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SYSTEM-DYNAMIC APPROACH TO ASSESSING SUSTAINABLE DEVELOPMENT: THE EXAMPLE OF THE USA

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Abstract. The aim of the article is to study the influence of the sectoral structure of the economy and technological efficiency on ensuring continuous positive growth of the total useful capacity of the socio-economic system during the selected period. The novelty of the approach lies in the fact that, based on the analysis of socio-economic, technical and environmental factors that determine the sustainable development, natural science meters are determined, reduced to one unit of measurement in systems that are open at the input and output in terms of energy. The article focuses on the main questions related to the creation of the dynamic model of the sustainable development model of the system for different scenarios of useful power changes with two types of the impact parameters and algorithms. The results of the main positions of the dynamic models of the systems and their interpretation are presented based on the historical statistical data of the United States of America in the period from 1950 to 2019. The correction was made four times over the period from 1949 to 2019 with different impact factors and scenarios. The purpose of the correction was to model the changes in the useful power of the industry and technological efficiency in order to obtain a continuous positive increase in the total useful power of the system during the selected period.

Key words: sustainable development, system dynamic, industry, technology, power.

JEL code: E19, F69, Q59, R10

Introduction

Existing tools for economic and mathematical descriptions do not allow us to identify the place and time of origin of the root causes of economic changes, taking into account the forecasting of the nature of their growth. In addition, traditional economic and mathematical methods are not able to identify the paths and rates of change in economic structures from the place and time of their occurrence to the place and time of their future manifestation. Economy is the purposeful activity of people in resource management, based on a comparison of projected acquisitions and losses of resources with the planned expenditure of resources necessary to achieve set goals. It follows that without the skills of planning the distribution of resources and the ability to predict future gains and losses from the implementation of planned management, it is impossible to solve any specific economic problem and sustainable development tasks. The main reasons for the weakness of traditional methods of economic and mathematical tools for the formation of proposals for economic management include several provisions (Kulik, 2016). *Firstly*, traditionally, for current economic management, statistical information is used, which is information from the past. It follows that it is impossible to calculate and predict the results of statistically independent events. Statistics approaches are most suitable for assessing the quality of past management and for preparing the initial conditions for forecasting economic dynamics. It must be taken into account that future economic changes arise on the basis of future economic structures, which are currently still uncertain and are not predicted by stochastic methods. Stochastic methods of economic forecasting, for example extrapolation of time series, are based on the hypothesis that future changes depend only on time, but not on the controls performed in the current

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and future times and the resulting structural changes in the economy. Therefore, such economic forecasts about future states that last more than a year are always not correct enough. *Secondly*, when extrapolating time series, the dependence of the rate of change of the resulting parameter on the values of any resource investments is not modelled, and this leads to the fact that traditionally it is not the speeds and accelerations of parameters that are predicted, but the states of the system, which rarely come true. *Thirdly*, the real economy operates in conditions of continuous changes in its structures (Kuznetsov, 2015). Namely, these structural changes, not detected by traditional forecasting methods, mainly serve as the reasons for the generation of unpredictable chaotic dynamics of future real processes. A real socioeconomic system is a dynamic system with many structural feedbacks. Real economic systems always have many dynamic elements, and a large number of different (positive and negative) structural feedbacks. Forecasting future structural changes in socio-economic systems can be performed by methods of dynamic modelling of the economic original based on a system of nonlinear differential equations that take into account in their calculations not only the time factor, but also feedback and structural changes. Such dynamic models with a high degree of correctness predict the speed and acceleration of changes in system parameters (i.e. economic dynamics), as a consequence of the effects of various internal controls and expected external influences on it. The results obtained can model not only crisis-free processes, but also future sudden changes that reduce the degree of sustainable development (Kuznetsov, 2015). Within the framework of the concept of ecological economic (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 designing model was developed using the method of power and energy flows changes analysing in open dynamic socio-economic systems (Trusina, Jermolajeva, 2022). 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. A sufficient condition is the increase in the technological efficiency of the system (Kuznetsov, 2015; Bolshakov, Karibaev & Shamaeva, 2019).

The aim of the article is to study the influence of the sectoral structure of the economy and technological efficiency on ensuring continuous positive growth of the total useful capacity of the socio-economic system during the selected period. The authors were faced with the task: the development of the socio-economic system's useful power dynamic model under various industrial and technological scenarios, based on the methodology of system dynamics and socio-economic system energies flows' changes analysis a as a necessary condition for sustainable development. The results of the main positions of the dynamic models of the systems and their interpretation are presented based on the historical statistical data of the United States of America in the period from 1950 to 2019. The correction was made four times over the period from 1949 to 2019 with different impact factors and scenarios. The authors used the United Nations, the World Bank and the International Energy Association databases to develop the research.

The novelty of the approach lies in the fact that, based on the analysis of socio-economic, technical and environmental factors that determine the sustainable development, natural science meters are determined, reduced to one unit of measurement in systems that are open at the input and output in terms of energy. The relevance of the topic is associated with the growing requirements for the rational justification of management decisions that affect various aspects of the functioning of socio-economic systems.

Methodology

Dynamic modelling is a new direction in the technology of economic and mathematical research. The new direction contains a fundamentally new logic of synthesis, conditioned by taking into account the influence of the time factor in the economy. Often it is more significant than a change in proportions in the distribution of material, financial, information and other resources. Such parameters of a socio-economic object as the speed of flows and accumulation of resources, the lag time in decision making, the time sequence of resource allocation, the forecasting time interval, the time intervals of weaning or getting used to something, the length of time to tolerate something and a number of other parameters, being function of time, largely determine the nature of socio-economic processes. To avoid serious mistakes when making decisions in managing the real economy, it is necessary to learn to understand the influence of time factors on social processes. Since time flows continuously and endlessly, and social systems (economic, political, social, etc.) are non-stationary and also continuously change their structure, there cannot be stable algorithms and unshakable recommendations in economic management. The ability to manage the economy is not only the ability to redistribute resources, but also the ability to predict the results of this redistribution. In economy, results do not appear immediately and often in the form of processes. If we accept that economy is a social activity of people based on comparing the results of activities with costs, then the ability to predict the nature of losses, the magnitude and time of their occurrence and compare them with useful gains allows us to avoid many mistakes. In this regard, there are several problems (Kuznetsov, 2015). *Firstly*, it is necessary to determine the criterion for the quality of management and what changes in this criterion are expected in the future. *Secondly*, to establish what losses will be and when they will be. *Thirdly*, to justify the value of the predicted time interval taken to evaluate the criterion. *Fourthly*, to determine the strategy for evaluating the criterion (when, frequency). *Fifthly,* to find out what should serve as the levers for controlling the object, in what sequence and with what intensity they should be used to obtain the desired socio-economic processes.

Dynamic simulators are based on dynamic models of these objects. The main difference between dynamic models and statistical ones is the presence of dynamic algorithms. They form changes in model parameters taking into account the influence of time factors. In addition to the ability to take into account the time factor, dynamic models of simulators have a number of properties that transfer economic and mathematical calculations from the field of traditional methods to fundamentally new technologies (Radziski, 2010). *Firstly,* dynamic models have many feedbacks similar to those in real objects. One part of the feedback (negative) under certain conditions contributes to the stabilization of the dynamic model, and the other part (positive) gives rise to avalanche-like socio-economic processes. The continuously changing imbalance of positive and negative connections affecting the dynamics of modelling leads to processes of different nature. One of the most difficult tasks of managing socio-economic objects is finding and correctly implementing such a ratio of positive and negative feedbacks that will allow the desired rate of development of the object to be achieved without its destruction or stagnation at every moment of its life. *Secondly*, socio-economic models have a non-stationary structure, which means that ongoing continuous changes lead to the disappearance or emergence of new connections between model elements. Nonstationary structures lead to many unexpected consequences. *Thirdly,* nonlinear dynamic models with a non-stationary structure used in simulators require compliance with three necessary conditions:

- logical and mathematical correspondence between all information transformation algorithms;
- correspondence of the starting digital information to the initial structure of the model;
- compliance of the completeness of the set of parameters with the given modelling accuracy.

Of particular importance is the parameter of impact on the object (algorithm) in material or information form. The impact parameter in its form can be constant, not changing throughout the entire duration of the study, or variable. Three main types of changes in the impact parameter can be distinguished:

- "smooth" change in the form of a smooth differentiable function;
- "step" change in impact, when the impact instantly changes by an amount that significantly affects the calculation results;
- "impulse" change in the form of an impulse of a certain size.

Thus, the main problem of modelling complex systems with insufficient information about their functioning is to ensure the adequacy of the created model to the modelled object. The task of such modelling goes beyond formal formulations and significantly limits the possibility of using mathematical methods for describing the behaviour of systems based on statistical material. In addition, modelling socio-economic systems involves modelling the behaviour of systems in situations that have not previously been encountered and modelling situations the observation of which is complicated by the long duration of their development (Bolshakov et al., 2019).

A dynamic model of a real socio-economic system with many feedbacks, non-stationary structure and non-linear transformations of parameters are represented as a "black box" with stochastic switching of communication circuits of model elements. However, all changes in the structure of the dynamic model are completely deterministic, and the emerging processes are generated by a complex non-stationary structure, the changes of which are determined by deterministic algorithms (Radziski, 2010). The search for ways to overcome problems in the study of socio-economic systems led to the emergence in the 1960s of a specialized method of simulation modelling - the method of system dynamics (Forrester, 2003). This method, proposed by Jay Forester, has proven to be an effective approach to studying the behaviour of complex systems that are difficult to formalize. Unlike "traditional" methods of computer modelling, system dynamics does not require constructing a mathematical model of the object under study in a traditional form, but provides the researcher with tools for modelling. This allows you to build models of completely different degrees of complexity and quickly obtain simulation results for different model parameters. System dynamics is aimed at studying not the systems themselves, but the problems associated with these systems. The process of synthesizing system dynamics models is very difficult. It is based on mental models: dynamic models are created by teams of experts and the synthesis of a dynamic model acceptable for practical use can take a lot of time.

Research results and discussion

Modelling socio-economic systems to obtain practically significant results forces us to consider them as complex dynamic systems with a large number of external and internal connections, and also to take into account a variety of information, financial, material, and energy flows, and to provide for an analysis of the consequences of changes in their structure. In an interdisciplinary study, a methodology for evaluating indicators of sustainable development of socio-economic systems (countries) was developed, perfecting the theory of sustainable development, using the processes of natural sciences and connecting the regularities of economy, mathematics, physics and the environment. In context of system dynamic approach, the mental model of the energy flows (power) for socio-economic systems was created and presented on Fig. 1 (Trusina & Jermolajeva, 2023).

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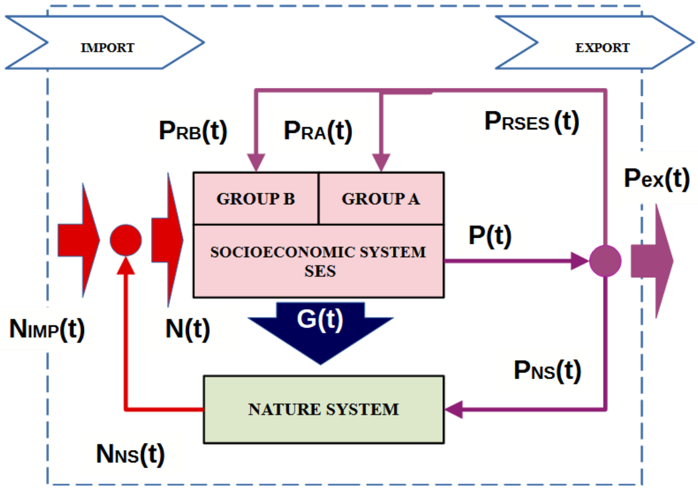


Source: Trusina, I., Jermolajeva, E. & Gopejenko, V. (2023)

Fig. 1. **The mental model of socio-economic system with energy flows**

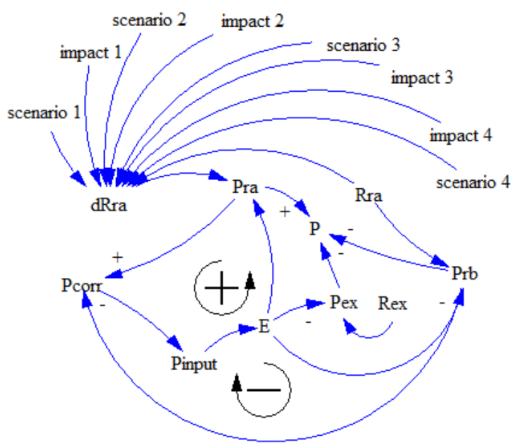
The mental model construction is based on the law of conservation of the power in units of energy necessary for the development and provision of all processes of the socio-economic system in invariant coordinate system (Trusina, Jermolajeva, 2022). During the modelling process, the authors used two types of impact parameters on the object (algorithm) and two types of objects (algorithm or scenario). The process of modelling changes in useful power was considered from the point of view of the industrial approach and the technological approach.

Industrial approach

The industrial approach assumes that changes in the useful power of the system depend on the structure of the economy and the proportion between the production and non-production sectors of the economy. For the modelling process construction, the authors used as:

- types of impact parameters on the object (algorithm or scenario) - change in the share of the manufacturing industry sector of the economy, impulse type of impact;
- types of objects (algorithm or scenario) – the influence of the sectoral structure of the economy on the level of useful power of the socio-economic system, as a necessary condition for sustainable development.

The causal relationship diagram (industrial approach) in accordance with the conditions is presented in Figure 2.



Source: Trusina, I., Jermolajeva, E. & Gopejenko, V. (2023)

Fig. 2. **Causal relationship diagram (industrial approach)**

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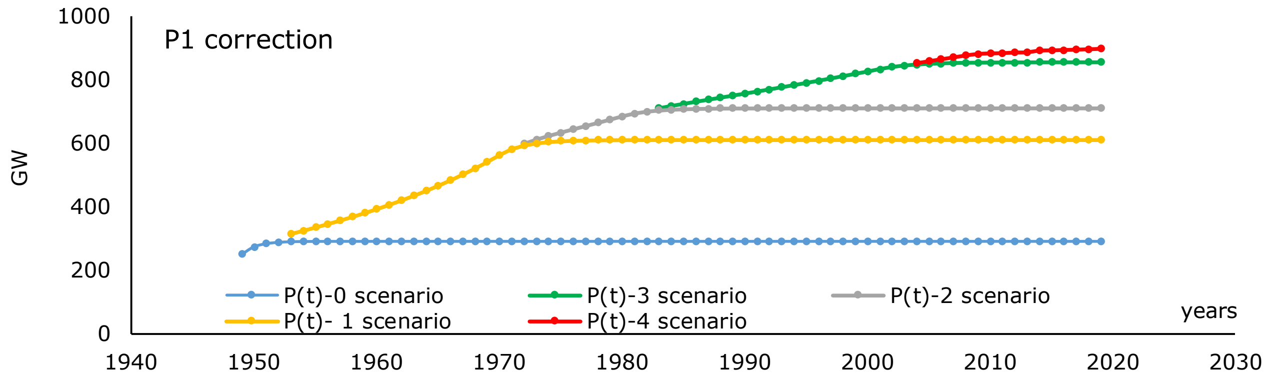
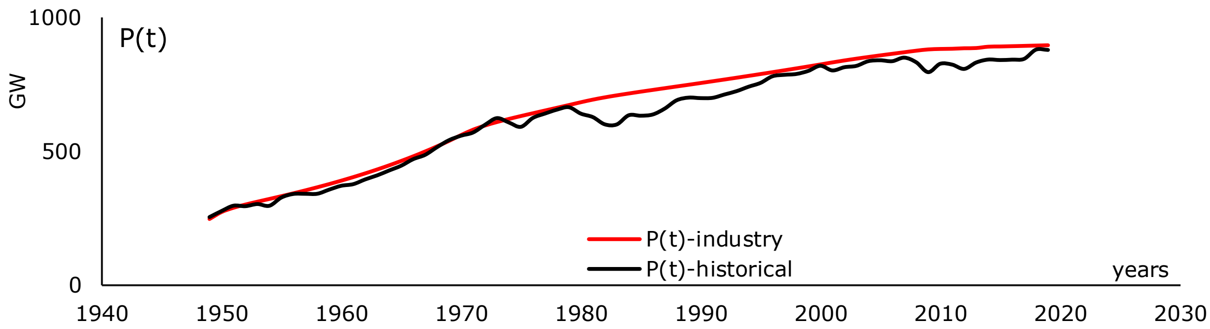
A dynamic model of changes in useful power for the US socio-economic system was implemented as a result of four impulse impacts in 1949, 1972, 1983 and 2001. The scheme of impact on the system is presented in Fig. 3.



Source: the authors' calculations

Fig. 3. **The scheme of useful power $P(t)$ dynamic as impact on the USA system for the period 1949-2019 (Industrial approach)**

The data of the USA system dynamic modelling and calculated historical useful power p(t) for the period 1949–2019 (industrial approach) are presented in Fig. 4



Source: the authors' calculations

Fig. 4. **The USA useful power $P(t)$ dynamic modelling and calculated historical for the period 1949-2019 (industrial approach)**

Historical data were used to validate the model. Correlation coefficients of final scenario and historical data in the frame of industrial approach is $R^2 = 0.99$.

Technological approach

The technological approach assumes that changes in the useful power of the system depend on the level of technological development. For the modelling process construction, the authors used as:

- types of impact parameters on the object (algorithm) - change in the technological efficiency of the economy, type of impact stepwise;
- types of objects (algorithm or scenario) – the impact of the technological efficiency of the economy on the level of useful power of the socio-economic system, as a sufficient condition for sustainable development.

According the mental model, the useful power $P1(t)$ correction as function of technological efficient $F1(t)$ is modelled using formulas 1, that is adapted to research from Kuznetsov model (Kuznetsov, 2015):

$$\frac{dP1(t)}{dt} = -\frac{t}{T}P1(t) + (F1(t) + \Delta F1)N1(t) \qquad (1)$$

where initial conditions are:

$P1(0) = 254GW;\ N1(0) = 953GW;\ F1(0) = 0.27$

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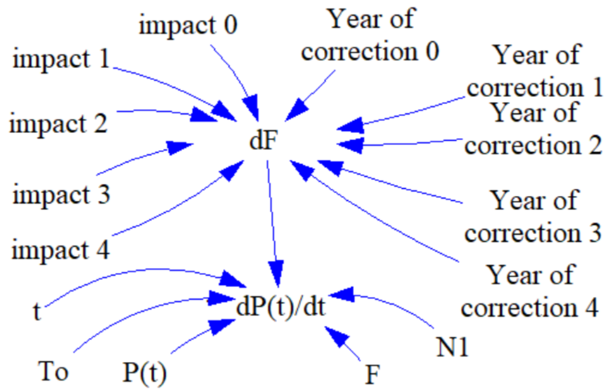
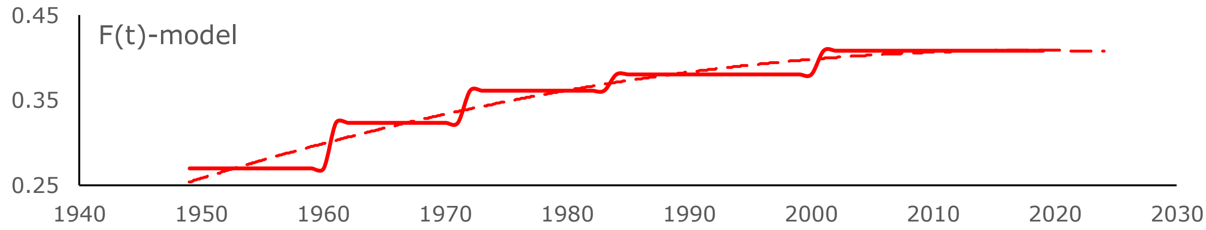
The causal relationship diagram (technological approach) in accordance with the conditions is presented in Figure 5.



Source: created by the authors

Fig. 5. **Causal relationship diagram (technological approach)**

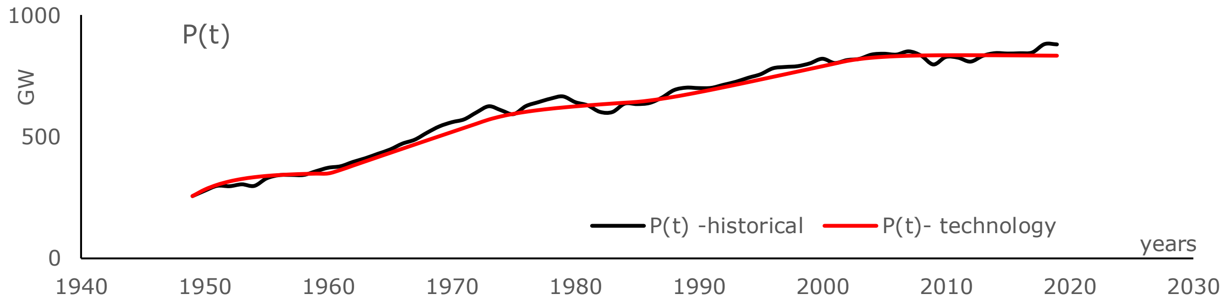
A dynamic model of changes in useful power for the US socio-economic system was implemented as a result of four step change in impact in 1960, 1972, 1983 and 2001 (Fig. 5). The scheme of impact on the system is presented in Fig. 6.



Source: the authors' calculations

Fig. 6. **The scheme of technological efficiency $F(t)$ dynamic as impact on the USA system for the period 1949–2019 (technological approach)**

The data of the USA system dynamic modelling and calculated historical useful power $P(t)$ for the period 1949–2019 are presented in Figure 7. Correlation coefficients of final scenario and historical data in the frame of industrial approach is $R^2 = 0.98$.



Source: the authors' calculations

Fig. 7. **The USA useful power $P(t)$ dynamic modelling and calculated historical for the period 1949–2019 (Technological approach)**

Modelling data show that, the structure of the economy and the technological level of socio-economical system are an important factor in building the sustainable development dynamic model.

Conclusions, proposals, recommendations

1) The authors in an interdisciplinary study have developed a methodology for evaluating indicators of sustainable development of socio-economic systems (countries), thus supplementing the theory of

sustainable development, using the processes of natural sciences and connecting the regularities of economy, mathematics, physics and the environment.

2) Existing tools for economic and mathematical descriptions do not allow us to identify the place and time of origin of the root causes of economic changes, taking into account the forecasting of the nature of their growth. In addition, traditional economic and mathematical methods are not able to identify the paths and rates of change in economic structures from the place and time of their occurrence to the place and time of their future manifestation.

3) The modelling of the data of the USA useful power dynamic shows 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.

4) The modelling of the data of the USA useful power dynamic also reveals that the technological level and efficiency of socio-economical system are important factors in building the transition to sustainable development.

5) System dynamics is a contemporary approach for modelling sustainability issues using the long-term perspective and feedback dynamics inherent in such issues. System dynamics is aimed at studying not only the systems themselves, but the problems associated with these systems. The process of synthesizing system dynamics models is very difficult. It is based on mental models and causal relationship diagrams.

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