

Scenarios of sustainable development of metallurgical industry: simulation modeling

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Abstract. Due to a complicated epidemiological situation, current economic situation in Russia and the world gives a push to new researches in the field of ensure sustainable development in all branches of industry. Methods and tools available today cannot fully provide this, so modern economics needs to develop fundamentally new approaches to the study of industries. Within the framework of this research it is proposed to use simulation modeling to predict scenarios of sustainable development of certain industries, in particular metallurgy, mining of metal ores and production of finished metal products. The research is based on systemic-synergistic approach based on the theory of industrial organization, economic growth and development, system dynamics and mathematical economics. The simulation model of metallurgy and related industries development, which is based on a system dynamic flow – streaming stratification, was designed and developed as a result of this research. Ideas of three-sector model, adapted to the sectoral aspects of the functioning of the economic system, are used in the simulation model. The development allows to simulate various scenarios of the development of the industries under study in order to determine the trajectory of their sustainable development. As a demonstration, three scenarios of the development of industries are presented, taking into account changes in the most important component of the economic system - labor force.

1 Introduction

Sustainable development of heavy industry remains the most important priority of the national economy, which is reflected in the industrial policy of the Russian Federation, individual national projects and programs [1]. Methods for achieving sustainable development are reflected in different aspects in many Russian and foreign studies [2–5]. The conclusions proposed in these works persuade researchers to use fundamentally new tools and methods for studying the sustainable development of the national economic system as a whole, and its individual sectors.

It should be noted that a huge pool of studies on the sustainable development of individual industries, and, in particular, metallurgy, is devoted to the analysis of the current situation [6–8]. Some works develop to the identification of certain linear and nonlinear

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relationships built using econometric regression models [9-10]. However, such models practically do not take into account, firstly, the nonlinear behavior of economic systems and, secondly, the presence of cause-and-effect relationships between individual indicators of these systems. Therefore, the authors propose to use a fundamentally different approach - the construction of simulation models to study the sustainable development of the metallurgical industry.

In this work, an attempt is made to use the ideas of mathematical economics, in particular the modeling of macroeconomic dynamic systems, in synthesis with simulation modeling to study the development of sectoral economic systems. This synthesis is possible through the use of casual and flow simulation modeling notations. A feature of the proposed approach is the use of system dynamics methods, first proposed in the works of J. Forrester [11–12] and D. Meadows [13–14], and subsequently developed in the works of A. Akopov [15], A. Borshchev [16] and other researchers. Dynamic models of macroeconomic systems are, as a rule, based on first-order differential equations, which can be transformed into the system dynamics notation using flow stratification.

The aim of this study is to develop a concept of a simulation model of the sustainable development of the metallurgical industry. In accordance with the purpose of the study, the following tasks were set:

1. Highlight the main ideas of simulation modeling of complex economic systems and choose the most suitable approach for the research goal.
2. Draw up the basic equations of the model of sustainable development of the metallurgical industry and, on their basis, design a simulation model.
3. To test the developed simulation model, to simulate scenarios of the development of the metallurgical and related industries, taking into account changes in the growth rate of the labor force.

2 Material and Methods

Nonlinear small-scale models are used to study long-run trends, growth factors, and assess the consequences of certain variants of macroeconomic decisions. In such models, the structure of the economy is reflected in the form of sectors, each of which produces some aggregate output. The basis here is the single-sector Solow–Swan model [17], where the economic system is viewed as a kind of unstructured apparatus that produces a single universal output. This model reflects the reproduction process and allows you to analyze the relationship between consumption and accumulation. The development result of this model was a dual-sector model [18] and a three-sector model [19].

The mathematical tools presented in the three-sector model of the economy are a set of differential equations, balance equations, and nonlinear production functions. Within the framework of this study, it is proposed to use a fundamentally different approach - simulation modeling. Simulation modeling is an experimental method for studying a real or projected system according to its simulation model, which combines the features of an experimental approach with specific conditions for using computer technology [20]. According to the accepted classification, there are three approaches to creating simulation models: discrete-event modeling, system dynamics, and agent-based modeling.

When describing meso- and macroeconomic systems, it is advisable to use system dynamics and agent-based modeling. At the same time, agent-based modeling is used when the system explicitly identifies individual subjects with discreteness, sociality, activity, autonomy and flexible behavior. However, models of system dynamics make it possible to identify cause-and-effect relationships in economic systems. As a rule, they consist of

accumulators (levels), which are accumulations in feedback circuits, flows that regulate the rate of change of accumulators, auxiliary variables and cycles (feedback loops).

System dynamics models are based on differential equations, which justifies their use when trying to breathe new life into classical dynamic (continuous) economic models. H.B. Яндыбаева и В.А. Кушников developed a complex system dynamic model for predicting the indicators of the economic security of the Russian Federation, which compiled 11 system levels, including the level of consumer price growth, unemployment, etc., 4 functional dependencies and several dozens of auxiliary variables [21].

Particular attention is paid to the study of the interaction of economic growth and resource consumption, which can also be expressed using differential mathematical models. Thus, in work [22], a model was developed in the notation of system dynamics, in which economic growth and resources are considered from a system point of view in order to identify the dependence of economic growth on delayed feedback effects from resource depletion. The model consists of two subsystems: renewable natural resources and economies, where the level of resources and GDP are included as accumulators.

Modeling the processes of economic dynamics by industry is presented in [23], where a simulation model of the region's supply chain system has been developed. The model consists of four main interconnected blocks: population, agriculture, manufacturing and transport. The model made it possible to identify the cyclical nature and interdependence of the efficiency of the main industries and their mutual influence on each other.

Thus, a large number of economic studies use simulation modeling tools, in particular, system dynamics in the analysis of macroeconomic systems. However, such models consider either the national economy as a whole or its individual enlarged sectors. Within the framework of this study, was made an attempt to apply the tools of system dynamics to study the model of sustainable development of a separate group of industries based on a three-sector model of the economy.

3 Results and Discussion

The objects of research are the branches of metallurgy, production of finished metal products, ore mining and mechanical engineering, within the framework of this study. The choice of the research object was not made by chance, since it is metallurgy is one of the leading industries in the Urals macroregion. Other industries are not directly considered in this model, but are counted as a kind of "other" industry. The material sector is represented here by the production of objects of labor (iron ores, ores of non-ferrous metals, cast iron, steel, ferroalloys, steel pipes, precious and non-ferrous metals, casting), labor instruments (machinery and equipment) are considered as a fund-creating sector, and consumer goods are consumption (finished metal products). It should be noted here that consumers can be both other sectors of the economy and households. Only the metallurgy sector and the industries closest to it are considered within the framework of this model.

Thus, the mathematical model consists of five first-order dynamic elements, three static distribution elements and four non-linear static elements. Equations of capital changes in each industry and changes in the number of workers in industry as a whole are considered as dynamic elements. Static distribution elements are the equations of the distribution of labor force by industry, the distribution of investment by industry and the distribution of products in the material sector (metallurgy). Nonlinear static elements represent the Cobb-Douglas production functions for each of the studied industries.

The endogenous variables are FPA (fixed production assets) and industry outputs. Exogenous variables are the rate of increase in the number of employees, the wear rates of the FPA (fixed production assets) in industries, the coefficients of direct material costs, the

initial value of the number of employees, the initial distribution of the employed by industries, the initial values of the FPA (fixed production assets) of industries, and the parameters of production functions. Accordingly, the management in the model is carried out by allocating labor and investment resources.

Based on the equations and basic postulates of system dynamics developed by the authors, a simulation model of sustainable development of metallurgical and related industries has been designed and developed in the software environment. This model is designed in accordance with the following principles:

1. Dynamic elements are represented as flow and accumulators diagrams, each dynamic element represents an accumulator, and the flow sets the rate of change of these accumulators.
2. Non-linear static elements are specified as functional variables, the values of which are calculated based on the values of other variables, parameters and accumulators.
3. Static distribution elements are specified in the form of parameters, which values are adjusted by the user of the model.

Thus, in the developed simulation model there are 5 flow diagrams, 4 of which have almost identical appearance (Fig. 1).

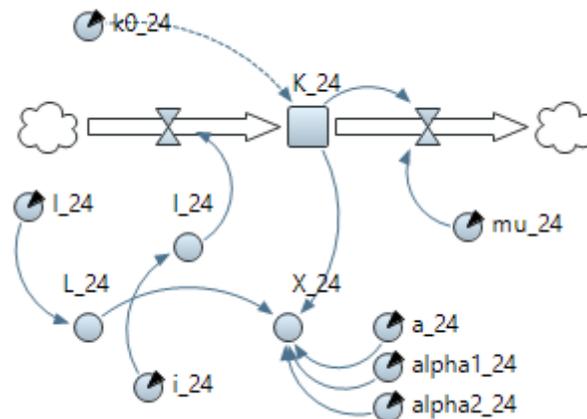


Fig. 1. Flowchart of the metallurgy industry

In general, the simulation model is a complex of flow and cause-effect diagrams, where each element is calculated dynamically, in continuous time. The volume of fixed production assets (capital) of each of the studied industries and the number of employed in industry are presented, as accumulators in the model, which are calculated according to the given differential equations using special elements - flows. Flows set the rate of change of accumulators per unit of time in a dynamic way, i.e. continuously. With the use of dynamic variables, we describe the output of the industry, as well as the number of employees and the amount of investment.

The parameters in the simulation model designate those values that are set and changed by the user, but not functionally. That is, these are data obtained statistically and empirically, calculated mathematically and econometrically, and entered into the model. The parameters can be both static and changing over time (this property is useful when modeling various scenarios of economic growth). Static parameters are mainly the initial values of accumulators and the coefficients of production functions.

Thus, the structure of a simulation model of the development of several industries is described, including metallurgy, mining of metal ores, mechanical engineering and the production of finished metal products.

For empirical testing of the model, it is necessary to calculate the values of the exogenous variables (parameters) of the model and set the equations in the corresponding variables.

As indexes X_i , we used indicators of the volume of shipped goods of own production for each of the studied industries (mining of metal ores, metallurgical production, production of finished metal products, except for machinery and equipment, production of machinery and equipment not included in other groups). The K_i index is calculated as the value of the index of fixed assets of commercial organizations for each of the industries. The L_i index is calculated as the value of the index of the average annual number of employees in organizations (Table 1).

Table 1. Descriptive statistics of the initial data for the construction of production functions

Index	Mean	Standard error	Median	Minimum	Maximum	Dispersion	RMS deviation
X_07	845326,6	46944,1	988000,0	343633,8	484446,1	2034227172	45102,4
X_24	2931380,2	220461,5	2768500	1061710	1837724,9	4,4865E+10	211812,6
X_25	1249980,8	91035,0	1186500	455018,6	768581,6	7649879809	87463,6
X_28	1062462,9	80704,7	1125420	376389	646794,0	6012228031	77538,6
K_07	812229,2	85864,8	697009	274479	548720,3	6805624929	82496,2
K_24	1544764,4	139333,0	1320351,5	570974,3	984168,4	1,792E+10	133866,8
K_25	327405,5	29339,2	280074,6	121115,8	210779,5	794574579	28188,2
K_28	352826,8	12066,6	354314	153625,6	191204,4	134402506	11593,2
L_07	245,9	85,7	1090000	167	357,5	6781,9	82,4
L_24	557,0	108,3	1076803	440,7	731,8	10822,8	104,0
L_25	393,7	74,4	513309	292,9	487,8	5114,5	71,5
L_28	742,0	313,2	13,1	299,4	1205,0	90548,1	300,9

In Table 1 indexes X_i are calculated in million rubles, indexes K_i are calculated in million rubles, indexes L_i are calculated in thousand people. As a result of calculations, the following production functions of the studied industries were found:

$$\begin{aligned}
 X_{07} &= K_{07}^{0,89} \times L_{07}^{0,28} \\
 X_{24} &= 0,68 \times K_{24}^{0,74} \times L_{24}^{0,55} \\
 X_{25} &= 5,9 \times K_{25}^{0,38} \times L_{25}^{0,49} \\
 X_{28} &= K_{28}^{0,97} \times L_{28}^{0,22}
 \end{aligned}
 \tag{1}$$

All constructed functions and coefficients in them are statistically significant at the level of 5%, the coefficients of determination range from 0.4 for the metallurgy industry to 0.99 for the mechanical engineering industry. The values of all exogenous variables (parameters) described in table 2 are calculated and presented in table. 2.

Table 2. Values of model parameters as of 2018

Variable name/ Industry	07 – Mining of metal ores	24 – Metallurgy	25 – Manufacturing of finished metal products	28 – Engineering
k_i	1709200	3255000	699600	509900
μ_i	0,013	0,009	0,007	0,011
l_i	0,032127	0,043398	0,04877	0,039027
i_i	0,207959	0,250129	0,06384	0,033877
a_i	1	0,68	5,9	1
$\alpha1_i$	0,89	0,74	0,38	0,97
$\alpha2_i$	0,28	0,55	0,49	0,22
l_0	9887,1			
v	-0,00036			

The main idea of simulation models is to be able to simulate various situations that arise in the system - to simulate scenarios. Within the framework of this work, six different scenarios for the development of metallurgy and related industries were investigated. The first scenario is the development of the economic system without significant changes in accordance with the specified production functions. In this scenario, it is assumed that all the parameters of the model are constants (i.e., all the growth rates of the main indicators are preserved). This scenario reflects the existing picture and allows predicting the development of economies in various industries. The indicator of gross output (Fig. 2) was selected as the analyzed variable.

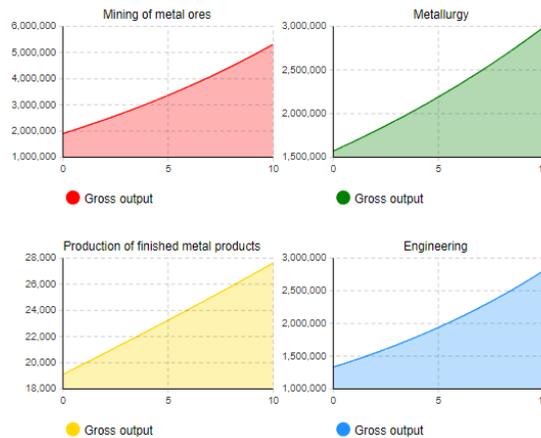


Fig. 2. Dynamics of changes in gross output according to scenario No. 1

It should be noted right away that the total volumes of output in some industries may not reflect the actual values at the beginning of the analyzed period, since, firstly, production functions were built at prices in 2002 and, secondly, the initial value of output in this model was not set. The main goal here is to track the growth rates of individual industries.

So, with the existing growth rate of the number of workers in industry (and as of 2018 this rate was -0.36% per year) and the growth rate of capital investment in fixed assets, the capital-labor ratio of all studied industries gradually reaches the level of labor productivity in 10 years. With unchanged indexes, the growth in output in the mining industry of metal

ores will grow 2.78 times, metallurgy - 1.9 times, production of finished metal products - 1.44 times and machine building - 1.95 times over 10 years.

The second scenario here is a reflection of the already existing trend towards a reduction of the number of workers in the industry. The simulation model specifies a reduction in the growth rate of the number of workers in industry by 1% per year (Fig. 3).

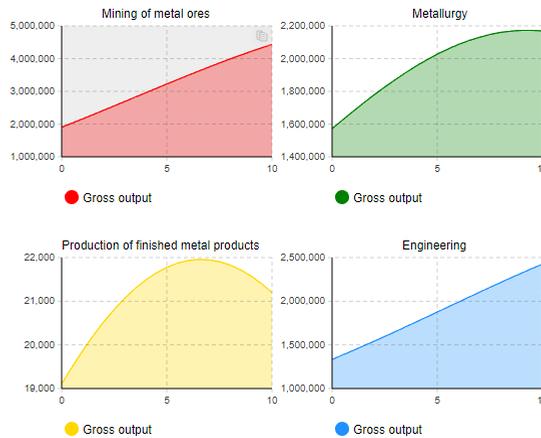


Fig. 3. Dynamics of changes in gross output under scenario No. 2

First of all, the reduction in the inflow of new labor force into industry as a whole will affect the industries in which labor productivity influences the output to a greater extent than the capital-labor ratio. According to the calculated values, output in the metallurgy industry will gradually slow down and practically stop in the 9th year. In the production of finished metal products, the situation is even more negative - already in the 6th year, production volumes will begin to decline. The metal ore mining and mechanical engineering industries will not suffer so much, however, their production growth rates will also decline.

The third scenario is optimistic - an increase in the growth in the number of workers in industry while maintaining their distribution by industry by 1% per year (Fig. 4).

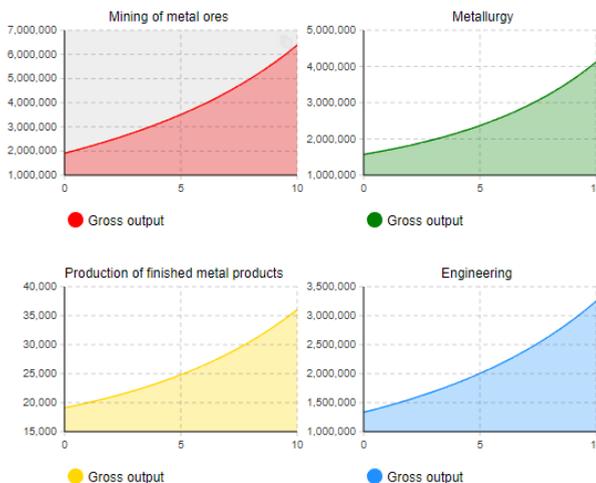


Fig. 4. Dynamics of changes in gross output according to scenario No. 5

The increase in the number of employees has a positive effect on the growth rate of products in all sectors. Moreover, a feedback loop is actively starting to work, which links the output of fund-forming industries (in particular, mechanical engineering) with capital gains in other industries. Thus, the further we build our forecast, the greater the share in the increase in output is occupied by the increase in capital investments in fixed assets. This effect is called a self-replicating feedback loop.

Thus, the possibility of using the developed simulation model for the analysis and forecasting of the development of metallurgy and related industries has been demonstrated. Naturally, this set of scenarios is the most probable and conditional. However, the simulation model allows new scenarios in line with Russian industrial policy.

4 Conclusion

As a result of this study, the following results were obtained:

1. As a result of the analysis of research in the field of simulation modeling, it was revealed that to build a model for the sustainable development of metallurgy, it is necessary to use the notation of system dynamics.

2. On the basis of a three-sector model of the economy, an imitation model of sustainable development of metallurgy and related industries has been developed in the notation of system dynamics. The accumulators are determined - the basic production assets of each industry and the number of workers in the industry, - flows that change them, as well as dynamic variables and model parameters. The constructed simulation model is a complex of flow causal diagrams that reflect not only the structure of the economic system under study, but also its behavior over several periods of time.

3. Constructed simulation model was tested taking into account the available data for 2002–2018. The production functions were constructed and all exogenous variables of the model were calculated empirically. To demonstrate the work of the simulation model, 3 scenarios for the development of the economic system under study were proposed. The scenario analysis showed the main points of management of the model and, as a consequence, of the entire economic system under study in order to achieve sustainable development of metallurgy. The results of this study can be applied, first of all, by public authorities in the field of adjusting industrial policy.

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