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A COMBINED MANAGEMENT MODEL FOR RESTRUCTURING A REPRODUCTION SYSTEM

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Abstract. This paper considers a management model for a reproduction system with the synchronous change of the technological matrix during its restructuring. Such models can be characterized as models with combined (direct and indirect) control links. In the case of production resource reserves, the processes of changing control parameters and transforming technological links should be simultaneous. Invariants are obtained for the relationship between the volume of inputs and outputs of a multi-sector (diversified) economy. As a result, the formalized representation of the structural management model of a reproduction system is modified, and the linear reproduction model is replaced by a nonlinear one. The results of numerical calculations using this model and the real data of a diversified economy are presented. Based on the results, the obtained model is compared with the original restructuring model of a reproduction system.

Keywords: structural management, nonlinear model, reproduction system, transformation of the technological matrix, optimal restructuring process.

INTRODUCTION

The technological core model of reproduction, reflecting the state of a multi-sector (diversified) economy at a certain stage, can be based on the data on the use of resources and services [1]. The standard input-output model assumes direct costs to be linearly dependent on outputs and prices. Several economic management models are built under this assumption, in particular, those proposed in [2, 3]. For small changes in the control parameters, this assumption can be considered valid. However, under finite ranges of these parameters, the linearity assumption becomes incorrect since the values of outputs and prices directly affect the estimates of the technological coefficients for the corresponding sectors.

Let the value V_i of the output of sector i in a diversified economic system with n sectors form the vector $\mathbf{V}$. The values of inputs (costs) and outputs also depend on prices P_i for the corresponding products. The change in prices and output volumes at stage k is given by the vectors of price indices $\mathbf{p}$ and output indices $\mathbf{v}$:

$$v_i^k = V_i^k / V_i^{k-1},\ p_i^k = P_i^k / P_i^{k-1},\ \ i = 1,..., n\ .$$

We denote by $\mathbf{Z} = \left[Z_{ij} \right],\ \ i,\ j = 1,...,\ n,$ the matrix of resource inputs in the reproduction, where sector j uses resource i in its production processes. With this matrix, the coefficients a_{ij} are calculated by the formula

$$a_{ij} = Z_{ij} / V_j\ ,\ \ i,\ \ j = 1,..., n.$$

They form the technological matrix $\mathbf{A} = \left[a_{ij} \right]$ with a spectrum (the set of eigenvalues) $\mathbf{S}$. The spectrum is used to determine the properties of transformations of the technological matrix and sustainable reproduction models.

Following [2], the *productivity* of an economic system is defined as the ratio of value added to intermediate costs: $\pi = Y/Z$, where Y is the gross value added (GDP) and Z is the sum of intermediate costs by sectors. Let V denote the gross output; then the material intensity is given by $a = Z/V$, $V = Y + Z$, and productivity satisfies the relation $\pi = 1/a - 1$.

The targeted restructuring of the technological core is intended to increase its productivity. When building management models for a reproduction system, the output V_i and prices P_i for products can be used as the control parameters of sector i.

The standard input-output model assumes direct costs to be linearly dependent on outputs and prices. However, this assumption is incorrect. Indeed, under the linearity assumption, the coefficients a_{ij} are fixed at each stage of the control action. However, note that as the control parameters vary, the technological matrix $\mathbf{A}$ will also change from stage to stage.

In this regard, the technological core can undergo two types of transformations: without changing the spectrum **S** (rotation) and with changing the spectrum **S** (deformation).

When output indices vary, the matrix $\mathbf{A}$ is multiplied by diagonal matrices **D** (on the right) and $\mathbf{D}^{-1}$ (on the left) with the coefficients $D_{jj} = v_j$ and $D^{-1}{}_{jj} = 1/v_j$, respectively. When price indices vary, the matrix $\mathbf{A}$ is multiplied by diagonal matrices **C** (on the right) and $\mathbf{C}^{-1}$ (on the left) with the coefficients $C_{jj} = p_j$ and $C^{-1}{}_{jj} = 1/p_j$, respectively.

If $\mathbf{A}$ is a Schur matrix (max|S| < 1), the following assertions are true [3, 4].

• If a and r are the maximum eigenvalues of the matrices $\mathbf{A}$ and $\mathbf{A}^{\mathrm{T}}$, respectively, then the reproduction system is sustainable and in a stable state satisfies the equations

$$a\mathbf{v} = \mathbf{A}\mathbf{v},$$

$$r\mathbf{p} = \mathbf{A}^{\mathrm{T}}\mathbf{p}.$$

The sustainability of the reproduction system here is ensured by the stability of the matrix $\mathbf{A}$ and is understood as the convergence of the iterative process

$$\mathbf{x}^{k+1} = \mathbf{A}\,\mathbf{x}^k \frac{\|\mathbf{x}^k\|}{\|\mathbf{A}\mathbf{x}^k\|},\ k = 0, 1, 2, \ldots.$$

This process can be interpreted as a stage-by-stage transition to a stable state (in output and price indices) or a monotonic (highway) growth in absolute values.

• The transformations induced by the matrices **D** and **C** have several invariants. The spectrum **S** of the matrices obtained after the transformation remains unchanged. These transformations can be called output and price rotations, respectively.

• For each price index vector **p**, there exists an output index vector **v** corresponding to a stable state of the reproduction system with the maximum eigenvalue a of the technological matrix $\mathbf{D}^{-1}\mathbf{A}\mathbf{D}$.

• Similarly, for each output index vector **v**, there exists a price index vector **p** corresponding to a stable state of the reproduction system with the maximum eigenvalue r of the technological matrix $\mathbf{C}^{-1}\mathbf{A}\mathbf{C}$.

• The stable state eigenvalues a and r coincide and are independent of the transformation matrices **D** and **C**.

• The technological core may be deformed under a non-multiplicative change of the intermediate cost matrix $\mathbf{Z} = \left[Z_{ij}\right]$, e.g., when a new technology is introduced or when the final consumption structure is modified.

The output restructuring problem

This problem is stated in terms of Leontief's linear model [5]. Consider the bilinear structural reproduction optimization model. The production cost vector $\mathbf{Z}$ consists of the components

$$Z_i = \sum_{j=1}^{n} Z_{ij} = \sum_{j=1}^{n} a_{ij} V_j,\ i = 1, \ldots, n. \tag{1}$$

Assuming the dependence of material intensity coefficients on outputs, the upper bound of the direct cost coefficient is determined from the relation

$$av_i \ge \sum_{j=1}^{n} a_{ij} V_j.$$

The output structure optimization problem has the form

$$\min_{a,\mathbf{V}} a \tag{2}$$

under the implementability condition of the optimal solution:

$$\theta \ge v_i \ge 1,\ \ \theta > 1.$$

For details, see [2].

The plan-forecast of economic development in output indices is calculated as follows. Consider the output growth criterion $\gamma = 1/a$. The indicative dynamics of the output indices maximizing this criterion at stage k, k = 1, 2,..., are calculated using the process

$$\left.\begin{aligned} &\max_{\gamma,\mathbf{v}^i} \gamma, \\ &\mathbf{v}^k \ge \gamma \mathbf{A}^k \mathbf{v}^k, \\ &\mathbf{I} \le \mathbf{v}^k \le \theta \mathbf{I},\ k = 1,\ 2,\ 3, \ldots, \\ &\mathbf{A}^{k+1} = (\mathbf{D}^k)^{-1} \mathbf{A}^k \mathbf{D}^k, \end{aligned}\right\} \tag{3}$$

where the vector **I** consists of units.

The challenge is that the technology matrix iteratively changes, while it is considered to be fixed within problem (3). In the limit case, under small admissible ranges of the output indices, this can be justified. However, for finite sizes of these ranges, the solution becomes inaccurate. Hence, the constraints of problem (3) should be modified.

The restructuring problem in value terms

The output is $V_j p_j$, and the coefficients a_{ij} are transformed to $a_{ij} p_i / p_j$.

The components of the cost vector $\mathbf{R}$ for resource production are given by

$$R_j = \sum_{i=1}^{n} x_{ij} = \sum_{i=1}^{n} a_{ij} V_j,\ j = 1,\ldots, n.$$

The upper bound of the cost coefficient c is determined from the relation

$$cV_j p_j \le \sum_{i=1}^{n} a_{ij} V_j p_i.$$

Then the optimization problem of the price indices at a certain price stage has the form

$$\left.\begin{aligned} &\min_{c,\mathbf{p}} c, \\ &cp_i \le \sum_{j=1}^{n} a_{ji} p_j, \\ &\eta \ge p_i \ge 1,\ \eta > 1. \end{aligned}\right\} \qquad (4)$$

When passing to the next stage, the matrix $\mathbf{A}^k$ is transformed to the matrix $(\mathbf{C}^k)^{-1}\mathbf{A}^k\mathbf{C}^k$. It is reasonable to solve output restructuring and price restructuring problems sequentially, one after another, so that the marginal productivity reaches a higher value. Then the stages for the corresponding problems are assigned odd and even numbers, respectively.

1. THE MODIFIED NONLINEAR MODEL OF STRUCTURAL REPRODUCTION OPTIMIZATION

Considering the dependence of the material intensity coefficients a_{ij} on the control parameters necessitates the transition to a nonlinear model. Let the material intensity coefficients continuously depend on the outputs in the steady-state mode of synchronously changing intermediate costs and rotating technological links. Under this assumption, we will obtain rotation invariants.

Proposition 1. *Under a synchronous transformation of the direct (volume) rotation of the technological matrix and a linear change of the intermediate costs, the relations between the costs and output are constant:*

$$Z_{ki} = c_{ki} V_i^2 / V_k,$$

where $c_{ki} = Z_{ki}^0 V_k^0 / \left(V_i^0\right)^2 = a_{ki} V_k^0 / V_i^0$, Z_{ki}^0, Z_i^0, V_i^0 *denote the initial values of the cost and output components. These relations are equivalently written as*

$$Z_{ki} = \left(a_{ki} V_k^0 / V_i^0\right) V_i^0 / V_k.$$

Proposition 1 is proved in the Appendix.

Corollary 1. Consider application of the invariant for $Z_i = \sum_{j=1}^{n} Z_{ij}$.

The synchronous rotation of the technological matrix yields

$$Z_i = \left(V_i^0 / V_i\right) \sum_{j=1}^{n} Z_{ij}^0 V_j^2 / \left(V_j^0\right)^2$$

$$= \left(1/V_i\right) \sum_{j=1}^{n} a_{ij} \left(V_i^0 / V_j^0\right) V_j^2 = \left(1/V_i\right) \sum_{j=1}^{n} c_{ij} V_j^2,$$

where $c_{ij} = a_{ij}\left(V_i^0 / V_j^0\right)$. ♦

Corollary 2. The volume rotation with the output vector $\mathbf{V}$ transforms the sectoral coefficients a_{ij} to $a_{ij} V_i / V_j = Z_{ij} / V_j$, where $i, j = 1,\ldots, n$. In this case, the reproduction condition is given by

$$aV_i^2 \ge \sum_{j=1}^{n} c_{ij} V_j^2.$$

For the output indices $v_i = V_i / V_i^0$,

$$Z_i = 1/v_i \sum_{j=1}^{n} Z_{ij}^0 v_j^0,$$

the reproduction condition takes the form

$$av_i^2 \ge \sum_{j=1}^{n} b_{ij} v_j^2,$$

where the aggregates are $b_{ij} = Z_{ij}^0 / V_i^0 = a_{ij} V_j^0 / V_i^0$. ♦

With $(\mathbf{v})^2$ denoting the vector with squares of the coefficients v_i^2, the restructuring problem is formulated as

$$\left.\begin{aligned} &\max_{\gamma,\mathbf{v}^i} \gamma, \\ &\left(\mathbf{v}^k\right)^2 \ge \gamma \mathbf{B}^k (\mathbf{v}^k)^2, \\ &\mathbf{I} \le \mathbf{v}^k \le \theta \mathbf{I},\ k = 1,\ 3,\ 5,\ldots, \\ &D^k{}_{ij} = \begin{cases} v^k{}_i, & j = i, \\ 0, & j \ne i, \end{cases} \\ &\mathbf{B}^{k+1} = \left(\mathbf{D}^k\right)^{-1} \mathbf{B}^k \mathbf{D}^k. \end{aligned}\right\} \qquad (5)$$

Corollary 3. As $\theta \to 1$, the solution of problem (5) continuously depends on the parameter θ and, consequently, turns into the solution of problem (3).

Indeed, for $\theta = 1$, the unit vector $\mathbf{I}$ is the solution in both cases. Due to the constraint

$$\mathbf{I} \le \mathbf{v}^k \le \theta \mathbf{I},\ k = 1,\ 3,\ 5,\ldots,$$

the smaller θ is, the closer to **I** the vector $\mathbf{v}^k$ will be. Moreover, in both cases, the objective function has the same optimum equal to

$$\gamma = 1 / \min_i \sum_j b_{ij}.$$

As $\theta \to 1$, the values v_k also tend to 1. ♦

The following result, similar to Proposition 1, is valid for the restructuring problem in value terms.

Proposition 2. *Under a synchronous transformation of the price rotation of the technological matrix, the relations between the costs and output are given by*

$$R_{ki} = d_{ki} P_i^2 / P_k,$$

where $d_{ki} = R_{ki}^0 P_k^0 / \left(P_i^0\right)^2 = a_{ki} P_k^0 / P_i^0$, R_{ki}^0, R_i^0, P_i^0 *are the initial values of the cost and price components.*

Problems (2) and (5) have symmetric formulations, and Proposition 2 is established using the same scheme as Proposition 1. The corollaries symmetric to Corollaries 1–3 are formulated and proved by analogy.

Corollary 4. Consider application of the invariant for $R_i = \sum_{j=1}^{n} R_{ij}$.

The synchronous rotation of the technological matrix yields

$$R_i = \left(P_i^0 / P_i\right) \sum_{j=1}^{n} R_{ij}^0 P_j^2 / \left(P_j^0\right)^2$$

$$= \left(1 / P_i\right) \sum_{j=1}^{n} a_{ij} \left(P_i^0 / P_j^0\right) P_j^2 = \left(1 / P_i\right) \sum_{j=1}^{n} c_{ij} P_j^2,$$

where $c_{ij} = a_{ij} \left(P_i^0 / P_j^0\right)$. ♦

Corollary 5. The volume rotation with the output vector **V** transforms the sectoral coefficients to $a_{ij} P_i / P_j$, where *i*, *j* = 1,..., *n*. In this case, the reproduction condition is given by

$$c P_i^2 \ge \sum_{j=1}^{n} c_{ji} P_j^2.$$

For the output indices $p_i = P_i / P_i^0$, the reproduction condition takes the form

$$c p_i^2 \ge \sum_{j=1}^{n} b_{ij} p_j^2,$$

where the aggregates are $b_{ij} = a_{ij} P_j^0 / P_i^0$. ♦

Consider the process of calculating the indicative dynamics of the output and price indices leading to concerted output and prices. For this purpose, we select the profitability growth criteria $r = 1/c$:

$$\left.\begin{aligned} &\max_{r,p} r, \\ &\left(p^m\right)^2 \ge r \mathbf{B}^{m\mathrm{T}} \left(p^m\right)^2, \\ &\mathbf{I} \le \mathbf{p}^m \le \eta \mathbf{I},\ m = 2,\ 4,\ 6, \ldots, \\ &C^m{}_{ij} = \begin{cases} p_i^m,\ j = i \\ 0,\ j \ne i \end{cases} \\ &\mathbf{B}^{m+1} = \left(\mathbf{C}^m\right)^{-1} \mathbf{B}^m \mathbf{C}^m. \end{aligned}\right\} \qquad (6)$$

Problems (4), (6) are solved sequentially under a given upper bound θ, $\eta > 1$ for the profitability r and the intermediate consumption index a. At stage k, the indicative outputs and prices can be obtained in absolute units.

Corollary 6. As $\eta \to 1$, the solution of problem (6) continuously depends on the parameter η and, consequently, turns into the solution of problem (4).

Indeed, for η = 1, the unit vector **I** is the solution in both cases. Due to the constraint

$$\mathbf{I} \le \mathbf{p}^k \le \eta\, \mathbf{I},\ k = 1,\ 3,\ 5, \ldots,$$

the smaller η is, the closer to **I** the vector $\mathbf{p}^k$ will be. Moreover, in both cases, the objective function has the same optimum equal to

$$r = 1 / \min_i \sum_j b_{ji}.$$

As $\eta \to 1$, the values p_i also tend to 1. ♦

The computational procedures for solving the nonlinear problems (5), (6) can be constructed by modifying the gradient projection method [3]. In this case, all changes consist in replacing, first, the boundary indices θ, η with θ^2, η^2 and, second, the resulting vectors **v**, **p** with $\left((\mathbf{v})^2\right)^{1/2}$, $\left((\mathbf{p})^2\right)^{1/2}$.

As for the linear model, the concerted pair of prices and outputs behaves similarly since the profitability *r* and the intermediate consumption *a* are, in this case, the same for all sectors. In the long run, this property leads to a uniform development of the economic system (the highway effect [6]). However, as for the linear model, the sectoral indices change quite unevenly at the initial disproportion elimination stages.

2. RESULTS AND DISCUSSION

To obtain an indicative plan considering the joint change in output and prices, a series of optimization problems are solved provided that the indices vary within given admissible ranges. The bounds on the price indices are determined from the requirements of permissible inflation or deflation. The lower bound for the indices is set equal to 1: the plan provides for no reduction in outputs and prices for all sectors.

Consider an example of joint planning of outputs and prices. The calculation results are presented below. In the calculations, the values v_i are interpreted as the output indices (products or services) whereas the values p_i as the price indices. Under the non-decrease assumption, constraints on these indices have the form

$$v_i(t) \geq 1, \quad p_i(t) \geq 1, \; i = 1, \ldots, n.$$

We took the official data on the multi-sectoral economy of the Russian Federation for 2020 [1] and obtained the indicative dynamics curves of the output and price indices leading to a concerted structure after a certain number of stages. This corresponds to the highway effect for the optimization models of an economy [6].

The computational process of restructuring automatically generates three groups of sectors, i.e., those with growing outputs (invested sectors), with growing prices (investing sectors), and with constant outputs and prices (neutral sectors). According to [7], the mechanism of excise duties can be applied to the sectors with growing outputs in order to implement investments in the sectors with growing prices.

In total, 60 sectors were used from the All-Russian Classifier of Types of Economic Activity (OKVED). The invested sectors have output indices greater than one, and the investing sectors have price indices greater than one. To obtain numerical results, we applied a modified software package for solving bilinear programming problems and executing transformations of the technological matrix. Figure 1 shows the interaction scheme of the sectors.

The plan was calculated under the following admissible ranges of the indices: [1, 1.01] for outputs (Fig. 2) and [1, 1.01] for prices (Fig. 3).

The graphs in Figs. 2 and 3 slightly differ from each other, confirming the validity of Corollaries 3 and 5.

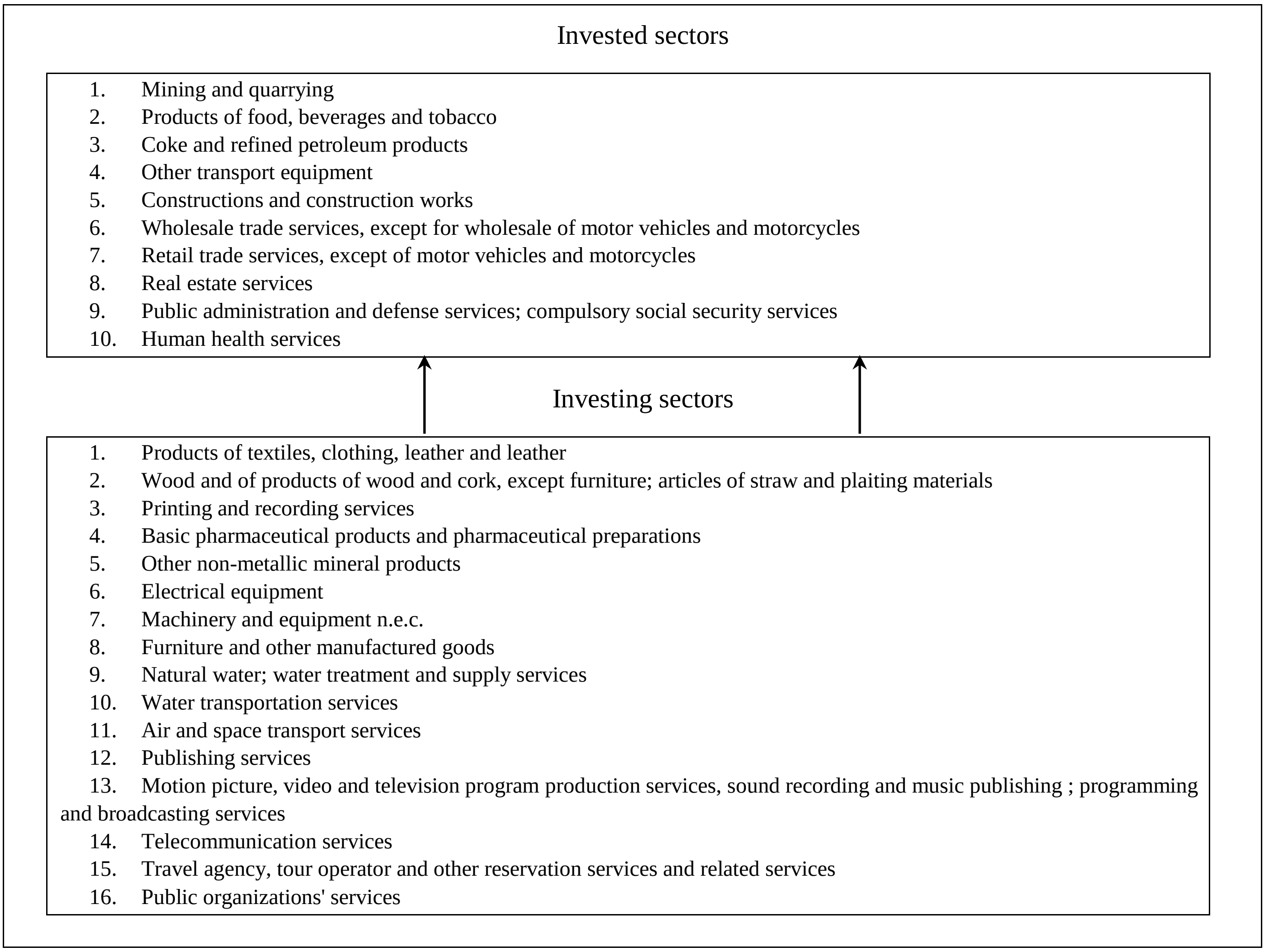

Fig. 1. The interaction scheme of different sectors in the restructuring process.

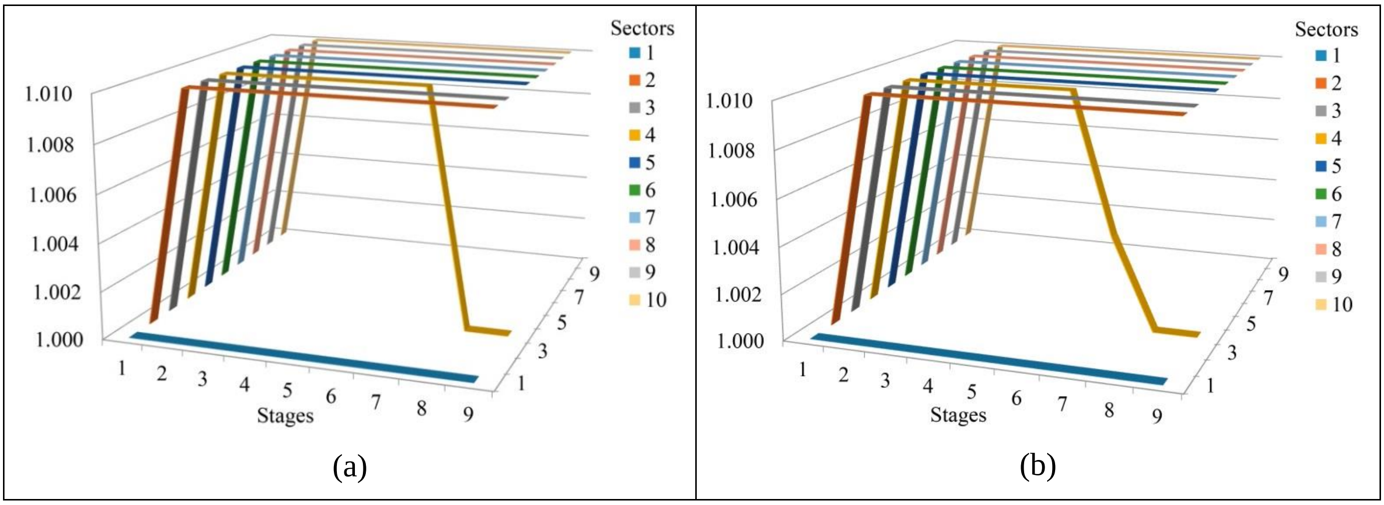

Fig. 2. The dynamics of output indices under the admissible range [1, 1.01]: (a) the linear model and (b) the nonlinear model.

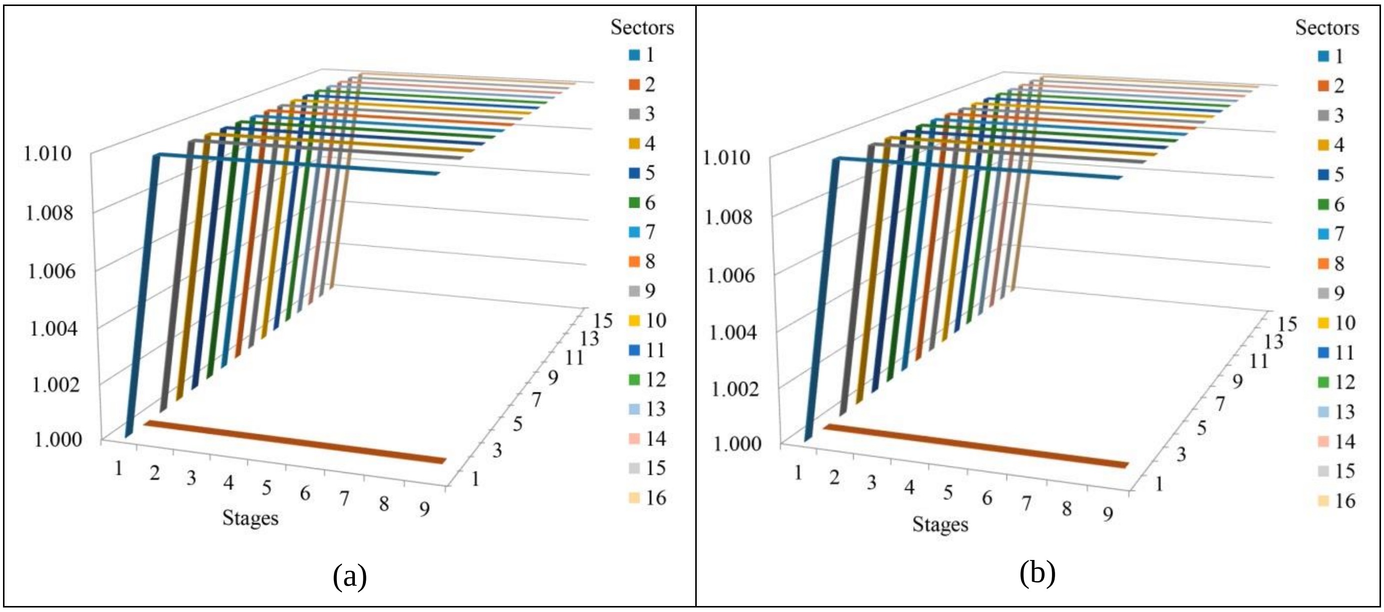

Fig. 3. The dynamics of price indices under the admissible range [1, 1.01]: (a) the linear model and (b) the nonlinear model.

Under the extended ranges of the control parameters, the difference between the dynamics of their optimal values for the linear and self-consistent nonlinear model becomes larger (see Figs. 4 and 5).

The maximum differences in the optimal output indices for the linear and nonlinear models are observed at the initial restructuring stages.

The optimal price indices for the nonlinear model decrease slower compared to the linear counterpart. Thus, the calculation results are qualitatively similar, but the larger the range of the control parameters is, the higher value the calculation error of the linear model will take.

Productivity has different dynamics for the linear and nonlinear models, being lower for the nonlinear one. However, the limit level for the nonlinear model is somewhat higher (Fig. 6).

According to the figures, for both models, the prices went up in the sectors where the output plan did not increase and, considering the output growth in other (invested) sectors, relatively decreased. This result resembles the effect of market price regulation. However, the scale of price growth here is determined based on the productivity growth of the reproduction system instead of the maximum sectoral profit criterion.

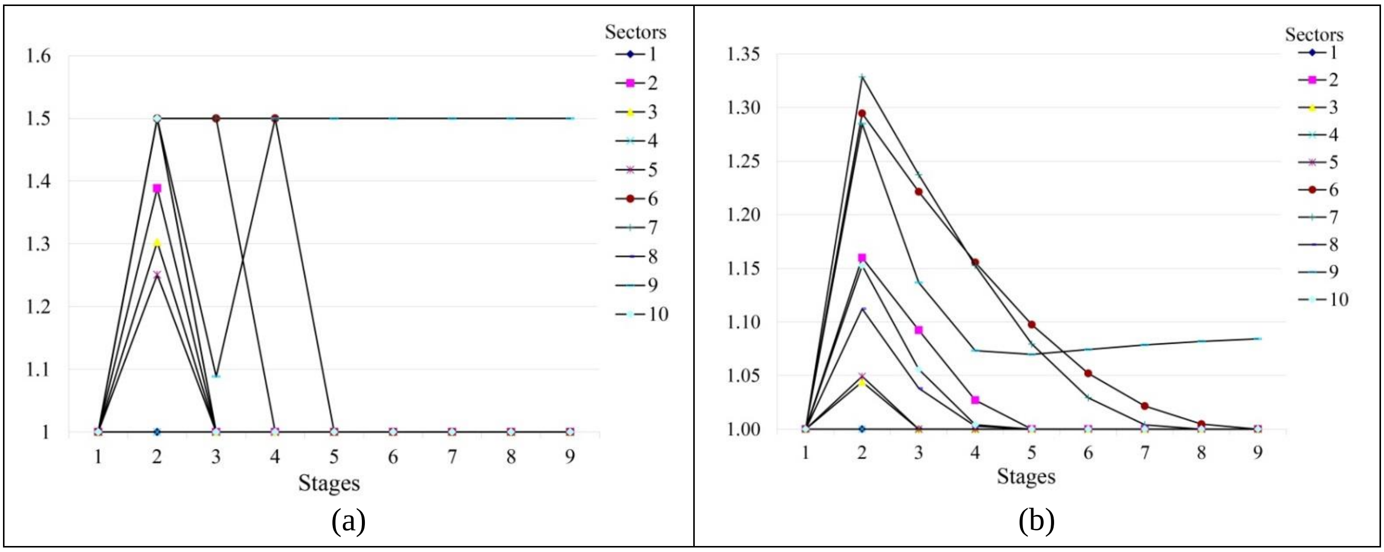

Fig. 4. The dynamics of output indices under the admissible range [1, 1.5]: (a) the linear model and (b) the nonlinear model.

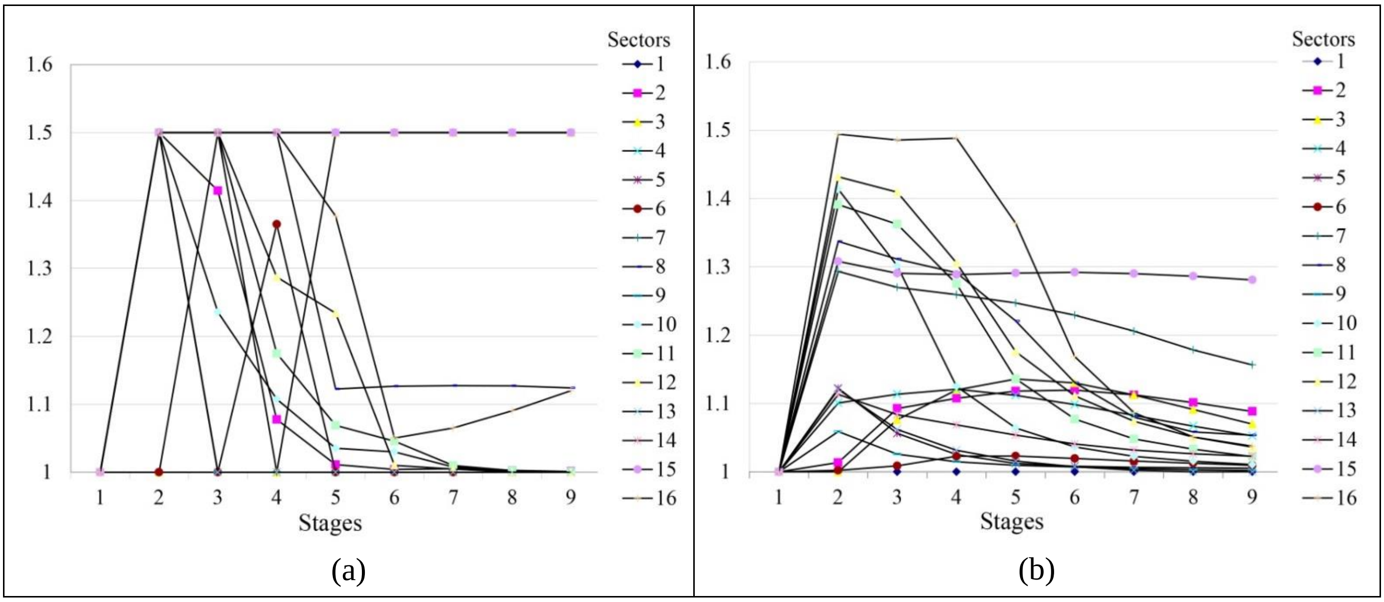

Fig. 5. The dynamics of price indices under the admissible range [1, 1.5]: (a) the linear model and (b) the nonlinear model.

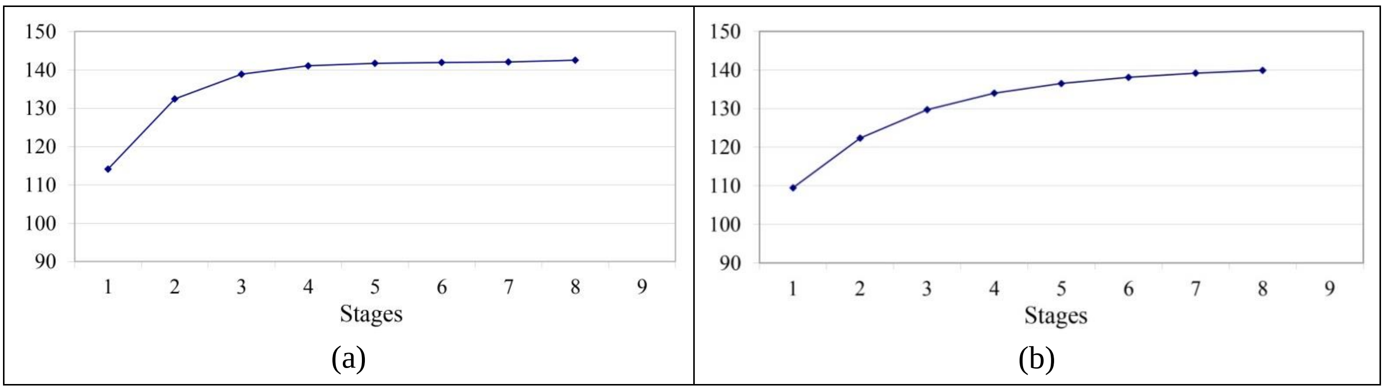

Fig. 6. Productivity dynamics: (a) the linear model and (b) the nonlinear model.

CONCLUSIONS

One needs to develop a self-consistent management model for the reproduction process because, while preserving the structure of the original linear model, its structural parameters also depend on the control variables. Such models can be characterized as models with direct and indirect control links. As a result, an optimal solution is found with some inaccuracy. This inaccuracy directly depends on the admissible range of the control variables. One way to solve this problem is to restrict the control variables to a small admissible range. By passing to the self-consistent nonlinear model, we have eliminated this effect for any admissible range. The results of calculations for the real data of Russia's diversified economy have confirmed the theoretical conclusions and the effectiveness of the computational procedures developed.

The results presented above can improve the adequacy of the models used in economic theory [8]. In the author's opinion, this circumstance should be considered in practical strategic planning and national accounting standards [9].

The self-consistent model developed in this paper can be applied in several fields, e.g., the analysis of environmental protection processes [10], agriculture [11], and territorial development [12].

APPENDIX

P r o o f of Proposition 1.

Assume that the technological matrix **A** is reduced to a form enabling to operate output indices via the transformation $\mathbf{D}^{-1}\mathbf{AD}$, where $\mathbf{D}$ is a diagonal matrix with the components V_i on the principal diagonal. Let v_i denote the price index for product *i*:

$$v_i = 1 + \Delta V_i / V_i.$$

Then

$$Z_{ki} + \Delta Z_{ki} = a_{ki}(1 + \Delta V_i / V_i) / (1 + \Delta V_k / V_k) \times (\Delta V_i + V_i)\ k,\ i = 1, ..., n.$$

If $\Delta V_i = 0$, we have

$$\partial Z_{ki} / \partial V_k = -Z_{ki} / V_k,$$
$$\partial \ln Z_{ki} = -\partial \ln V_k,$$
$$Z_{ki} V_k = V_k^0 Z_{ki}^0.$$

In the case $\Delta V_k = 0$,

$$\partial Z_{ki} / \partial V_i = 2 Z_{ki} / V_i,$$
$$\partial \ln Z_{ki} = \partial 2 \ln V_i,$$
$$Z_{ki} / V_i^2 = Z_{ki}^0 / \left(V_i^0\right)^2.$$

Thus, the rotation of the technological core yields

$$Z_{ki} = \left(b_{ki} / V_k\right)\left(d_{ki}\left(V_i\right)^2\right),$$

where

$$b_{ki} = V_k^0 Z_{ki}^0,\quad d_{ki} = Z_{ki}^0 / \left(V_i^0\right)^2,$$

or

$$Z_{ki} = \left(Z_{ki}^0 V_k^0 / \left(V_k^0\right)^2\right) V_i^2 / V_k = c_{ki} V_i^2 / V_k.$$

The invariant is

$$c_{ki} = Z_{ki}^0 V_k^0 / \left(V_i^0\right)^2 = a_{ki}\left(V_k^0 / V_i^0\right).$$

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