova & Ivanova, 2020; Salīte, Ivanova & Fjodorova, 2020; Salīte et al., 2022) and others. A special attention is drawn to the editorial article "Does Sustainability Languish in Education?" which analyzes the goals and results of education: JTES articles on the search for the essence of sustainability provide an opportunity to see the personally relevant and holistic nature of the phenomenon of sustainability in a living system. Everything personally relevant is related to the sustainability of the whole system, which largely depends on the relationship between nature and people and the realization of their understanding in real-life actions (Salīte et al., 2023).

Latvian and foreign scientists explore what methods and approaches to apply in order to accelerate the understanding of sustainable development, for example, the articles "The Prospects of Transdisciplinary Approach to Promote Learners' Cognitive Interest in Natural Science for Sustainable Development" (Jurgena et al., 2018),

"Student Teachers' Change Agency in Education for Sustainable Development" (Koskela & Kärkkäinen, 2021). Scientists write about the necessity of wider action research initiated at the beginning of this century to explore the *reorientation of education in general and teacher education in particular towards sustainability in today's world* (Salīte, Briede et al., 2021; Salīte, Fjodorova et al., 2021).

Linearity of the "Old" World

The basis of modern science and technology is the mathematical description of processes using differential equations, the foundations of which were laid by the great mathematicians and natural scientists Newton and Leibniz. For systems of linear differential equations, a general mathematical theory and methods for practical solutions have been developed. Over the past 300 years, science has developed according to *two main principles* (Rubin & Riznichenko, 2014).

The first is the idea of unambiguous cause-and-effect relationships. This principle is widely confirmed in practice; great achievements are associated with the description of physical processes, solving problems in technology, construction, mechanical engineering, and theoretical radio engineering. In fact, the application of this principle made the entire modern technical civilization possible. The development of information technologies has not introduced anything significantly new into these ideas. Today, most people deeply believe that the result obtained on a computer is the only correct one. The main result is that the uniqueness and stability of solutions ensure the unambiguity of cause-and-effect relationships because behind it there is a mathematical statement that permeates our entire perception of the world and gives us confidence in our daily activities.

The second important principle of modern science is based on the concept of experiment – it is generally accepted that the subject of scientific research can only be those phenomena that can be reproduced by different scientists in different laboratories. We can say that the observed pattern objectively exists. When observing any process in nature or in the laboratory, there is a large number of random influences that practically cannot be completely excluded. Therefore, experimental reproducibility means that scientific processes include only those processes for which the mathematical model has an unambiguous stable solution. Processes and phenomena that cannot be reproduced from a scientific point of view do not seem to exist.

Representatives of natural sciences and economists have repeatedly expressed the idea that a field of knowledge becomes a science when it expresses it laws in the form of mathematical relationships and models. At the same time, each of us is faced with one-time and irreproducible phenomena every day. For biologists and psychologists, the possibility of reproducing results is more a welcome exception than the rule, but for sociologists, political scientists, and historians, the subject of study is irreproducible processes.

The authors list the main principles of linear thinking and their application (Wrigley & Smith, 2020; Bratianu & Vasilache, 2009):

1. Most processes can be described with a high degree of accuracy using linear equations. The simplest laws of growth, based on the assumption of proportionality to the rate of population growth, describe unlimited growth in the form of a geometric progression or its continuous analogue – the law of exponential growth. Already Malthus in his work "An Essay on the Principle of Population" (Malthus, 1998) warned about the danger of this

kind of unlimitedly growing processes. Charles Darwin, impressed by Malthus's arguments and reflecting on the possible reasons for the limited number of natural populations, named competition between species under conditions of limited vital resources as one of the reasons. Modern civilization in its development has taken the path of overcoming any limitations of linear growth. A theory has emerged about unlimited technological progress, the unlimited growth of needs and consumption, and the limitless expansion of humanity. Such linear growth implies unlimited use of natural resources for the needs of humanity.

2. Uniqueness of the stationary solution in a system of linear equations. The only possible state is achieved sooner or later regardless of the initial conditions. This corresponds to unambiguous goal setting, the idea of the only true goal, which should be strived for by any means.
3. Stability of the solution with respect to the initial conditions. This corresponds to the idea of an objective pattern, which, in fact, cannot be influenced by individuals and circumstances. In the development of personality, everything is determined by the initial conditions.
4. Possibility of unambiguous identification of parameters in the system in the case of fully observable states. This means that the cause can be unambiguously determined from the effects, in particular, to determine who is to blame and roughly punish the perpetrators.
5. The ability to identify the determining, limiting factor in any process, which means the existence of a thread that one just pulls, and the process begins. It is just necessary to find this thread correctly.

Thus, linear thinking establishes an insurmountable barrier between events in real life, phenomena of consciousness and art, and natural sciences. Unambiguousness underlies a very important principle of human thinking – the idea of the only correct decision, type of behavior –, and this corresponds to scientific ideas about an unambiguous linear stable world. In a linear world, given the initial conditions, there is a single correct trajectory of movement towards a single stable stationary state.

Towards Understanding a "New" – Nonlinear World

The first breach was made at the beginning of the 20th century by the theory of relativity and quantum mechanics with their uncertainty principle and probabilistic concepts. There was still hope that uncertainty and relativity concerned only cosmic velocities and microworld phenomena, and that on a real human scale all linear concepts were valid. However, the development of nonlinear dynamics has shown that uncertainty and relativity also exist in human dimensions (Riznichenko et al., 2009).

Nonlinear science contrasts linear and unambiguous ideas about natural processes with much more complex and ambiguous ideas, which require careful research, doubt and reflection in each specific case. Despite the relativity of any general judgments, one has to come to terms with the obvious fact that *the world is more complex than simple*. The simple and clear postulates of linear thinking listed above are contrasted with the following "nonlinear" objections (Trubetskov, 2015; Kohr, 1967).

1. All processes in living nature and most processes in inanimate nature are described by nonlinear equations. This is due to the fact that living systems are open in matter and energy and are removed from thermodynamic equilibrium.

2. The nature of the stationary regime in a nonlinear system depends on the type of nonlinearity, the parameters of the system and its environment, and the initial conditions. In a system, the final state depends on its initial state. It is not possible to come to the desired result from any initial conditions. Therefore, one must first change some external and internal parameters, for example, obtaining appropriate education and moving to another city. At the same time, the variety of possibilities removes the fatalism of the unambiguous development paradigm and gives scope for choosing the area of space that is preferable.
3. The stability of the system to small deviations is not a general property. In nonlinear systems, there are areas where the system becomes extremely sensitive to small external influences. This is defined as bifurcation boundaries, on different sides of which the system has qualitatively different behavior. In historical bifurcation situations, the role of individuals becomes especially important. This pattern was noted by Plekhanov at the beginning of the century.
4. In nonlinear systems, unambiguous identification of parameters is usually impossible. This circumstance greatly limits the possibilities of science. We can only propose one of the possible variants of patterns that could determine the totality of the observed consequences. The consequences cannot clearly indicate the cause. Instead of looking for the culprits of our disastrous state, we should focus our efforts on a constructive search for a way out of the current situation and a transition to another area.
5. In nonlinear systems, the principle of the "bottleneck", "Ariadne's thread", unfortunately, is not always valid. General principles for controlling nonlinear systems, in contrast to linear ones, have not yet been found.

To sum up, all complex systems contain properties and can be described using nonlinear natural models: limited solutions, oscillatory and multiple modes, quasi-stochastic spatial and temporal behavior. The idea of a nonlinear world was especially readily accepted by biology, which had never truly accepted the linear paradigm. The individuality and diversity of living systems and the irreproducibility of the results of biological experiments are too obvious.

System Analysis

On the way to formalizing and understanding the linear and nonlinear world, the authors of the paper will consider the concept of systems and systems thinking. A system is an entity that, as a result of the interaction of its parts, can maintain its existence and function as a whole. A set of unrelated parts does not form a system, but is simply a heap. A system has a function, boundaries, hierarchy and structure (Table 1). All systems have a goal, like a desired state, even if this goal is simply self-preservation, survival.

As a result of these properties, the system has emergent or emergent properties that none of the parts have. Having disassembled the system into parts and analyzed each of them, it will not be possible to predict the properties of the entire system. The only way to know what a system is to make the system work. The system ensures self-preservation through the interaction of parts and their number. Therefore, systems can be complex or simple in all system parameters. The suddenness of change has an impact on how smoothly a system function and how it behaves under special circumstances.

The connectedness of system elements gives rise to patterns in their behavior, the inability to make targeted changes and the presence of side effects.

Table 1
Main Parameters of System

Parameters	System	Conglomeration
Function	Interconnected parts function as a whole	A collection of disparate parts
Boarders	Interconnected parts function as a whole	Properties change if something is removed or added
Hierarchy	The layout, the relative position of the parts, is critical	The location of the parts is not critical
Target	The parts are interconnected and work together to achieve a goal	The parts are not interconnected and can function separately
Structure	The behavior of the system depends on the structure	Behavior depends on the size and number of items

Source: Created by the authors

Systems thinking is nonlinear; it occurs in cycles, loops, and contours. All parts of the system are connected directly or indirectly, and, therefore, changes in one part generate waves of changes that reach all other parts. These parts also change, and the waves from this process eventually reach the part in which the change began, and it will have to react to this new influence. Thus, the change returns to the starting point in a modified form. This creates a feedback loop. Feedback suggests that part of the system output flows back into its input, or that the system uses information from the previous step to make changes to what it does in the next. Our experiences are the result of these kinds of feedback loops, as we perceive the results of our actions and this influences our next steps. Thinking in terms of feedback is called circuit thinking.

The presence of feedback is an integral characteristic of the system – if there is no feedback, there is no system. There are two main types of feedback:

- Reinforcing feedback – when a change in the state of the system serves as a signal to strengthen the initial change. In other words, the system provides a greater change in the same direction.
- Balancing feedback – when a change in the state of the system serves as a signal to start moving in the opposite direction in order to restore the lost balance.

Feedback provides chains of cause-and-effect relationships in which each action influences the next. Cause-and-effect relationships form a vicious circle: what was a cause from one point of view becomes a consequence from another. In time, the cause always precedes the effect. Systems thinking reveals *three main misconceptions about the nature of cause-and-effect relationships* (Trubetskov, 2015; Janzing, 2019).

The first misconception is that cause and effect are separable, the effect comes after the cause.

Cause and effect have different meanings, but depending on the point of view, they can refer to the same event and mean the same thing. If the movement goes in a circle, then what comes first and what comes second depends on where we started.

The second misconception is that in time and space the effect follows immediately after the cause. There is always a delay in the system, and the effect may appear in another part of it. When dealing with systems, one needs to be prepared for the fact that the consequences will last far in time and space. With a systems approach, the explanation of change is not any single cause, but the structure of the system and the relationship of factors within it. The key to understanding the hidden structure of a system is the pattern or repeating a stable image of the system.

The third misconception is that the effect is proportional to the cause. This statement is true for material objects. In living systems, the relationship of cause and effect can be astonishing, and tiny changes can cause large-scale catastrophes. Sometimes an action does not cause consequences because the system has a threshold of perception.

Socio-Economic System

The study of open socio-economic systems that must interact with their environment in order to survive is known as a systems theory approach. The open systems approach was pioneered by Katz and Kahn, who adapted general systems theory to organizational behavior (Bertalanffy, 1950; Katz & Kahn,1978; Broom, 2006). This approach defines the behavior of organizational systems by mapping repeated cycles of input, throughput, output, and feedback between the system and its external environment. Systems receive input from their environments in the form of information and energy. The systems then process the inputs internally, called throughput, and release the outputs to the environment in an attempt to restore equilibrium to the environment. The system then seeks feedback to determine whether the outcome was effective in restoring equilibrium. The systems approach focuses on the means used to support the survival of the organization and emphasizes long-term goals rather than the short-term goals of the goals-based approach.

Theoretically, systems can be considered both open and closed. Open systems exchange information, energy, or resources with their environment, whereas closed systems do not. In fact, since no social and economic system can be completely closed or open, they are usually called relatively closed or relatively open. The difference between closed and open systems is determined by the level of sensitivity to the external environment. Closed systems are insensitive to environmental variations, whereas open systems respond to changes in the environment (Bauer, 2002, Podolinsky, 2004).

The systems approach is an external standard that measures performance based on long-term growth or sustainability. Efficient systems are characterized by a steady state, which systems theorists call homeostasis (Buckley, 1967). If an organization is able to maintain homeostasis, which includes not only survival but also growth, then it is effective. This perspective is broader and more comprehensive than the goals-based approach because it is not limited to measuring performance as the achievement of goals defined by powerful internal coalitions that may or may not be favorable to the entire organization.

According to the systems theory, the most effective organizations adapt to their environment. Pfeffer and Salancik (2015) described the environment as events occurring in the world that have some impact on the activities and results of an organization. Organizations that exist in dynamic environments must be open systems to maintain homeostasis. As the dynamic environment is constantly changing, it creates

great uncertainty about what an organization must do to survive and grow. The key to dealing with uncertainty is information. An open organization monitors its environment and collects information about variations in the environment, which is flagged as input. Input can also be thought of as a form of feedback. According to systems theorists, the most important information is negative information because this information alerts the organization to problems that need to be corrected. Negative data tell the system that it is doing something wrong and that it needs to make adjustments to correct the problem. Positive input tells the system that it is doing something right and that it should continue or expand that activity.

Systems then organize and process this information to formulate decisions or responses to these changes. As Broom noted (2006), open systems use information to respond to environmental changes and adapt accordingly. Adjustments affect all system parameters. Adjustments are intended to reduce, maintain, or increase deviations. As information is transmitted, the system analyzes it and strategically adapts it according to the goals, values, and context of relationships in the system.

Nonlinear dynamics is one of the modern and promising areas of economic theory. The widespread use of developed mathematical methods, primarily topological and differential geometric, makes it possible to obtain meaningful qualitative results that clarify and make it possible to predict the nature of the behavior of the economic system. In mathematical economics, there are two fundamentally different ways of constructing models: equilibrium and dynamic. The first approach is quite well developed and widely presented in the literature. Its essence lies in finding and studying the equilibrium state achieved by the system when implementing an optimal, in a certain sense, regime. The key point of dynamic analysis is the rejection of the assumption of the existence of a single equilibrium (Brock, 2001).

Methodology

The perspective offered by the authors, perhaps even a new methodology in perspective, assumes a holistic approach to education. In this paper, the authors show how using two completely different approaches (monetary values and energy values) in sustainable development assessment can produce different results at the national level. Therefore, the changing world and the available methods allow for a more qualitative and professional evaluation of various processes, and this, of course, requires broader knowledge based on education. Within the framework of the above-described ideological concepts and new concepts, the authors propose to consider the developed methodology for system-dynamic modeling of sustainable development using the concept of energy flows in nonlinear socio-economic systems and the power change analyzing approach.

System Dynamics

System dynamics (SD) is a direction in the study of complex systems that explores their behavior over time and depending on the structure of the system elements and the interaction between them, including cause-and-effect relationships, feedback loops, reaction delays, environmental influences and others. The method of system dynamics involves representing the system under study as a structure based on the action of a set of direct and feedback connections that express their inherent internal patterns. The method makes it possible to study complex multiconnected systems that depend on the

history and include nonlinearly interacting components. It allows taking into account the current situation by setting initial conditions corresponding to this state, and makes it possible to predict the development of processes in the system over significant time intervals. Moreover, the method allows assessing the effectiveness of possible development alternatives in the system under study. This method has been actively used in the West over the past 20 years, in particular, in the work of the Club of Rome (Meadows et al., 1972) for the analysis of different systems. Any real system can be the object of the method. The direct result of the functioning of system dynamics models should be considered a forecast of trends in their changes.

The method of system dynamics assumes the presence of many feedback loops, which can be not only positive (accelerating), but also negative (stabilizing and stagnating the system) with variable, endogenously formed coefficients (Forrester, 2003). The presence of negative feedback and the endogeneity of feedback coefficients have a fundamental nature. They sharply increase the flexibility of the model, the possibility of a sufficiently detailed description of various types of imbalance phenomena (their occurrence and elimination). Both socio-economic and environmental objects belong to the class of stably nonequilibrium systems that exist under the conditions and due to the energy flows through them (Bolshakov, Karibaev & Shamaeva, 2019). The emergence of circulation in such systems serves as an objective source of feedback loops.

The Systems Power (Energy Flows) Changes Analysis Methods

Within the framework of the concept of natural science approach in economics (Capra & Jakobsen, 2017) and taking into account the conclusions of the energy theory of cost (Costanza, 2004), in order to formalize the tasks of sustainable development, a sustainable development monitoring model was developed using the analysis method of power (energy flows) changes in open dynamic socio-economic systems (Trusina & Jermolajeva, 2021).

The analysis of socio-economic systems is based on the law of conservation of the power (the energy flow) (Kuznetsov, 2015; Bolshakov, Karibaev & Shamaeva, 2019) in time necessary for the development and provision of all processes of the socio-economic system – the energy flow (full power) $N(t)$ entering the system over the period Δt is equal to the sum of the output flow of useful energy (power) $P(t)$ and power losses $G(t)$ (Formula 1):

$$N(t) = P(t) + G(t). \quad (1)$$

The sustainable development model includes the main provisions (Bolshakov, Karibaev & Shamaeva, 2019; Shamaeva, 2023; Trusina, Jermolajeva & Sloka, 2022) listed below.

1. In the context of the model, sustainable development is a continuous process of increasing the opportunities of the socio-economic system in terms of energy units to meet current needs, as well as the needs of future generations, while increasing the level of the system useful power, reducing power losses and without increasing the level of consumption power in the face of negative external and internal influences.

2. The introduction of the term "power" into the formulation of sustainable development makes it possible to create an invariant system of coordinates in energy units.
3. The development of the socio-economic systems, or changes of state, must be supported by new ideas, projects, technologies or intellectual opportunities, which can be defined as innovations. The formalized concept of innovation lies in the fact that during implementation, the efficiency of using the full power of the system changes (increases or decreases).
4. The development of society is considered a creative process, the purpose of which is to change the direction, density and speed of free energy flow (useful power) in Space and Time. This change is achieved by implementing the ideas that arise in people's minds.

Based on certain parameters, it is possible to formulate different development directions of socio-economic and natural systems, which can be used as important indicators for evaluating internal changes and external influences. The useful power is a function of the level of technological development of the system and the energy consumption structure. Useful power determines the level of intellectual capabilities and technological innovation of a socioeconomic system. Finally, the useful power of all technological processes is materially embodied in national income.

Based on the main provisions of the model, a necessary condition for the sustainable development of a socio-economic system is a positive increase in useful power. We can say that the entire system behaves like a power amplifier. Usually, such systems are called dynamic systems, and they develop in the direction of a continuous increase in free energy. The exponential growth of available power can be considered an empirical fact characterizing an open thermodynamic system. The behavior of such systems can be modeled by a useful power amplifier with a variable feedback value. It is known that amplifiers with high gain and weak negative feedback sometimes break into a self-oscillation mode. The manifestation of the above-mentioned in economic systems is the "lack of effective demand", "fluctuations in business activity" and other phenomena in the economics of capital, which we can combine into one word – "crisis" (Kuznetsov, 2015, Bolshakov, Karibaev & Shamaeva, 2019).

In the economy, this kind of phenomenon can be observed when the distribution of internal gross income is disproportionate between groups A and B. Group A includes the industrial and agricultural part of the economy, and group B includes services and non-production activities (Kaldor, 1967, 1996). In the scheme, the role of positive and negative feedback belongs to objects of groups A and B. We can view items in group A as positive feedback precisely because the creation of the new production facilities increases the total capacity available to the state. On the other hand, Group B represents negative feedback in the amplifier model. It can be assumed that there is such an area of distribution of national income between groups A and B, when the maximum rate of growth of power and, at the same time, the maximum rate of growth of national income are possible (Kuznetsov, 2015). This mode of economic functioning can be found in the model of energy flow distribution.

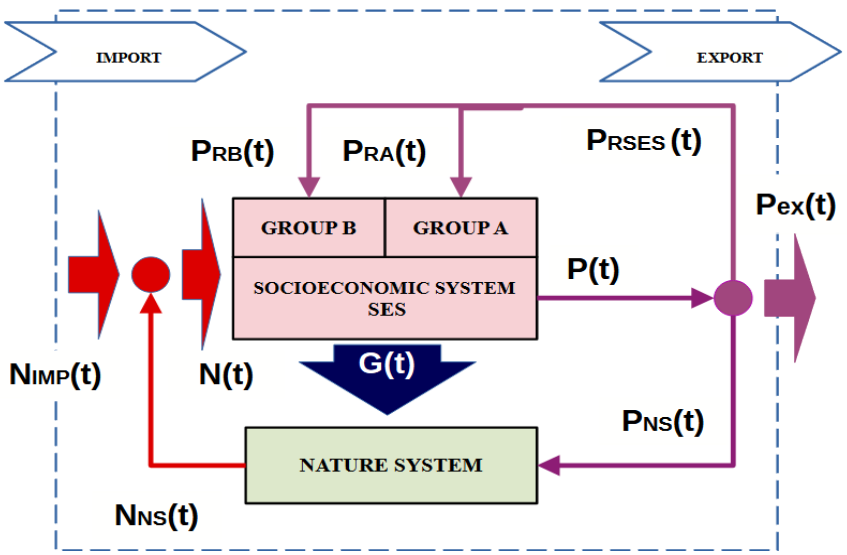
A System Dynamics Methodology for Systems Power Change Analysis

The goal is to create the model of the system sustainable development under various scenarios of changes in the useful power of the industrial sector based on two approaches: SD modeling (in Vensim) in combination with modeling of the socio-

economic systems energy flows changes. *At the first stage*, the model is presented in two forms: as a set of mathematical relationships and in a graphical form of a mental model. The mental model of the systems energy flows (Figure 4) is described by a mathematical model in the form of a system of equations. The final consumption energy flow $N(t)$ of the socio-economic system includes all types of energy resources for the support of life, production, technological and other processes. These are societal needs or potential opportunities. The full power of the system final consumption $N(t)$, which the socio-economic system receives in a certain area, includes the power $N_{NS}(t)$ from the natural system and external imports power $N_{IMP}(t)$ (Formula 2). As a result of the activities, the SES loses part of the power $G(t)$ and produces useful power or energy flow $P(t)$ (Formula 1). Useful power $P(t)$ is directed to export outside the system $P_{EX}(t)$ to influence the natural system for receiving the resources $P_{NS}(t)$ and back to the system $P_{SES}(t)$ (Formula 3). The socio-economic system includes the industrial sector (group A) as the production part of the economy and the non-industrial sector (group B) as the non-production (services) part of the economy.

Figure 4

The Mental Model of Socio-Economic System Energy Flows



Source: Created by the authors

The power $P_{SES}(t)$ returned to the system is respectively directed to the industrial sector $P_{RA}(t)$ and the non-industrial sector $P_{RB}(t)$ (Formula 4).

$$N(t) = N_{NS}(t) + N_{IMP}(t). \quad (2)$$

$$P(t) = P_{RSES}(t) + P_{NS}(t) + P_{EX}(t). \quad (3)$$

$$P_{RSES}(t) = P_{RA}(t) + P_{RB}(t). \quad (4)$$

Society develops sustainably if there is a chrono-integral process of maintaining a non-decreasing growth rate of useful power *P(t)* in the long term while maintaining the rate of full power and reducing power losses.

At the next stage, a cause-and-effect diagram is built (Figure 5) and additional modeling parameters are entered. In accordance with the definition of the dynamic model, part of the useful power flow is directed to increase the power of the system itself. The rate R_{ra} is the coefficient that determines the share of returned useful energy to the industrial sector, respectively the rate R_{rb} determines the share of returned useful energy to the non-productive service part and R_{ex} – share of export – is constant. The parameter *E(t)* is the total useful energy of the system accumulated over previous periods and its change *dE/dt* is modeled using Formulas 5 and 6:

$$\frac{dE(t+1)}{dt} = \quad P_{input}\,(t) + P_{corr}(t+1). \tag{5}$$

$$P_{corr}(t+1) = P_{ra}(t) - P_{rb}(t) - P_{ex}(t), \tag{6}$$

where
P_{input} (t) – useful power of the system for the previous period of time *t*;
P_{corr}(t+1) – change in the useful power of the system over the simulation time period *t+1*.

The dynamics of changes in the power of the industrial sector is described by Formula 7, where the modeling parameter dR_{ra} is introduced.

$$P_{ra}(t) = E(t) \text{ x } [R_{ra}(t) + dR_{ra}]. \tag{7}$$

The remaining power flows of the non-industrial sector and exports are the result of recalculations (Formulas 8–10):

$$P_{rb}(t) = E(t) \text{ x } [1 - R_{ra}(t)]. \tag{8}$$

$$P_{ex}(t) = E(t) \text{ x } R_{ex}\,(t). \tag{9}$$

$$R_{ra}(t) + R_{rb}(t) + R_{ex}\,(t) = 1. \tag{10}$$

Since the power dynamics of the industrial $P_{ra}(t)$ and non-industrial $P_{rb}(t)$ sectors have different impacts on the power of the entire system, two loops with different signs are formed on the causal relationship diagram (Figure 5). This is a feedback loop to all changes, a central concept in systems modeling. Feedback refers to what makes a relationship non-linear. Nonlinearity occurs when two variables ($R_{ra}(t)$ *and* $R_{rb}(t)$) are not independent of each other over time, but mutually instead influence one another as they change. Several N scenarios for N correction can be developed during the modeling process. For each N of scenario, a change parameter (N of impact) and a change period are determined as follows:

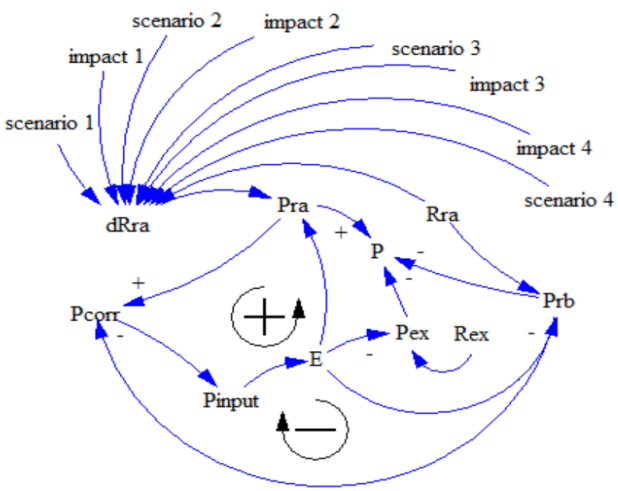
N of scenario >>> N of impact >>> N of correction.

Based on the use of connections between activities and processes in the socio-economic system and calculated data on useful power and Figure 5, the dynamic model of useful power changes was built. The constructed cause-and-effect diagram includes two main feedback loops:

– Reinforcing feedback (positive) loop (P_{ra} – P_{corr} – P_{input} – E – P_{ra}), when a change in the useful power P_{ra} (group A) of the system serves as a signal to intensify the initial change and the system provides a larger change in the same direction.
– Balancing feedback (negative) loop (P_{rb} – P_{corr} – P_{input} – E – P_{rb}), when a change in the useful power P_{rb} (group B) of the system serves as a signal to start moving in the opposite direction in order to restore lost balance.

Feedback provides chains of cause and effect in which each action influences the next.

Figure 5
Causal Relationship Diagram



Source: Created by the authors

External influence on the system occurs through a change in the parameter dR_{ra} in accordance with the scenario.

Results and Conclusions

As already mentioned in the introduction of the article, the authors use economics, mathematics and physics to explain how the modern perspective proposed in the field of education should change, which provides a more holistic understanding and explanation of sustainability phenomena. Within the framework of the proposed model of socio-economic system power changes, calculations were carried out, and the data obtained were presented in the form of tables and figures. The data of the World Bank (World Bank data base) and the United Nations Organization (UNDATA) were used for

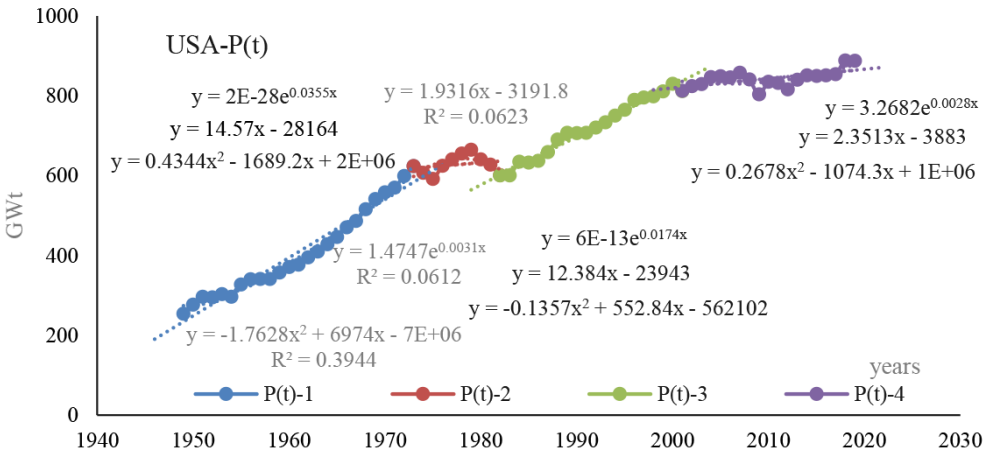
calculations. The choice of the USA for the analysis of sustainable development was determined by several parameters:

- availability of statistical data for a long period of time from 1949 to 2019;
- during the period under study, the USA economy had different parameters characteristic of industrial growth, post-industrial society and stagnation;
- the USA economy after the Second World War for 60 years became the largest economy, determining trends in global and regional development.

Figure 6 presents the useful power *P(t)* as the sustainable development parameter of the USA in the period 1949–2019 using the invariant coordinate system and energy units of measurement.

Figure 6

Changes of the Useful Power P(t) of the USA in the Period 1949–2019 (Historical Data)



Source: The authors' calculations based on data of the World Bank

According to Figure 6 in an invariant coordinate system, four periods of the USA development have been identified for the period from 1949 to 2019. Development trends and coefficients for each period are presented in Table 2.

The goal of system dynamics modeling was to understand how a dynamic pattern of behavior is generated by a system and to find leverage points within the system structure that can change a problematic trend to a more desirable one. The key steps in the modeling process were to identify the trends that characterize the problem, describe the structure of the system that generates the behavior, and find and test leverage points in the system to change its behavior.

Table 2
Development Trend Coefficients of the USA for Period 1949–2019

NN of ***P(t)***	Periods of ***P(t)***	Duration years	a average velocity (Linear coefficient of x)	b average acceleration (Parabolic coefficient of x^2)	k (Exponential growth coefficient)	Trend description
1	1949–1972	24	14.57	+ 0.434	0.035	Growth
2	1973–1982	10	1.93	- 1.76	0.003	Sharp and short changes
3	1983–2000	18	12.38	- 0.136	0.017	Growth with stunting
4	2001–2019	19	2.35	+ 0.268	0.003	Stagnation

Source: The authors' calculations

A dynamic model of useful power changes for the USA socio-economic system was implemented in four scenarios, exerting four political impacts in 1949, 1972, 1983 and 2001. Data and parameters of impact on the system and the obtained correction data are presented in Table 3. The correction was made four times over the period 1949–2019 with different impact factors and scenario periods. The purpose of the correction was to model changes in the useful power of the industry to obtain a continuous positive increase in the total useful power of the system for the selected period. The correction was carried out at a constant value of the final consumption power of *N(t)* energy resources. Based on the modeling results, correction of annual growth rate R_{ra} and annual growth of *P(t)* were calculated (Table 3).

Table 3
Dynamic Simulation Model Parameters of the USA Useful Power P(t) Changes

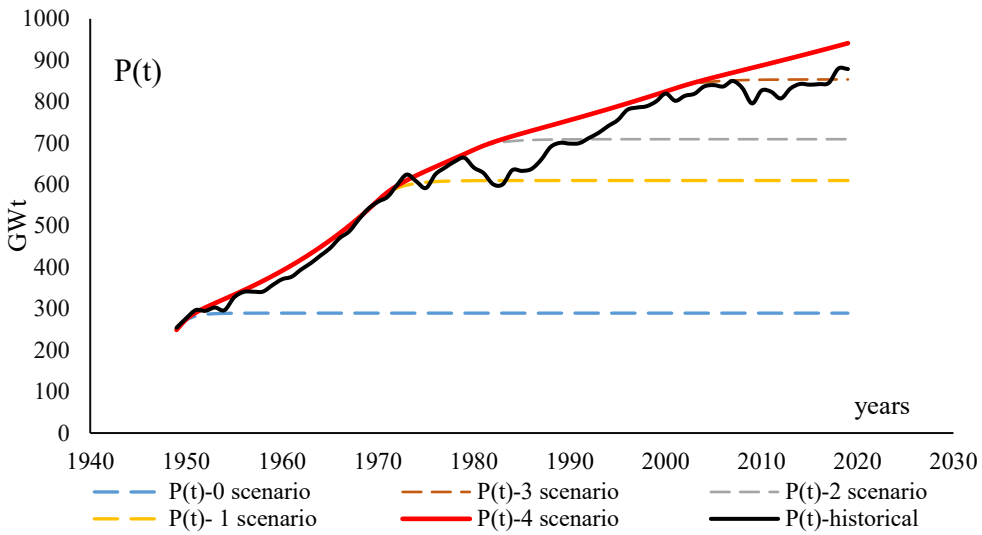
	Scenario No.	Impact start point	Scenario period		Duration years	Impact coefficient S	Annual growth of rate *Rra*	Annual growth of ***P(t)***
	x	year	start year T1	finish year T2	x	x	%	%
		1949	Initial time		x	x	x	x
P(t)-1	1	1949	1949	1972	24	0.0089	2.2	3.9
P(t)-2	2	1973	1973	1982	10	0.0029	0.5	1.6
P(t)-3	3	1983	1983	2000	18	0.0015	0.3	0.9
P(t)-4	4	2001	2001	2019	19	0.0010	0.2	0.7
		2019	Final time		x	x	x	x

Source: The authors' calculations

The data of the USA system dynamic modeling and calculated historical useful power *P(t)* for the period 1949–2019 are presented in Figure 7. Scenario *P(t)-4* is a summary curve over the entire period and the total impact on the system. Historical data were used to validate the model.

Figure 7

The Data of the USA System Dynamic Modeling and Calculated Historical Useful Power P(t) for the Period 1949–2019



Source: The authors' calculations

Modeling data in Figure 7 show that:

- the structure of the economy and the ratio of the industrial and non-industrial parts of GDP are important factors in building the transition to sustainable development;

- an increase in total useful power, as a result of an increase in industrial power, starting from 1983 could ensure sustainable growth by no more than 1 %.

This model did not consider adjustments for population parameters, as well as final consumption of full power, electricity and other types of energy resources. *System dynamics is a suitable approach for modeling sustainability issues because of the long-term perspective and feedback dynamics inherent in such issues. One of the key benefits of collaborative system dynamics modeling is the study of system connections and feedback, both about the system and the external environment.*

The authors conclude that the goal of the article has been achieved by holistically explaining the main conditions of sustainable development within the concept of non-linear systems. Based on an interdisciplinary study that uses mathematics, physics, economics, the complexity of the modern world is explained with the help of specific examples. Continuing the authors' previous research, the methodology of system dynamics and the analysis of energy flows and changes in energy flows in socio-economic systems are used.

The authors offer a core that looks at nature-society and human interrelationships with the new and the old world perspectives and methodological approaches. Complex approaches and complicated approaches are touched upon, which open up the need to understand and explain the formation of the connection of various processes, in which the unity of various contents and the learning process is important. The diversity of experiences, individual engagement with the environment, depth of sustainability and the experience of non-linear complex processes make it possible to question the dominant approaches of traditional teaching in education.

The foundations of natural science learning can contribute to the development of more sustainable learning for the future, which will not limit each person's unique natural capacity for development and its use in building a sustainable education-oriented society.

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