Adhibe rationem difficultatibus

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Production of commodities by means of processes

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1. Introduction and summary

The study of boundaries and functioning of business organisations involves three distinct but interdependent levels of analysis regarding:

1) The production of commodities by means of commodities, i.e. the analysis of the relation between inputs and outputs.

2) The production of commodities by means of processes, i.e. the flow-fund analysis of the organization of processes.

3) The production of processes by means of creation of knowledge, i.e. the cognitive perspective concerning innovative activity.

These three levels are based on different assumptions, methodologies, analytical tools and aims. Nonetheless, consideration of all these three levels of analysis is essential to a full understanding of organisational functioning and boundaries.

The analysis of the relation between inputs and outputs, such as in the production function or in input-output systems, is not sufficient in the study of production processes since a given input-output relation may correspond to numerous different ways of organizing production. The economic problem of production is far more complex than choosing the combination of inputs within the individual firm because it involves

the temporal coordination of the various intermediate processes and individual tasks according to the technical division of labour. The investigation of these latter aspects is made possible by the implementation of the flow-fund model, which allows us to consider the time profile and the organization of production processes. However, the processes of creation of knowledge and change of routines are beyond the field of analysis of the flow-fund model. This aspect has been addressed by various cognitive perspectives on the firm.[1] On the other hand, in spite of the fact that innovative activity greatly affects organization settings and the time profile of production, cognitive perspectives have so far paid little attention to the second level of analysis regarding production process organization.[2]

This paper has a twofold aim, to highlight and discuss:

i) the potentials of the application of the flow-fund model to the second intermediate level of analysis concerning the investigation of the organization of production processes;

ii) the links between the flow-fund model and the other two contiguous levels of analysis concerning the input-output relations and innovative activity.

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[1] By the expression "cognitive perspectives on the firm" I refer to the largely overlapping streams of research on the nature and functioning of business enterprises, which includes behavioural theories, capabilities-based approaches, evolutionary and neo-Schumpeterian theories of economic change. See, for instance: Teece, Pisano and Shuen (1997); Hodgson (1998); Loasby (1998); Richardson (1998); Dosi, Nelson and Winter (2000b); Egidi and Rizzello (2003, p. 2); Antonelli (2005a, 2005b); Augier and Teece (2006).

[2] Sidney Winter has stressed this lacuna, arguing that: "the major investment in building a truly knowledge-based production theory […] was never made" (2005a, pp. 223-4).

The paper shows that: (a) the flow-fund model is not only an input-output representation with a time dimension, since it includes an analysis of the task distributions and the organization of production processes; (b) the study of production settings, based on the flow-fund model, makes it possible to open the black box of production, evaluating the effects of innovative activity on the organization of production processes and the relative performance of firms; (c) there is a close interdependency between the evolution of organizational settings and the development of capabilities as the organization of production processes and productive knowledge co-evolve.

Section 2 is dedicated to a concise presentation of Georgescu-Roegen's original flow-fund model. Section 3 focuses on the potentials offered by the flow-fund model to analyse the arrangement of inputs specific to different organizational settings. Section 4 addresses the links between the three levels of analysis indicated above.

2. *The analysis of production processes: the flow-fund model*

Let us start the application of Georgescu-Roegen's original production model by discussing the fundamental distinction between flows and funds.

A flow is utilized in only one process as input, or 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. Funds are conceived as agents of constant efficiency, assuming that funds are maintained in efficiency by outside processes.

Interestingly, 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 (Georgescu-Roegen 1965, pp. 83-4, 86).

The fund and flow definitions make it clear that there is no possibility of substituting a fund with a flow 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, 1979, p. 129).

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 refers, and by the input flows and fund used in that process. The analytical boundary is considered in relation to the possibility of giving to various semi-processed products an independent existence from one place to another as commodities.[3]

The elementary production process is that whereby an economically

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[3] Georgescu-Roegen (1965, pp. 79-80); Tani (1986, p. 211). On this Georgescu-Roegen (1971a, pp. 40-41) gives a clear example: "[a]n engineer, for example, may draw a boundary between the furnace with melted glass and the rolling machines of a plate glass factory, but not so an economist [...]. For melted glass is not [...] a commodity."

indivisible unit of output is obtained by means of an elementary technical unit, or chain of elementary technical units, operating in sequence. 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), while technical indivisibility refers to the impossibility of dividing a particular item, once exchanged, into amounts usable for production or consumption. An elementary technical unit is the minimum set of production elements that can be activated separately to produce a unit of output (Morroni, 1992, pp. 25-8).

Let TEP 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 TEP $\in [0,T]$. The production process is thus represented by the following functional, which is 'a relation from a set of functions to one function' (Georgescu-Roegen, 1971b, p. 236):

$$O(t) = G[G_1(t), G_2(t), ..., G_I(t), F_1(t), F_2(t), ..., F_H(t), U_1(t), U_2(t), ..., U^K(t)], \qquad [1]$$

where $G_i(t)$ (i = 1, 2, ..., I,) are the functions indicating, at any time t, the cumulative quantity of the ith outflow; $F_h(t)$ (h = 1, 2, ..., H) are the functions indicating, at any time t, the cumulative quantity of the hth inflow; and $U_k(t)$

($k = 1, 2, ... K$) 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 $U_k(t)$, which 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.[4]

Figure 1 provides an illustration of a possible shape of these functions

in the case of the following list of co-ordinates.

Output flows: 1) product $G_1 (t)$; 2) waste $G_2 (t)$.

Input flows: 3) raw material $F_1 (t)$; 4) energy $F_2(t)$.

Funds: 5) worker $U_1(t)$; 6) loom $U_2(t)$; 7) area of plant $U_3(t)$.

In the list of flow co-ordinates, two outputs are shown (i.e. the product

and waste), but we can assume any number of output flows.[5] Functions $U_k(t)$

allow for the various time profiles of funds to be compared. For instance, in

Figure 1 the time profiles of the three funds considered are different because of

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[4] The function UK(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. 203-206) and Morroni (1992, pp. 58-60).

[5] This is a simplified exposition of the flow-fund model. In Georgescu-Roegen's original example (1965, p. 88), different symbols are used and more production elements are included.

the unequal distribution of the fund 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. In Figure 1, the time of presence is indicated with a dotted line and utilization time with a continuous line.

FIGURE 1 AROUND HERE

3. The analysis of different production arrangements

In this section, the application of the flow-fund model is aimed at illustrating the possibilities offered by this model to analyse the arrangement of inputs specific to various organisational settings. The implementation of the flow-fund model makes it possible to study the properties of different possible patterns of division of labour – among a plurality of feasible patterns – each of which is associated with a particular sequence of activities, arrangement of tasks and characteristics of productive knowledge.

To illustrate this point let us give an example. Suppose that initially a worker performs all operations needed for the production process to be completed. As illustrated in Figure 2, function $W_1(t)$ indicates, at any time t, the degree of use of the services provided by the worker during the elementary process. Functions $U_k(t)$ indicate the degree of use of the four funds which

correspond to as many tools, one for each fund. In this example, depicted in Figure 2, the worker carries out an elementary process performing four different activities. Activities consist of different operations which require the performance of one or more elementary tasks. An elementary task is an operation which, by definition, is not further divisible (for instance, loading or unloading an intermediate product or cutting a piece of fabric). Suppose that the first activity performed by the worker requires the execution of three elementary tasks (ET1.1, ET1.2 and ET1.3), the second and the third require the execution of two elementary tasks (respectively ET2.4, ET2.5 and ET3.6, ET3.7), and the fourth the execution of four elementary tasks (ET4.8, ET4.9, ET4.10 and ET4.11). Therefore the whole elementary process implies eleven elementary tasks to be performed one after another. For the sake of simplicity, let us assume that activities are divided in such a way that each activity takes the same time (say an hour) and that each task requires a distinct productive knowledge. The duration of the elementary process (TEP) is four hours. The worker starts an elementary process when the previous one ends (Georgescu-Roegen, 1971a, p. 43). This arrangement in series of the production processes is typical of artisan production in which a single unit of output is produced at each time according to the customer's specification.

The worker uses four funds (U_1, U_2, U_3 e U_4): one for each activity.[6] These four funds are tools available in the plant, but three of them (out of four) remain constantly idle throughout the duration of the process because the worker performs one activity at a time. However, if the cost of tools is

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[6] For simplicity we abstract from the possible presence of other funds.

negligible in relation to total costs, as it is often the case in artisan production, this is not a problem.

FIGURE 2 AROUND HERE

Since the worker carries out all activities and performs all of the eleven elementary tasks, each of which requiring a specific productive knowledge, he or she must have wide productive knowledge which implies a great number of abilities and skills. It goes without saying that this requires prolonged training times and long on-the-job experience. The different productive knowledge corresponding to different elementary tasks is indicated at the bottom of Figure 2.

Summing up, this kind of production, labelled artisan or craft production, has three basic characteristics:

a) High flexibility because the production process allows for single units to be produced, and virtually each product may be different from any other.

b) Long idle times for tools because the artisan moves from one operation to the other, using his or her tools one at a time.

c) Long training times for workers due the fact that the craftsman performs all activities necessary to complete the production process and therefore must have various different abilities and skills.

Let us now suppose that demand increases to the point that it would be possible to hire four workers (W_1, W_2, W_3, W_4). If the

organization of production processes remains unchanged, each one of the four workers carries out in parallel an entire elementary process performing the various activities one after another according to the arrangement in series. Each worker performs consecutively all eleven of the tasks required to complete the production process. In comparison with the previous example with only one worker, in this second case the volume of production increases four times, but tool idle times are not reduced and the required productive knowledge, corresponding to each one of the eleven elementary tasks, remains entirely unaffected (see Figure 3, Example a).

INSERT FIGURE 3 AROUND HERE

However, if the tasks of workers are reshaped according to the factory system (arrangement in line), we obtain a reduction in idle times of funds and a change in the nature and distribution of productive knowledge. In fact, considering the same increase in demand of the example above, it would be possible to hire four workers (W_1, W_2, W_3, W_4) each performing only one activity in a linear sequence (see Example b in Figure 3). Then, the various elementary processes can start in succession with every interval corresponding to an equal fraction of the duration of the elementary process (TEP). With this re-organization of production, the number of elementary tasks performed by each worker is drastically reduced with a subsequent decrease in range of abilities and skills required. It becomes possible to divide labour among the four

workers who now perform from two to four elementary tasks (according to which specific activity is undertaken) instead of eleven elementary tasks of the whole four activities.

Furthermore, in the above example idle times for funds are annulled. As mentioned, the need to reduce idle time of tools depends on the share of the investment in fixed capital in relation the total cost of production. It is evident that the higher the investment in fixed capital, the greater the need to decrease idle.

With the scaling-up of the processes and the shift to the factory system, the various operations may be progressively assigned in a linear sequence to a number of different workers. The maximum technical division of labour is achieved when the volume of production increases to the point that each worker performs only one elementary task.

The difference between artisan and industrial production lies in the fact that the latter permits a reduction in idle times of funds and a radical modification in the abilities and skills required as a consequence of the modification of the distribution of tasks. Of course, changes in individual abilities and skills entail mutations in the firm's capabilities.

As highlighted by Georgescu-Roegen (1971b, pp. 248-9), the economy of time achieved by the factory system is independent of technology. Nothing prevents us from using the most primitive technique of cloth weaving in a factory system. The factory system is not a technological innovation; it is rather an "economic" and organisational innovation. According to Georgescu-Roegen, it is, together with money, one of the most important organisational and

economic innovations of human beings.

Let us now examine a further example in which there are idle times for workers. Suppose that a worker (W1) performs all four activities required, implying eleven elementary tasks, and works four units of time, as in the above example, but now the duration of the elementary process (TEP) is six hours with two units of idle times owing to a break of two units of time in which the semi-finished product is kept in a technical warehouse in order, for instance, to settle or dry (Figure 4). Therefore the worker is active for 3/6 of the duration of the elementary process, inactive for 2/6 and active again for the remaining 1/6.

INSERT FIGURES 4 AND 5 AROUND HERE

It is possible to eliminate idle times for workers by activating one process after another in a predetermined sequence. In our example, this is obtained by employing four different workers (W_1, W_2, W_3, W_4). The first three workers (W_1, W_2 and W_3) undertake three different activities (1, 2 and 3) for a total of seven elementary tasks, while the fourth worker executes only the fourth activity, which implies four elementary tasks. The duration of the elementary process is still 6 hours and every semi-finished product is stored in the warehouse 2/6 of the duration of the elementary process before passing to worker w_4 (see Figure 4). 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 TEP/6. 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 Example a), on the assumption that these intervals are commensurable. The number of elementary processes carried out in six hours passes from one to six. Therefore, the new organisational setting involves an increase in productivity. In fact, in our example the number of workers is increased fourfold but the volume of production undergoes a sixfold increase. It is evident that this improvement in efficiency derives from the elimination of idle times. The larger growth of output, in proportion to the increase in labour input, gives rise to increasing returns. An interesting property of increasing returns emerges from this application of the flow-fund model: increasing returns are commonly associated with a scaling up of a process that involves *a change in proportion* among inputs.[7]

INSERT FIGURE 6 AROUND HERE

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[7] By contrast, traditional microeconomic theory assumes that processes "would be scaled up or down at will while maintaining the same proportional relations among inputs and outputs, and the results of activities performed simultaneously would be additive" (Winter, 2005a, p. 228). The practice of separating the analysis of variations in proportions (partial or short-term adaptation) from variations in quantities (full or long-term adaptation) seems to be misleading, as there are good reasons for thinking that the proportions and quantities vary together. As pointed out long ago by Piero Sraffa, increasing returns to scale derive from the possibility of augmenting the inputs in optimal proportions to the various dimensions of scale, while decreasing returns to scale occur when there is a restriction that prevents some elements of production from increasing in optimal proportions (Sraffa, 1925, pp. 7, 23-4, 1926, p. 44ff.; cf. Morroni, 1998a, p. 209ff.; and 1998b, p. 402).

The pursuit of efficiency may determine a scaling-up of processes that can bring about changes in division of labour and knowledge. Adopting the flow-fund model makes it possible to show that an increase in the volume of production is a necessary, but not sufficient, condition that allows for an increase in division of labour and knowledge. This is clear if we compare Figures 5 and 6. In both examples, which illustrate two out of many conceivable patterns of division of labour, we have an elementary process performed by four workers and activated in line at regular intervals of TEP/6. However, in the example of Figure 5, workers w1, w2, w3 perform in sequence three different activities which imply seven elementary tasks, while worker w4 always repeats one activity, which involves the execution of four elementary tasks, throughout the whole duration of the elementary process. Therefore only worker W_4 is specialised in a single activity. In the example depicted in Figure 6, idle times are zero as in Figure 5, but the division of labour and knowledge is greater because the four workers each perform only one activity out of the total four activities. Worker W_1 continuously repeats the first activity (three elementary tasks), worker W_2 the second (two elementary tasks), worker W_3 the third (two elementary tasks) and worker W_4 the fourth (four elementary tasks). This organisational setting has brought about a reduction in tasks executed by the first three workers. This minute division of labour now implies skills that require less lengthy learning times. Moreover, in both cases increasing returns, owing to the elimination of idle times, are

exactly the same, while in the example depicted in Figure 6 there could be a further increase in productivity associated with a more minute division of labour because of an improvement in dexterity and a decrease in labour costs deriving from less prolonged learning times. Technical division of labour not only has the effect of simplifying and reducing learning time, but it also has other well-known important effects that are worth mentioning. First, division of labour facilitates repetition-based improvements that augment workers' dexterity; it also involves a reduction in production costs because, by dividing the work to be executed into different operations each requiring different degrees of skill, the firm can pay for the precise skill required for each operation. Moreover, technical division of labour brings about a growth in productivity because it reduces idle times and thereby favours a more efficient utilisation and allocation of productive capacities of different production elements.[8] Last but not least, technical division of labour saves on the selection and internal transmission of information. This saving appears to be of major importance today with the emergence of the new knowledge-based economy.

Comparison of the two above-mentioned organisational settings demonstrates that there is no deterministic link between technical conditions of production and actual organisational choice. The actual

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[8] Augmenting dexterity is part of Adam Smith's argument, while Charles Babbage stressed the reduction in costs obtained by allotting workers according to skill (and therefore wages) and reducing idle times through division of labour. See Smith (1776, pp. 17-21) and Babbage (1832, pp. 169, 172-3). For discussion and references on these themes see, for instance, Leijonhufvud (1986, pp. 206-12); Morroni (1992: Chapter 4).

degree of division of labour and knowledge adopted depends on the entrepreneurial choice according to the characteristics of basic conditions in which the firm operates.[9] In short, there is not a "one best way" but there is a multiplicity of organisational solutions depending on the peculiarities of variables that make up the environment, and the adaptive responses provided by the production unit itself, in a complex reciprocal interaction. Line production is a precondition for the division of labour, but does not in itself make the technical division of labour necessary. The factory system and line production may be compatible with very different degrees of technical division of labour and different distribution of tasks and productive knowledge.

4. Links between the three levels of analysis

In the Introduction we made a distinction between three levels of analysis regarding the production of commodities by means of commodities (i.e. the analysis of the relationship between inputs and outputs), the production of commodities by means of processes (i.e. the flow-fund analysis of the organization of production processes), and the production of processes by means of knowledge (i.e. the cognitive perspective regarding innovative activity). In the remaining part of the paper, let us briefly consider dissimilarities and links between the flow-fund model and the first and third level of analysis.

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[9] For an analysis of the basic conditions in which firms operate, see Morroni (2006a: Chapter 1).

The first level focuses on the mere relationship between output and input quantities, abstracting from the sequence of operations and the distribution of tasks which are linked to the pattern of division of labour and knowledge actually adopted. Input-output coefficients depend on the speed of rotation of flows, which is affected by the actual arrangement of production processes and in particular by the scale of production. "The *speed of rotation* of flows" is ignored in the input-output framework.[10] By contrast, the second level of analysis is not limited to the scrutiny of input-output relation, but puts to the forefront the analysis of the organization of processes through which outputs are obtained. In fact, the flow-fund model addresses the sequence of operations performed and the time dimension of production processes, which is characterized by the irreversibility of historical time. Moreover, the flow-fund model permits the examination of the efficiency properties of different patterns of division of labour associated with the distribution of tasks and the division of productive and transactional knowledge adopted in relation to specific organisational settings.[11]

As far as the third level of analysis is concerned, the cognitive perspective addresses the creation of new production processes through the development of capabilities that consist of the abilities to produce and sell specific goods and services that satisfy potential demand. Capabilities are related to the set of specialized activities, routines and skills that are embodied in a firm and are built up according to the

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[10] Vittucci Marzetti (2010, p. 36), who quotes Piacentini (1995, p. 465) on this point.

[11] See for instance, Morroni (1992, pp. 39-41, 96-7, 111-23, 166-9). In the same vein, Scazzieri (1993, pp. *vi*, 83-4) explicitly represents production as a network of tasks.

entrepreneur-manager's strategy and "business conception", which involves judgement and conjectures that are mostly firm-specific and largely non-tradable.[12] Designing a strategy entails the formation of new skills, enhancing the firm's ability to learn and to innovate processes and products. Innovative activity is the result of an accumulation of experience and takes place in historical time, in which different "states" represented by successive techniques are not independent but are linked by a causal relationship.[13]

Innovative activity is a source of substantive radical uncertainty since it creates the possibility of unexpected outcomes.[14] In fact, post-invention applications and improvements are at first very difficult to forecast or even imagine because judgements about the feasibility of an activity of a novel kind are subject to hazards. But even after their technical feasibility has been established, the inability to anticipate the future impact of innovations may still remain.[15] Substantive radical uncertainty implies incomplete theoretical knowledge of the list of possible outcomes and therefore prevents agents from computing any

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[12] On the entrepreneurial strategy and business conception, see Teece, Pisano and Shuen (1997, p. 205); Cohendet, Llerena and Marengo (2000, pp. 96-8, 106); and Witt (2000, p. 735). On non tradability of entrepreneurial judgement and conjectures see Knight (1921a, pp. 211, 251).

[13] On the notion of historical time, see Hicks (1976, p. 135).

[14] For the definition of substantive uncertainty see Dosi and Egidi (1991, pp. 183-5); cf. Morroni (2006a, pp. 61-70). Since substantive uncertainty refers to a situation that may change in an unexpected manner, it is independent of personal abilities to process information.

[15] On genuine innovations which are characterised by a high degree of uncertainty, see Rosenberg (1996, p. 334); and Winter (2005a, p. 235).

probability distribution of future contingencies and from knowing future pay-offs. The outcome cannot be predicted as it represents a novelty for the decision makers. An endogenous creation of a novelty causes incomplete theoretical knowledge in that a party may be surprised by unexpected actions of other agents. Indeterminacy of outcomes is linked to interdependence and subjective reaction based on individual interpretation of private information (Morroni, 2006b, pp. 47ff.).

In the analysis of the relations between inputs and outputs, such as in standard microeconomic theory, learning and "process of creation of new processes" are not considered since knowledge is assumed as given and unchanging. In this context, changes in techniques do not involve changes in productive knowledge because they do not take place in "real" historical time, in which there is an accumulation of experience, but in a logical time in which it is possible to move in either direction, as in space.[16] Moreover, in standard microeconomics, heterogeneity and scarcity of productive knowledge are ignored because it is necessarily assumed that knowledge is homogeneous, full and free, i.e. that production techniques are readily available to all firms. The assumption that all commodities are scarce apart from knowledge is due to the fact that the hypothesis of scarcity of knowledge is not compatible either with partial equilibrium price theory or the Arrow-Debreu model,

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[16] For instance the production possibility set is "a description of the state of the firm's knowledge about the possibilities of transforming commodities" (Arrow and Hahn, 1971, p. 53, quoted in Winter, 2005a, p. 229).

in which the market develops its own informative and self-regulatory role only if we assume that individuals are able to acquire or are already in possession of all the relevant information.[17]

As far as the flow-fund model is concerned, the object of the analysis is limited to the organization of production processes[18] and therefore it is beyond the analytical boundaries of the flow-fund model to analyze the "process of creation of new processes" by means of the development of the capabilities of the firm. However, differently from traditional microeconomic theory, both the cognitive perspective and the flow-fund model analyse processes that take place in "real" historical time. Moreover, cognitive perspective assumes that knowledge could be tacit, local, non-tradable and heterogeneous across firms. These characteristics are incompatible with the assumptions made by traditional microeconomic theory, but they are not at all incompatible with the flow-fund model.

If we take into account the relationships between the three levels of analysis considered in this paper, interestingly the upward levels are not incompatible with the analysis contained in the downward levels. In fact, the flow-fund model addresses the relation between input and output (which is considered in the first level), while the third level of analysis is not

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[17] On this, see Stiglitz (1989, p. 23); Egidi (1992, p. 9); Loasby (1999, pp. 72, 84), Levinthal (2006, p. 391).

[18] The flow-fund model has been implemented, adopting slightly different methodologies, in order to investigate a wide range of problems regarding costs, productivity, warehouses, flexibility and profitability in various sectors of activity. For bibliographical references on applications of the flow-fund model see: Piacentini (1995); Morroni (1992, 1999); Bertolini and Giovannetti (2003); Mir-Artigues and González-Calvet (2007). For a recent critical survey on Georgescu-Roegen's original model and later developments, see Vittucci Marzetti (2010).

incompatible with the analytical representation of production processes provided by the second level through the application of the flow-fund model.

The second and the third levels of analysis are closely interdependent since:

- the flow-fund model can be useful to analyse the effects of innovative activities on the organization of production processes;

- the growth of the firm is characterized by the co-evolution production settings and productive knowledge.

Let us examine these two aspects.

In order to investigate the effects of innovative activities on the organization of production processes and relative performance, a development of the original flow-fund model based on the matrix of production elements has been proposed in Morroni (1992, pp. 75-77, 1999, pp. 205-209). This matrix has been transformed for empirical analysis into three separate tables: the output table, indicating the characteristics of the product under consideration (technical and service characteristics, production time of the output flows, annual production, adaptability and level of utilization of the plant); the process matrix, which includes prices, costs and the cumulative quantities of single production elements; and the organisational scheme that provides indications for dimensional, temporal and organisational aspects of the production unit (Morroni, 1992: chapters 8 and 9; 1999, pp. 209-224). This framework 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

tables for empirical analysis are designed in order to transform information present in the theoretical model into numerical data, thus allowing for comparison of data of single production processes in operation before and after the introduction of some technical or organisational innovation. This analytical framework has been applied to some case studies using the programme KRONOS Production Analyzer, which has been designed for the input, computation and printout of data derived from firms.[19]

Applying the flow-fund model, the analysis of the economic effects of technical changes on production processes may be carried out on two levels of disaggregation: on the microeconomic level considering individual case studies, or on the aggregate level analyzing a set of production units in sectors of activity.

At the microeconomic level, production process analysis is obtained by collecting a time series of data regarding the same production processes at successive moments. Comparing data concerning the same production unit at different times enables 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 at individual firm level on: margins and costs, input requirements, demand for labour, inventories, degree of utilization of equipment, dimension of scale, adaptability, operational flexibility, and, more generally, the way of organizing production.

At the aggregate level, by choosing a statistically representative sample

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[19] Moriggia and Morroni (1993). This software has been utilized in case studies regarding the textile industry and electronic devices for telecommunication networks (Morroni, 1992, 1999, 2003); the shoe industry (Birolo, 2001), and the tile industry (Mir-Artigues and González-Calvet, 2003).

of production units and processes one can analyse the evolution of different industrial sectors regarding not only variations in productivity, costs, and profitability but also organisation, 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 labour, changes in organisation and employment of human resources and investment choice.

As far as the co-evolution of production settings and productive knowledge is concerned, the development path of a firm is characterized by the continuous interaction between organizational changes, mutations in productive knowledge and technical innovations on equipment.[20] Each given organisational setting and technique, which can be chosen by the firm, corresponds to a different stage of the development of abilities facilitating the use of specific machines and equipment. Any given pattern of production is associated with a particular arrangement of tasks and with the specific characteristics of the firm's capabilities. For instance, the adoption of Toyotism involved a major redefinition of the nature and distribution of productive and transactional knowledge.[21] Moreover, the actual operational scale depends on technical and organizational knowledge that makes it possible to take advantage of the particular properties of production elements and processes. On the other hand, a re-organization that involves an increase in the dimension of scale of production processes entails a modification in the abilities and skills

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[20] On "actual capital" as a manifestation of organizational knowledge, see Andres and Harper (2010, p. 11).

[21] Coriat and Dosi (1998, p. 114ff.); cf. Chandler (1992, p. 84), Dosi, Faillo and Marengo (2008, p. 1167).

of some members of the firm, in accordance with the new tasks linked to the changed organizational structure.[22]

The co-evolution of a firm's capabilities and organisational settings may take on a large variety of forms that bring about the development of a plurality of organisational solutions resulting from trial and error processes. Successful re-organization processes may have radically different features. This variety of organisational settings and results is due to the heterogeneity of productive knowledge, differing basic conditions and the presence of radical uncertainty.

There is a two-way relationship between the division of labour and the firm's capabilities. On the one hand, division of labour and the subsequent distribution of tasks are shaped according to the development of the firm's capabilities. On the other, a reorganisation of production processes and the distribution of tasks may cause a transformation of individual abilities and skills that brings about a modification of the firm's capabilities. In other words, problem solving activity leads to modifications in the internal division of labour by breaking down complex problems recursively into sub-problems that can be solved more easily by different functional subsystems of the firm.[23] This splitting of activities into elementary operations may promote the creation of new abilities that influence the firm's capabilities. Therefore, in the first case division of knowledge precedes the division of labour, while in the latter case division of labour drives division of knowledge (Becker et al. 2005, pp. 8-10).

In conclusion, the analysis of the relationships between the organisation

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[22] On the growth of the firm as the result of the interplay between scale-based and capabilities-based aspects, see Morroni (2006a, pp. 177-188, 240ff.).

[23] Egidi and Rizzello (2003, p. 8); Loasby (1998, p. 178).

of production processes and the development of capabilities is undoubtedly a

promising line of enquiry, although much work still has to be done.

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²⁴ Pages quoted in the text always refer to the original edition unless the reprint or the translation date is indicated in this bibliography between square brackets.
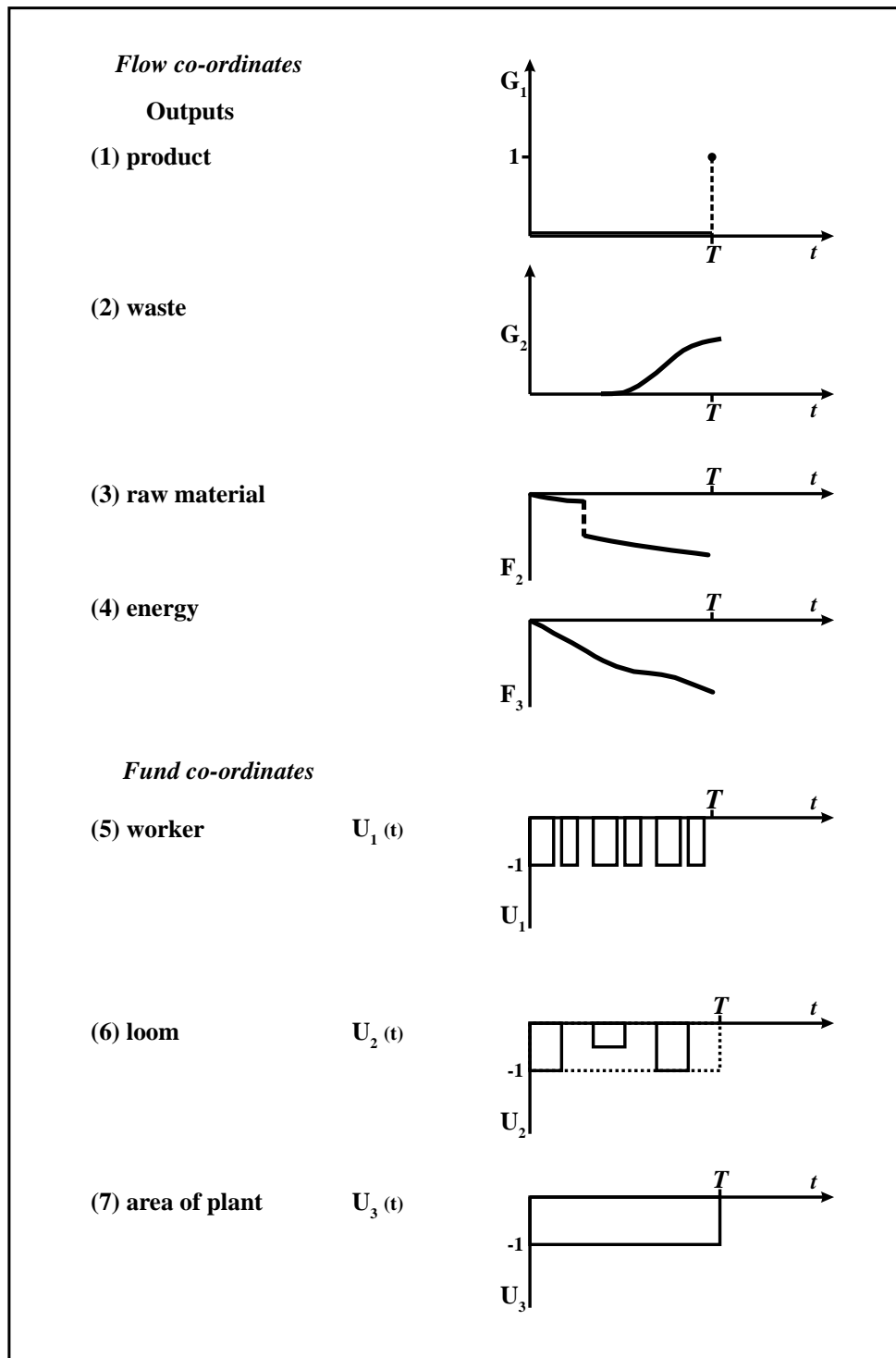
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Figure 1 Flow and fund co-ordinates

Flow co-ordinates

Outputs

(1) product

(2) waste

(3) raw material

(4) energy

Fund co-ordinates

(5) worker $U_1 (t)$

(6) loom $U_2 (t)$

(7) area of plant $U_3 (t)$
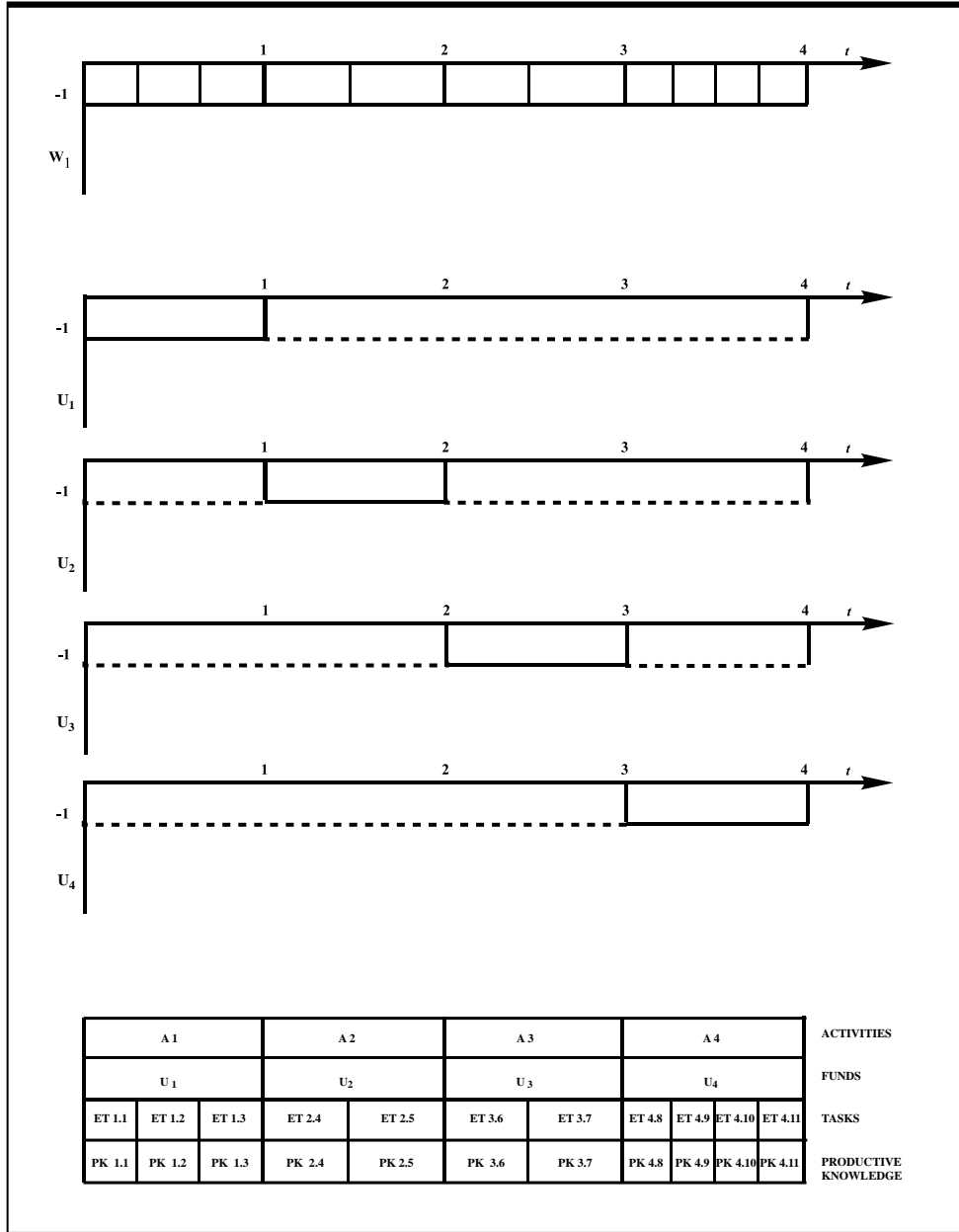
Source: Based on Georgescu-Roegen (1970, p. 89)

Figure 2 One worker, four activities and eleven elementary tasks


A 1			A 2		A 3		A 4				ACTIVITIES
U 1			U 2		U 3		U 4				FUNDS
ET 1.1	ET 1.2	ET 1.3	ET 2.4	ET 2.5	ET 3.6	ET 3.7	ET 4.8	ET 4.9	ET 4.10	ET 4.11	TASKS
PK 1.1	PK 1.2	PK 1.3	PK 2.4	PK 2.5	PK 3.6	PK 3.7	PK 4.8	PK 4.9	PK 4.10	PK 4.11	PRODUCTIVE KNOWLEDGE

Figure 3 Four workers, four activities and eleven elementary tasks

Example a: Craft production

		4 A
		4 Funds
W_1	W_1	11 ET
		11 PK
		4 A
		4 Funds
W_2	W_2	11 ET
		11 PK
		4 A
		4 Funds
W_3	W_3	11 ET
		11 PK
		4 A
		4 Funds
W_4	W_4	11 ET
		11 PK

Example b: Line production.

W_1	1 A / 1 Fund / 3 ET / 3 PK
W_2	1 A / 1 Fund / 2 ET / 2 PK
W_3	1 A / 1 Fund / 2 ET / 2 PK
W_4	1 A / 1 Fund / 4 ET / 4 PK
W_1	1 A / 1 Fund / 3 ET / 3 PK
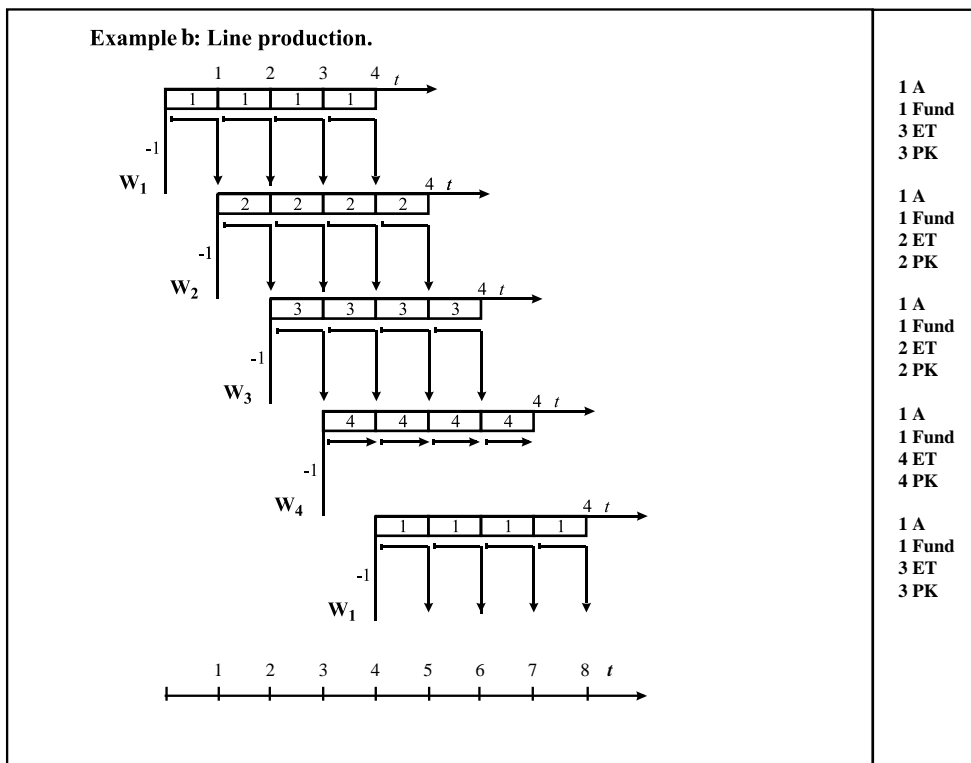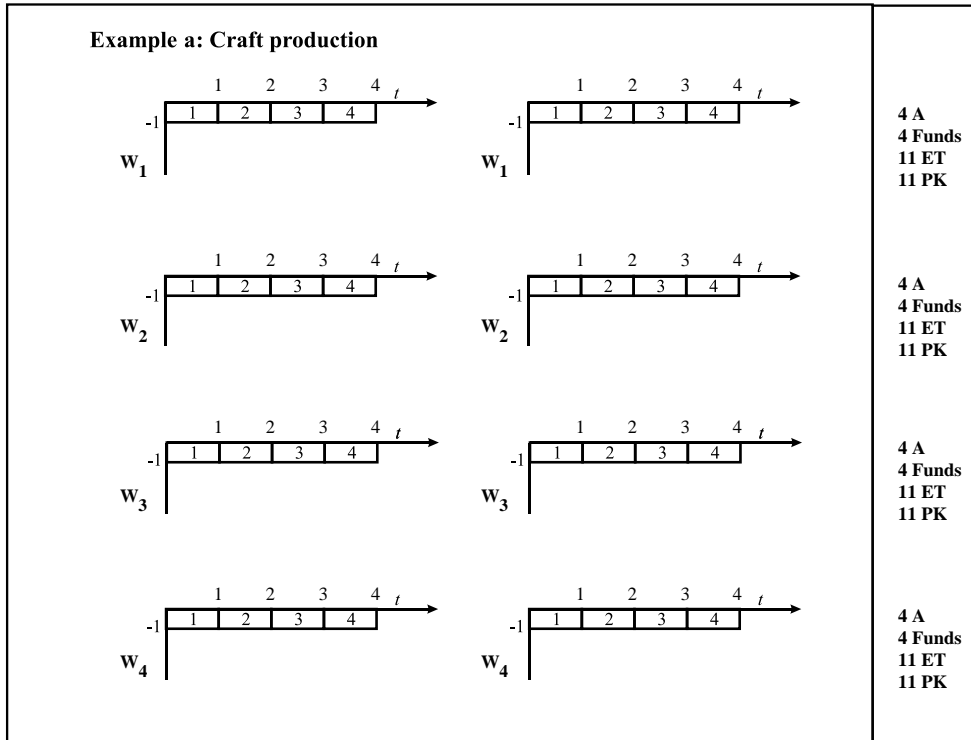
Figure 4 An elementary process with idle times.
One worker, four activities and eleven elementary tasks.
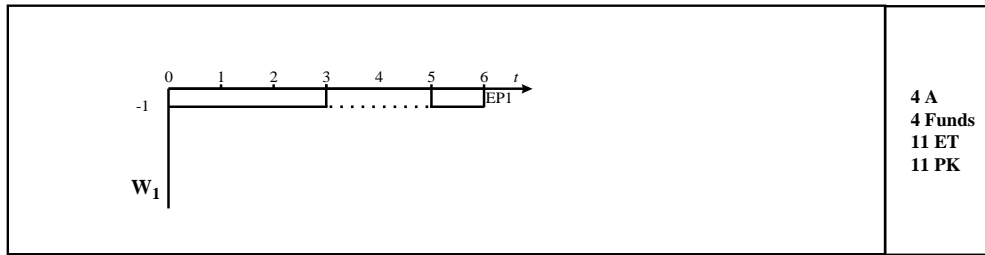
Figure 5 Line production with idle times.

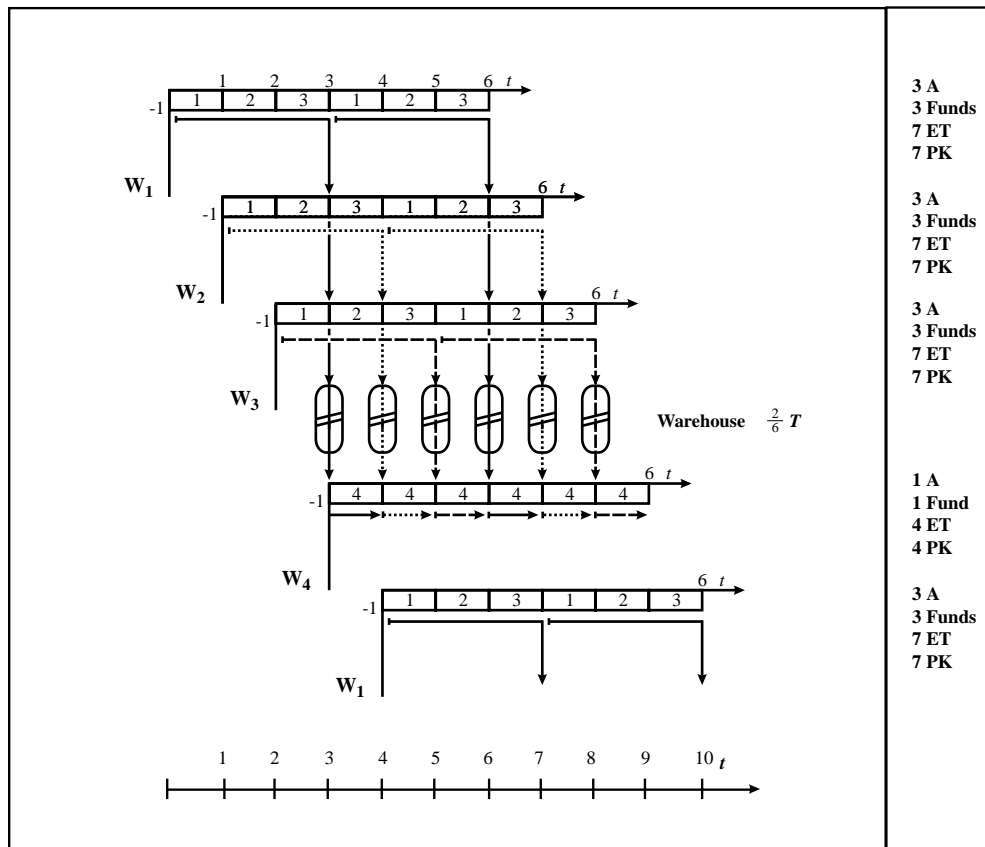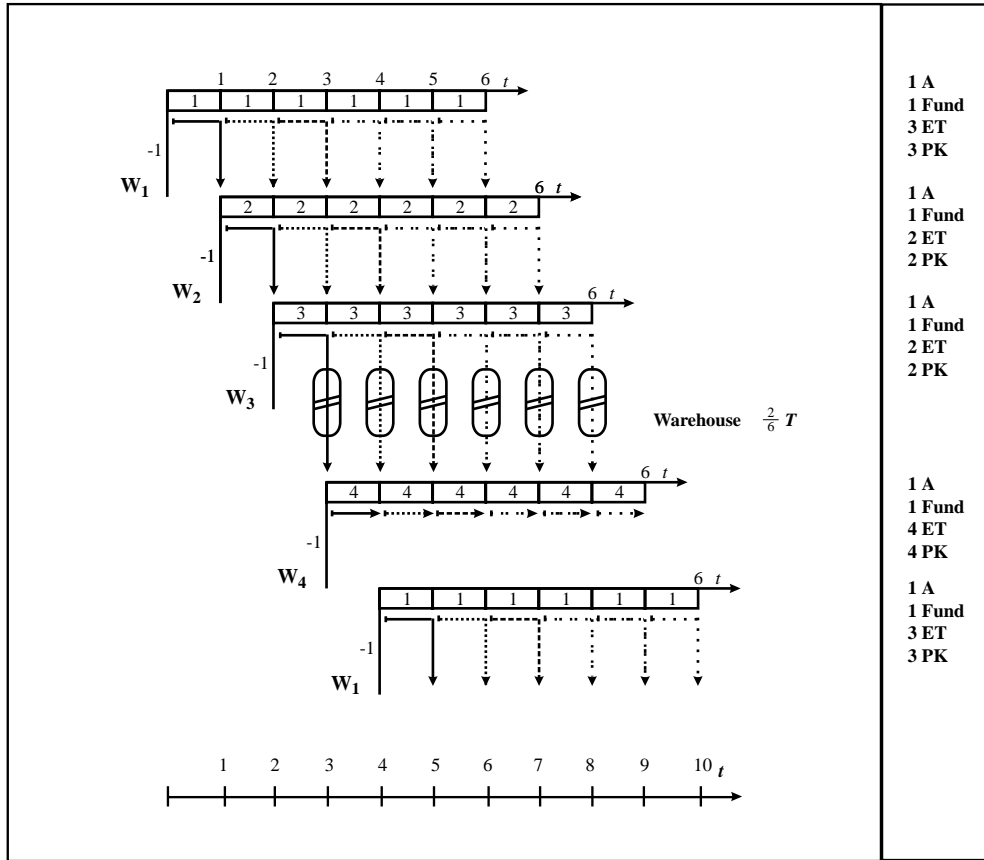**Four workers and eleven elementary tasks: example a.**

**Figure 6 Line production with idle times.
            Four workers and eleven tasks: example b.**