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OPTIMIZATION OF PRODUCTION RESOURCES IN SCIENCE-BASED COMPANIES: A MATHEMATICAL MODEL INCLUDING A FIXED SHARE OF IMPORTS

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Abstract. The Russian economy is highly import-dependent, which is also relevant for the enterprises of the science-intensive industry. The later is based on the emerging realities, and strives to develop and introduce a strategy that would allow for the most efficient implementation of the planned import substitution program. In this research the authors have developed a comprehensive mathematical model that takes into account the peculiarities of the local labour and technical capital market, as well as their impact on the production costs of the science-based enterprise. The practical application of indicators that can define the current state and the level of dependence of science-based production on foreign raw materials will provide grounds for a revision of the existing development strategy. What is more, it will be possible to take into due consideration the mission of import substitution, based on the available resources of the enterprise and the maximum permissible share of imports in production.

Keywords: mathematical model, production estimation, production efficiency, science-based industry, import, import substitution

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ОПТИМИЗАЦИЯ ПРОИЗВОДСТВЕННЫХ РЕСУРСОВ НАУКОЕМКИХ ПРЕДПРИЯТИЙ: МАТЕМАТИЧЕСКАЯ МОДЕЛЬ С УЧЕТОМ ФИКСИРОВАННОЙ ДОЛИ ИМПОРТА

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Аннотация. Российская экономика, безусловно, зависит от импорта, в том числе и от предприятий наукоемкой отрасли, что, в свою очередь, исходя из складывающихся реалий, ставит перед ними задачу разработки и внедрения стратегии, позволяющей наиболее эффективно реализовывать запланированную программу импортозамещения. В данном исследовании авторами была разработана математическая модель, которая позволяет учитывать особенности местного рынка рабочей силы и технического капитала, а также их влияние на стоимость производственного процесса наукоемкого предприятия. Применение на практике показателей, способных охарактеризовать текущее состояние и уровень зависимости наукоемкого производства от зарубежного сырья, позволит пересмотреть текущую стратегию развития предприятия с учетом задачи импортозамещения, исходя из имеющихся ресурсов предприятия и максимально допустимой доли импорта.

Ключевые слова: математическая модель, оценка производства, эффективность производства, наукоемкая отрасль, импорт, импортозамещение

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Introduction

Since science-based enterprises make the engine of economic growth in our country, effective assessment of production provides grounds for timely process optimization, identification of new development paths, and implementation of innovations. Production evaluation in science-intensive industries is important and requires modern approaches for their analysis, including the development of architectural solutions for IT support of R&D, thus contributing to the integration of enterprise systems, process automation, and data security. The benefit that are brought in via the implementation of standards (e.g. TOGAF) and conceptual architectures improve performance, reduce costs, and help enterprises adapt to changing conditions. These approaches are especially important for modelling resource optimization processes of science-based enterprises. The problem with evaluating the impact of imported components on production derives from the lack of developed tools for assessment and adaptation of production processes with due consideration of the ongoing changes that result in import substitution in all sectors of the economy, including science-intensive industries.

The main measure aimed at the development of science-intensive production is the refusal of imports, which, in turn, is likely to put excessive burden on the available resources of the

Russian production. With the resource shortage, chances are that the price for local resources of Russian production will grow; their appreciation will become a consequence of demand growth, thus leading to higher prices for the final product and increased cost of the production process. Therefore, the shift to domestic resources should be well planned and, ultimately, should increase the efficiency of science-intensive production, thereby reducing dependence on imported resources and increasing the sustainability of the economy as a whole.

Materials and Methods

The present day economy invites various mathematical multi-factor models for assessing import dependence in terms of the impact of foreign trade on domestic production, including in the science-intensive industry, employment, and other economic parameters. Such models allow determining the changes in import conditions that affect the economic sustainability of the country (Batkovskiy, Fomina, Semenova, Khrustalev, Khrustalev, 2016). The study by Urrutia et al., 2015, articulated a mathematical model of imports and exports in the Philippines. Paired tests show that there is no significant difference between the predicted and actual value of both import and export (Urrutia et al., 2015; Drath, Horch, 2014).

For many years, scholars have been studying the short-run adjustment of the economy to sustained increases in the prices of imported goods. On the other hand, they have paid attention to the impact of imported inflation on the terms of trade (Shinkai, 1973). The foreign sector in conventional macroeconomic models has not been properly integrated with behavioural relationships in the rest of the economy. The aggregate-producing sector is usually depicted as employing primary factors, capital and labour, to produce a single output that simultaneously meets the demands of consumers, producers, governments, and foreigners. In this one-sector model, imports are implicitly assumed to be either final goods that enter the utility functions of consumers, or intermediate goods that are separable from primary factors in production (Fayoumi, Williams, 2021). The first assumption conflicts with empirical evidence that the bulk of international trade occurs in intermediate goods, while the second assumption involves a substantive restriction on the form of the technology that ought to be examined and justified empirically rather than assumed (Burgess, 1974).

For a comprehensive consideration of the issues raised in this research, the authors also studied works related to the development of an economic mechanism for optimizing the innovation and investment program in the development of agro-industrial production (Brockova, Rossokha, Chaban, Zos-Kior, Hnatenko & Rubezhanska, 2021; Kalugin, 2013), as well as issues of adaptation of high-tech science-intensive enterprises to the challenges of Industry 4.0 (Poloskov, Zheltenkov, Braga & Kuznetsova, 2020). It is worth noting that Industry 4.0, in a broad sense, characterizes the current trend of automation and data exchange. It includes cyber-physical systems, the Internet of Things, cloud computing, and represents a new level of production organization and value chain management throughout the entire life cycle of manufactured products (Rossini et al., 2021). At the same time, estimation of production in science-intensive industries involves certain difficulties (Guevara-Rosero, Carriyn-Cauja, Simbaca-Landeta, and Camino-Mogro, 2023). For instance, assessment of production in science-intensive industries is important and requires the use of modern approaches for their analysis, including the development of architectural solutions for IT support of R&D (Chemeris, Dubgorn & Tick, 2022), which allows for the integration of enterprise systems, process automation, and data security.

In order to achieve the aim of this research, the authors employ the following methods: observation, system analysis, economic, mathematical and experimental modelling, abstract-logical and graphical methods.

Results and Discussion

Since the existing mathematical assessment models do not take into account a fixed share of imports, there is an urgent need for development of a mathematical model aimed at estimation of production at Russian science-based enterprises with due consideration of imports. Thereby, it is essential to:

– reflect the impact of international economic and political changes on the development of production in a modern way;

– analyze the impact of foreign goods on competition and demand for Russian products;

– improve the accuracy of productivity and efficiency assessment of Russian industrial companies;

– determine the dependence of science-intensive enterprises on import supplies;

– develop new technologies to promote economic independence from foreign raw materials and, as a consequence, increase the resistance to change in the foreign market.

In order to find the optimal parameters of production in science-intensive industries a mathematical model should be built. Let the production function of a science-based enterprise be defined as follows:

$$Q = f(L, K), \tag{1}$$

where:

Q is a volume of output;

L is labor resources;

K is a volume of used technical capital.

Technical capital is a set of tangible and intangible resources that are necessary for the production of science-intensive enterprises. It includes equipment, components, materials and semi-finished products, software, licenses and patents for the use of technical solutions and other resources that implemented in production.

Let us assume that technical capital includes local (national) and external (imported) components:

$$K = K_{out} + K_{local} \tag{2}$$

where:

K_{out} is external (imported) technical capital;

K_{local} is local (national) technical capital.

The share of external capital in total capital K is given as:

$$K_{out} = \theta * K, \; K_{local} = (1-\theta) * K \tag{3}$$

where:

K is total technical capital;

θ is a share of external (imported) capital ($0 \le \theta \le 1$).

The share of external (imported) technical capital (parameter θ) is of practical importance because the enterprise sometimes faces the need to use external technical capital with a not more than a pre-approved and strictly regulated share of the total value of technical capital.

Taking into account the introduced parameter θ, the production function takes the form:

$$Q = f(L, K, \theta) \tag{4}$$

Total labor costs, local capital K_{local} and external capital K_{out} should not exceed the C budget:

$$C_L(L) + C_{local}(K,\theta) + C_{out}(K,\theta) \le C \tag{5}$$

where:

C is total production budget (a given constant);

$C_L(L)$ is labor costs (cost of labor);

$C_{local}(K,\theta)$ is expenditures on local (national) technical capital, a function of the technical capital K involved in production and the share of the external (imported) component in it θ;

$C_{out}(K,\theta)$ is the cost of external (imported) technical capital, a function of the technical capital K involved in production and the share of the external (imported) component in it θ.

The problem of finding the optimal production parameters L^*, K^* *and* θ^* is an issue of maximizing the production function (4) under the budget constraint (5). To solve the problem using the Lagrangian method, the Lagrangian function is introduced (Cranmer, Greydanus, Hoyer, Battaglia, Spergel & Ho, 2020):

$$\mathcal{L}(L,K,\theta,\lambda) = f(L,K,\theta) - \lambda(C_L(L) + C_{local}(K,\theta) + C_{out}(K,\theta) - C) \tag{6}$$

where:

λ is Lagrange multiplier, reflecting the growth of the production function $f(L,K,\theta)$ when the budget constraint is changed by one.

In order to find the optimal production parameters L^*, K^* *and* θ^* it is necessary to calculate partial derivatives of the Lagrangian function on the variables.

In the considered mathematical model it is assumed that the increase in production volumes by a science-based enterprise located in a certain closed system (region, country, group of countries) has a significant impact on the local labor market and resource market. At the same time, the impact of this enterprise on the international (external, in relation to the closed system) resource market is considered insignificant and can be ignored.

The matter is that in the real economy, as the demand for labor increases, the cost of hiring additional workers begins to grow faster than linearly. The first reason is the limited labor resource, since in the local labor market the qualified workers are scarce. In order to attract additional resources, the enterprise is forced to offer higher wages. Another reason for the rising cost of labor is the incentive to overwork. When already hired workers are forced to do overtime, their labor is paid at higher rates, leading to a growth of labour costs with increasing volume.

Based on the specifics mentioned above, it is possible to assume that the labor cost W(L) has the following dependence on the volume of labor:

$$W(L) = w_0 + k * L^2 \tag{7}$$

where:

w_0 is base labor cost;

k > 0 is a coefficient of labor cost growth depending on the volume L.

Considering (7), the following dependence of labor costs is obtained:

$$C_L(L) = W(L) * L = w_0 * L = k * L^3 \tag{8}$$

In the local market, the supply of technical capital is limited. As demand increases, enterprises begin to compete for limited resources, which leads to higher prices. Let us assume that as demand grows, local producers start to raise prices linearly to compensate for the growth of their costs and take advantage of market conditions. Then, the dependence of the cost of local technical capital, as follows $R_{local}(K_{local})$, will have the form of:

$$R_{local}(K_{local}) = r_0 + m * K_{local} \tag{9}$$

where:

r_0 is base (initial) cost of a unit of local technical capital;

m is a coefficient of price growth of technical capital depending on its consumed volume.

Considering (9), the dependence of costs on local technical potential goes as follows:

$$C_{local}(K,\theta) = R_{local}(K,\theta) * K_{local} = (r_0 + m * K_{local})K_{local} \tag{10}$$

Given (3), it turns out that:

$$C_{local}(K,\theta) = (r_0 + m * (1-\theta) * K) * (1-\theta) \tag{11}$$

Let us assume that the change in the consumption volume of technological capital at the local enterprise is not able to have a significant impact on pricing in the international market.

Thus, the cost of external technical capital will be considered unchanged:

$$R_{out}(K,\theta) = p_{out} \tag{12}$$

Considering (12), the dependence of expenditures on external (imported) technical potential is obtained:

$$C_{out}(K,\theta) = R_{out}(K,\theta) * K_{out} = p_{out} * K_{out} \tag{13}$$

Taking into account (3), we obtain:

$$C_{out}(K,\theta) = p_{out} * \theta * K \tag{14}$$

In order to model the production process of a science-based enterprise, we will employ the Cobb-Douglas production function. This function is universal and reflects the key aspects of production in high-tech industries, including labor, capital and their interaction (Douglas, 1928):

$$Q(L,K) = A * L^{\alpha} * K^{\beta} \tag{15}$$

where:

Q is the output volume;

L is labor resources;

K is the amount of technical capital utilized;

A is a coefficient reflecting the level of technology;

α, β is elasticity of output by labor and capital.

Substituting (15), (14), (11), (8) into (6) we obtain the Lagrangian function in the following form:

$$\begin{aligned} \mathcal{L}(L,K,\theta,\lambda) = A * L^{\alpha} * K^{\beta} - \lambda((w_0 * L + k * L^3) + \\ +(r_0 + m * (1-\theta) * K) * (1-\theta) + p_{out} * \theta * K - C) \end{aligned} \tag{16}$$

To find the optimal values of L^*, K^*, θ^* we will take partial derivatives of the obtained function (16) on the variables L, K, θ, λ and equate them to zero.

The derivative of L (labor) will be as follows:

$$\frac{\partial \mathcal{L}}{\partial L} = A * \alpha * L^{\alpha-1} * K^{\beta} - \lambda * (w_0 + 3k * L^2) \tag{17}$$

The derivative of K (technical capital):

$$\frac{\partial \mathcal{L}}{\partial K} = A * \beta * L^{\alpha} * K^{\beta-1} - \lambda * (m * (1-\theta)^2 + p_{out} * \theta) \tag{18}$$

The derivative of θ (the share of imported technical capital):

$$\frac{\partial \mathcal{L}}{\partial \theta} = \lambda * (r_0 + 2m * (1-\theta) * K - p_{out} * K) \tag{19}$$

The derivative of λ (budget constraint):

$$\frac{\partial \mathcal{L}}{\partial \lambda} = (w_0 * L + k * L^3) + (r_0 + m * (1-\theta) * K) * (1-\theta) + p_{out} * \theta * K - C \tag{20}$$

To find the values of $L^*, K^*, \theta^*, \lambda^*$ it is necessary to solve the resulting system of equations, which consists of 4 equations (17), (18), (19), (20) with respect to the variables L, K, θ, λ:

$$\begin{cases} A * \alpha * L^{\alpha-1} * K^{\beta} - \lambda * (w_0 + 3k * L^2) = 0 \\ A * \beta * L^{\alpha} * K^{\beta-1} - \lambda * (m * (1-\theta)^2 + p_{out} * \theta) = 0 \\ \lambda * (r_0 + 2m * (1-\theta) * K - p_{out} * K) = 0 \\ (w_0 * L + k * L^3) + (r_0 + m * (1-\theta) * K) * (1-\theta) + p_{out} * \theta * K - C = 0 \end{cases} \tag{21}$$

The resulting system of 4 equations is nonlinear and has no analytical solution for the general case. For specific values of parameters ($A, \alpha, \beta, w_0, k, r_0, m, C, p_{out}$) the solution can be found only numerically using optimization methods.

If the variable θ is considered as a predetermined parameter, for example, the enterprise has a task to use imported capital by no more than 30% (θ_c = 0,3), then the system of equations (21) will take the following form:

$$\begin{cases} A*\alpha*L^{\alpha-1}*K^{\beta}=\lambda*(w_0+3k*L^2) \\ A*\beta*L^{\alpha}*K^{\beta-1}=\lambda*(m*(1-\theta_c)^2+p_{out}*\theta_c) \\ w_0*L+k*L^3+(r_0+m*(1-\theta_c)*K)*(1-\theta_c)+p_{out}*\theta_c*K=C \end{cases} \quad (22)$$

The resulting system of 3 equations is also nonlinear and has no analytical solution for the general case. For specific values of parameters ($A,\alpha,\beta,w_0,k,r_0,m,C,p_{out},\theta_c$) the solution can be found only numerically using optimization methods.

The economic essence of the developed model is to apply a mathematical model that takes into account a fixed share of imports θ to optimize the production resources of knowledge-intensive enterprises. Fig. 1 schematically depicts the optimization directions of import substitution strategies using the proposed mathematical model.

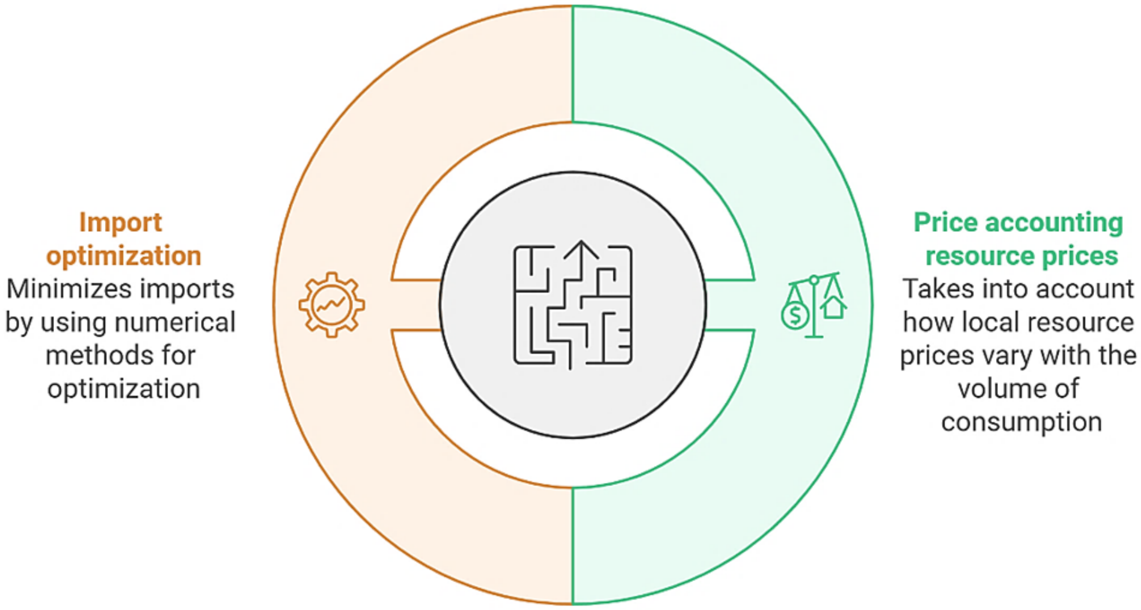

Fig. 1. Optimization directions of import substitution strategies using the proposed mathematical model (designed by the authors)

Overall, the mathematical model suggested in this research allows to:

– Take into account the dependence of prices of local resources on their planned consumed volume when generating the import substitution strategy;

– Determine the optimal strategy to reduce the share of imports involved in production using numerical methods.

This model makes a tool for resource optimization, improvement of management decisions, and strategic planning in the science-intensive industry as a whole. As the analysis shows, the cost of labour and local technical capital nonlinearly depend on the volume of their use, which is explained by the resource scarcity, competition in local markets, and rising costs. Taking into account these factors, the enterprises can plan costs more accurately and avoid price fluctuations.

Conclusion

The model developed in this research provides enterprises with a tool for strategic planning, allows them to respond quickly and adapt production processes to changes in the external environment, allocate resources more efficiently, reduce costs, and increase productivity. Its application contributes to the overall development of strategies aimed at reduction of dependence on imports and higher resilience to external economic challenges. In the further research it is planned to make the model more accurate via expanding and including additional criteria, such as the impact of technological innovation, and the dependence of prices for technical capital and labour resources on time (inflationary component). To sum up, the suggested model proves to be very promising in terms of its potential use in various branches of science-intensive production to ensure efficiency and competitiveness.

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