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Organizational Structure and Choice of Technology: Analysis of Dual Relations

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

We study relations between technological and organizational aspects of production and, particularly, a role of high-ability agents. We construct a theoretical model in which n physical resources and one informational resource (such as talented individuals, high-ability managers) are used in production process. We show that both the production function and its conjugate function, which describes spending of the informational resource, are generated by a choice of technology from a technological menu. These two dual choice problems correspond to decisions made by two interest groups in the organization. The group interested in increasing the output is referred as 'operatives', and the group interested in diminishing the expenditures of the costly informational resource – as 'minimizers'. We show that if technological progress is not accompanied by organizational changes, it leads to an incompatibility: the choices of the interest groups diverge. If the final decision is made by 'minimizers', it leads to a bottleneck role of the 'non-talented' labor. The exit from this trap can consist in continuous change of the social technology when the economy moves along the growth path. Two examples are provided, in which the model is applied to theoretical analysis of the learning-by-doing process in industrial firms and to dynamics of structural changes in a university occupying teaching and research activities.

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1. INTRODUCTION

An important topic in economic literature is the role plaid in production and economic growth by a few of the most talented individuals and, correspondingly, the role of the organizational structure. The internal organization of production was studied, in particular, by [1-8]. Hall and Jones [9] consider social infrastructure as one of determinants of economic growth. Nelson and Sampat [10] and Nelson [11] relate institutions to social technologies which are used in production, in a definite sense symmetrically to physical technologies. Papandreou [12] argues that "Though it is often difficult to distinguish institutional and physical constraints impinging on production and consumption sets, it is important to do so, as it provides a starting point for what can and cannot be controlled by human agency".

In the present paper, we study relations between organizational and technological aspects of production. We develop the Lucas' [1] idea that, though the production technology exhibits constant returns with respect to basic resources, such as labor and capital, the result of the use of this technology depends in a nonlinear way on one more factor, 'management', in Lucas' terms.

We propose a theoretical model, in which *physical resources* (such as labor, physical capital, natural resources in use, etc.) and a separate *informational resource* are distinguished. The informational resource includes talented individuals, and, in particular, high-ability managers, whilst less talented assistants are one of the physical resources[1].

Production function is assumed to exhibit constant returns to scale with respect to physical resources, while the informational resource influences production in a more complex way. Lucas [1] proposes to use an additional function to express the action of the informational resource[2]. We, instead, introduce a social technology function which reflects the quantity of the informational resource needed to produce a product unit.

Technically, our analysis is based on a representation of the production function as a result of optimal choice of a 'local' Leontief technology from a given technological menu [13-17]. We show that, symmetrically to the production function, its conjugate function related to the social technology can be represented in a similar way as a result of choice of technology from the same technological menu. We interpret this pair of choice problems as decisions made by two interest groups in the organization, referred as *operatives* and *minimizers*. A goal of the operatives is to maximize the output, while the goal of the minimizers is to minimize the expenditure of the costly informational resource, such as the number of talented and high-paid individuals in the organization.

In the framework of the model, we study a question of *compatibility*, i.e. coincidence of the technological choices made by the two interest groups. We find that a necessary and sufficient condition of the compatibility is a full use of all resources, physical and informational. Technological progress in the model transforms the technological menu and, as result, influences the compatibility. If the technological progress is not accompanied by institutional changes (changes in the social technology), it leads to an *incompatibility*: the choices of the operatives and the minimizers diverse, and if the final decision is made by minimizers, it leads to a bottleneck role of the "non-talented" labor. The exit of this trap can consist in a continuous improvement of the social technology when the economy moves along the growth path.

We provide two detailed examples of applications of our model. The first example relates to *learning-by-doing* – the processes of a growth of labor productivity evoked by an accumulated experience on a firm level. Attention to such processes was attracted by Arrow [18] who gave two historical examples of growth in labor productivity independently on investments. The first of his cases is so called *Horndal effect*: the Horndal iron works in Sweden "had no new investment (and therefore presumably no

[1] Relation between a few talented individuals and many less-talented assistants is one of the basic points in modern organizational economics (see e.g. [6]).

[2] Lucas [1] assumes that if $f(k,n)$ is a production function under "normal" management (where k is capital, n is labor), and the firm's manager is endowed with a managerial talent level x, then the firm produces $xg[f(n,k)]$ units of output, where $g(.,.)$ is an increasing, strictly concave function.

significant change in its methods of production) for a period of 15 years, yet productivity (output per man-hour) rose on the average close to 2% per annum" ([18], p. 156). By now this case has been perfectly studied by economic historians (e.g. [19]). The second Arrow's case relates to a practice of American military aircraft-building: a time of building of a frame of bomber diminished more than 2 times after each 20 built frames.

In the Arrow's cases, no equipment no labor did change. Changes concerned only experience and skills of the workers. Probably, these changes were connected also with changes in organization of the production process and in the use of some informational resource, such as the time of high-skilled experts and constructors of the aircraft who directed actions of the workers[3]. We can suppose that the learning-by-doing is closely related to a change in social technology and to improvement of organizational capital of the firm.

However, despite he stressed the role of accumulated experience improving skills and increasing technological knowledge, Arrow himself in his formal model described somewhat different process which would be impossible without investments. In the Arrow's model, new knowledge is embodied in new generations of capital possessing a more perfect production function; i.e. the main engine of growth in his model is an improvement of the physical technology and the structure of physical capital. A necessity to construct for explanation of the Horndal effect a theoretical model, in which an increase in labor productivity would not be based on investments, was stressed by Sheshinski [20]. Analysis of the learning-by-doing effect is still an open problem, and we contribute to it by use of our model.

Another, quite different of industrial firm, example of an economic system whose dynamics essentially depends on its structural organization. is university. Two basic sides of activity of a university are teaching and research, and the latter plays an increasing role; e.g. at the end of 1990s a half of fundamental research in US were done in the universities [21]. In the literature these two sides of activity of university are usually considered in isolation, despite success of the best universities is based on a high degree of integration and synergy of educational and research activities. Production functions are often used in analysis of educational system, but usually they reflect only the teaching activity (e.g. [22-24]). The research activity of the American universities, almost totally out of touch with their teaching activity, is studied in [25,22].

Beside the choice of the ratio between teaching and research activities, there are two other important structural conflicts accompanying development of a modern university [26,27]. The first is a relation between two types of workers: high-paid tenured professors and temporary partially-paid instructors; the latter group holds in the modern university mostly a high teaching burden. The second is a presence ahead of the university two groups with non-coinciding interests: professors and professional managers.

Attempts of modeling dynamics of organizational structure and developing of the university are not numerous. Del Rey [28] and De Fraja and Iossa [29] study a model of competition of two universities with teaching and research activities. Beath et al. [30] propose a model of time distribution between teaching and research (a tragic choice, by the authors' words) in dependence on financing and with account for a quality of results of these two kinds of activity. Gautier and Wauthy [31] study a distribution of efforts between teaching and research in multi-faculty and single-faculty universities.

We apply our main model to analysis of such structural relations in universities.

The paper is organized as follows. Section 2 introduces the basic model and some tools from mathematical economics needed for analysis, defines the compatibility conditions, and deals with the questions of balanced growth and incompatibility. In Section 3 the basic model is applied to analysis of the learning-by-doing in industrial production and of the development of a university combining teaching and research activities. Section 4 concludes.

The basic theoretical results are formulated in the form of theorems; the proves are provided in the Appendix.

2. THEORETICAL FRAMEWORK AND MODEL

2.1 Some Background from Mathematical Economics

The theoretical model studied in the paper is based on the use of the neoclassical production

[3]The use of outside managers is typical on stage of launching of new production, while for developing countries typical is a permanent use of foreign specialists paid much higher than local ones.

function. Let $F(x)$ be a production function defined on the space R^n_{++}, which consists of all *n*-dimensional vectors *x* with strictly positive coordinates and of the origin[4]. We use notation $x > y$ if $x_i > y_i$, $i = 1,...,n$. As usually, it is assumed that $F(0) = 0$, and $F(x) > 0$ for $x > 0$. Function $F(.)$ is called *increasing* if $x > y$ implies $F(x) > F(y)$. We assume that the production function $F(.)$ is increasing, positively homogeneous of degree one function *(IPH function).* In a similar way, a case of homogeneity of any degree could be studied, but for simplicity we restrict ourselves only by the standard case of the constant returns to scale.

The background fact from mathematical economics which we use in the paper is that for any neoclassical production function $F(x)$ there exists such a set of Leontief production technologies, Λ, – so called *technological menu* – that $F(x)$ is a result of optimal choice of a 'local' Leontief technology from the menu Λ. Thus, the Leontief production functions can serve as elementary "bricks" in analysis of any structures related to neoclassical production functions. The notion of technological menu was studied from different positions by [13,14,17].

More precisely this fundamental fact is formulated in the following way. Let M_1 be the unit level set of production function $F(.)$, i.e. $M_1 = \{x : F(x) = 1\}$. The following theorem is proved in [17].

THEOREM 1. *For any IPH function there exists a set Λ of productivity vectors $l = (l_1,...,l_n)$ – referred as the technological menu – such that*

$$F(x) = \max_{l \in \Lambda} \min_i l_i x_i, \; x \in R^n_{++}.$$

Here $\min_i l_i x_i$ is the 'local' Leontief production function. Thus, according to Theorem 1, production function $F(.)$ corresponds to a family of Leontief production functions. In other words, $F(.)$ is generated by an optimal choice of a 'local' Leontief technology from the technological menu Λ.

The unique technological menu for this production function is the vector set $\Lambda = \{l : l^{-1} \in M_1\}$, where $l^{-1} = (l_1^{-1},...,l_n^{-1})$. Following [13], *conjugate function* can be defined as

$$F^{\circ}(l) = \max_{x \in M_1} \min_i l_i x_i$$ [5.]

The latter has an evident economic meaning: for each Leontief technology *l* it shows the maximal output which can be received if a bundle of physical resources is taken from the set M_1. Another economic interpretation of the conjugate function, more useful for us, will be received if the conjugate function $F^{\circ}(.)$ is represented in a similar way to how production function $F(.)$ is represented by Theorem 1. Such representation is provided by the following theorem.

THEOREM 2.

$$F^{\circ}(l) = \min_{x \in M_1} \max_i l_i x_i, \; l \in R^n_{++}.$$

Proof: see the Appendix.

The following formula (see [17]) can be used to calculate conjugate functions:

$$F^{\circ}(h) = \frac{1}{F(h^{-1})}, \; h > 0 \cdot$$

As an example, applying this formula to Leontief, Cobb-Douglas and CES production functions we obtain the conjugate functions collected in Table 1.

2.2 Description of the Model

Now, we introduce the main theoretical model studied in the paper. The model describes the dual structure of production. In our model there are *n physical resources*, $i = 1,2,...,n$, such as labor, physical capital, natural resources in use, etc. There is also an *informational resource* which possesses one of the characteristic properties of public good – *non- rivalry*: a unit of the informational resource can serve

[4] *Thus, except the origin, vectors with zero components are not considered as arguments of the function. This does not narrow the class of production functions itself.*

[5] *It can be checked that the conjugate function,* $F^{\circ}(.)$ *is IPH and* $(F^{\circ})^{\circ}(.) = F(.)\cdot$

Table 1. Some production functions and their conjugate functions

	Production function	Conjugate function
Leontief	$F(x) = \min_i l_i x_i$	$F^\circ(h) = \max_i l_i^{-1} h_i$
Cobb-Douglas	$F(x) = A x_1^{\alpha_1} \ldots x_n^{\alpha_n}$, where $A > 0,\ \alpha_i > 0,\ \sum_{i=1}^{n} \alpha_i = 1$	$F^\circ(h) = A^{-1} h_1^{\alpha_1} \ldots h_n^{\alpha_n}$
CES	$F(x) = [\alpha_1 (A_1 x_1)^p + \ldots + \alpha_n (A_n x_n)^p]^{\frac{1}{p}}$, $A_i > 0,\ \alpha_i > 0,\ \sum_{i=1}^{n} \alpha_i = 1$, $p < 1,\ p \neq 0$	$F^\circ(h) = [\alpha_1 (A_1^{-1} h_1)^{-p} + \ldots \alpha_n (A_n^{-1} h_n)^{-p}]^{-\frac{1}{p}}$

simultaneously all physical resources $i = 1,2,...,n$ taken in some quantities. The most talented individuals in the firm or high-ability managers are examples of such informational resource. The output is defined by the physical resources if there is no scarcity in providing of the informational resource.

The physical side of production is defined by a given technological menu Λ . Any technology from the technological menu Λ is a vector of productivities of physical resources, $l = (l_1,...,l_n)$. Each such technology defines 'local' Leontief production function $\min_i l_i x_i,\ x \in R^n_{++}$. Correspondingly, inputs l_i^{-1}, $i = 1,...,n$ are needed to produce a unit of product. The informational side of production is described by a *social technology* characterized by a vector $h = (h_1,...,h_n)$, where h_i is the minimal quantity of the informational resource needed per unit of physical resource *i*, $i = 1,2,...,n$.

Thus, there are two (mutually conjugate) 'elementary' functions closely related to the production process:

1) *Leontief production function* $F_l(x) = \min_i l_i x_i$ which shows the output produced under the technology $l = (l_1,...,l_n)$ given the vector of physical resources $x = (x_1,...,x_n)$;
2) *Social technology function* $F_l^\circ(h) = \max_i h_i l_i^{-1}$ which shows the quantity of the informational resource needed to produce a product unit under the social technology $h = (h_1,...,h_n)$ and the Leontief production technology $l = (l_1,...,l_n)$.

Let the vector of social technology *h* be an argument in the conjugate function, $F^\circ(.)$. Then, by Theorem 2,

$$F^\circ(h) = \min_{x \in M_1} \max_i h_i x_i = \min_{l \in \Lambda} \max_i h_i l_i^{-1}.$$

This means that for each social technology *h* the conjugate function $F^\circ(h)$ shows the minimal quantity of the informational resource needed to produce a product unit under the technological menu Λ .

2.3 Conditions of Compatibility

We have come to the following pair of dual problems.

PROBLEM 1. *Choose from the technological menu Λ such Leontief technology l, for which, given a bundle of physical resources x, the output is maximal:*

$$F(x) = \max_{l \in \Lambda} \min_i l_i x_i,\ \ x \in R^n_{++},$$

PROBLEM 2. *Choose from the technological menu* Λ *such Leontief technology l, for which given a social technology h, expenditures of the informational resource per unit of output are minimal:*

$$F^{\circ}(h)=\min_{l\in\Lambda}\ \max_i l_i^{-1}h_i,\ \ h\in R_{++}^n.$$

These two problems reflect non-coinciding interests of interest groups in a typical organization. The interest groups will be referred as *operatives* and *minimizers*; the problem 1 is solved by the operatives, while the problem 2 is solved by the minimizers. A natural question is: in what case the problems 1 and 2 are *compatible,* in the sense that their solutions provide the same Leontief technology l^*?

Theorem 3. *Problems 1 and 2 are compatible iff*

$$h^{-1}=\lambda x\text{, where }\lambda>0. \quad (1)$$

Proof: see the Appendix.

Remind that the informational resource has a feature of public good, non-rivalry: a unit of the informational resource can serve simultaneously the volumes h_i^{-1} of all physical resources $i=1,...,n$. Thus, Equation (1) is a condition of the *full employment of the informational resource.* Under this condition, it is impossible to increase the use of the physical resources and the output without increase of the expenditure of the informational resource.

Similarly, each unit of output demands expenditures of physical resources l_i^{-1}, $i=1,...,n$. A condition of *full employment of physical resources* consists in the proportionality of vectors l^{-1} and x, i.e. in the equality $l^{-1}=\mu x$, where $\mu>0$. Evidently, in the operative's solution the physical resources are always fully employed.

2.4 Technological Progress, Balanced Growth, and Incompatibility

Now, let the 'global' production function $F(x,\,t)$ and, correspondingly, the unit level set $M_1(t)$ and the technological menu $\Lambda(t)$ depend on time. A *factor-augmenting technological progress* takes place if $F(x,\,t)=F(A_1(t)x_1,...,A_n(t)x_n)$. A special case is the *Hicks-neutral technological progress* in which case $F(x,\,t)=A(t)F(x)$, where $A(t)$ is the total factor productivity (TFP). The homogeneity implies that the presence of the factor-augmenting technological progress is equivalent to the following equality which links the unit level sets at any two moments of time, $t_2>t_1$:

$$M_1(t_2)=\{x: x_i=\frac{A_i(t_1)}{A_i(t_2)}x_i(t_1),\, i=1,...,n,\, x(t_1)\in M_1(t_1)\}.$$

Correspondingly, for the technological menus:

$$\Lambda(t_2)=\{l: l_i=\frac{A_i(t_2)}{A_i(t_1)}l_i(t_1),\, i=1,...,n,\, l(t_1)\in\Lambda(t_1)\}$$

.

In particular, if $A_i(t)=\gamma_i^t A_i(0)$, then for $t>0$:

$$M_1(t)=\{x: x_i=\gamma_i^{-t}\bar{x}_i,\ i=1,...,n,\ \bar{x}\in M_1(0)\},$$

$$\Lambda(t)=\{l: l_i=\gamma_i^t\bar{l}_i,\ i=1,...,n,\ \bar{l}\in\Lambda(0)\}. \quad (2)$$

In case of the Hicks-neutral technological progress,

$$M_1(t_2)=\frac{A(t_1)}{A(t_2)}M_1(t_1),\ \ \Lambda(t_2)=\frac{A(t_2)}{A(t_1)}\Lambda(t_1),$$

where, as usually, the multiplication of a set by a number means multiplication of each element of the set. It is important to notice that the Hicks-neutral technological progress expands the technological menu $\Lambda(t)$.

Let us consider a typical situation in growth theory: balanced growth path (BGP) with labor-augmenting technological progress. There are two physical production factors: capital, *K*, and labor, *L.* Time is discrete. Capital *K*, output, *Y*, and consumption, *C* grow at a common growth factor, φ, while labor *L* grows at a lower growth factor, $\beta<\varphi$; and there is a *labor-augmenting (Harrod-neutral) technological progress* with a growth factor $\gamma=\varphi/\beta>1$. In such case in (2): $\gamma_K=1,\,\gamma_L=\gamma$; thus, each particular technology $l(0) = (l_K(0),\ l_L(0)) \in \Lambda(0)$ is transformed in time in the following way:

$$l_K(t) = l_K(0) = const,\ \ l_L(t) = \gamma^t l_L(0). \qquad (3)$$

If initially (at period $t = 0$) the condition of full employment of physical resources is fulfilled, i.e.

$$\frac{K(0)}{L(0)} = \frac{l_L(0)}{l_K(0)} = \chi ,$$

then this condition is fulfilled along the whole BGP:

$$\frac{K(t)}{L(t)} = \frac{l_L(t)}{l_K(t)} = \gamma^t \chi .$$

It means that if the operative initially chooses the optimal technology $l(0) = (l_K(0),\ l_L(0))$, then the technology $l(t) = (l_K(t), l_L(t))$ is transformed according to (3).

Opposite to this, the minimizer under an unchanged social technology chooses an optimal path in such way that $l_K(t)/l_L(t) = const$.

Thus, the technical progress leads to an incompatibility: the minimizer's choice does not coincide with the operative's choice. Moreover, if initially the condition (1) of full employment of the informational resource is fulfilled and the social technology does not change, then the condition (1) is violated soon: the ratio h_K / h_L is constant, while the ratio $K(t)/L(t)$ changes.

In **case of the Cobb-Douglas production function**, $\gamma^t A_0 K(t)^\alpha L(t)^{1-\alpha}$, the technological menu develops in time in the following way:

$$\Lambda(t) = \{(l_K,\ l_L):\ l_K^\alpha l_L^{1-\alpha} = \gamma^t A_0\}.$$

Assuming that the social technology, *h*, is unchangeable, let us compare the BGP which would be chosen by the operative and by the minimizer.

The operative at time *t* chooses technology $l(t) = (l_K(t),\ l_L(t))$ which solves the system of equations:

$$\begin{cases} l_K K(t) = l_L L(t), \\ l_K^\alpha l_L^{1-\alpha} \left(\dfrac{K(t)}{L(t)}\right)^{1-\alpha} = \gamma^t A_0 \end{cases}.$$

THEOREM 4. *Under the decision of the operative,* $\varphi = \beta\gamma^{1/(1-\alpha)}$.

Proof: see the Appendix.

If the decision is made by the **minimizer,** then technology is found as a solution of the system of equations:

$$\begin{cases} l_K h_K^{-1} = l_L h_L^{-1}, \\ l_K^\alpha l_L^{1-\alpha} = \gamma^t A_0 \end{cases}.$$

This implies

$$l_K(t) = \gamma^t A_0 \left(\frac{h_K}{h_L}\right)^{1-\alpha},\quad l_L(t) = \gamma^t A_0 \left(\frac{h_L}{h_{1K}}\right)^{\alpha}.$$

Thus, in the BGP, Leontief factor productivities $l_K(t), l_L(t)$ grow at a joint constant growth factor equal to γ. Since the output is equal to $\min\{l_1(t)K((t),\ l_2(t)L(t)\}$, it grows at growth factor φ. Hence, the equation $\varphi = \min\{\gamma\varphi,\ \gamma\beta\}$ is fulfilled, which implies that $\varphi = \gamma\beta$.

Thus, under a fixed social technology, the growth rate of the economy controlled by the operative is higher than of the one controlled by the minimizer. In the latter case the labor becomes a limiter of growth.

3. EXAMPLES OF APPLICATIONS

3.1 Learning-by-Doing

Now, we turn to the first of the examples of applications of our model. Our approach provides several ways to model the learning-by-doing. In particular, one can assume that the technological menu, Λ, labor, *L*, capital, *K*, and the volume of informational resource, *H*, are fixed, and the learning-by-doing consists in changes in the social technology, *h*. Since $F^\circ(h)$ is the minimal volume of the informational resource which ensures the unit output, the informational resource H allows (under absence of restrictions from the physical side of production) to produce $H / F^{\circ}(h)$ units. Hence, the maximal output which is possible under the production function $F(.)$, the social technology h, and the informational resource H is

$$Y = \min\left\{F(x), \frac{H}{F^{\circ}(h)}\right\}. \quad (4)$$

Learning-by-doing diminishes components of the vector h; correspondingly, $F^{\circ}(h)$ decreases. The output Y increases until the second term in the R.H.S. of (4) becomes equal or greater than the first term. A further improvement of the social technology does not lead to any increase in output, and only an improvement in the physical technology (development of the technological menu Λ) allows further increase of the output.

Another modeling strategy is to assume that the informational resource H is not fixed and that the firm is controlled by a minimizer. Let us consider a numerical example. Let $K = 10,\ L = 100$. The technological menu is described by the equation $l_K^{1/2} l_L^{1/2} = 10$. Then the maximal possible output is equal to 316 and is achieved under the Leontief technology $l_K = 31.6$, $l_L = 3.16$. Let the social technology be characterized by fixed expenditures of the informational resource per unit of capital, $h_K \equiv 10$, but variable expenditures per unit of labor, h_L.

First, let us consider the following scenario. Let initially be $h_L(1) = 1000$; at the next period $h_L(2) = 500$; and after that

$$h_L(t+1) = (0.9)^{\Delta_t} h_L(t), \quad t = 2,3,..., \quad (5)$$

where $\Delta_t = Y(t) - Y(t-1)$.

Such change of the social technology reflects the effect of learning and, under a decline in output, can be explained as an increase in spending of the time of high-skilled experts to confront the output fall.

It can be noticed that Eq. (5) implies that the social technology depends on the cumulative increment of the output:

$$h_L(t+1) = (0.9)^{\Delta_2 + \Delta_3 + ... + \Delta_t} h_L.$$

Such kind of dynamics quite corresponds to the Arrow's idea of dependence of workers' skills on cumulative investments.

For the case when decision is made by the minimizer, the dynamics of output in dependence on time are shown in Fig. 1. The output fluctuates on a level considerably lower than the maximal possible level of 316. The low output can be explained by the "overlearning" of the workers: they have learned to use the social technologies which correspond to the minimizer's criterion.

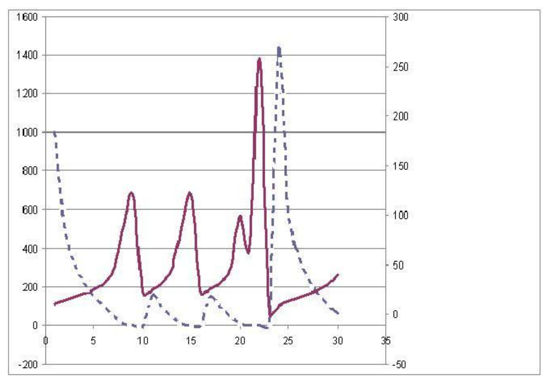

Fig. 1. Dynamics of the output in case when the process of learning is described by Eq. (5) for all $t = 2,3,...$. Output in dependence on time is depicted by the red (unbroken) line. The blue (broken) line shows the endogenous change in parameter h_L

Now, let us consider another scenario. Starting from the 9th period, the operative achieves that the expense of the informational resource does not decrease so fast:

$$h_L(t+1) = (0.99)^{\Delta_t} h_L(t), \quad t = 8,9,... \quad (6)$$

The resulting path is presented in Fig. 2. The output now fluctuates on a level close to the maximally possible one.

3.2 Structure of University

In this section we apply our model to analysis of the relation between two basic activities of university: teaching and research. Let a university receive a gain, *Y*, e.g., a reputation or a money income, defined by two 'physical resources': the number of students, x_s, and the number of research projects, x_p: $Y = F(x_s, x_p)$. The function $F(.,.)$ satisfies conditions of Theorem 1 and, hence, can be represented in the form

$$F(x_s, x_p) = \max_{l \in \Lambda} \min\{l_s x_s,\ l_p x_p\},$$

where Λ is a technological menu. Each 'local' Leontief technology, $l = (l_s, l_p)$, represents a way of combining teaching and research activities to achieve a gain for the university.

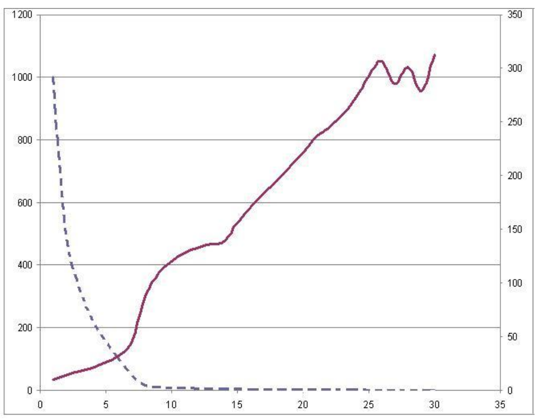

Fig. 2. Dynamics of the output in case when the process of learning is described by Eq. (5) under $t = 2,...,7$ and by Eq. (6) under $t = 8,9,...$ Output in dependence on time is depicted by the red (unbroken) line. The blue (broken) line shows the endogenous change in parameter h_L

Beside the "physical resources", there is also an "informational resource" – high-paid tenured professors. They can simultaneously teach students and do research by use of a "social technology", $h = (h_s, h_p)$, where h_s is the average number of professors per student, and h_p is the number of professors per research project. Thus, the number of high-paid professors needed for producing a unit of the university's gain under social technology *h* and physical technology *l* is

$$\max\{h_s l_s^{-1},\ h_p l_p^{-1}\}.$$

It seems natural to assume that in a short run the social technology, *h*, is less flexible than the physical technology, *l*. The Problems 1 and 2 take the following form:

PROBLEM $1'$. *To find a technology* $l \in \Lambda$ *maximizing the gain for the university.*

PROBLEM $2'$. *To find a technology* $l \in \Lambda$ *minimizing the number of the high-paid professors.*

The groups interested in solving these problems will be, as earlier, referred as 'operatives' and 'minimizers'. It will be assumed that an average research project demands more attention of high-paid professors than an average student: $h_p > h_s$. Let us compare two universities: a "teaching" university in which the number of students is relatively high comparably to the number of research projects: $x_s^t > x_p^t$, and a "research" university in which the number of research projects is higher: $x_s^r < x_p^r$. In the "teaching" university, if it is controlled by the operative, a technology with a low l_s and a high l_p will be chosen, which allows to increase the gain by teaching a bigger number of students and doing a relatively small number of research projects. In the "research" university controlled by the operative, vice versa, a technology with a low l_p and a high l_s will be chosen. If the minimizer controls any of these two universities, he/she will choose a technology with a high l_p and a low l_s. Thus, in the "research" university a conflict between the operative and the minimizer would be sharper and a degree of incompatibility would be higher than in the "teaching" university.

If by any reasons financing increases considerably, then it is natural to expect that the control will be given to an operative. If a minimizer was in power before, then in the "teaching" university a structural change will be not so visible as in the "research" university; in the latter the share of research in the university gain will considerably fall and the share of teaching will increase. Beath et al. [30], by use of a different model, also point to a possibility of a shift from a research strategy to a teaching strategy under an increase in financing.

4. CONCLUSION

In the present paper we study relations between organizational and technological aspects of production. We propose a model, in which physical resources (such as labor, physical capital, natural resources in use, etc.) and a separate informational resource are distinguished. Informational resource includes talented individuals, and, in particular, high-ability managers. In the framework of the model, we study a question of compatibility, i.e. coincidence of the choices made by two interest groups in the organization, referred as 'operatives' and 'minimizers'. We show that if the technological progress is not accompanied by institutional changes (changes in the social technology) it leads to an incompatibility, and if the decision is made by minimizers, it leads to a bottleneck role of the "non-talented" labor. The exit from this trap can consist in a continuous change of the social technology when the economy moves along the growth path.

We consider two examples of application of our model: learning-by-doing in a firm and structure of a university providing research and teaching activities.

One way to interpret changes in the social technology is *education of managers* and, correspondingly, an improvement of their abilities. Under such interpretation, the results obtained in the paper say that only an adequate human capital of managers allows the economy to entirely use possibilities provided by technological progress.

For the first time, an approach to economic growth as depending on education of managers was proposed by Nelson and Phelps [32], who claimed that "in a technologically progressive or dynamic economy, productive management is a function requiring adaptation to change, and the more educated a manager is, the quicker will he be to introduce new techniques of production". In our interpretation, educated managers (to whom a modified social technology corresponds) choose an adequate physical technology.

However, in [32] the education level of managers is a fixed parameter – it is a typical example of a model in which institutions have a quantitative (but not a structural) nature and create a one-time incentive (or an obstacle) for economic growth. The Nelson-Phelps model was developed further by [33], where the education level ensuring the growth must correspond to a growth strategy – imitation or innovation –, and the choice of such a strategy in its turn depends on a proximity to the world technological frontier.

In our model, interpreted in such way, the educational level of managers (a social technology) must change as the economy moves along a growth path. This is entirely compatible to the Nelson-Phelps's claim that "the progressiveness of the technology has implications for the optimal capital structure in the broad sense." The 'broad sense' certainly includes the organizational structure.

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Author has declared that no competing interests exist.

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APPENDIX: PROOFS

Proof of Theorem 2. If $x \in M_1,\ l \in \Lambda$ then $\max_i l_i x_i \geq 1$. (Otherwise $\min_i x_i^{-1} l_i^{-1} > 1$, which contradicts to Theorem 1). Hence, for $l \in \Lambda$:

$$F^{\circ}(l) = 1 = \min_{x \in M_1} \max_i l_i x_i ;$$

The minimum is achieved under $x = l^{-1}$. For other *l* equation $F^{\circ}(l) = \min_{x \in M_1} \max_i l_i x_i$ still holds because of the homogeneity.

Proof of Theorem 3. Necessity. Let the problems be compatible; l^* is their joint solution. Then, solving the problems, we obtain:

$$l_1^* x_1 = l_2^* x_2 = \ldots = l_n^* x_n ,$$

$$l_1^* h_1^{-1} = l_2^* h_2^{-1} = \ldots = l_n^* h_n^{-1} ,$$

which implies (1).

Sufficiency. Let $\bar{l}$ and $\hat{l}$ be solutions of the problems 1 and 2 correspondingly. Then

$$\bar{l}_1 x_1 = \bar{l}_2 x_2 = \ldots = \bar{l}_n x_n = \bar{\mu} ,$$

$$\hat{l}_1 h_1^{-1} = \hat{l}_2 h_2^{-1} = \ldots = \hat{l}_n h_n^{-1} = \hat{\mu} .$$

Equation (1) implies

$$\hat{l}^{-1} \hat{\mu} = \lambda \bar{\mu} \bar{l}^{-1} .$$

Hence, the vectors $\hat{l}$ and $\bar{l}$ are proportional, and, moreover, since they both belong the same technological menu Λ, they are equal. □

Proof of Theorem 4. We find:

$$l_K(t) = \gamma^t A_0 \left(\frac{L(t)}{K(t)} \right)^{1-\alpha} , \quad l_L(t) = \gamma^t A_0 \left(\frac{K(t)}{L(t)} \right)^{\alpha} .$$

Thus, in BGP the Leontief productivities have constant growth factors:

$$\gamma_K = \gamma \left(\frac{\beta}{\varphi} \right)^{1-\alpha} , \quad \gamma_L = \gamma \left(\frac{\varphi}{\beta} \right)^{\alpha} ,$$

and

$$\gamma_K \varphi = \gamma_L \beta ,$$

$$\min\{\gamma_K \varphi, \gamma_L \beta\} = \varphi .$$

The latter two equations imply $\gamma_K = 1,\ \gamma_L = \varphi / \beta$; i.e. the case of labor-augmenting technological progress takes place: the technological progress "hauls" the growth factor of the effective labor up to the growth factor of the economy. The latter is equal to $\varphi = \beta\gamma^{1/(1-\alpha)}$.

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