Professor Georgescu-Roegen, in contrast to many other mathematical economists, was interested in the problems of economic theory and not in demonstrating his command of mathematical methods. He made a significant contribution to the advancement of economics by using not only his good knowledge of economics but also his perfect command of mathematics.

Wassily Leontief

Bioeconomics and Sustainability

Essays in Honor of Nicholas Georgescu-Roegen

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11. Production and time: a flow–fund analysis*

Mario Morroni

INTRODUCTION

This chapter addresses Georgescu-Roegen's flow–fund model, which focuses on the time profile of production processes and makes it possible to analyze the way in which production processes combine in order to reduce input idle times. The attempt to make compatible the different productive capacities of indivisible inputs, and consequently to decrease input unutilized capacities, is an important factor in determining the scale of production and the organization of markets.

In the following pages the main characteristics of the matrix of production elements are presented. The matrix, which may be considered a development of Georgescu-Roegen's production theory, allows for the measuring of the level of input utilization at each stage and the analysis of the relationships between the various intermediate stages which form the elementary process. For purposes of empirical analysis, the matrix of production elements will be transformed into three tables concerning the product, the process and the production unit, respectively.

The chapter is in four sections. The first examines Georgescu-Roegen's production theory and its methodological roots. The second presents the model based on the matrix of production elements. The third treats the tools for applied analysis, making reference to a case study of a firm producing appliances for telecommunications. The fourth illustrates the usefulness of the proposed scheme in dealing with analytical problems linked to changes in the dimension of scale and degree of flexibility. In this last section some conclusions about the analytic perspectives offered by this line of research are drawn.

GEORGESCU-ROEGEN'S PRODUCTION THEORY: EFFICIENCY AND ORGANIZATION

The contribution of Georgescu-Roegen to the theory of production essentially consists of these three points: (1) the critical analysis of the meaning of the

production function;[1] (2) the theorem of substitutability of Leontief's static system;[2] and (3) the elaboration of a flow–fund model.[3]

The following pages primarily concern the third point, though some brief references are made to the methodological questions raised by the first point.

Logical Consistency and Degree of Abstraction

Georgescu-Roegen observes that, despite the analytical symmetry between the theory of consumption and that of production, there is a sharp asymmetry in the development of these two theories because production theory has not been subject to such extensive revisions as consumer theory. In Georgescu-Roegen's opinion, this was due to the fact that difficulties, linked to the measurability of utility and to preferences characterizing consumer analysis, did not seem to arise in the case of production, as 'a physico-chemical process'. Hence mathematical economists directed their efforts to defending consumer theory which seemed weaker than production theory ([1969] 1976, p. 72).

Georgescu-Roegen maintains that production theory presents even more serious analytical difficulties than consumer theory. These difficulties concern two different but connected analytical levels: (1) logical consistency, linked to the use of mathematical formalization, and (2) methodological conception, concerning the relationship between theories and facts. With respect to mathematical formalization, Georgescu-Roegen notes that, if we consider a map of isoquants

> to illustrate the substitution of capital for labour, we often speak of passing from hand-made . . . [products] to machine-made ones . . . . [But the] *product changes* from one recipe to another. . . . Surprising though it may be, the same semantic sin is absent from the theory of consumer behaviour. . . . Mathematics thus is more at home in the utility than in the production theory. (1986, p. 261, emphasis added) [4]

A similar 'semantic sin' regards inputs. In the production function, K must be the cardinal measure of homogeneous capital, and H the cardinal measure of homogeneous labor. However, an increase in fixed capital may cause, and indeed causes in most cases, a change in the quality of capital. An example may clarify this point. If we consider an excavating operation with two inputs, such as shovels and units of labor, it makes little economic sense to say that, when the production becomes capital-intensive, the number of shovels increases and the units of labor decrease. In the case of an excavating operation, an increase in capital can require, rather than a simple multiplication of the number of shovels, a change in the quality of capital, with a shift from shovels to a more sophisticated tool. Of course, the problem does not arise only with capital, but also with labor. In general, it is logical to think that a different organization of production determines a change in the quality of inputs by favoring the utilization of new types of workers and tools. Referring to the difficulty of having homogeneous inputs for substitutability, Georgescu-Roegen observes that capital goods

> K_i ... are not all qualitatively identical and, hence, have no common measure. For the same reason, there is no sense of speaking of the elasticity of substitution between homogeneous capital and homogeneous labor. [Physical] marginal productivity, too, comes out as an empty word. . . . All this shows that the theorems which adorn the theory of marginal pricing are in essence misleading analytical ornaments. In fact, to explain the adaptation of production to prices . . . we do not require the existence of either Neoclassical substitutability or marginal physical productivity. . . . Cost is the only element that counts in this problem. (1971, p. 244)

These words are indisputable, but at the same time it is difficult for a neoclassical economist to accept them because of the implications for the concept of marginal productivity.

To summarize, the internal logical consistency problem of the mathematical formalization of production is that production function cannot reflect the *qualitative transformations* that take place as a consequence of *quantitative changes* in products and inputs. This does not mean that Georgescu-Roegen was against the use of mathematics in economics: he was against its misuse.[5]

The discussion of the misuse of mathematics and the qualitative residual in production leads to a second point: the methodological problem concerning relationships between theories and facts that theories set out to explain. Georgescu-Roegen believes that theoretical work is concerned primarily 'with the problem of valid analytical representation of the relations between facts'.[6] Criticizing what he calls 'blind symbolism', he laments that often economists have been carried away 'by mathematical formalism to the point of disregarding a basic requirement of science; namely, to have as clear an idea as possible about what corresponds in actuality to every piece of our symbolism'.[7]

The 'total lack of concern for what the symbol-letters' of the production function 'stand for in actual terms' creates the tendency not only to ignore the *qualitative changes* that may occur as a consequence of *quantitative changes*, as we have seen above, but also to neglect the fact that there are two important distinct types of productive processes, the agricultural and the industrial, 'neither of which is described completely by the traditional production function' (Georgescu-Roegen, 1971, pp. 211–12; [1969] 1976, p. 73). The production function, expressed either in absolute quantities or in rates of variations per unit of time, indicates the relationship between the maximum obtainable output from a given level of inputs. Within the production function it is not necessary to consider the time profile because the most efficient organization of time profile of inputs is assumed. In other words, the production function tells us only what the corresponding system may do, not what it does according to the different possible situations, following different kinds of organization. It is precisely the absence of any reference to the organizational aspects and, in particular, to the time profile of use of inputs that prevents the production function from analyzing the important differences between agricultural and industrial processes. Georgescu-Roegen tries to overcome this failure of the production function by elaborating a flow–fund model which takes into account the dimension of time and organization.[8] The main characteristics of Georgescu-Roegen's flow–fund model will be examined in the following two sections.

Flows and Funds

Georgescu-Roegen divides production elements into flows and funds. Flows are utilized in only one process as input, or they can emerge from a single process as output. A flow always corresponds to a certain quantity of material, substance or energy, which enters into or exits from the process in a given instant. A flow may result from either the decumulation of a stock or from the transformation made by the production process. A fund, on the other hand, provides its services in several processes that occur over time and consequently cannot be decumulated in an instant.[9] In short, fund elements represent the 'unchangeable agents' that transform the inflows into the outflows. Funds are conceived as agents of constant efficiency. Georgescu-Roegen assumes that funds are maintained (in efficiency) by outside processes. The flow elements are the objects changed by the agents ([1969] 1976, pp. 83–4, 86).

The same commodity may be a flow in one process and a fund in another. For instance, a computer is a flow in its process of production, but it is a fund in the process in which it provides its services. Likewise, 'the clover seed in a process the *purpose* of which is to produce clover seed is a fund, but in a process aimed at producing clover fodder, it is a flow' (ibid., p. 85).

The fund and flow definitions make it clear that there is no possibility of substituting a flow for a fund in the same production process. For example, in making a shirt one cannot replace the sewing machine, which represents a fund, with the fabric, which is a flow element transformed in the production process thanks to the services of the funds, or vice versa (Georgescu-Roegen, ibid., p. 65; 1992, p. 144). Consequently, with limitational flows (such as the fabric for the production of shirts) the physical marginal productivity cannot be computed, as in all forms of complementarity between inputs.

A production process is defined by its analytical boundaries that determine the object of our analysis; that is, the output flow, to which the elementary process is referred, and the input flows and fund used in that process. Thus the boundary of an elementary process defines the level of vertical integration. The choice of the analytical boundaries depends on the purposes of the analysis. For economic analysis, the analytical boundaries are necessarily chosen 'in strict reference to' production elements which are 'commodities'. In other words, a process that does not produce a commodity cannot be isolated, as with, for instance, the production of melted glass at the point where it pours into the rolling machine during glass manufacturing (Georgescu-Roegen [1969] 1976, p. 80). As pointed out by Piero Tani, the analytical boundary is considered in relation to the possibility of giving to various semi-processed products an 'independent existence' as commodities. In concrete terms, this means that they can be moved from one place to another, and therefore 'remain unaltered for a certain time outside the production process' (Tani, [1976] 1987, pp. 78–91; 1986, p. 211). Note that this interpretation of the analytical boundary of the production process is very close to the one adopted by Oliver Williamson in his definition of transaction.[10]

Let T_{EP} be the duration of an elementary process from the starting time (0), when the process begins with the input of raw materials, to the moment (T), when the process is completed with the production of a unit of the commodity under consideration, obtained through the transformation of those raw materials. For each individual element of the production process, whether input or output, Georgescu-Roegen determines a function of time within the closed interval $T_{EP} \in [0,T]$. The production process is thus represented by the following functional which is 'a relation from a set of functions to one function' (Georgescu-Roegen, 1971, p. 236):

$$0(t) = G[G_1(t), G_2(t), \dots, G_I(t), F_1(t), F_2(t), \dots, F_H(t), U_1(t), U_2(t), \dots, U_K(t)], \quad (11.1)$$

where $G_i(t)$ ($i = 1, 2, \dots, I$,) are the functions indicating, at any time t, the cumulative quantity of the ith outflow; $F_h(t)$ ($h = 1, 2, \dots, H$) are the functions indicating, at any time t, the cumulative quantity of the hth inflow; and $U_k(t)$ ($k = 1, 2, \dots, K$) are the functions indicating, at any time t, the degree of use of the kth fund. By convention, we can give a positive sign to the functions of outflows $G_i(t)$ and a negative sign to both the functions of inflows $F_h(t)$ and the functions of funds $U_k(t)$.

$G_i(t)$ are non-decreasing monotonic output functions of t, while $F_h(t)$ are non-increasing monotonic inflow functions of t. Functions $G_i(t)$ and $F_h(t)$ may be discontinuous because some flows may be accumulated or decumulated in a single instant. The value of $U_k(t)$, that indicates the degree of use of the fund, may vary between 0 (presence with no use) and –1 (maximum use of the productive capacity of the fund). Therefore functions $U_k(t)$ show the fund idle times when the value is zero.[11]

Figure 11.1 provides an illustration of a possible shape of these functions in the case of the following list of coordinates:

- output flows: (1) product G_1 (t); (2) waste G_2 (t);
- input flows: (3) from nature $F_1(t)$; (4) raw material F_2 (t); (5) energy $F_3(t)$;
- funds: (6) worker $U_1(t)$; (7) loom $U_2(t)$; (8) area of plant $U_3(t)$.

In the list of flow coordinates, two outputs are shown (the product and waste), but we can assume any number of output flows.[12] Functions $U_k(t)$ allow for the various time profiles of funds to be compared. For instance, in Figure 11.1 the time profiles of the three funds considered are different because of the unequal distribution of the funds times of presence and utilization times. The worker is present only when the process is in operation. By contrast, the loom, in the same example, is present during the whole duration of the elementary process, even if it remains inactive during the pauses when the process is suspended – unless, as we shall see, it is used in other processes. The time of presence is indicated in Figure 11.1 with a dotted line and utilization time with a continuous line.

The flow–fund model allows for the study of the arrangement of inputs specific to each production. This makes it possible to highlight the differences, so relevant to economic analysis, between farming and manufacturing processes, and within manufacturing between craft production and the factory system.

Efficiency and Organization

The main differences among agriculture, craft and factory production systems concern the ways in which the elementary processes are organized. Apart from some very few exceptions, the processes in agriculture are arranged in parallel. In the craft system the elementary processes are in series, performed one after another. In a factory, the elementary processes are arranged in line; equal groups of processes start together one after the other with every interval corresponding to an equal fraction of the duration of the elementary process (T_{EP}). Functions of the degree of utilization of funds $U_k(t)$, in relation to time, may help to clarify this point and to illustrate the differences between parallel, series and line production.

In agriculture, all processes begin at the same time and are performed in parallel because, generally, they must start at 'the appropriate phase of the climatic annual cycle in each place' (Georgescu-Roegen, [1969] 1976, p. 98). Production in parallel is illustrated in Figure 11.2. For the sake of simplicity, this figure represents the case of only a single fund with a productive capacity of three elementary processes performed in parallel, although any number of processes in parallel could be considered. In agriculture, every elementary process usually employs only a very small part of the productive capacity of the land fund. Figure 11.2 shows that production in parallel allows for a better use of the productive

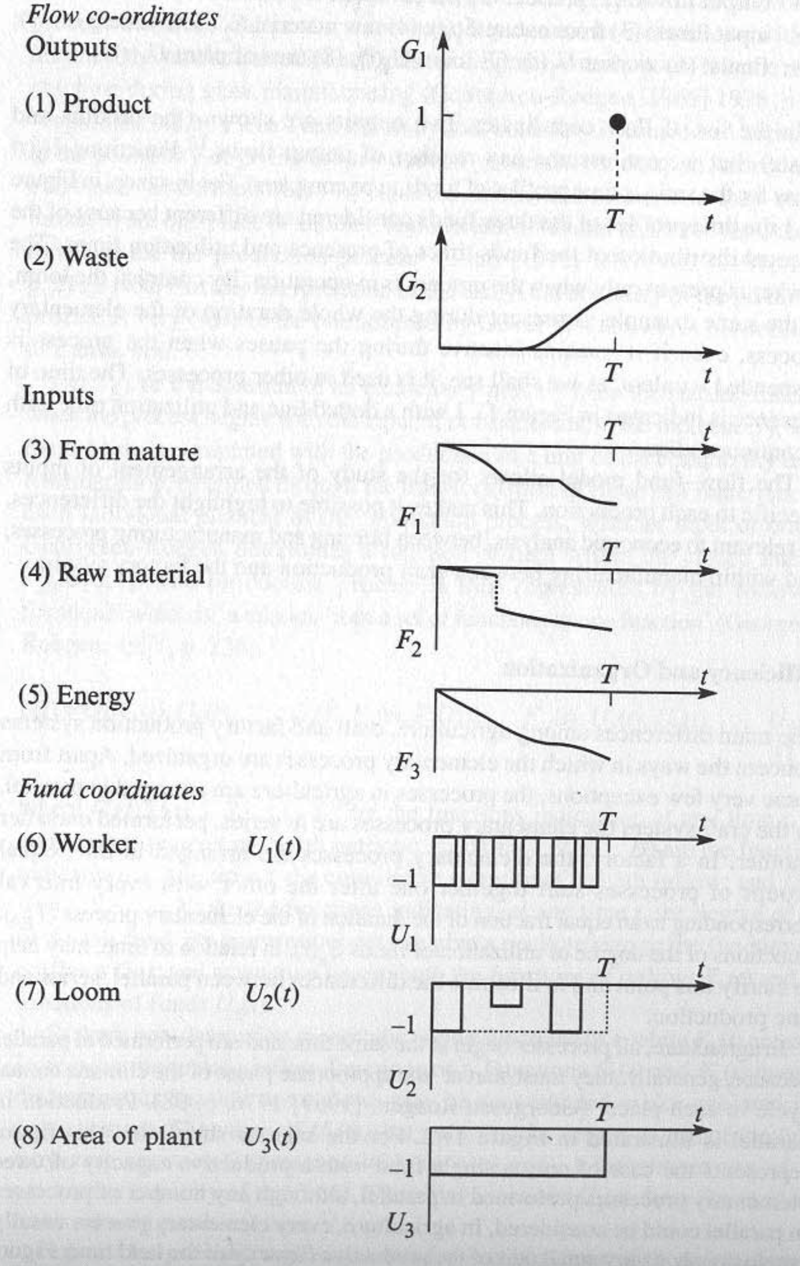
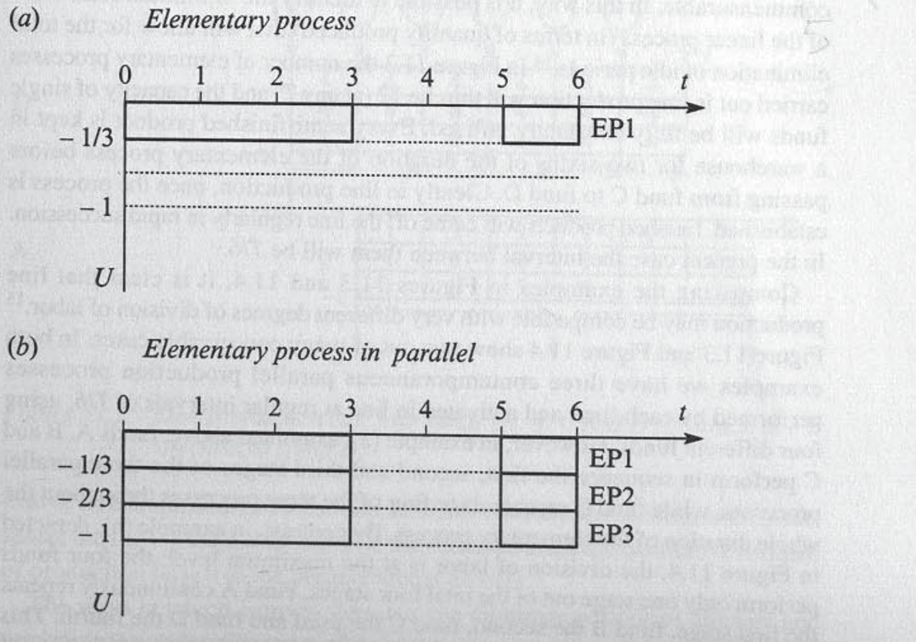


Figure 11.1 Flow and fund coordinates

capacity of funds. However, if the fund under consideration undergoes periods of idleness, parallel production is not sufficient to eliminate the excess of productive capacity. This is the case of agricultural production, in which there is some idleness with respect to land, capital and labor 'over the production period and complete idleness on every fund factor during the rest of the year' (ibid., p. 99). High idle times of funds in agriculture inevitably involve high unit cost.

Long idle times for tools also characterize craft production in which a worker performs a variety of heterogeneous operations moving from one tool to another. With craft production, when an artisan performs one particular operation, the tool of all other operations remains idle. Usually in craft production, tools are not very expensive, but it is clear that, the greater the cost of the equipment used, the more profitable it is to reduce idle times of funds. Craft production can be characterized by high flexibility because production in series allows very small batches or even single units to be produced.[13]

The only way to reduce idle time of funds is to move toward line production adopted in the factory system. In agriculture, this possibility is restricted to



Note: The duration of the elementary process is 6 units of time, of which 2 units are idle time.

Figure 11.2 Parallel production with idle time particular climatic situations or to the use of some specific techniques (greenhouses, chicken factories and so on). In manufacturing, the possibility of changing from craft production to the factory system is linked to the extension of the market. An increase in demand makes it possible to reshape the organization following the principles of line production and the division of labor by means of activating one process after another in a predetermined sequence. To illustrate this point, consider the very simple case of Figure 11.2 applied now to manufacturing production. In Figure 11.2, an elementary process uses just one indivisible fund (say a stove) at one-third of its productive capacity. This process is active for three-sixths of the duration of the elementary process, inactive for two-sixths and active again for the remaining one-sixth. In order to eliminate idle times, it is necessary to employ four different units of the same fund (A, B, C and D), producing in parallel three elementary processes that start at regular intervals of $T/6$, where T is the duration of the elementary process (see Figures 11.2 and 11.3). This regular interval in the activation of the elementary processes, which permits the elimination of idle times, corresponds to the maximum common divisor of the intervals of use and idleness of the element involved (in our example 1), on the assumption that these intervals are commensurable. In this way, it is possible to identify the 'minimum scale size' of the linear process (in terms of quantity produced) that will allow for the total elimination of idle periods.[14] In Figure 11.3 the number of elementary processes carried out in line production will thus be 12 (at any T) and the capacity of single funds will be fully constantly utilized. Every semi-finished product is kept in a warehouse for two-sixths of the duration of the elementary process before passing from fund C to fund D. Clearly in line production, once the process is established, finished products will come off the line regularly in rapid succession. In the present case the interval between them will be $T/6$.

Comparing the examples in Figures 11.3 and 11.4, it is clear that line production may be compatible with very different degrees of division of labor.[15] Figure 11.3 and Figure 11.4 show two out of many conceivable cases. In both examples we have three contemporaneous parallel production processes performed by each fund and activated in line at regular intervals of $T/6$, using four different funds. However, in example (a), examined above, funds A, B and C perform in sequence the first, second and third stages of the three parallel processes, while fund D repeats stage four of the three processes throughout the whole duration of the elementary process. By contrast, in example (b), depicted in Figure 11.4, the division of labor is at the maximum level: the four funds perform only one stage out of the total four stages. Fund A continuously repeats the first stage, fund B the second, fund C the third and fund D the fourth. This example demonstrates that line production is a precondition for the division of labor, but does not in itself make the technical division of labor necessary.[16] Therefore the organizational outcome is not univocally determined but is the

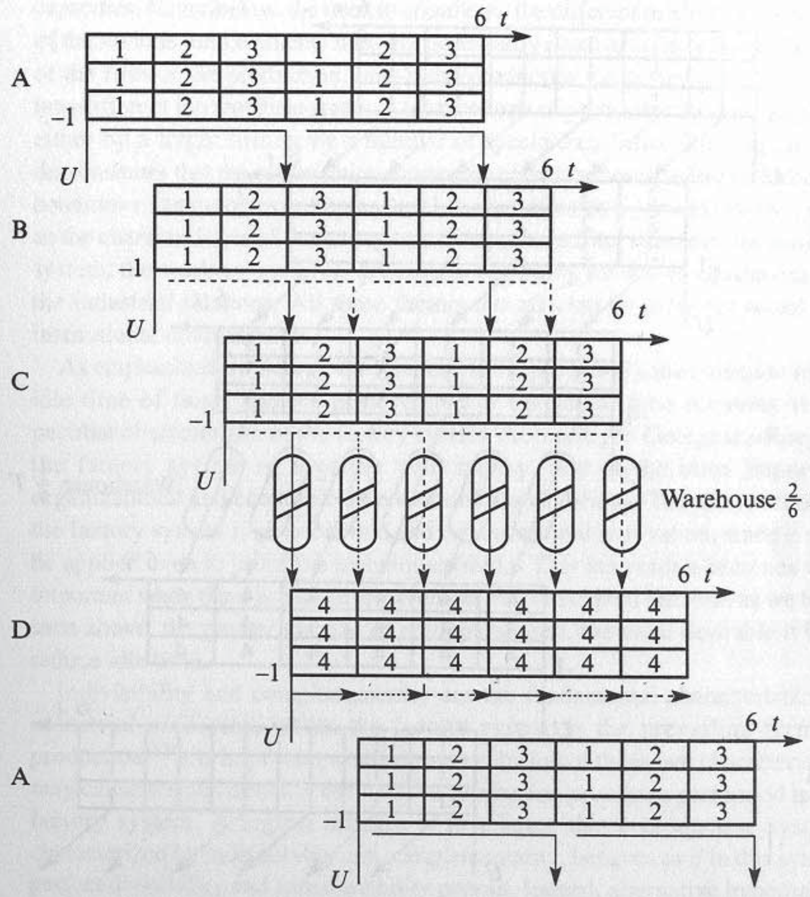


Figure 11.3 Line production (a): four funds (A, B, C and D) of which one is specialized (fund D)

fruit of an entrepreneurial choice depending on environmental conditions. In this sense, the flow–fund model can take into consideration the qualitative residual of production linked to the organizational aspects.

The ways in which a production unit can eliminate periods of idleness and minimize the underutilization of the productive capacity of the different fund elements may affect its size and organizational structure. The organization of processes and the size of the production unit reflect the necessity of minimizing

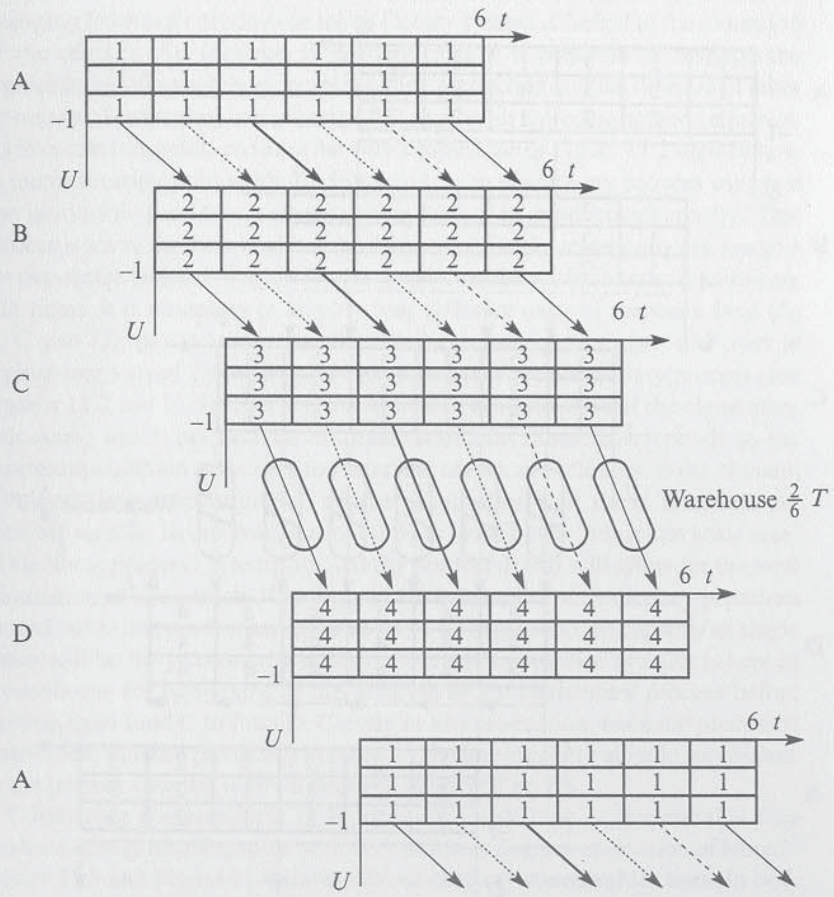


Figure 11.4 Line production (b): four specialized funds (A, B, C and D)

both idle time and the underutilization of the productive capacity of funds, by synchronizing the use intervals in the various processes and by balancing the productive capacities of various phases. In order to avoid using individual machines at suboptimal levels, the overall scale of a production unit must be equal to the lowest common multiple of the productive capacities of the individual machines. Following Babbage's Law, once a scale is established that eliminates idle time for equipment, any expansion in the scale of production has to occur in discrete jumps of (integer) multiples of the scale achieved (Landesmann, 1986, pp. 308–9).

In the presence of specialized and indivisible funds, a high volume of production is often necessary to render compatible their different productive capacities. Nevertheless, the need to coordinate the different productive capacities of the various fund elements does not necessarily involve an increase in the size of the firm or the production unit. If the production processes can be divided into different intermediate stages, a high volume of production may be obtained either by a larger firm or by a number of specialized firms. Once again, this demonstrates that the organizational outcome cannot be based solely on technical conditions, but involves entrepreneurial choices affected by several factors, such as the characteristics of the entrepreneurship, the market structure, the training system, the workers' *concrete knowledge* regarding the use of equipment and the industrial relations. All these factors are affected by different social and institutional environments.

As emphasized by Georgescu-Roegen (1971, pp. 248–9), the reduction of the idle time of funds and the achievement of maximum time economy is the peculiar characteristic of the factory system. According to Georgescu-Roegen, the factory system is, together with money, one of the most important organizational and economic inventions of human beings. The introduction of the factory system is an economic and organizational innovation, since it may be applied even to primitive techniques (ibid.). This innovation becomes very important when there is a large involvement of fixed capital because, as we have seen above, the greater the cost of equipment used, the more desirable it is to reduce idle time.

Indivisibility and complementarity are the fundamental characteristics of industrial processes, where the factory system is the prevailing form of production.[17] It is important to stress that exclusion of these two characteristics may cause serious errors in the study of production processes performed in the factory system. A logical mistake is to assume that a productive system, characterized by indivisibility and complementarity, behaves *as if* in this system perfect divisibility and substitutability prevail. Indeed, alternative hypotheses, about the characteristics of indivisibility and complementarity of production processes, lead to quite different results insofar as the organization and size of firms, the innovative activity and the market structures are concerned.

THE MATRIX OF PRODUCTION ELEMENTS

This section is dedicated to a development of Georgescu-Roegen's flow–fund model. In the following pages the methodology based on the matrix of production elements will be presented.[18] The matrix of production elements enables us to deal with interconnections between the different intermediate stages and to take into account the quantitative, temporal, organizational and dimensional aspects of production.

Let us begin with the definitions of an elementary process and decomposability. The elementary production process is the process whereby an economically indivisible unit of output is obtained by means of an elementary technical unit, or chain of elementary technical units, operating in sequence.[19] An elementary technical unit is the minimum set of production elements that can be activated separately for producing a unit of output.

A production process is decomposable when it is possible to identify individual intermediate stages (or subprocesses) separable in time and space, and when the product of one stage is a commodity utilized as an input in at least one other stage (Tani, 1986, p. 211). As we have seen in the previous section, the number of intermediate stages to include depends on the aims of the analysis. The elementary process considered may then embody any degree of vertical integration.

The output is defined by its specific characteristics and its date of availability. Following the methodology proposed by Stan Metcalfe and Pier Paolo Saviotti,[20] a product may be defined by two sets of characteristics, describing the internal structure of the technology and the service performances for users. These two sets of characteristics are represented by two n-vectors $\mathbf{x}$ and $\mathbf{y}$, whose components indicate respectively the technical and the service characteristics of the product:

$$\mathbf{x} = [x_1, x_2, \ldots, x_n] \tag{11.2}$$

$$\mathbf{y} = [y_1, y_2, \ldots, y_n] \tag{11.3}$$

The elementary process necessary to produce the output, associated with vectors $\mathbf{x}$ and $\mathbf{y}$, can be represented by a matrix of functions of time, which I call matrix of production elements or matrix $\mathbf{L(t)}$. Matrix $\mathbf{L(t)}$ refers to the ex ante analysis of an organized elementary process. That is to say, a 'plan' of a feasible production process, using a number of funds that renders their different productive capacities compatible. Each element of matrix $\mathbf{L(t)}$ indicates, at time t, the cumulative quantities of production elements going in or out at each intermediate stage of a decomposable organized elementary process. Matrix $\mathbf{L(t)}$ has as many columns as there are intermediate production stages, and as many rows as there are production elements, such that:

$$\mathbf{L(t)} = \begin{bmatrix} G_{ij}(t) \\ F_{hj}(t) \\ U_{kj}(t) \end{bmatrix} \tag{11.4}$$

In matrix $\mathbf{L(t)}$, $G_{ij}(t)$ indicates the functions of the ith ($i = 1, 2, \ldots, I$) output flow or intermediate input/output flow, entering (or leaving) the production of the jth ($j = 1, 2, \ldots, J$) intermediate stage; $F_{hj}(t)$ indicates the functions of the hth ($h = 1, 2, \ldots, H$) input flow, entering the production process of a given jth intermediate stage; and finally $U_{kj}(t)$ indicates the functions of the services of the kth ($k = 1, 2, \ldots, K$) fund element, used in the production of the jth stage. Let us assume that the number of elements utilized is finite and that each element is a homogeneous entity measurable in cardinal terms. As mentioned in the previous section, a positive sign is given to the functions of output flows $G_{ij}(t)$, and a negative sign to the functions of input flows $F_{hj}(t)$ as well as funds services $U_{kj}(t)$.

Of course, the total quantity produced during the elementary process depends on the way in which the elementary process is organized. This quantity may vary according to whether the elementary process is organized in series, in sequence or in parallel, or according to the time of various pauses and to the size of inventories.

For purely illustrative purposes, let us look at the example shown in Figure 11.5 of an organized elementary process, decomposable into three elementary intermediate stages, that employs two input flows and four funds. Assuming that each intermediate stage produces a waste product, we have six output flow functions (one function of the final output flow $G_{5,3}(t)$, two of the intermediate output flows $G_{1,1}(t)$ and $G_{3,2}(t)$, and three of the waste flows $G_{2,1}(t)$, $G_{4,2}(t)$ and $G_{6,3}(t)$). It can be seen that the intermediate output flow of one sub-process becomes an input flow in the following one ($G_{1,1}(t)$ becomes $G_{1,2}(t)$, and $G_{3,2}(t)$ becomes $G_{3,3}(t)$]. With regard to input flows coming from outside the production unit, the first is utilized only in the first intermediate process (function $F_{1,1}(t)$), while the second input flow is used in all three intermediate stages (functions $F_{2,j}(t)$). Each of the first three funds are used in only one subprocess (respectively, functions $U_{1,1}(t)$, $U_{2,2}(t)$ and $U_{3,3}(t)$), while the fourth fund is used in all the intermediate processes (functions $U_{4,j}(t)$). Finally, we have to consider the functions regarding organizational inventories (functions $U_{5,j}(t)$), the semi-processed output in technical inventories (functions $U_{6,j}(t)$) and the quantity of output constantly in progress on machines (functions $U_{7,j}(t)$).

Matrix $\mathbf{L(t)}$ constitutes a concise representation of the elementary process, which makes it possible to take into account the specific characteristics of production techniques: in particular, the indivisibility of processes and production elements, the complementary relationship between processes and production elements, and the organization and time profile of production. As mentioned, the matrix of production elements brings out the links between intermediate stages along the production *filière* (or cluster).[21]

$$\mathbf{L}(t) = \begin{bmatrix} G_{1,1}(t) & G_{1,2}(t) & - \\ G_{2,1}(t) & - & - \\ - & G_{3,2}(t) & G_{3,3}(t) \\ - & G_{4,2}(t) & - \\ - & - & G_{5,3}(t) \\ - & - & G_{6,3}(t) \\ F_{1,1}(t) & - & - \\ F_{2,1}(t) & F_{2,2}(t) & F_{2,3}(t) \\ U_{1,1}(t) & - & - \\ - & U_{2,2}(t) & - \\ - & - & U_{3,3}(t) \\ U_{4,1}(t) & U_{4,2}(t) & U_{4,3}(t) \\ U_{5,1}(t) & U_{5,2}(t) & U_{5,3}(t) \\ U_{6,1}(t) & U_{6,2}(t) & U_{6,3}(t) \\ U_{7,1}(t) & U_{7,2}(t) & U_{7,3}(t) \end{bmatrix}$$

Figure 11.5 Matrix of the production elements

To obtain the functions of revenue and costs, we must multiply each function of the matrix $\mathbf{L(t)}$ respectively by the price of each output, denoted by P_i, and by the cost of each input, denoted by C_h for the input flows and C_k for the input funds. We then have:

$$\mathbf{Z(t)} = \begin{bmatrix} G_{ij}(t) \cdot P_i \\ F_{hj}(t) \cdot C_h \\ U_{kj}(t) \cdot C_k \end{bmatrix} \tag{11.5}$$

Let us suppose that (1) the input flows and funds services (machines, equipment and premises) are paid for at the beginning of the elementary process, and (2) labor and the output of the production unit are paid for at the end of the process. The monetary cost of labor can be calculated very simply. The number of hours of presence is multiplied by the hourly cost of the corresponding level of occupation. However, for funds consisting of equipment and machines, the calculation of cost is more complicated, since the cost of their services depends, not only on the time of presence, but also on the intensity of use. It may be postulated that each machine during its lifetime is able to carry out a finite quantity of production processes. On the basis of the intensity of its use, one can then determine the period of technical depreciation and thereby calculate the cost per hour of use.

For the real estate of an establishment the calculation of the hourly cost presents few difficulties, as it is given by means of the relation between the annual depreciation and the total hours worked. The hourly cost of the products in progress and semi-finished products held in warehouses is measured on the basis of the rate of interest on the value of the locked up monetary capital. Since it is assumed that the input flows are paid for at the beginning of the process, the cost of inventories increases in conjunction with the duration of the elementary process (owing to interest).

The hourly cost of fixed capital (equipment and premises) depends on the degree of utilization and it is therefore not independent of the production organization. In short, the relationship between costs and organization is reciprocal: costs of inputs affect organization, but at the same time organization influences the level of average input costs.

EMPIRICAL APPLICATION

In the preceding section we have seen that an elementary process can be represented by the functions of revenue and cost which are listed in the matrix of production elements, and that the characteristics of the output can be represented by two vectors. For purposes of empirical analysis it is preferable to transform information contained in these tools into three separate tables, sharply distinguishing the different levels of analysis: product, process and production unit. This transformation allows one to standardize the data of the various elementary processes under consideration in order that a homogeneous database can be created on which to make the comparisons required for empirical analysis. In other words, the three final tables for the empirical analysis are designed in order to transform information present in the theoretical model into numerical data, thus allowing comparisons among processes. In the output table, data on the technical and service characteristics of output retain the same form as in the original vectors. In this case no transformation is needed. By contrast, the transformation problem arises with the matrix $\mathbf{Z(t)}$ presented above because information deducible from the shapes of the functions of production elements in relation to time have to be transformed into comparable data. The matrix $\mathbf{Z(t)}$ provides information on revenue and costs, on the cumulative quantities of production elements and, at the same time, on the time profile of the production process which is linked to the organization of production and to the structure of pauses and idle times. The information provided by matrix

Z(t) is transformed into numerical data following this method: (1) prices, costs and the cumulative quantities of single production elements are included in the process matrix, which indicates the elementary production process cost and productivity; (2) data on time profile and on process organization are included in the organizational scheme.

As we shall see, the output table and the organizational scheme provide additional data that are not directly deducible from the theoretical model but that may be useful to empirical analysis. In the following pages the three final tables concerning respectively, the output, the process and the production unit, will be presented in some detail using real data from a case study. The case study must be considered a mere numerical example, useful for explanatory and descriptive reasons. Data for the case study have been gathered by questionnaire from firms and put onto on an electronic sheet. The construction of the three final tables has been facilitated by the programme *KRONOS Production Analyzer* which has been designed for the input, computation and printout of data derived from firms.[22]

The Output Table

The output table (Table 11.1) represents the characteristics of the product under consideration.[23] The output table is divided into five blocks. The first block (a) concerns the technical and service characteristics of the product which are the components of vectors **x** and **y** mentioned in the previous section. In the case study a production unit specializing in telecommunication devices has been interviewed. This production unit engages in differentiated production, with a very wide range of goods for telecommunication networks, such as civil communication systems and high-security communication systems (for police and government agencies, and air traffic control devices). Among the output mix, the production of a professional two-way radio, model H9, is analyzed in the case study. This professional two-way radio is representative of the output mix constituting almost 50 per cent of electronic devices sold by the production unit. For the sake of simplicity, model H9 is identified only by the following characteristics: range of frequency, power, communication protocol, display, keyboard, size and weight (see Table 11.1). This list may be widened according to the purposes of the analysis.[24]

Block (b) is dedicated to the production time of the output. Production time may be considered an inherent qualitative characteristic of the product and often represents important elements of competitiveness. At any given rate of efficiency – which is expressed by the ratio between output and inputs – there may be very different durations of the production process. In many manufacturing and service activities a reduction of the duration, or response time, increases the efficacy of production, represented by the adequacy of production in relation to the market.

Table 11.1 Output table: two-way radio, model H9

(a) Characteristics			
Range of frequency		400 Mhz	
Power		2 Watt	
Protocol of communication (private and public networks)		1327 Mpt	
Display		liquid crystals	
Keyboard		18 keys	
Dimensions		200 × 69 × 30mm.	
Weight		400g (approx.)	
(b) Times			
Net process time		1:26:42 hours	
Times of the technical inventory:			
product in progress		2 days	
gross process time		3 days	
Times of organizational inventory and in-house transport:			
semi-finished mechanical product		76 days	
electronic components		76 days	
product in progress		6 days	
two-way radio		76 days	
Working time		159 days	
Net duration		160 days	
Response time		90 days	
Gross duration		220 days	
(c) Annual production			
	output under cons.	total production	percentage
In-house	19312.00 units	19312:00:00 units	100.00
External	0.00 units	0:00 units	
Sold	19312.00 units	19312.00:00 units	100.00
(d) Adaptability and utilization level of the plant			
		MIN	MAX
The range of the variation of the volume of production with increases in the average transformation cost less than 5%		–50.00%	60.00%
(e) Flexibility			
Minimum produced lot		50.00 units	

Table 11.2 shows the various intervals of time which compound the gross duration of an elementary process. The gross duration can be divided into the following components.

1. Net process time, which is equal to the sum of the net machine time of the elementary technical unit utilized in the production process, including loading–unloading, set-up and maintenance times. The net process time excludes the time of internal transport and all technical and organizational pauses which allow the use of the same fund in other elementary processes.[25]
2. Technical inventory time, the time needed to mature or settle the production elements.
3. Gross process time, equal to the net process time plus the technical inventory time.
4. Organizational inventory and internal transport times, caused by the pauses required in order to make the single phases of the process compatible. Internal transport times correspond to the time necessary for the shift of the work in progress from one operation to another.
5. Working time, the sum of the gross process time and the organizational inventories and internal transport time.
6. Net duration of the elementary process, defined as the time between the moment when the input flows begin to enter the process and the moment when the finished product, obtained by transforming these inputs, is ready for sale. Net duration includes seasonal pauses, night stoppages and Sunday or holiday times.
7. Response time, the time necessary from the instant of the arrival of customers' orders to delivery of the finished product.
8. Gross duration, the time required to obtain raw materials, from the moment when the production unit orders raw materials (or semi-finished goods) to the moment when the elementary process is completed.

Sometimes the difference between net process time and net duration of the process may be high owing to the presence of large inventories and long pauses. For instance, in Table 11.1 the net process time is about an hour and a half, while the net duration reaches 160 days. Technical inventories extend the process by two days because it is necessary to keep the product operating for 48 hours in order to verify proper functioning of print circuits. Organizational inventories have a much larger weight in relation to technical inventories, even if they do not seem to be oversized for this kind of production. Their cost is registered in Table 11.3 in the following section.

In our example, the response time, that is, the time from the instant of arrival of customers' order to delivery of the finished product, is 90 days, against a net duration of 160 days. The response time is lower than the net duration because

the organizational inventories make it possible to cope with orders in a shorter time in relation to the duration of the process.

Table 11.2 Components of the gross duration of the elementary process

Net process time	Technical inv. time	Organizational inv. time	Pauses (nights) holidays, etc.)	Delivery time for raw materials
Gross process time				
Working time				
Net duration				
Gross duration				

Block (c) of the output table is dedicated to annual production of the output under consideration, in absolute value and in percentage share in relation to the total range of outputs of a particular model (and not to the entire range of products). This section distinguishes between internal production and external production supplied by subcontractors.

Block (d) concerns the characteristics of adaptability. A production of a given commodity is adaptable if it does not lose efficiency when there are changes in the quantity produced. Included in this block is the production variation range – above and below current output – within which the average transformation cost varies by less than 5 per cent. The transformation cost is the sum of direct cost and machine costs. The degree of adaptability depends on how the production is organized. For instance, adaptability may be attained by means of (1) numerical flexibility (changes in the number of employees or in the hours per employee); (2) functional flexibility (the employees' mobility from one task to another); (3) hiring equipment; (4) keeping inventories that serve to compensate for fluctuations in demand; (5) retaining old machines and equipment, that are already depreciated but are brought back into use when demand is particularly high; (6) employing subcontractors.

It is worth noting that maintaining large inventories increases both the adaptability of individual lines of production and the duration of the production process (indicated in block (b) examined above) and consequently the costs of the locked monetary capital, as calculated in the process matrix, to be examined in the next section. Employing subcontractors allows for greater adaptability because fixed cost is reduced and the problem of coping with the variability of demand is shifted to the supplier.

The adaptability of the production considered in our numerical example is very high: production of the two-way radio H9 may be increased or decreased (up 60 per cent or down 50 per cent) with negligible variations in transformation costs (within 5 per cent). As we shall see in the following sections, where the process matrix and organizational scheme will be examined, the large 'downward adaptability' (when production decreases) is the result of the low burden of equipment on transformation cost, while the high 'upward adaptability' (when the production increases) is due to the large reserve of productive capacity linked to the low utilization of equipment.

The last block (e) of the output table records the lot of production. A small number of goods per lot indicates the potential for high operational flexibility, that is, the capacity for varying the composition of the mix of outputs. Production lot size is just one of several elements that influence flexibility. The degree of flexibility is also linked, for instance, to reset times, the net working time of individual machines or the size of inventories (associated with the amount of time during which the various flows are unused) and their cost (included in the process matrix).

In the production under consideration, the lots equal fifty units (see Table 11.1). The size of the lot, in this case, is not very significant. It gives us no information about the degree of production flexibility for the two lines, because they are utilized in a continuous manner exclusively for production of the output considered. Variations within the range of products are attained through the high adaptability of individual production lines.

The Process Matrix

The process matrix denotes the quantity of flows and the service time of funds necessary to produce a unit of output. More precisely, the process matrix shows dated input and output flows, and fund services, required by an elementary technical unit (or chain of elementary technical units) to produce one economically indivisible unit of the product emerging from a given organized elementary process. In the process matrix, the columns show the different intermediate stages considered. The rows present the quantities of input and output flows and productive services provided by the fund elements necessary to produce one unit of the final commodity. The unit of the final commodity obviously appears as the output of the last intermediate stage.

Since the output of an elementary process is by definition equal to an economically indivisible unit of the corresponding commodity, the quantities of input flows and services of funds in the process matrix represent indices of physical cost or technical coefficients of production for the elementary process under examination. As in the input–output analysis, these coefficients correspond to the quantities of production elements necessary to produce one physical unit of the final commodity. From the inverse of the input flows and services of funds we obtain an index of average physical productivity for each production element.[26]

The process matrix is divided into three blocks: block (a) concerns the flows of output, waste and services provided by subcontractors, block (b) deals with input flows, and block (c) is devoted to services provided by funds (workers, machines and the estate) and inventories. To the columns that register the quantity produced or used in the various intermediate stages, three columns are added. They are (1) the sum of quantities produced or utilized in the elementary process (the quantities in each line are homogeneous and therefore addable); (2) the unit price of individual elements of production; and (3) revenue and costs obtained by multiplying the total physical quantities by their respective prices.

In Table 11.3 there is just one column to indicate the quantities of flows and the times of services of funds, since, for the sake of simplicity, the elementary process has not been decomposed into its intermediate stages. However, each individual production line might be divided into three possible intermediate stages: automatic assembly (one machine), manual assembly, and automatic performance check (two machines).[27] The process matrix registers the quantities of the various production elements, employed in their specific measurement units (physical units for flows and time units for services provided by funds). In our numerical example, computation of the quantities of flows of input is very simple because an assembly kit given by the various components utilized has been considered. It is therefore unnecessary to mention the components individually.

The cost of services provided by workers is obtained by multiplying the number of hours of presence by the hourly cost of the corresponding level of occupation. The hourly cost of services of equipment used is calculated on the basis of depreciation data supplied by firms. To simplify, I have considered maintenance costs as a percentage of the hourly cost of plant services.[28] Hence the total cost of equipment services is given by the interest, the depreciation and the cost of maintenance. The hourly cost of equipment depends on intensity of use and idle time; that is, on the production organization.

As far as the first column of the process matrix is concerned, it should be noticed that the service time of individual machines corresponds to the various net process times, while the service time of the real estate of the establishment (in the last row) corresponds to the net process time of the elementary process as a whole.

As we have given a positive sign to output flows and a negative sign to input and fund service flows, the sum of the elements of the last column gives us a gross margin that indicates the gross profitability of each intermediate stage.

In the case study, mechanical and electronic components represent by far the largest share of industrial cost (69 per cent), while the cost of workers' services, equipment, real estate and inventories is very low by comparison (27 per cent).

Table 11.3 *Process matrix: two-way radio, model H9*

	Quantity	Unit price, unit costs	Price, costs
(a) *Output and waste flows: subcontracted services*			
Two-way radio (output)	1.00 units	1300000.00 L/unit	1300000.00 L
Waste of the final product	0.06 units	–455000.00 L/unit	–29050.07 L
(b) *Input flows*			
semi-finished mechanical product	–1.00 kit	55000.00 L/kit	–55000.00 L
Electronic components	–1.00 kit	350000.00 L/kit	–350000.00 L
Material used	–1.00 kit	50000.00 L/kit	–50000.00 L
(c) *Services of the funds*			
Workers:			
floor manager 8 level	–0:04:53 hours	50955.41 L/hour	–4142.50 L
technician 6 level	–0:04:53 hours	35668.79 L/hour	–2899.75 L
assistant 5 level	–0:48:47 hours	32611.46 L/hour	–26512.01 L
assistant 4 level	–1:37:33 hours	20382.17 L/hour	–33140.02 L
Machines:			
automatic assembly	–0:12:52 hours	84458.78 L/hour	–18123.45 L
equip. for manual assembly	–0:50:06 hours	1550.21 L/hour	–1294.53 L
automatic check	–0:23:44 hours	65476.85 L/hour	–25890.64 L
Technical inventories:			
product in progress	–0.01 units	55232.88 L/unit	–572.01 L
Organizational inventories:			
two-way radio (output)	–0.21 units	156000.00 L/unit	–32311.52 L
semi-finished mechanical product	–0.21 kit	6600.00 L/kit	–1367.03 L
electronic components	–0.21 kit	42000.00 L/kit	–8699.25 L
product in progress	–0.02 units	84000.00 L/unit	–1304.89 L
Plant area(400sqm)	–1:26:42 hours	15255.03 L/unit	–22044.57 L

The low share of the cost of machinery and the high share of raw materials and components over transformation cost determine the large 'downward adaptability' of the output considered. In short, when the two-way radio production diminishes, the cost of input flows lessens proportionately, while the unit cost of machinery increases. However, this increase is irrelevant because of the low burden of machinery cost on transformation cost.

Industrial cost and transformation costs represent, respectively, only 51 per cent and 46 per cent of the price.[29] Consequently, the production considered is characterized by a very high gross margin (118 per cent on transformation costs and 136 per cent on direct cost). The high gross margins depend on the large share of (non-industrial) general fixed costs, due to administration, planning, marketing and R&D costs. The large share of (non-industrial) general fixed costs represents an element of rigidity because a decrease in the total volume of production would cause a rise in the total unit cost. In this case, a strong adaptability of individual production line does not involve an equally strong adaptability of the total volume of the production.

The Organizational Scheme of the Production Unit

The organizational scheme provides indications for dimensional, temporal and organizational aspects of the production unit. It is divided into two blocks, concerning workers and equipment. The first block indicates the distribution of different occupational positions among workers according to shifts, sex, age and educational level. It also indicates actual and contractual average weekly time. Actual and contractual weekly time may diverge owing to factors such as overtime, absenteeism and temporary layoffs. Table 11.4 shows that, for the year under consideration, contractual worktime is equal to actual worktime.[30]

The first block of the organizational scheme examines the distribution of jobs according to tasks, occupational positions and skills. The various occupations involve tasks that often require the performance of different jobs. In other words, jobs are subsets of tasks. The content of tasks is valued on the basis of the amount of time devoted to different jobs, such as (1) loading and unloading of machines and transport either from machine to machine or from an intermediate stage to another intermediate stage, (2) transformation of input flows, (3) organization, (4) maintenance work and (5) innovative activity.[31]

The second block is devoted to equipment. The main data concern the number of machines per type, utilization time, speed, set-up time, loading and maintenance breaks, and idle times. Utilization time of machines is linked to the organization of work shifts, indicated in the first part of the organizational scheme. Obviously, the unit cost of machines increases when idle time increases. Idle time of individual machines can be caused not only by the various pauses of the process – due to rules, norms and trade union agreements – but also by

Table 11.4 Organizational scheme of the production unit: Rifredi

(a) Workers

(a1) number of workers per shift, sex, age, education

	number	shifts	actual timetable hours/day	actual timetable days/week	days/year	contractual timetable hours/day	contractual timetable days/week
floor manager 8 level	5	1	7:51:00	5	200	7:51:00	5
technician 7 level	30	1	7:51:00	5	200	7:51:00	5
technician 6 level	30	1	7:51:00	5	200	7:51:00	5
assistant 5 level	20	1	7:51:00	5	200	7:51:00	5
assistant 4 level	40	1	7:51:00	5	200	7:51:00	5
worker 3 level	10	1	7:51:00	5	200	7:51:00	5

	sex		age			education			
	male	female	14–24	25–49	50–64	PS	JHS	HS	UN
floor manager 8 level	5	0	0	3	2	0	0	4	1
technician 7 level	30	0	0	25	5	0	20	10	0
technician 6 level	25	5	3	25	2	0	25	5	0
assistant 5 level	10	10	2	15	3	3	10	7	0
assistant 4 level	10	30	5	28	7	10	30	0	0
worker 3 level	5	5	5	5	0	6	4	0	0

(a2) percentage of average time per job

	loading–unloading	transformation	organization	maintenance	innovation	Total
floor manager 8 level	0	0	80	0	20	100
technician 7 level	0	20	50	20	10	100
technician 6 level	30	0	30	40	0	100
assistant 5 level	20	70	10	0	0	100
assistant 4 level	20	80	0	0	0	100
worker 3 level	0	70	0	30	0	100

(b) Machinery

(b1) number of each type, times and degree of utilization, maintenance and idle time

	number	speed	gross utilization hours/day	gross utilization days/year	loading–unloading hours/day	loading–unloading days/year
automatic assembly	3	–	8:00:00	240	00:30:00	0
equip. man. assem.	1	–	8:00:00	240	00:30:00	0
automatic check	6	–	8:00:00	240	00:30:00	0

	set-up operation hours/day	set-up operation days/year	maintenance hours/day	maintenance days/year	idle times hours/day	idle times days/year
automatic assembly	00:30:00	0	00:00:00	2:05	16:00:00	125
equip. man. assem.	00:00:00	0	00:00:00	0:05	16:00:00	125
automatic check	00:30:00	0	00:00:00	5	16:00:00	125

Note: PS = primary school; JHS = junior high school; HS = high school; UN = university.

a possible excess in the productive capacity, associated with weak demand or bottlenecks along the production line caused by difficulties in balancing different productive capacities of various machines. It is evident that, the higher the investment in fixed capital, the greater the need to decrease idle time. Finally, it should be noted that set-up time, indicated in the organizational scheme, is an important source of information for measuring the degree of the technical flexibility of machines which consists of the capacity to change quantities produced within a given mix of outputs.

Table 11.4 shows that, in the production unit under consideration, idle times are almost equal in the various phases of the process. Machines are not therefore underutilized because of process bottlenecks or disproportion in the productive capacities of various phases of the production process. The high idle times per day depend basically on the organization of production in one shift of about eight hours. However, these long idle times have little effect on the industrial unit cost since the cost of machines represents a very small share of the industrial cost (about 7 per cent). In the case of increased demand, the large reserve of productive capacity makes an increase in production possible by augmenting the utilization times of plants, thus lowering the unit cost of production. The high idle times explain the remarkable 'upward adaptability' mentioned in the preceding section.

DEVELOPMENTS AND APPLICATIONS

The analysis carried out in the two previous sections illustrates the capacity of the flow–fund model to measure idle times for funds involved in each particular production organization and, as a result, corresponding levels of efficiency. The relationship between organization and efficiency assumes particular relevance in the economic analysis of the firm, and in all problems associated with the dimensions of scale and degree of production flexibility. The usefulness of the flow–fund model in analyzing these two aspects and some possible empirical applications of the model based on the matrix of production elements will be discussed in the following pages.

Dimension of Scale, Production Flexibility and Flow–Fund Analysis

The dimension of scale is defined on the basis of the productive capacity, which is given by the optimal number of processes carried out per unit of time. The dimension of scale is affected by the presence of increasing returns to scale, which are closely linked to indivisibility of processes.[32] With indivisibility and complementarity, a scale increase of a process may create a better balance between different processes, thus reducing idle times for funds. As anticipated

earlier, in the section Efficiency and organization, this means that the overall dimension of scale must correspond to the lowest common multiple of the productive capacities of individual complementary units.

In short, indivisibility, decomposability and complementarity of processes are significant factors in determining the dimension of scale of production. All these production process characteristics are considered within the flow–fund scheme. For this reason the model presented in the previous pages appears particularly suitable for studying the dimension of scale at both the analytical and the empirical levels. The model may be useful in ascertaining the changes in idle times for funds, and therefore in unit costs, owing to variations in dimension of scale. The model may also be implemented to collect statistics on costs in relation to differently-sized production units, as an alternative to other more traditional systems based on production function or engineering estimates.

Let us turn our attention to the possibilities offered by the flow–fund model in analyzing production flexibility. Flexibility signifies the capacity to adjust to variations in external conditions. In other words, it derives from the ability to learn from experience and to change plans over time. In changing market conditions, production flexibility assumes a predominant role in affecting the competitiveness of a firm. Production flexibility is comprised of either strategic flexibility, defined as the ability to modify the mix of outputs, changing processes and goods produced, or operational flexibility, which is the ability to vary the quantities produced of a particular mix using a given organizational and technical structure.

As far as operational flexibility is concerned, the possibility of changing the quantities of single goods within a mix of goods is linked to short reset times of various machines or to large warehouses, in which the production elements lay unutilized. Cutting down set-up times and warehouses cost is a key element in reducing the cost of producing differentiated goods using the same equipment. The greatest operational flexibility is obtained when the same degree of economies of scale can be enjoyed for producing single-unit lots (that is, one-of-a-kind) just as they can be in producing a large lot of numerous homogeneous products. In this way, it is possible to have economies of scope and economies of scale at the same time.[33]

The spread of information technology makes it possible to reduce set-up times and significantly increase operational flexibility within the factory system. Industrial production tends to be flexible, like traditional artisan production, but it also allows for both economies of scale and reduced idle times. The possibility of reconciling economies of scope and economies of scale leads to the spread of a new organizational model of the firm, which can be called large-scale flexible industrial production. The latter is destined to coexist with other forms of production and market organization, such as small-scale flexible industrial production, industrial production based on rigid technologies and flexible organizational systems, mass production, and traditional artisan production. The prevalence of one form of production over another in a geographical region or sector of activity depends on the interaction of environmental and institutional elements.[34]

In conclusion, the study of the input arrangement specific to each production, using the flow–fund model, sheds light on some important differences among artisan production, mass production and flexible industrial production. Moreover, as remarked above, since operational flexibility is strictly linked to set-up times and warehouses, it is absolutely impossible to analyze the economic aspects of operational flexibility without a model that explicitly takes into account the time dimension of production processes.

Some Possible Applications

In this last section, possible applications and developments of the methodology based on the matrix of production elements are outlined. The case study examined concerns only the manufacturing production. It would be interesting to extend the application of the model from manufacturing production to service activities as separate processes or intermediate stages. This extension of the analysis does not seem to present significant analytical problems. The flow–fund model is particularly suitable for analyzing the relationship between efficiency and organization in the service supply, since in many such activities the duration of the process and response times are part of the qualitative characteristics of the product. Short duration and response times contribute to efficacy of production.

In general, a change in techniques entails not only a variation in quantities used and produced, but also a change in quality, organization and time profile. As a consequence, the proposed methodology, which takes into account the quantitative, qualitative, organizational and temporal aspects of production, ought to be used for fully evaluating the economic effects of change in techniques.

First let us consider qualitative improvements in the technical and service characteristics of the output due to technical change. The importance of measuring qualitative changes in goods in order to have accurate estimates of the real output growth has been recently stressed by William Nordhaus.[35] Technical change may involve variations in service characteristics of a commodity so that a good may deliver more service per unit of the good over time. If a commodity provides more service per unit of good, we have a quantitative change determined by improvements in the commodity quality. Therefore accurate quantitative measures of the output require the computation of qualitative characteristics included in the output table. The model presented offers the possibility of studying quality changes in production using vectors of technical and service characteristics of output.

Applying the flow–fund model, the analysis of the economic effects of technical changes on production processes may be carried out at the ex post or ex ante level. The former deals with a production process in actual operation, while the latter corresponds to the formulation of a production process 'plan'. Both ex post and ex ante analysis can, in turn, be carried out at two levels of desegregation: at the microeconomic level, considering individual case studies, or at the aggregate level, analyzing a set of production units in sectors of activity.

At the microeconomic level, an ex post analysis of some production processes may be obtained by collecting a time series of data regarding the same production processes in successive moments. Comparing data concerning the same production unit at different times allows quantitative and qualitative input variations and differences in production times to be grasped. In this way it is possible to evaluate the effects of technical change on margins and costs, input requirements, demand for labor, inventories, degree of utilization of equipment, dimension of scale, adaptability, operational flexibility and, more generally, on the way of organizing production. For instance, with regard to individual demand for labor, job displacement can be identified, as well as changes in skill requirements and labor force composition. For purposes of analysis, one can broaden parts of the three final tables to take into account additional data related to the specific research interests.

With regard to ex ante microeconomic analysis, starting from a production process in operation (or even a plan of a production process) it is possible to estimate by simulations the effects of varying the quantity produced, the quantities and qualities of inputs, and the organization of the production process. Of course, this requires the formulation of specific hypotheses about the behavior of the agents, the structure of the market and the inputs endowment. The ex ante analysis of individual case studies may help in the analysis of the size of the production unit, which minimizes idle times of equipment, the balance of the different productive capacities of indivisible funds, the degree of the division of labor, which brings about greater efficiency, and the effects of possible changes in worktime on costs.

At the aggregate level, the ex post analysis allows one to study the evolution of different industrial sectors. Choosing a statistically representative sample of production units and processes, one can obtain an accountability of industrial sectors that is intermediate between the level of firm and national accounts. Such an analysis of industrial sectors would permit the collection of data, not only of variations in productivity, costs and profitability, but also of organization, production time, inventory management and degree of production flexibility. These data could then be used to study the effects of technical change on the demand for labor, changes in organization and employment of human resources and investment choice. In this way, for example, it is possible to obtain microeconomically founded estimates on the function of investment and on the demand for labor. The same methodology can finally be applied to the ex ante aggregate analysis, estimating the possible effects on industrial sectors of changes in production processes.

NOTES

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1. Georgescu-Roegen ([1935] 1966a, ch. 7; [1964] 1976, ch. 11; [1966b] 1976, ch. 10; 1967, pp. 31ff). The discussion of the analytical problems involved in the production function are also partially taken up in the beginnings of his essays and articles dedicated to the flow–fund model (see note 3 below). An interesting overall appraisal of Georgescu-Roegen's methodology, his works and impact may be found in Mirowski (1992).
2. Georgescu-Roegen ([1951] 1966a, ch. 9). The theorem of substitutability is usually attributed to Paul A. Samuelson, although Samuelson himself has always acknowledged Georgescu-Roegen's priority; see Georgescu-Roegen (1992, p.154). For a recent discussion of the substitution theorem, see Kurz and Salvadori (1995, pp. 26–7).
3. The first complete exposition of Georgescu-Roegen's flow–fund model was presented in the paper at the Conference of the International Economic Association, held in Rome in 1965 and published in 1969 (1976, ch. 5). Georgescu-Roegen dedicated at least six other articles and essays to the flow–fund model with some minor additions and changes (cf. Georgescu-Roegen [1970] 1976, ch. 4; 1971 ch. 9; [1972] 1976, ch. 2; 1986, ch. 8; 1990, ch. 8; 1994 ch. 15). As far as the development of the flow–fund model is concerned, it is interesting to note that the distinction between stocks and flows is made by Georgescu-Roegen in a critical article on Paul Sweezy's mathematical proof of the breakdown of capitalism (Georgescu-Roegen [1960] 1966a, ch. 12), while the expressions 'fund-factors and flow-factors' appear in a postscript, dated 1964, to one of his first essays, 'Fixed coefficients of production and the marginal productivity theory', published in 1935. The postscript, with the essay, has been included in *Analytical Economics*, but in the 'Index' of this first book, published in 1966, the word 'fund' is not yet recorded (Georgescu-Roegen [1935] 1966a, p. 292).
4. The last sentence is peculiarly emphatic considering Georgescu-Roegen's critique of measurability in consumer theory. On this point, see Chapter 7 of the present publication.
5. On the use of mathematics in economics, the following sentence in his biographical paper dispels any doubt: 'In my earliest contributions I even ran with the current, which was then to expand the legitimate use of mathematics in economics, a program in which I have never ceased to believe . . . . My opposition is to the abuse of mathematics' (Georgescu-Roegen, 1992, p. 156).
6. Georgescu-Roegen (1992, pp. 129–30). 'My philosophy', Georgescu-Roegen wrote, 'is Machian in spirit' (ibid.). Ernest Mach's doctrine attributes to concepts and scientific theories only a function of pragmatic tools useful in organizing – in the most economic way – the multiplicity of sensorial data.
7. Georgescu-Roegen ([1970] 1976, p. 61). A quite similar methodological position has been recently expressed by Ronald Coase in his Nobel Lecture: 'What is studied is a system which lives in the minds of economists but not on the earth. I have called the result "blackboard economics". The firm and the market appear by name but they lack any substance' (Coase [1991] 1997, p. 13).
8. On the close connection between the critique of the production function and the elaboration of the flow–fund model, Georgescu-Roegen is explicit in stating that 'It is precisely such a critique that led the author [G.-R.] to the results presented in this paper' ([1969] 1976, p. 72).

9. Georgescu-Roegen ([1969] 1976, pp. 84 ff). As Georgescu-Roegen (1986, p. 256; 1994, pp. 247–9) acknowledges, the concepts of flow and fund derive from the classical economists. Nevertheless, we can find a similar distinction within different theoretical schemes; see, for instance, Walras ([1874] 1954, p. 212) and Lowe (1976).
10. 'A transaction may . . . be said to occur when a good or service is transferred across a technologically separable interface. One stage of processing or assembly activity terminates and another begins' (Williamson, 1981, p. 1544).
11. The function $U_k(t)$, which indicates the degree of use of a fund, may be transformed into a function that represents the cumulative quantities of the services provided by a fund. On this point, see Tani (1986, pp. 203–6) and Morroni (1992, pp. 58–60).
12. This is a simplified exposition of the flow–fund model. In Georgescu-Roegen's original example, different symbols are used and more production elements are included, such as inputs from nature, land, the process fund, stores, and inputs from other processes like current inputs and maintenance (Georgescu-Roegen, [1969] 1976, p. 88).
13. On flexibility, see section 4.
14. Georgescu-Roegen ([1969] 1976, pp. 90–92); Tani (1986, p. 219; 1988, p. 10).
15. On this point, see Tani ([1976] 1987, pp. 82–3).
16. These examples are drawn from Morroni (1992, pp. 61–5).
17. The importance of the characteristics of complementary, indivisibility and the non-convexity of processes has been recently maintained by scholars who do not apply the flow–fund model, such as Milgrom and Roberts (1990, pp. 515 ff).
18. The matrix of production elements was introduced in Morroni (1992, ch.7). It stems from Georgescu-Roegen's production theory, even if it is not presented in his works. On different lines of research within the flow–fund methodology, see the interesting review of literature by Piacentini (1995).
19. An economically indivisible unit is the minimum exchangeable unit not subsequently reducible for exchange purposes in a specific market (for instance, a keyboard or a box of laundry detergent).
20. See Saviotti and Metcalfe (1984, p. 147); Saviotti (1996, pp. 64ff).
21. A *filière* consists of the total of technical and transaction operations needed to obtain a finished product from a given raw material, using a process that can be decomposed in successive intermediate stages. The methodology based on the matrix of production elements makes it possible to deal with the problem of decomposability of the different intermediate stages. It is thus unnecessary to assume the independence among costs in different intermediate stages, as in the analysis based on static curves of average and marginal costs (see, for instance, Stigler, 1951).
22. The two disks of the programme *KRONOS Production Analyzer* are available. At present, the programme is ready in four versions: English, Italian, Spanish and Catalan (Moriggia e Morroni, 1993a).
23. The output table has been included only in this last version of the model; in previous works, the qualitative characteristics of outputs were indicated instead in the title of the process matrix.
24. The name of the model H9 has been fabricated because the firm prefers to remain anonymous. Since the aim of this chapter is not to present a model of manufacturing accounting, but to study production process organization, it suffices to consider a product representative of the whole range of outputs. Given the strongly seasonal aspects of production, the final tables refer to an organized elementary process for the (solar) year. The case study refers to data for 1993.
25. The net process time is calculated also in the process matrix and corresponds to the time of services of the real estate for an elementary process.
26. The process matrix is in some way akin to the fixed coefficient production models and, in particular, to the activity analysis approach. However, production time profile and organization, considered in the process matrix and organizational scheme, are for the most part neglected in the economic literature.
27. In the production unit considered there are three lines. Two lines are dedicated entirely to the model H9, while the third is employed for the production of a wide range of outputs.
28. For the computational procedures of *KRONOS Production Analyzer*, see Moriggia and Morroni (1993b, ch. 6).

29. Industrial costs are equal to transformation costs (given by direct costs and by costs of machines) plus costs of inventories and of the establishment's real estate.
30. During the two years before the interview the adoption of overtime work was frequent.
31. In order to make the organizational scheme homogeneous with the other two final tables, which list only the quantitative data, the information in the 1992 version of the model – concerning final demand and degree of specialization, polyvalence, autonomy, interaction and flexibility – has been removed. This new version of the organizational scheme distinguishes actual worktime and contractual worktime. Moreover, vacation days for different occupational levels have been added. Loading–unloading times and reset time of various machines have been separated. Finally, in the case of various intermediate processes, the organizational scheme gives data concerning the different processes row by row and no longer in columns.
32. A process is indivisible if it is impossible to activate processes on a smaller scale. It may be indivisible even in the presence of divisible production elements. For a discussion on this point, and bibliographical references, see Morroni (1992, ch. 11).
33. On this point, see Carlsson (1989); Del Monte and Esposito (1992); Steinmueller (1992).
34. On the factors which determine the increasing importance of the flexible organizational model in industrial countries, see, for instance, Morroni (1991) and Spina *et al.* (1996).
35. Nordhaus convincingly argues that the inability to capture the extent of quality change in products has caused significant underestimates of the real output growth. An accurate measure of real output requires the calculation of the true index of the cost of living which should take into consideration 'the prices of the useful services delivered by . . . goods' that have been purchased, 'rather than the prices of the purchased goods themselves'. 'Traditional price indexes can go wrong because of the goods' improved efficiency or because new goods have been created. Errors arise when the service–good price ratio is lower for the new good than for the old good. Nordhaus offers the example of lighting. He maintains that, over the period 1830–1992, because the nominal spending on lighting has been deflated by a price index that has grown too rapidly, the growth of the volume of lighting has been underestimated by a factor of around 1000 (Nordhaus, 1997, pp. 1549–51, *passim*).

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12. A theory of resilient flow–fund linkages

Roberto Scazzieri

INTRODUCTION: FLOWS, FUNDS AND RESILIENT STRUCTURES