WORKING PAPER

TECHNOLOGICAL STRUCTURE OF ECONOMY AND AUTOMATION: AN ECONOMETRIC MODEL TO ANALYZE INVESTMENT STRATEGIES IN AUTOMATION

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FOREWORD

Macro-econometric impacts of modern production automation are at present widely discussed in special literature. The current paper describes a neoclassic econometric growth model for the analysis of various scenarios of automation dissemination and its impacts on economic growth. The results of some experiments are given in this paper.

Its relevance to the CIM activity is as follows: the approach under consideration provides an instrument for the study of structural and technological changes (their influence on growth rates, labor and capital productivity) based on the diffusion of a cluster of automation technologies. As a consequence of their dynamically changing technical characteristics and their close connection to many directions of Technological Advance, these technologies constitute a significant and rapidly expanding sector in the economy. This is why the special study of the problems of development of this sector is useful within the framework of the CIM activity.

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SUMMARY

This paper describes an econometric growth model of the neoclassic type for the analysis of changes in the technological structure of the economy. The main purpose of the model analysis is to compare the influence of different investment policies on the formation of the technological structure in the economy and to estimate its impacts on basic economic indicators of growth and efficiency.

The central model construction consists in the disintegration of the whole economy into three technological levels (high-tech, medium-tech and low-tech). The development of each level is described by its own production function (CES or the Cobb-Douglas type). The levels are added by capital formation, investment and the labor demand models. All of them are united in one economic growth model. The long-term development for these three levels is illustrated and forecasted up to the year 2010.

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1. State-of-the-Art

Intensification of economic growth supposes changes in the technological structure, and, first of all, improvements in the quality of production machinery equipment used in technological processes [1]. These improvements depend mainly on the advantages in the capital producing industries, especially in the engineering industry. The most important factors of the intensification process are robotization and computerization of production [4].

There are tremendous opportunities for improving the labor productivity to increase the technical level of production in the economy, primarily through the creation of new automatic production lines. A corresponding redesigning of the operation of the enterprise should lead a processing technique toward flexibility and be effective enough to connect the production process with suitable methods of process control. Just these elements of modern production automation can considerably improve all components of the technical level of production.

In fact, the technical level of production is defined by the following components:

1) technical level of products produced;
2) technical level of machinery and equipment used in the production processes;
3) technical level of technological process control.

These three components determine production technology in the wide sense of the term.

When there is a need for frequent changes to improve consumer characteristics of products produced and when there is a scarcity in production resources, it is automation that offers an opportunity for a considerable increase in the technical level of production (see, e.g., [3]).

Speaking of machinery systems and having in mind the automation level of production processes, the following types of equipment may be identified on the basis of their technological and functional parameters:

Type I: Machinery and equipment used for mechanization and automation as well as for separate operations in production. These systems are based on production machinery with semi-automated and manual control.

Type II: Automated production systems based on fully automated control by separate machines along with the use of minicomputers (of the first and second generations), numerical control (NC), automatic control (AC), machine tools, etc. The machinery and equipment systems of this type are based on a much more expanded structure of the main technical elements: machines for transformation of power (engines, transformers, current generators, etc.), machine tools, handling equipment, and control systems.

Type III: Complex automated systems of production are based on fully automated control with devices for adaptation to external influences and self-diagnostics, with micro-processors, micro-computers combined into local networks and multi-functional devices (flexible manufacturing systems, computer-aided design, etc.).

Considering the decisive role of automation (and mechanization) in raising the technical level of production at the present stage of development of science and technology, the following scheme of analysis of the technological structure of the economy has been suggested. With regard to the classification of machinery and equipment according to the degree of their automation and mechanization, all the production links of the economy have been divided into three interconnected macro-groups (clusters) of enterprises.

Sector A includes enterprises with technological processes based on machinery and equipment of a high automation level.[1] Since the degree of automation and mechanization of production processes has been taken as a criterion of division for macro-groups, the given enterprises have been attributed to sector A, as they are based on integrated and complex automation and comprehensive mechanization of technological processes. In terms of the description given above, the enterprises of types II and III of machinery and equipment belong to Sector A.

Sector B consists of those enterprises which, on the whole, use technological processes based on machinery and equipment of the "average" automation degree, i.e., which have separate, complex mechanized and automated processing lines and productive departments. Their basic production comprises the machinery and equipment of types I and II.

Sector C includes enterprises with low automation and mechanization, characterized by automation of separate operations in production and by using semi-automated machines and autonomous automatic lines. The share of

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[1]The present classification is not based on ISIC, but on special indicators from Soviet statistical data.

manual labor is high, combined with a wide use of machinery and equipment of earlier generations.

The main purpose of the analysis is to determine the economic conditions for the progressive change in technological structure, characterized by the ratio of these sectors (A, B, C), taking into account the following indices: volume of gross and net product, volume of fixed and current assets, labor and manufacturing expenditures and total plant investment.

Putting machinery and equipment into operation at a particular level for each sector depends on the relative investment strategy. Since each sector of the enterprises has its own natural development reflected in corresponding economic indicators (say, in changes of return on investment or in changes of factor productivities), the growth rates of the economy and other macro-economic indices depend greatly on the interrelation dynamics of these sectors. To estimate the different ways of production automation in the economy, it is thus necessary to analyze and compare the different investment policies of technological structure development.

Two main ways of intensifying the investment policy are: the investment in new machinery and the modernization of production, which transfers machinery and equipment from sectors B and C to sectors A or B. These two ways were considered as key factors in the following model.

2. Formulation of the Dynamic Model of the Economy with Differentiation by Automation Levels of Production

The operating process of each economic sector is described here in a special production function derived from thoroughly analyzed statistics of the last decade. The analysis of statistic data shows the principal difference between the sectors -- in labor/capital productivity, growth rate, etc. The functioning of each sector is regarded as interlinked with the other sectors; therefore these sectors are connected through balanced relationships (by investment, capital, labor resources, etc.). The model consists of several blocks: investment policy, capital formation, total employment dynamics, and production function (see Figure 1).

Block of Investment Function

Variant 1. The investment function is based on the hypothesis of relative constancy of the accumulation rate in the economic system:

$$I_t = rY_{t-1} - IP_t \qquad (1)$$

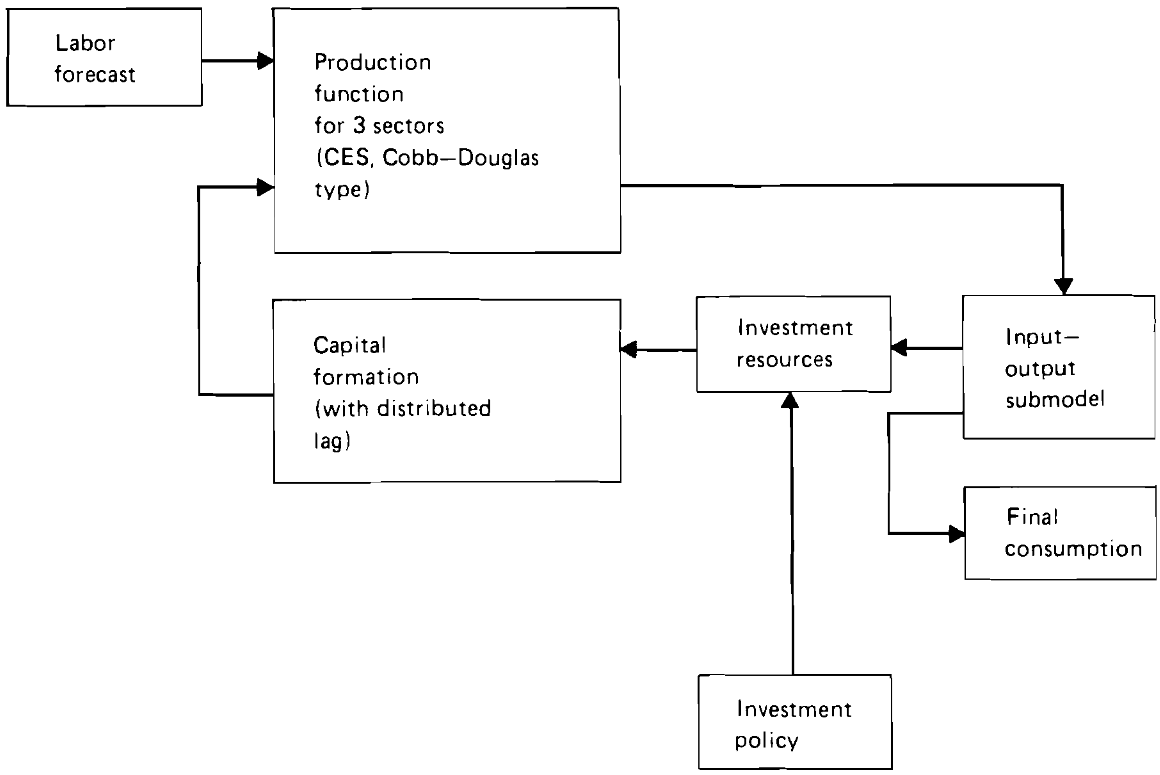


Figure 1. Scheme of the model.

where

r = coefficient of investment function defined on the basis of analyzed retrospective data;

I_t = volume of investment in year t planned for putting machinery and equipment into operation;

Y_{t-1} = gross output in year t-1;

IP_t = volume of reinvestment to support the current technical level in year t.

Variant 2. The investment function is based on the hypothesis on the definition of the quantity of "desirable fixed capital". It is Grunfeld's hypothesis which looks upon "desirable fixed capital" as a linear function of current gross output and investment of the previous year:

$$I_t = r_1 + r_2 Y_t + r_3 I_{t-1} - IP_t \tag{2}$$

where

r_1, r_2, r_3 = non-negative coefficients.

Block of capital formation

The dynamics of fixed capital may be expressed as a system of equations to describe fixed capital changes in the three sectors simultaneously. Growth in the fixed capital is determined by either new construction or technological renovation. The replacement is a natural way of liquidation of obsolete machinery and equipment and of the transfer of some of it to a higher level in the renovation process. In experimental calculations the following system of equations has been used:

$$K_{tA} = K_{t-1A}(1-\mu_A) + \beta^H(1-L^{TM})L^H{}_A I_t + \beta^{TM}L^{TM}L^{TM}{}_A I_t + \\ + \beta^{TM}\tau_{C/A}\delta_{C/A}K_{t-1C} + \beta^{TM}\tau_{B/A}\delta_{B/A}K_{t-1B} \tag{3}$$

$$K_{tB} = K_{t-1B}(1-\mu_B) + \beta^H(1-L^{TM})L^H{}_B I_t + \beta^{TM}L^{TM}(1-L^{TM}{}_A)I_t + \\ + \beta^{TM}\tau_{C/B}\delta_{C/B}K_{t-1C} - \delta_{B/A}K_{t-1B} \tag{4}$$

$$K_{tC} = K_{t-1C}(1-\mu_C) + \beta^H(1-L^{TM})(1-L^H{}_A-L^H{}_B)I_t - (\delta_{C/B}+\delta_{C/A})K_{t-1C} \tag{5}$$

where

$K_{tA,B,C}$ = volume of fixed capital used in technological processes at automation levels A,B,C, respectively, in period t;

I_t = total volume of investment in year t;

$1-\beta^H$ = integrated coefficient of incomplete construction;

β^{TM} = coefficient of investment utilization in fixed capital renovation process;

$\mu_{A,B,C}$ = coefficients of liquidation of machinery used at levels A,B,C, respectively;

L^{TM} = renovation process investment share, then $L^H = 1-L^{TM}$ (L^H - share of investment in new construction process);

L^{TM}_A = share of the renovation investments in the renovation process at level A, then $L^{TM}_B = 1-L^{TM}_A$ ($L^{TM}_C = 0$ by definition);

$L^H_{A,B}$ = share of the new construction investments in the new construction process at levels A,B respectively, then $L^H_C = 1- L^H_A - L^H_B$;

$\delta_{j1/j2}$ = share of fixed capital which is intended to be transferred from level j1 to level j2 during the renovation process;

$\tau_{j1/j2}$ = share of transferring the capital (from level j1 to j2) left after the renovation process.

In equation (3) the fist member reflects a decrease of the volume of fixed capital used in technological processes of sector A by the quantity of liquidation as a result of full senescence. The second member determines the course of investment in extensive growth of fixed capital at level A, i.e., new construction. The third equation member defines the course of investment in the replacement of fixed assets by other ones at the same technical level. The fourth member describes the renovation course of fixed capital at level C up to the production plant and equipment of a higher level, namely, of level A. The last member defines the course of renovation of fixed capital at level B up to technologies of a higher technical level, namely of level A. The members in equations (4) and (5) can be explained analogously.

The most complicated problem is to define the share of capital transfer from a low to a higher level during the renovation process.

For the C level this share is:

$$\delta_{C/A} + \delta_{C/B} = \delta$$

then

$$\delta_{C/A} = \delta_C \cdot \delta$$

and

$$\delta_{C/B} = (1-\delta_C) \cdot \delta \qquad (6)$$

where

δ = common share of fixed capital transferred from level C to higher levels, and δ_C to the highest level A only.

Parameter δ is defined by the least-squares method on the basis of equation:

$$K_{t-1C}(1-\mu_C) - K_{tC} + \beta^H(1-L^{TM})(1-L^H_A-L^H_B)I_t = \delta K_{t-1C} + e_t \qquad (7)$$

where e_t is the appropriate error term.

Then equation (3) can be rewritten as:

$$\delta^{(3)}_{B/At} =$$

$$= \frac{K_{tA}-K_{t-1A}(1-\mu_A)-\beta^H(1-L^{TM})L^H_A I_t-\beta^{TM}L^{TM}L^{TM}_A I_t-\beta^{TM}\tau_{C/A}\delta_C\delta K_{t-1C}}{\beta^{TM}\tau_{B/A}K_{t-1B}}, \qquad (8)$$

and equation (4) as:

$$\delta^{(4)}_{B/At} =$$

$$= \frac{K_{t-1B}(1-\mu_B)-K_{tB}+\beta^H(1-L^{TM})L^H_B I_t+\beta^{TM}L^{TM}(1-L^{TM}_A)I_t+\beta^{TM}\tau_{C/B}(1-\delta_C)\delta K_{t-1C}}{K_{t-1B}} \qquad (9)$$

To estimate the equation system of capital formation (3)-(5), it is necessary to find thirteen parameters:

β^{TM}, β^H, $\mu_{A,B,C}$, L^{TM}_A, L^{TM}, $L^H_{A,B}$, $\tau_{C/A}$, $\tau_{C/B}$, $\tau_{B/A}$, δ_C

such as to meet the equation:

$$\delta^{(3)}_{B/At} = \delta^{(4)}_{B/At}, \qquad t \in T \qquad (10)$$

This is a mathematical programming problem of a rather common type with concave functional and linear limitations:

$$F = \sum_{t \in T} (\delta^{(3)}_{B/At} - \delta^{(4)}_{B/At})^2 \rightarrow \min$$

$$0.5 \le \beta^{H,TM} \le 1; \qquad 0.0001 \le \mu_{A,B,C} \le 0.5$$

$$0 \le L^{TM} \le 1; \qquad 0 \le L^{TM}_{A} \le 1$$

$$0 \le L^{H}_{A,B} \le 1; \qquad 0 \le \tau_{B/A} \le 1$$

$$0 \le \tau_{C/A} \le 1; \qquad 0 \le \tau_{C/B} \le 1$$

$$0 \le \delta_{C} \le 1 \qquad (11)$$

The combined method of conjugate gradients and penalty functions is used here. Through the least-squares method the parameters found give us the quantity of the share of fixed capital to be transferred from level B to a higher level A - $\delta_{B/A}$.

Block of total employment dynamics

The model includes the equation of total employment defined by labor employed and fixed capital at the given automation level j in the year t-1 and by the increment rate of fixed capital per worker E_j.

$$LB_{tj} = \frac{LB_{t-1j}}{K_{t-1j}} \cdot K_{tj}/(1+Ej)$$

where

LB_{tj} = total employment at level j in year t;

K_{tj} = volume of fixed capital t at level j in year t;

E_j = increment rate of the fixed capital per worker at level j.

Block of production functions

The production function expresses the correlation between different technologically available combinations of production factors and results, i.e., the net product output Y_{jt} for the j-th automation level. In this model version the CES-functions were used:

$$Y_{jt} = Y_{jtn} \cdot A_j \cdot \exp^{(t-to)Pj} \cdot [b_j \cdot (K_{jt}/K_{jtn})^{-Sj} + (1-b_j)(LB_{jt}/LB_{jtn})^{-Sj}]^{-1/S_j} \qquad (12)$$

where

t_o and t_n = initial and normation periods, respectively;

A_j, P_j, b_j, S_j = parameters of the CES function for the j-th level, in our case they were calculated by Newton's modified method.

The common gross output volume is defined as a summary at three levels:

$$Y_t = \sum_{j=A,B,C} Y_{jt} \qquad (13)$$

3. Main Stages of Model Usage in the Analysis of the Technological Structure of the Economy

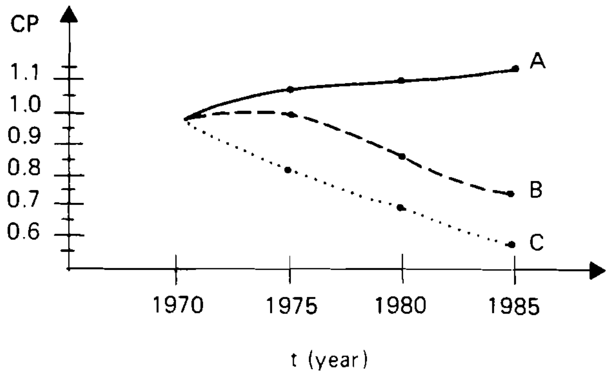
The first stage of the analysis consists of revealing qualitative trends which take place in the economy.

The main experimental results are the following. Scrutinizing production processes at different automation and mechanization levels during the retrospective period (1970-1985) reveals the existence of rather steady trends in the changes of labor productivity, returns on investment and fixed capital in different industries of the USSR economy.

The highest labor productivity is achieved in enterprises of sector A; the level of capital productivity was slightly less here than in the whole economy, but it is now rising. However, the dynamics of the high sector A and the lower sectors B and C during the last fifteen years have, in fact, been determined by contrary tendencies (see Figure 2). There is some growth of labor productivity in sector B, but the level of capital productivity is intensively decreasing. In sector C we can see a considerable increase of labor employed in production processes and a decline of capital productivity. These factors show great significance with regard to differentiating sectors A, B, C for decision making and planning. Another conclusion is that we must accelerate the speed of growth in sector A, to give priority to its dissemination in the economy. To obtain reliable results for the practical decision making process the quantitative measures are necessary, and the present econometric model provides an approach for their implementation.

The second stage of the analysis deals with problems of finding quantitative parameters of the relationship between the main macro-economic indicators and the technological structure. At the same time we perform a verification of the model adequacy, estimating and specifying additional parameters which are not available in the statistics reported, but are included in the axiomatic basis of the model.

Taking into account the model parameters obtained and specified after verification of the model adequacy, it is possible to forecast alternative technological structures of the economy, as well as to compare corresponding



A	1	1.09	1.10	1.14
B	1	1.00	0.85	0.75
C	1	0.86	0.72	0.59

Figure 2. The dynamics of capital productivity for three automation levels in the period 1970–1985 (each indicator is presented relative to its own level in the year 1970 and defined in 1970 as 1).

investment policies and technical strategies of economic growth (see analogous approach in [2]).

The correlation between volumes of production and different levels is a control quantity in the model and changes according to the wide range of parameters. In the estimation procedure these have been obtained by their fixation in the retrospective period. On the basis of a considerable number of computerized calculations these parameters have been divided into four groups according to the degree of their influence on economic growth.

The first group of control parameters includes the indicators of investment distribution according to the automation levels of production in the renovation and in the new construction processes. These parameters are as follows: L^{TM}, $L^{H}_{A,B}$, L^{TM}_{A}.

The second group contains eleven parameters and consists of: μ_{ABC}, β^{H}, β^{TM}, $\tau_{B/A,C/B,C/A}$, $\delta_{B/A,C/B,C/A}$. The changes of the given parameters are of particular importance for the technological structure of the economy. First of all, they influence the life cycle of the machinery used in technological processes. There is also a close dependence of the proximity of technical parameters of the different levels on the fixed capital flow from one automation level to another.

The third group includes the increment rates of fixed capital per worker of sectors A, B and C. As the analysis reveals, the achievement of desirable growth rates in gross product and labor productivity is as a rule impossible on the basis of changes in the first and second groups of parameters only. It is necessary to change the third group. These changes can only be provided by a wide variety of technological processes, and, first of all, by substituting older technologies by newer ones.

The fourth group of factors includes the rates of accumulation. They are characterized as extensive factors of changing the macro-indicators of the economic system.

Regarding the degree of the model sensibility to the above described groups of indicators, a considerable range of purposeful forecasts may be calculated with respect to the dynamics of the technological structure of the economy. Let us consider some of them, obtained on the basis of computerized forecasting data of the USSR economy.

Variant 1. This version of a forecast gives an opportunity to consider a kind of dynamics which will not entail any principal changes in the investment policy. The following quantities have been given as known beforehand:

LB_r = demographic forecast of capable working population in the forecast period;

r = coefficient of the investment function (of type (1)) estimated on the retrospective period.

The production function of each sector (A,B,C) is set and the values of all the parameters in the model are defined. The dynamics of these parameters as well as LB_r and r are control parameters of the forecast and they are given beforehand. The following indicators have been calculated: Y, L, K. I, as well as the derivative indicators: Y/L, Y/K, K/L for each economic sector and for the economy as a whole.

The main results of the forecast give evidence that, through the choice of the preservation of retrospective tendencies in the development of the technological structure, the labor-using technical progress is to prevail, and sector B increases and defines the direction of the economic growth on the whole.

Variant 2. The control parameters comprise all four groups of parameters considered above. The purposeful forecast consists of finding a technological structure of the economy (or a structure of the economy according to its level of automation and mechanization) allowing to achieve in the forecasting period the highest possible growth rates of production. The dynamics of labor resources in the forecasting period LB_r and the inequality $\Delta K_t \leq Q_{\mu t}$ are taken as initial limitations (where ΔK_t - introduction of fixed capital in year t, and $Q_{\mu t}$ - volume of gross production in capital producing industries).

The calculations were carried out as a four-graded local optimization. The structure of the investment level, corresponding to desirable growth rates of production and labor productivity indicators, was achieved by gradually varying each of the four groups' control parameters (considered before). It was observed that the growth rate of the main economic indicators are greatly dependent on the rate of accumulation and investment distribution by levels A, B, and C. The forecast trajectory of the dynamics of capital producing industries has been separately calculated as the first stage of the solution. The results of the forecast showed the need for outstripping growth of sector A and for declining the lower sectors, and, first of all, sector C.

Variant 3 of the forecast is aimed at the examination of such a strategy of dynamics for sector A, where technological processes are to obtain the highest possible technical level. LB_r and forecasted production volume of the capital producing industries were taken as limitations in the forecasting period. The additional value of the investment derived as the difference between the forecast obtained and the forecast by variant 1 was referred to developing level A. In this case the growth rates of the main economic indicators slightly differ from those of the foregoing version. The largest growth of national income was achieved through labor productivity growth and therefore there appeared an opportunity to save employed labor. A few results are presented in Figure 3.

Variant 4 presents a strategy of dynamics on the basis of raising the industrial efficiency. The technological structure, which should lead to the highest possible return on investment, as well as to a considerable increase in capital productivity -- or the lowest possible rates of their decrease -- was taken as a criterion of choice for the appropriate strategy of investment reallocation. In the given variant of forecasting, the percentage rate of complete automation and mechanization systems of production should be increased to cope with a recession of return on investment.

The results of the forecast carried out suggest a spectrum of versions of dynamics of technological structures. This presents an opportunity to choose the best versions of growth of the automation and mechanization processes, to examine possible versions of growth of technological processes, and to work out a strategy of technological renewal.

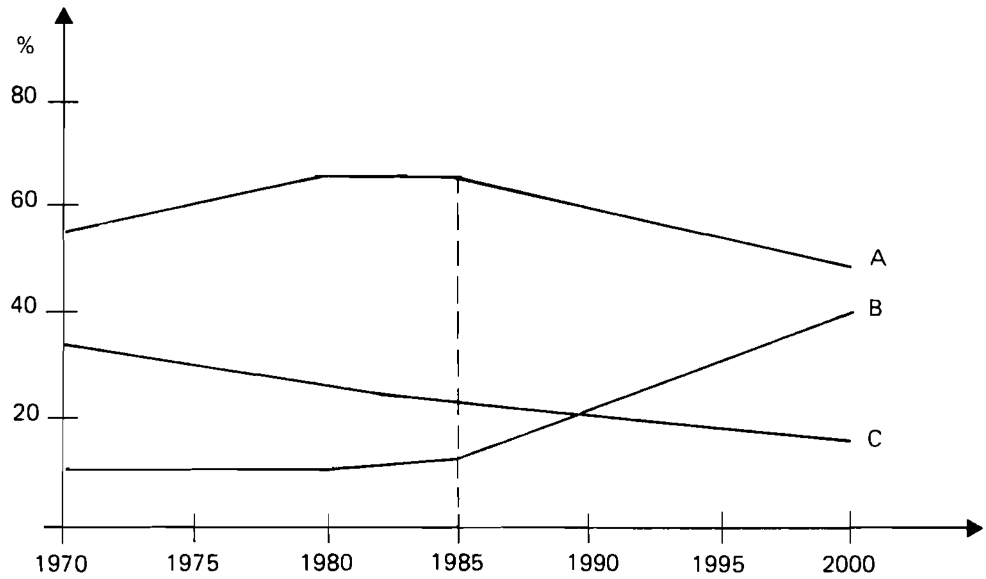


Figure 3. The shares of three types of automation levels in the USSR, in % of the total national product.

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