

Thermodynamics of the Production Processes

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Abstract: The process of creating goods and services, measured by their value, is considered a process of creating complexity. This allows us to consider the production system as an open thermodynamic system, and to develop a simple heuristic model of the production process. The model includes three production factors: the index of complexity of production equipment (physical capital K), human activity (labour L), and the substitutive capacity of equipment (substitutive work P). The thermodynamic approach also needs in technological characteristics of production equipment, such as labour requirement λ and energy requirement ϵ , which indicate the amounts of labour and energy required to operate production equipment. By applying thermodynamic principles, we can understand how labour can be replaced by capital and derive the production function with four different formulations. Two of them are known and used by researchers for interpretation the production phenomena; the thermodynamic approach provides some foundation for economic theory, allowing us to decompose unambiguously the growth rate of output over technological level and the growth rates of production factors. The introduction of substitutive work as a factor of production and the technological characteristics of capital expands our ability to simulate and analyze production processes.

Keywords: complexity; economic growth; open thermodynamic system; production function; technological progress

1. Introduction

The interdependence between the output of a production system and certain quantities that are considered as sources of value and are called factors of production is one of the main pillars of economic growth theory (production theory). According to common beliefs (see, for example, the monographs by Blanchard and Fisher [1] and by Aghion and Howitt [2], output Y is determined by fixed capital K and labour inputs L , so that this interdependence is formalized as follows:

$$Y = Y(L, K). \quad (1)$$

Labour expenses can be quantified, for example, by the number of working hours per year. Physical capital represents the amount of equipment used in production; it is measured in monetary units. Equation (1) implies that the two production factors can substitute for each other. In other words, the creation of value is attributed not only to the labour (a statement that researchers do not doubt), but also to the installed equipment.

To describe empirical observations which, according to investigations [1,2], do not fit into the simple Formula (1), researchers use various specifications and modifications of the function, assuming that there must be other factors in Equation (1) related to scientific and technological progress, which are represented in various ways, such as introducing a general productivity factor (Solow residual) or an uncertain time-dependent adjustment factor called exogenous technological progress. Thus, despite the ugliness of the theory, it is possible to describe the observations, but there is still a mystery: what is technological progress in production processes? Additionally, the question arises: how can labour be replaced by production equipment?



We omit the traditional interpretations of these phenomena, as we intend to find answers by considering the production system from a physical perspective, as a material system composed of atoms and molecules. In this case, we turn to thermodynamics, which offers research methods that allow us to describe complex systems, such as the production system, in terms of macroscopic quantities. When studying the production process from this point of view, we must first establish thermodynamic quantities corresponding to macroeconomic variables, that is to formulate a heuristic model of the production system. I will not list the existing attempts to find analogies between the economic and thermodynamic description of a production system; the studies that I am familiar with share a common flaw: the researchers turn to equilibrium thermodynamics in their search, while the production system is clearly in a non-equilibrium state and should be considered as a complex system that is open to the flow of matter and energy. The production processes are designed, in thermodynamic terms, to create complexity or, in other words, to reduce the entropy of our environment. In Section 8.4 of the eighth chapter of the author's monograph [3], the reader can find a simple case explaining the mechanism of creating non-equilibrium states (increasing in complexity and decreasing in entropy) and the role of information in the production processes. I will address the formulation of the simplest model of the production process in the next section of this article.

The principles of thermodynamics help to formulate the relationship between the production output and the consumed resources, that is, in traditional terms, to establish the production function, which contains also the technological characteristics of the production equipment. This approach leads to four forms of the relationship, one of which specifies the relationship (1). It is possible to think that these results provide a solid thermodynamic foundation for the theory of economic production. In any case, understanding the quantitative relationship between outputs and resources can be beneficial in the development of mathematical models of production.

2. Heuristic Model of the Production Process

The aim of production processes is to produce a range of desirable goods and services, such as food, clothing, building materials, household appliances and machinery, which are useful to people and valued by consumers. The output of the production processes, denoted by Y , is conventionally understood as the exchange value of products created. However, it does not imply that quantity is subjective, as the objective content of output seems to be complexity (or, in other words, a decrease in entropy, (Chapter 8 in [3])). The production of consumer goods can be understood in economic or thermodynamical terms as the creation of value or complexity, respectively. A double interpretation of Y seems to provide a fundamental link between thermodynamics and economic theory. This allows for the formulation of a description of production in terms of thermodynamics, and, incidentally, states that energy is the natural measure of value [4].

2.1. Production as an Open Thermodynamic System

The production system is represented as an open thermodynamic system that includes flows of raw materials transformed into useful products, and flows of energy needed for the transformation processes. The simplest diagram of this system is shown in Figure 1.

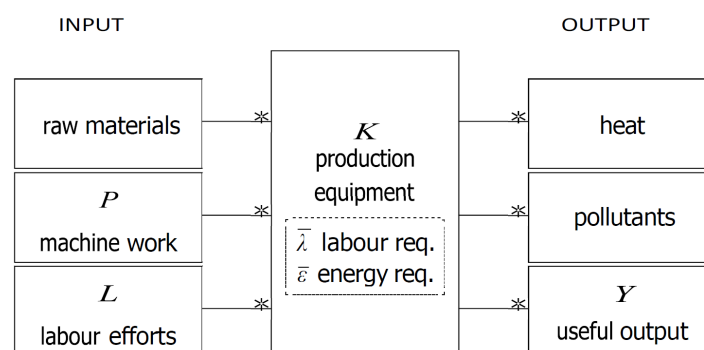


Figure 1. Scheme of the production process. The raw materials and substances (ores, water, air, energy sources, etc.) enter the core of the production process (production equipment K) and, after undergoing transformations under the influence of worker efforts L and machine work P come out of the process as a range of desirable products and services (food, clothes, buildings, appliances, machinery, etc.), which is the useful outcome of the production Y . The production process itself can be described in economic or thermodynamic terms as production of value or creating of complexity, respectively. The technology for transformation (characteristics λ and ϵ), is embodied in production equipment. Production processes generate heat and emissions, but these are separate issues; the “useful” side of production will be addressed in this article.

A core of the production system is a collection of equipment implemented as a set of tools for transforming raw materials into useful products. From a thermodynamic perspective, production equipment is simply a collection of atoms and molecules interacting with each other. These particles are organized into complex structures that can be viewed as a non-equilibrium thermodynamic state of the system. To characterize nonequilibria, we need additional variables called internal variables, or complexity variables (Chapter 2 in [3]). To fully describe the structure of a production system, we require many internal variables. However, every non-equilibrated system has a unique characteristic—the complexity index and all thermodynamic characteristics depend on this variable. Due to our interpretation of value as complexity, monetary estimate of the amount of equipment K can be considered as a measure of its complexity.

The production equipment is essential for modern enterprises, but it remains inactive unless the efforts of workers are applied and energy input come from external sources. Historically, political economists [5,6] have chosen the efforts of people—labour L (effort and work)—as the sole source of value, but this was a perfect solution until machines began to dominate in the production. To solve the problems that arise while understanding production at the machine stage, researchers have added another factor, coming up with relation (1) to describe the process. The thermodynamic approach takes into account the fluxes of energy that come to the production system from external sources. Primary production energy is distributed through the production system and loses most of its value during various transfers. A small portion of total energy P consumed in production seems to reach production facilities ([7], Section 2.5 in [8]). This small quantity truly replaces labor in production processes and acts as an important factor in production. It was crucial to separate substitutive labor and introduce it into the theory as a factor P . Therefore, behind the substituting labour with capital, situates substituting labour with the work of production equipment.

To keep the production system operating, one needs fluxes of external resources. These include the fluxes of substances and the two forms of fluxes of energy, one of them is labour L —efforts and work of people; the other—the work done by production equipment by external energy source P . During the production process, substances and materials enter the system and are directly influenced by energy fluxes. The amount of social resources used, L and P , depends on the technology embodied in production equipment. The quantity K , measured by its value, appears to be a passive production factor.

Interpreting the production of value as a reduction in the entropy of a collection of substances used in production processes allows us to write down an energy balance (first law of thermodynamics), and obtain an equation for output through production factors.

$$Y = Y(L, P). \quad (2)$$

We assume that the active factors of production are measured in energy units.

2.2. The Main Properties of the Production Equipment

To fix the property of the capital to attract labour force and productive energy, we can, according to the previous speculations (Chapter 4 in [9], Chapter 5 in [8]), introduce the main characteristics of the capital, which are labour and energy requirements,

$$\lambda = \frac{dL}{dK}, \quad \varepsilon = \frac{dP}{dK}. \quad (3)$$

These quantities indicate the amounts of labour and productive energy required to operate a unit of production equipment.

It is convenient to deal with non-dimensional technological coefficients

$$\bar{\lambda} = \frac{K}{L} \frac{dL}{dK}, \quad \bar{\varepsilon} = \frac{K}{P} \frac{dP}{dK}. \quad (4)$$

If the quantity is less than one, it means that labour-saving or energy-saving technologies have been used at that moment of time. In a stationary case, the quantities do not change with time.

The quantities (4) characterize the basic technological level of production equipment. They determine the amount of required production factors. If the non-dimensional technological coefficients are considered to be given characteristics, then the relations (4) appear to be equations that determine the required amounts of production factors

$$\frac{L}{L_0} = \left(\frac{K}{K_0} \right)^{\bar{\lambda}}, \quad \frac{P}{P_0} = \left(\frac{K}{K_0} \right)^{\bar{\varepsilon}}. \quad (5)$$

The symbols with zeros represent the values of the variables at a selected starting point.

The efficiency of the use of production factors is characterized by a technological index, which is a combination of dimensionless technological coefficients

$$\alpha = \frac{1 - \bar{\lambda}}{\bar{\epsilon} - \bar{\lambda}}. \quad (6)$$

The technological coefficients and technological index are internal parameters of the production system. Variable K represents the total amount (in monetary units) of production equipment, while the technological coefficients $\bar{\lambda}$ and $\bar{\epsilon}$ indicate its quality. We assume that these three quantities are given as the global characteristics of production equipment.

3. Specification of the Production Function

This section considers the output of the production process Y , as the market value of the product created at a given point in time, in the relation to its value Y_0 at an arbitrary initial point. This value can be expressed as a function of the production factors, L , P , and K , relative to their values at the beginning of the period: L_0 , K_0 , and P_0 . It will be convenient to use the dimensionless ratios of these variables.

3.1. The Mechanism of Substitution

From a thermodynamic point of view, the true and only sources of value (as relatives of entropy) are labour expenses L and the work of external energy sources P , as it is shown by relation (2). Human efforts are applied directly, whereas substitutive work arises from the prior exploration of natural laws, the development of technological systems, and the manufacturing of production machinery, among other things. The interpretation of the production process allows us to view the output Y as a function of two variables: the activity of workers—labour L —and the work done by production equipment—substitutive work P . The active production factors depend, according to Equation (5), on the amount of installed equipment K , so that we can write the following function

$$Y = Y[L(K), P(K)]. \quad (7)$$

As the amounts of work, the production factors are interchangeable and, in this sense, they are equivalent in all respect. The Smith-Marx theory of labour value is supplemented by the law of substitution, which says that work of third-party forces of nature via production equipment replaces human efforts. The labour acts as labour plus work of equipment in complex in the production of value.

The general form of dependence of output on production factors can be determined by simple assumptions. Universality of production function requires that a proposed function can be applied not only to a specific case, but also to many different situations. For instance, the starting point can be arbitrary, but the shape of the function should not be influenced by this arbitrariness, which determines the unique power form of the function. Uniformity requires the arguments of the function to be special combinations of production factors. These requirements lead (details can be found in the author's monograph (Chapter 6 in [8]) to the expression for the production function in the form

$$Y = Y_0 \frac{L}{L_0} \left(\frac{L_0 P}{L P_0} \right)^\alpha, \quad 0 < \alpha < 1. \quad (8)$$

The labour L and substitutive work of external energy sources P is measured in energy units. The index α —the technological index—in Equation (8) has the form defined by Formula (6); it was shown earlier (Chapter 4 in [9], Chapter 6 in [8]). The characteristics of technology are included in the law of value production; it determines the degree of substitution of labour with productive energy. Relation (8) was discussed in many details in the author's previous works ([7], Chapter 6 in [8]).

Relation (8) describes the effect of substitution labour efforts with machine work. Economists usually prefer to talk about substituting labour with capital [1,2]. Relations (5) allow us to represent the production of value (8) in terms of the variables L and K . The resulting production function can be written as follows

$$Y = Y_0 \frac{L}{L_0} \left(\frac{L_0}{L} \left[\frac{K}{K_0} \right] \bar{\epsilon} \right)^\alpha, \quad 0 < \alpha < 1. \quad (9)$$

The recorded relation is a specific form of function (1) and represents the law of labour substitution by capital. An increase in output can be achieved through increasing relative labour expenses, or the relative amount of capital.

An analysis of substitution mechanisms shows that workers' efforts to produce goods are substituted by the work of the production equipment, not by equipment itself. The substitution coefficient depends on technological characteristics of production equipment.

There are various empirical specifications of the dependence of output on the labour L and physical capital K , but no one coincides with thermodynamic results (9). Up to now the existing empirical formulae for the calculation of output do not contain the appropriate technological characteristics of production equipment.

Note that, due to the validity of Equation (5), the functions (8) and (9) can be reduced to a simple relation

$$Y = Y_o \frac{K}{K_o}. \quad (10)$$

The proportionality of the output to the amount (in value) of capital is confirmed by observations [1] p. 4. Existing deviations from this relationship may be due to different growth rates across industries (Chapter 9, Section 9.3.2 in [8]).

One of the relations (5) shows the amount of human effort for the presence of production equipment (physical capital K), so that the relations (9) and (10) can be represented in the form

$$Y = Y_o \left(\frac{L}{L_o} \right)^{\frac{1}{\lambda}}. \quad (11)$$

This relation gives us the reason to say that labour remains, to use the words of Adam Smith, “the only universal, as well as the only accurate measure of value, or the only standard by which we can compare the values of various goods at all times and in all places”. The law of the value production appears to be a non-linear, generally speaking, function.

Expressions (8)–(11) represent four forms of production function as a consequence of a thermodynamic approach. In the next section will be shown that, under the known technological coefficients λ and ϵ , the theory does not need to contain any arbitrary parameters to be consistent with empirical observations.

3.2. Empirical Verification

The case we are considering to test our considerations is the description of US economic dynamics [7,8]. The verification is based on time series of economic variables, such as output of production systems Y measured in monetary units, production equipment, estimated by its value (physical capital K), energy estimate of the efforts of individuals, denoted by L , and substitutive work of production equipment P , performed by machines powered by energy from external sources, such as wind, water, coal and so on.

3.2.1. Production Factors

The production factors are shown in Figure 2. The time series for K and L were based on direct observation of empirical data. The results were determined essentially by the methods of estimation and the availability of primary data, so accuracy of data is difficult to assess. The time series for the P is calculated (Section 7.1.2, Equation 7.4 in [8]) on the base of the time series for K and L with the known technological index α , which can be calculated along with the estimation of technological characteristics. Production factor P can be directly estimated from primary empirical data as the energy needed to replace human effort (Section 2.5.2 in [8]). This is a tedious process, but I think it's easier than estimating capital. The issue is not a lack of methods, it's a lack of results.

3.2.2. The Technological Characteristics

The internal technological characteristics of production equipment can be calculated using dynamic equations (Section 7.1.3 and Equation 7.5 in [8]). To calculate quantities, we need to know time series data for production factors L and P , as well as data on the introduction and depreciation of production equipment. The results are shown in Figure 3. Note that the requirements for the technological index α to fall within the range of 0 to 1 imposes some limitations on technological characteristics (Section 5.2.1 and Equation 5.15 in [8]). These limitations allow us to identify and eliminate erroneous values for technological characteristics.

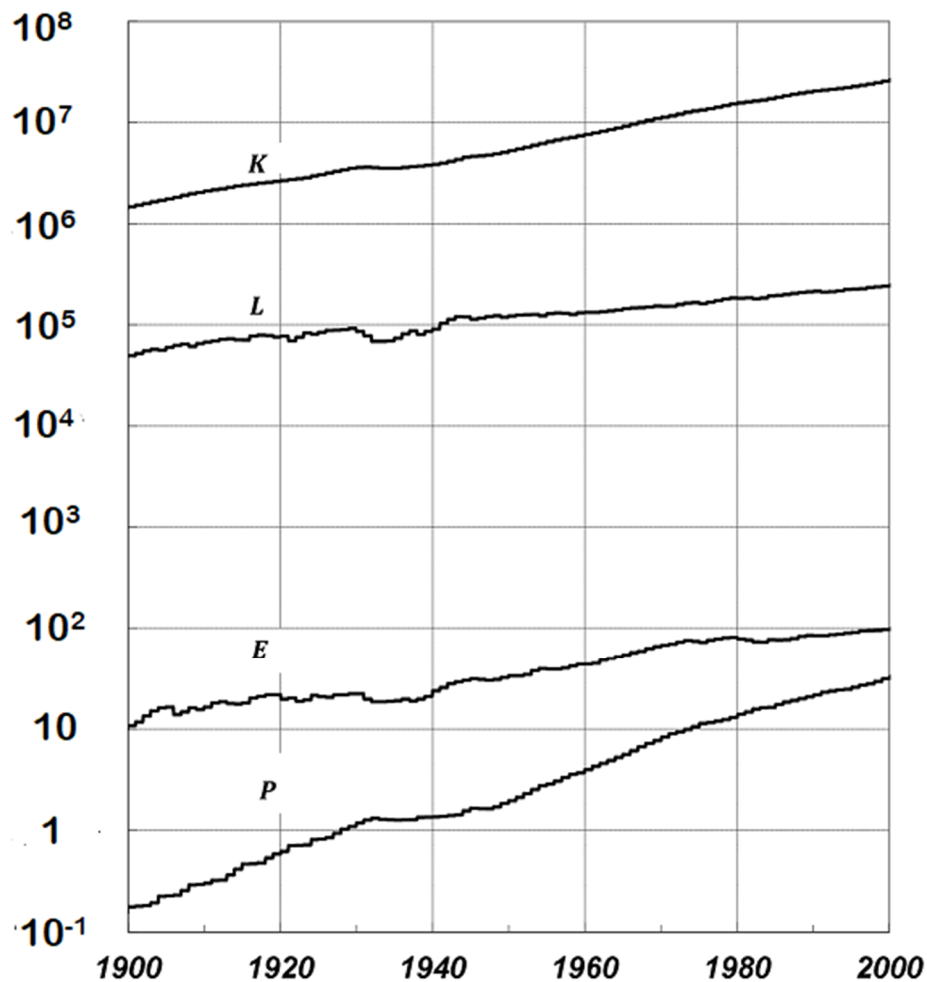


Figure 2. The production factors in the U.S. economy. Value of basic production equipment (fixed capital) K in millions of 1996 dollars; labour input L in millions of man-hours per year; primary energy E , substitutive work P in 10^{18} J per year. The primary energy values are shown for illustration purposes.

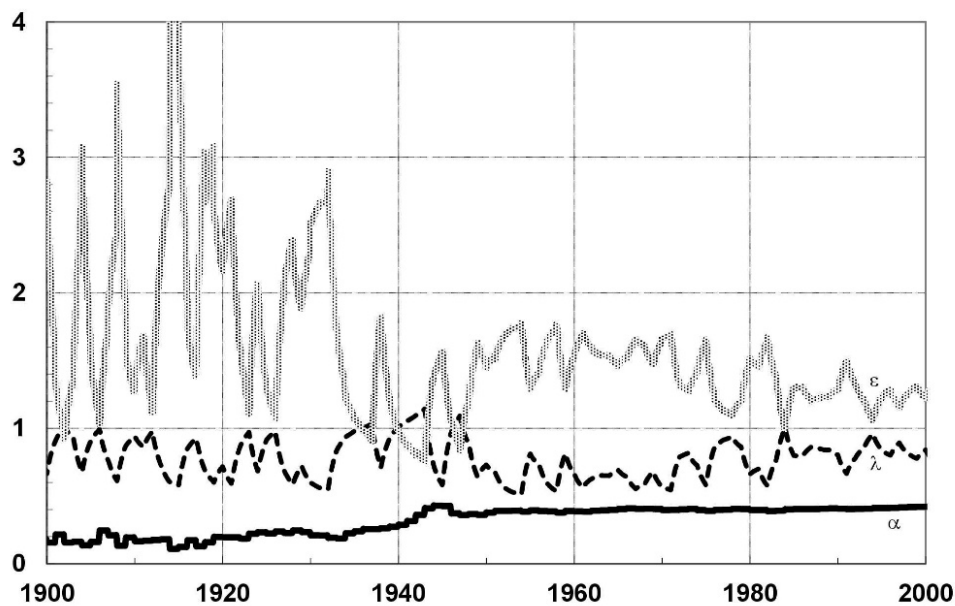


Figure 3. The technological characteristics of the U.S. production system. The picture represents empirical values, that was estimated earlier (Chapter 7 in [8]). The dotted line shows energy requirement ϵ , the middle line—labour requirement λ and the bold line—the technological index α .

3.2.3. The Comparison

Now we can compare the calculated output values obtained using Formulas (8)–(11) to the actual output values (line 1 in Figure 4). Line 2 shows the time dependence of the output calculated using relation (8) and independently determined values for the technological index. We can see that the calculated dependency (line 2) closely resembles the real one (line 1), and there is also a similarity between lines 1 and 5, which was calculated according to relation (10). Significant deviations in dependencies (3) and (4) in the second half of the XX century can be attributed to insufficient accuracy in estimating the technological characteristics during that period. Empirical values of labor requirements turned out to be overstated, and correspondingly, values of energy requirements were understated. Overall, we can say that the results obtained from relations (8)–(11) are consistent with both the actual values and each other, with any deviations being due to unavoidable inaccuracies in the estimation of primary values.

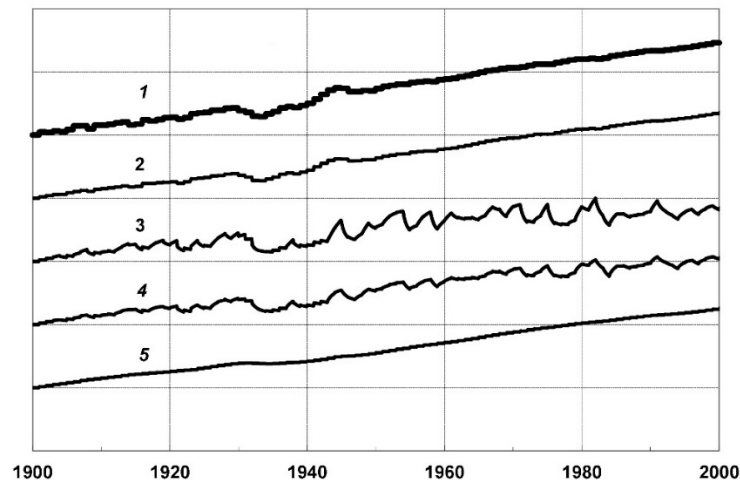


Figure 4. The output of the production system. The picture presents the relative values Y/Y_0 , that is the US GNP in XX century, in the logarithmic representation with arbitrary initial values. Line 1 shows empirical quantities; line 2—the values, calculated as function of L and P according to relation (8); line 3—the values, calculated as function of L according to relation (11); line 4—the values, calculated as function of L and K according to relation (9); line 5—values, calculated as function of K according to relation (10).

4. The Marginal Productivity of Capital

As can be seen from the production process description, the useful output Y is determined by three production factors, L , P and K . Only two of them, L and P , perform work; they are active factors from thermodynamic point of view. In contrast to this, capital K appears to be the means, which allows the active factors to perform work, and should be considered as a passive factor of production.

Four forms of production function give rise to four different interpretations of processes of value production. Economists usually prefer to interpret the situations in terms of labour and capital [2]. Within the framework of this interpretation, the concept of the production power of capital has been formed, and the idea of the capital productivity has become ingrained in the public consciousness. This applies not only to physical capital, but also to financial capital in various forms. For example, if we own shares in a company, we receive dividends; if we deposit money in a bank, we earn interest. Shares and money represent capital in its broadest sense.

Thermodynamic interpretation allows us to find an expression for capital productivity. To separate the individual contribution of production factors to the production of value we refer to the so-called marginal productivity of production factors. The active factors are characterized by the marginal productivities

$$\beta = \frac{\partial Y}{\partial L} = Y_0 \frac{1-\alpha}{L_0} \left(\frac{L_0}{L} \frac{P}{P_0} \right)^\alpha, \quad 0 < \alpha < 1. \quad (12)$$

$$\gamma = \frac{\partial Y}{\partial P} = Y_0 \frac{\alpha}{L_0} \left(\frac{L_0}{L} \frac{P}{P_0} \right)^{\alpha-1}, \quad 0 < \alpha < 1.$$

Unlike factors L and P , physical capital is not a source of value itself, but due to its role in production the ‘marginal productivity of capital’ can be formally calculated. After differentiating relation (7) we find that.

$$\frac{dY}{dK} = \beta \frac{dL}{dK} + \gamma \frac{dP}{dK} \quad (13)$$

This expression shows that capital productivity is determined by marginal productivities of active production factors (12), and technological coefficients. One can see from Equation (13) that the productive capacity of capital for the production of value is actually due to the productive capacity of labour and substitutive work.

5. Decomposition of the Output Growth Rate

Expressions (8)–(11) demonstrate that, according to empirical data, at any moment the value of manufactured products Y , measured in monetary units of constant purchasing power, is determined by the technological characteristics of production equipment: energy requirement ϵ and labour requirement

$\bar{\lambda}$, also as by the aggregated amounts of social resources (production factors) used: physical capital K , direct efforts of people L (physical and mental, we cannot separate them) and the substitutive work of machines P that is obtained with the help of natural energy sources such as wind, water, coal and so on. The production factors are determined by the availability of social resources and technological capabilities (the technological characteristics) of the production equipment and are, generally speaking, functions of time.

The influence of production factors and technological characteristics on economic growth is clearly demonstrated when calculating the growth rate of output Y , for which it is necessary to write down the total differential of output, referring to the relations (8)–(11). For example, referring to the expression (8) and (11) allows one to write down the relations

$$\frac{1}{Y} \frac{dY}{dt} = (1 - \alpha) \frac{1}{L} \frac{dL}{dt} + \alpha \frac{1}{P} \frac{dP}{dt} + \ln \left(\frac{L_o}{L} \frac{P}{P_o} \right) \frac{d\alpha}{dt} \quad (14)$$

$$\frac{1}{Y} \frac{dY}{dt} = \frac{1}{\bar{\lambda}} \left[\frac{1}{L} \frac{dL}{dt} - \ln \left(\frac{L}{L_o} \right) \frac{1}{\bar{\lambda}} \frac{d\bar{\lambda}}{dt} \right] \quad (15)$$

The growth rate of output is determined by the growth rate of production factors, while the ‘structure’ of the production system remain unchanged, and by the technological characteristics of the equipment (the latter terms are on the right side of Equations (14) and (15)). With a constant value of the technological index, an increase in output is associated with an increase in the use of production factors with their constant characteristics, $P/L = \text{const}$, which is defined as extensive economic growth. The last term in Formulae (14) and (15) is directly related to structural and/or technological changes in the production system, that is, to the evolution of the production system itself. As the technological indexes increase, the P/L ratio also increases, and the case of intensive economic growth is realized.

To exclude the presence of zero values in the right-hand sides of ratios (14) and (15), which indicates that a change in technological characteristics with constant resource consumption ($L = L_o$, $P = P_o$) does not lead to any change in output, the last terms in these ratios can be written in a different form when using an expression that is valid in linear approximation by increment

$$\ln \left(\frac{L}{L_o} \right) \approx \frac{1}{L} \Delta L.$$

The relations (14) and (15) now take the form

$$\frac{1}{Y} \frac{dY}{dt} = (1 - \alpha - \Delta\alpha) \frac{1}{L} \frac{dL}{dt} + (\alpha + \Delta\alpha) \frac{1}{P} \frac{dP}{dt} \quad (16)$$

$$\frac{1}{Y} \frac{dY}{dt} = \frac{1}{\bar{\lambda}} \left[1 - \frac{1}{\bar{\lambda}} \Delta\bar{\lambda} \right] \frac{1}{L} \frac{dL}{dt} \quad (17)$$

The latter formula is convenient for analysing and evaluating the two policy options for increasing output: direct labour expenses can be increased (additional labour is attracted) or technology and third-party energy consumption can be improved. The technological coefficient (labour requirement) $\bar{\lambda}$ decreases with increasing machine work, and with a decrease equal to the coefficient value, the effect of changing the technological characteristics of the system is compared with the effect of a direct increase in labour expenses.

For the actual decomposition of the output growth rate, time series on output Y and production factors are required. The decomposition of the output growth rate is unambiguous and does not require additional information: there are no arbitrary parameters included in the theory.

6. Concluding Remarks

The principles of thermodynamics could apply to all objects, regardless of how complex they are. The production process, in the simplest approximation, can be considered as two interacting streams: matter fluxes and energy flows. We assume that matter is conserved in terms of mass, but the organization of matter, under influence of production equipment, changes, leading to complexity. When considering energy-entropy balance, the change in complexity, or equivalently the change in entropy of matter, is taken into account. The quantitative estimation of the production of value, or in other words the creation of complexity, is determined by production equipment capabilities, defined by labour requirement λ and energy requirement ϵ , and the availability of energy resources. It has been shown that to calculate the production output only three variables (the production factors) are needed: the index of production equipment complexity (physical capital K), human activity (labour L), and substitutive capacity of the production equipment (substitutive work P). Four forms of production function follow an energy-entropy balance.

According to the presented theory, technical progress is mainly connected with the creation and dissemination of devices that allow human labour to be replaced by machine work, which results in increase in the consumption of external energy; this explains and describes the increase in labour productivity due to mechanization. In addition to the processes of replacing human labour with machine work, there are other processes of substitution that should be considered. A person equipped with more advanced tools and using more suitable materials can produce more products with the same amount of labour. For example, if a worker uses a sharp iron axe instead of a dull stone axe, they can cut more wood per unit of time with the same amount of effort. In this case, the efficiency of the process of replacing human effort with machine work increases, which is described by the change in the technological characteristics of physical capital. The dynamics of these quantities also as dynamics of the production factors was described earlier (Chapter 4; 2003 in [9], Chapter 6 in [8], [10]).

Thermodynamics helps to solve one of the fundamental economic problems—the problem of the origin of wealth in an era when various machines and mechanisms are widely used. In this article, we have demonstrated the law of value production based on fundamental principles. The thermodynamic approach provides a solid foundation for the relationships of the production theory. In fact, a physical justification of the theory of wealth production is presented. The theory does not contain any adjustable parameters. This issue is particularly relevant for mathematical modelling of production processes, as it is unlikely that the model will produce accurate results if the initial assumptions are not adequate. The introduction of substitute work as a production factor and the technological features of capital expands the possibilities for modelling and analysing economic processes.

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

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References

1. Blanchard, O.J.; Fischer, S. *Lectures on Macroeconomics*; MIT Press: Cambridge, MA, USA, 1989.
2. Aghion, P.; Howitt, P.W. *The Economics of Growth*; MIT Press: Cambridge, MA, USA, 2009.
3. Pokrovskii, V.N. *Thermodynamics of Complex Systems. Principles and Applications*; IOP Publishing: Bristol, UK, 2020.
4. Beaudreau, B.C.; Pokrovskii, V.N. On the energy content of a money unit. *Phys. A Stat. Mech. Appl.* **2010**, *389*, 2597–2606.
5. Smith, A. *An Inquiry into the Nature and Causes of the Wealth of Nations*; Clarendon Press: Oxford, UK, 1976. <https://doi.org/10.1093/oseo/instance.00043218>.
6. Marx, K. *Capital*; Progress Publishers: Moscow, USSR, 1954; Volume 1.
7. Pokrovski, V.N. Energy in the theory of production. *Energy* **2003**, *28*, 769–788. [https://doi.org/10.1016/s0360-5442\(03\)00031-8](https://doi.org/10.1016/s0360-5442(03)00031-8).
8. Pokrovskii, V.N. *Econodynamics: The Theory of Social Production*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2018.
9. Pokrovskii, V.N. *Physical Principles in the Theory of Economic Growth*; Ashgate Publishing: Aldershot, UK, 1999.
10. Pokrovskii, V.N. Social resources in the theory of economic growth. *Complex Syst.* **2021**, *3*, 33–44.