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THE ANATOMY OF THE PRODUCTION PROCESS AND THE FLOW-FUND MODEL

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1. INTRODUCTION[1]

Georgescu-Roegen's flow-fund analysis provides a sound basis for rethinking many of the topics of the microeconomic theory of production. This paper focuses on some recent advances of the flow-fund analysis. In particular, attention is given on two fields of research: the empirical application of the matrix of production elements, and the theoretical treatment of the relationship between scale and costs of production.

There are different ways to address the economic analysis of the production process. Production may be regarded as:

1) A transformation of given inputs into outputs. This viewpoint takes into account the technical features of the production elements as well as the description of the operations performed.

2) A creation of value. This allows us to compute relative prices, but considers production process a black box.

3) A decision-making process with emphasis on the engineering and management aspects of planning and control.

Georgescu-Roegen's flow-fund analysis belongs to the first category. It is characterised by three main characteristics. First, time is the fundamental dimension. Second, the frontiers of the production process are clearly established. Third, an exhaustive list of complementary production elements is taken into account. These properties enable the flow-fund analysis to achieve a detailed picture of the internal organisation or anatomy of the production processes.[2] The time dimension of the model is linked to the procedural nature of the production activities: production is seen as a set of co-ordinated operations which are ordered in stages according to a temporal sequence. The analysis proposed by Georgescu-Roegen, as he

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[1] This is an extensively revised version of an earlier paper presented at the Conference on Georgescu-Roegen's Scientific Work, held at the *Université Louis Pasteur*, Strasbourg, 6-7 November 1998. The authors wish to thank the participants in this conference for interesting discussion. We gratefully acknowledge valuable comments on the draft version of this paper by Paolo Piacentini. Finally, we thank the participants in the seminar held at the Department of Economics of Pisa University (March 2001). Naturally, the authors take responsibility for possible errors and omissions.

[2] As it is well known, anatomy means the systematic description of the components of a given system, as well as the analysis of their interrelationship.

himself pointed out, is an attempt to overcome the parsimony of the conventional microeconomic point of view.

This paper has three main sections. In the first section, the basic concepts are introduced. In the second section, the application of the flow-fund analysis to applied research is addressed. Finally, in the third section, serial, in-line and parallel-in line arrangements are modelled in order to obtain average cost expressions. In this way it is possible to analyse the relationship between dimension of scale and costs.

2. BASIC CONCEPTS

Elements of the production process are divided into flows and funds. Flows enter as inputs or leave as outputs of the process. Funds provide their services during a certain period of time. Hence, they enter and exit numerous processes. All these elements are measured in cardinal terms (Tani, 1986:200). This fact explains why flows and funds must be gathered into homogenous categories.[3]

There are five kinds of flows: the main output (single or joint) at the end of the production process or from some intermediate phase; output below the established standard of quality; sub-products and waste materials; natural resources with or without a price (sun radiation, air, water and minerals, etc.) and, finally, goods produced in other previous processes such as commodities, semi-elaborated products and components, seeds and energy, etc.

Funds include workers, land (as a surface), assets (plant and equipment), inventories of commodities and items-in-progress. During the process, workers become tired and fixed-funds become depreciated. The activities devoted to the restoration, maintenance and reparation of these production elements are usually considered as separate processes (Georgescu-Roegen, 1969, 1971, 1976 and 1990).

The flow-fund analysis focuses on the temporal order and on the content of operations performed within the frontiers of the production processes. This is a work of dissection based on concepts of tasks, jobs, phases, elementary processes and production processes. These concepts are related to each other in the following way:

tasks $\subseteq$ jobs $\subseteq$ phases $\subseteq$ elementary processes $\subseteq$ production processes.

As observed, "a task is a completed operation usually performed without interruption on some particular object" (Scazzieri, 1993:84). A job is a general assignment of work, which includes one or more tasks. Since fund-inputs can be

[3] See Georgescu-Roegen (1969, 1971 and 1976); and Tani (1986 and 1993).

identified by different sets of characteristics related to their work-capabilities, every production process then contains a particular job-specification programme; that is, "a mapping from the set of capabilities (or skills) embodied in the different fund-input elements to the set of tasks to be performed in a particular production process" (Landesmann and Scazzieri, 1996a:198). The different job-specification programmes will probably be ordered according to some technical efficiency criterion (Landesmann, 1986:289).

The study of the production process involves the analysis of the temporal coordination patterns among funds, tasks and materials. This analysis takes into account the amount of output of a plant under different production arrangements. According to Georgescu-Roegen (1971 and 1976), the consideration of the time dimension in the flow-fund model sheds light on the differences among series, parallel and in-line arrangements. Series or jobbing production is associated with craft production; parallel disposition of the elementary processes is a characteristic of agriculture; while in-line arrangement is connected to the factory system and also to the mass production system.[4] On the basis of the flow-fund model it is possible to compute cost expressions in conjunction with the different production arrangements.[5]

Phases are the intermediate stages contained within processes. When the item to be produced requires very different treatments and/or components to be assembled, breaking the process down into various sub-processes can be useful. Often the phases are divided for technical or organisational reasons and they give rise to one or more (buffer) stocks. A phase is a set of adjacent jobs that are organised according to the order and number of tasks.

The elementary production process is the process whereby an economically indivisible unit of output is obtained by means of an elementary technical unit. Obviously, the elementary process is an analytical construction. In general, it cannot be directly observed, because a plant produces a large quantity of units of output over a period of time. An economically indivisible unit is the minimum unit exchangeable in a specific market. An elementary technical unit is the minimum set of production elements that can be independently activated for producing a unit of output. The output of an elementary process may not be a final product. All productive operations within an elementary process are performed according to a given state of technology.

The production process can be represented by the matrix of production elements. Within this matrix, every element denotes the rate of flow or the service time of funds by phase. The matrix of production elements refers to the *ex-ante* analysis of an organised elementary process; that is to say, a 'plan' of a feasible production

[4] Relevant discussions of this set of problems can be found in Wodopia (1986); Leijonhufvud (1989); Landesmann and Scazzieri (1996a:193-4 and 1996b), Fabrice and Arnaud (1998); Fries Guggenheim (1998); and Rowley (1998).
[5] For early works on this line of research see Piacentini (1989, 1995, 1996); Petrocchi and Zedde (1990). The cost expression based on the flow-fund analysis has been called a "temporally explicit cost function" by Piacentini (1995:474n.32).

process, using a number of funds that renders their different productive capacities compatible. Each element of matrix indicates, at time t, the cumulative quantities of production elements going in or out at each intermediate stage of a decomposable organised elementary process. The matrix of production elements has as many columns as intermediate production stages, and as many rows as production elements.[6]

3. THE APPLIED VERSION OF THE FLOW-FUND ANALYSIS

For the purpose of empirical analysis, the basic model, represented by the matrix of production elements, needs some modifications to facilitate the procedure of collecting and processing data. These modifications make it possible to standardise the data of the various processes under consideration so that a homogeneous data-base can be created for the purpose of comparisons required for applied research.

Data on a production process can be summarised in the following three tables: the output table, the process matrix and the organisational scheme. Each table focuses on one of the three different levels of the analysis: the product characteristics, process and organization of the production unit. The three tables, which are derived from the flow-fund analysis, register numerical data that allow for comparisons among processes. The three tables can be referred both to the *ex-ante* and *ex-post* analysis of production processes.

The output table can be used for evaluating qualitative changes in the output; in particular, improvements in delivery time and in technical and service characteristics.

The process matrix makes it possible to analyse the effects of technical change on: margins and costs, input requirements, demand for labour, inventories, degree of utilization of equipment, duration of the process, adaptability and operational flexibility.[7]

The organizational scheme may help in the analysis of the size of the production unit, which minimises idle times of equipment; the balance among the different productive capacities of indivisible funds; the degree of the division of labour, which brings about greater efficiency; and the effects of possible changes in work time and shift arrangements. For instance, in the analysis of individual demand for

[6] Although the concept of the matrix of production elements was not developed by Georgescu-Roegen, it derives directly from his work. A description of the analytical characteristics of the matrix of production elements can be found in Morroni (1992:75ff.). For a similar concept, see the analysis of production phases in Piacentini (1995:470ff.).

[7] In fact, the analytical representation of the production process, obtained by the implementation of the flow-fund model, is less complicated than that obtained following the engineering approach. The latter approach requires a large amount of detailed physical data on fund characteristics and performances which are not necessary in the flow-fund model.

labour, job displacement potentials can be identified as well as changes in skill requirements and labour force composition.

In the following pages, the empirical analysis will be presented using real data from a production unit specialising in telecommunication devices. This case study must be regarded as a mere numerical example, useful for illustrative purposes.[8]

The making of the three tables is facilitated by the KRONOS Production Analyzer programme, which has been designed for the input, computation and printout of data derived from firms (Moriggia and Morroni, 1993).

3.1. The output table

The output table represents the characteristics of the product under consideration. The output table is divided into five blocks. The first block (a) concerns the technical and service characteristics of the product. Within the output range of the production unit, the production process of a professional two-way radio has been analysed. The output under consideration, referred to henceforth as model H9, is identified only by the following characteristics: range of frequency, power, communication protocol, display, keyboard, size and weight (see all the tables at the end of this section).

Block (b) is dedicated to the production time of the output. Often, production time is a component of product competitiveness and therefore an inherent qualitative characteristic of the product. At any given level 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 competitivity.

Let us observe the sharp difference between net process time and net duration of the process. Net process time is about an hour and a half, while the net duration takes 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 excessive for this kind of production. Their cost is shown in Table 2.

In our example, the response time (i.e. the time from the instant of arrival of the customer's order to the delivery of the finished product) is 90 days, against a net duration of 160 days. Response time is lower than the net duration because the organizational inventories make it possible to deal with orders in a shorter time.

[8] The case study presented here is drawn from Morroni (1999:209 ff.).

Block (c) of the output table is dedicated to the 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 sub-contractors.

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 range of production variation, above and below current output, within which the average transformation costs vary less than 5 per cent. Transformation costs are obtained by adding direct costs and machine costs.

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 (+60% or -50%) with negligible variations in transformation costs (within 5%). The considerable adaptability is the result of the low burden of equipment on transformation cost and the large reserve of productive capacity linked to low average utilization of equipment.

The last block (e) of the output table records the lot or batch of production. In the production under consideration, the lots equal fifty units. A small number of goods per lot indicates the potential for high operational flexibility, i.e. 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).

3.2. 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 organised 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.

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, i.e. physical cost. From the inverse of the input flows and services of funds, we obtain an index of average physical productivity for each production element.

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. Block (c) is devoted to services provided by funds (workers, machines and the estate) and inventories.

Three columns are added to the columns that register the quantity produced or used in the various intermediate stages. These additional columns indicate:

1) The sum of quantities produced or utilised in the elementary process.

2) The unit price of individual elements of production.

3) Revenue and costs obtained by multiplying the total physical quantities by their respective prices.

In Table 2 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, in the case study, each individual production line might be divided into three possible intermediate stages: automatic assembly (one machine), manual assembly, and automatic performance check (two machines).

The sum of the elements of the last column gives us the gross margin that indicates the gross profitability of each intermediate stage. Mechanical and electronic components represent by far the largest share of industrial cost (69%), while the cost of workers' services, equipment, real estate and inventories is low by comparison (27%). 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' to output variations. In short, when the production of the two-way radio diminishes, the cost of input flows lessens proportionately, while the unit cost of machinery increases. This increase is of little relevance, however, because of the low burden of machinery cost on transformation cost.

The production here considered is characterised by a very high gross margin (118% on transformation costs and 136% on direct cost). The high gross margins also stem from the fact that these must account for a large share of (non-industrial) general fixed costs, attributable 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 the individual production line does not involve an equally strong adaptability of the total volume of production.

3.3. 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, one for workers and one for 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 working time. Actual and contractual weekly time may differ owing to factors such as overtime, absenteeism and temporary layoffs. Table 3 shows that, for the year under consideration, contractual work time is equal to actual work time.

The first block of the organizational scheme shows 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.

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. Table 3 shows that, in the production unit under consideration, idle times are nearly equal in the various phases of the process. Machines are therefore not under-utilised due to process bottlenecks or to disproportion in the productive capacities of various phases of the production process. The high idle times per day depend essentially on the organization of production in one single shift of about 8 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%). In case of increasing 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.

Table 1. Output table: two-way radio, model H9

a) characteristics

range of frequency	400 Mhz
power	2 Watt
protocol of communication (private and publ. networks)	1327 Mpt
display	liquid crystals
keyboard	18 keys
dimensions	200x69x30mm.
weight	400g. (approx.)

b) times

net process time	1:26:42 hours
times of the technical inventory:	
product in progress	2 days
gross process	3 days
times of organizational inventory and in-house transport:	
semi-fin. mechan. prod.	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	perc.
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 2. 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 £/unit	1300000.00 £
waste of the final product	0.06 units	-455000 £/unit	-29050.07 £
b) input flows			
semi-fin. mechan. prod.	-1.00 kit	55000.00 £/kit	-55000.00 £
electronic components	-1.00 kit	350000.00 £/kit	-350000.00 £
material used	-1.00 kit	50000.00 £/kit	-50000.00 £
c) services of the funds			
workers:			
floor manager 8° lev.	-0:04:53 hours	50955.41 £/hour	-4142.50 £
technician 6° lev.	-0:04:53 hours	35668.79 £/hour	-2899.75 £
assistant 5° lev.	-0:48:47 hours	32611.46 £/hour	-26512.01 £
assistant 4° lev.	-1:37:33 hours	20382.17 £/hour	-33140.02 £
machines:			
automatic assembly	-0:12:52 hours	84458.78 £/hour	-18123.45 £
equip. for manual assem.	-0:50:06 hours	1550.21 £/hour	-1294.53 £
automatic check	-0:23:44 hours	65476.85 £/hour	-25890.64 £
technical inventories:			
product in progress	-0.01 units	55232.88 £/unit	-572.01 £
organizational inventories:			
two-way radio (output)	-0.21 units	156000.00 £/unit	-32311.52 £
semi-fin. mechan. prod.	-0.21 kit	6600.00 £/kit	-1367.03 £
electronic components	-0.21 kit	42000.00 £/kit	-8699.25 £
product in progress	-0.02 units	84000.00 £/unit	-1304.89 £
plant area(400sqm)	-1:26:42 hours	15255.03 £/unit	-22044.57 £

Table 3. Organizational scheme of the production unit

a) workers

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

			actual timetable			*contractual timetable*	
	number	shifts	hours/day	days/week	days/year	hours/day	days/week
floor manager 8°	5	1	7.51.00	5	200	7.51.00	5
technician 7°	30	1	7.51.00	5	200	7.51.00	5
technician 6°	30	1	7.51.00	5	200	7.51.00	5
assistant 5°	20	1	7.51.00	5	200	7.51.00	5
assistant 4°	40	1	7.51.00	5	200	7.51.00	5
worker 3°	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°	5	0	0	3	2	0	0	4	1
technician 7°	30	0	0	25	5	0	20	10	0
technician 6°	25	5	3	25	2	0	25	5	0
assistant 5°	10	10	2	15	3	3	10	7	0
assistant 4°	10	30	5	28	7	10	30	0	0
worker 3°	5	5	5	5	0	6	4	0	0

a2) percentage of average time per job

	loading-unloading	transformation	organization	maintenance	innovation
floor manager 8°	0%	0%	80%	0%	20%
technician 7°	0%	20%	50%	20%	10%
technician 6°	30%	0%	30%	40%	0%
assistant 5°	20%	70%	10%	0%	0%
assistant 4°	20%	80%	0%	0%	0%
worker 3°	0%	70%	0%	30%	0%

b) machinery

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

			gross utilization		*loading-unloading*	
	number	speed	hours/day	days/year	hours/day	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

	setup operation		*maintenance*		*idle times*	
	hours/day	days/year	hours/day	days/year	hours/day	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

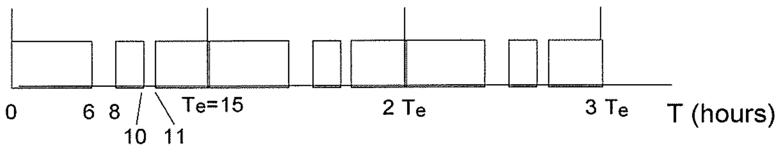
4. PRODUCTION ARRANGEMENTS AND AVERAGE COSTS

In this last section we present three models relevant for the analysis of the relationship between the dimensions of scale and costs of production. We compare the differentials in average costs, according to the various production arrangements. In this respect, the properties of serial, in-line and parallel-in-line arrangements will be illustrated. This is a development of the recent literature devoted to the cost analysis based on the flow-fund model.

4.1. Serial and in-line processes

Serial production arrangement is a consecutive activation of elementary processes; thus, tasks within the intermediate stages of the process are each performed before starting the following one. This method is the simplest way to deploy an elementary process. Craft production is an example of an in-series arrangement.[9] Figure 4.1 illustrates an example of the serial production process.

Figure 4.1. Serial process



The example in Figure 4.1 shows the production process of a given handicraft item which lasts T_e=15 hours. This process has three phases of d_1=6 hours, d_2=2 h and d_3=4 h. All these periods of work are executed by a craftsman equipped with some tools. There are also two intervals of inactivity of 2 and 1 hours for technical reasons. Therefore, $\sum_{j=1}^{j=3} d_j < T_e$.

Following Piacentini (1989:164-171 and 1995:473-476), let us assume that:

1) The process produces a single output.[10]

[9] Serial production is also common for goods characterised by a large size, unique design and exceptional technical features, such as the construction of large infrastructures like bridges, tunnels, very tall buildings and large transport systems, etc. (Georgescu-Roegen, 1986:257). In theory, all production processes can be arranged in series.

[10] This assumption covers all the models presented in the following pages.

2) There are three sets of tools. Each one is used in a particular phase of the process. The vector [σ_1, σ_2, σ_3] represents the rental cost of their availability for the period under consideration.

3) To produce each unit of output some flows are needed. The cost of flows is: $\sum_k f_k\, p_k$ (k=1, 2,..., K), where f_k are the technical coefficients of the process and p_k the flows' exogenous prices.

4) Only one worker is utilised.

The average total cost or average cost (AC) of a serial process is thus given by:

$$(1) \qquad AC = \frac{\sum_j \sigma_j + W + H \cdot \frac{1}{T_e} \sum_k f_k \cdot p_k}{H \cdot \frac{1}{T_e}} = T_e \cdot \frac{1}{H} \cdot \left(\sum_j \sigma_j + W \right) + \sum_k f_k \cdot p_k$$

where H stands for the number of hours of activity per year and W denotes the annual salary for labour services.[11]

The quantity produced (Q) can be expressed as the flow of product per unit of time, multiplied by the productive period (H). That is, Q = H·1/ T_e. This expression makes explicit the temporal factor in the unit cost of output.

Now let us examine the characteristics of in-line production.[12] In-line arrangement of production, coupled with division of labour, gave rise to the factory system which spread during the industrial revolution.[13] Smith, Babbage and Marx were among the classical economists most impressed by the level of productivity of the new production system characterised by the gathering of a large number of workers under the same roof and by using steam-powered machinery.[14] Specialisation of the employees by phases, which increased their dexterity, was combined with the in-line deployment of the elementary processes in order to avoid idle times for workers and machines. Thus, when a given worker had finished his/her activity on a unit of output, a following unit of output was ready to come into operation. But, normally, the different phases within an elementary process did not have the same length. This is the situation depicted by the diagram in Figure 4.2.

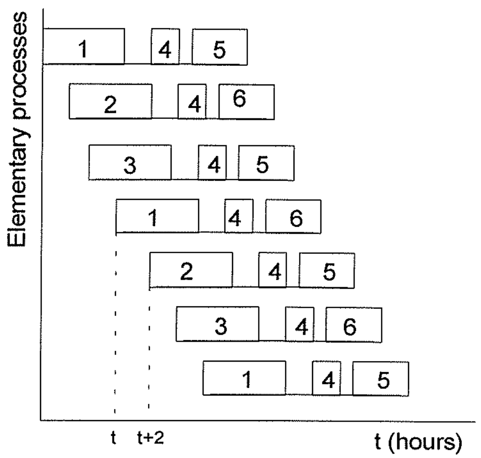
[11] Monetary costs are calculated according to an annual unit of time.

[12] Serial process is a term often used for this innovative manner of sequencing operations. Georgescu-Roegen (1969, 1976 and 1990), however, rightly re-named it a process-in-line.

[13] It must be noted that the factory system began with the manufacturing of weapons in the eighteenth century, though it seems there were some isolated cases before. On this point, see Mumford (1963); Heskett (1980:Ch. 3); and Best (1990:30-45).

[14] On the contributions of these authors to the analysis of factory system, see Landesmann (1986:294-299) and Scazzieri (1993:34-79).

Figure 4.2. A process-in-line



As in the first example above concerning serial production, the elementary process contains three phases of 6, 2 and 4 hours. Given the difference in these lengths, the in-line arrangement is feasible as long as the gap between consecutive processes has a particular duration and various units of specialised funds are available. As we can see in Figure 4.2, every two hours a new elementary process starts. Therefore, in order to sustain the process-in-line we need: three craftsmen specialised in the first phase; one specialised in the second phase; and, finally, two specialised in the last phase.

Once the optimum temporal interval has been computed, we can establish, for each fund the number of units, which guarantees the continuous activation of funds. Every phase (d_j) can be expressed as the product of two important factors: $d_j=\delta^*\cdot v_j$, where δ^* indicates the maximum common divisor of the length of the phases and v_j, shows the number of fund units to be purchased or hired. In our example, $\delta^*=2$ h. This is the optimum interval. We assume that:

1) The in-line arrangement of the process is not hindered by seasonal factors, as occurs, for example, in open-air agriculture.

2) The d_j are commensurable intervals. If they are not, some of them might be extended for convenience (Tani, 1986: 221).

3) It costs nothing to move the funds among the sequential elementary processes.

In general, the output per hour of an in-line arrangement will be $1/\delta^*$ and, therefore, $1/\delta^*\cdot H$ will be the total output. To check whether or not the in-line arrangement gives rise to economies of scale, we must compare the average cost of

serial production with the average cost of in-line production. The number of funds required is given by the vector ($\phi_1, \phi_2,\dots, \phi_j$) where,

$$\phi_j = \frac{d_j}{\delta^*} = v_j, \qquad \text{with } j=1, 2,\dots, J.$$

In our example: $\phi_1=3$, $\phi_2=1$ and $\phi_3=2$.

Following the assumptions above, the average cost of in-line arrangement is

$$AC = \frac{\sum_j \phi_j\sigma_j + W\sum_j \phi_j + \frac{1}{\delta^*}H\left(\sum_k f_k p_k\right)}{\frac{1}{\delta^*}H}$$

Or, by rearranging

$$(2) \qquad AC = \delta^* \frac{\sum_j \phi_j\sigma_j + W\sum_j \phi_j}{H} + \sum_k f_k p_k$$

To compare the cost expressions (1) and (2) means, on the one hand, to contrast $T_e\sum_j \sigma_j$ with $\delta^*\sum_j \phi_j\sigma_j$. Since this last term can be rewritten as $\sum_j d_j\sigma_j = T_e\sum_j \frac{d_j}{T_e}\sigma_j$ and $d_j/T_e<1$, then $T_e\sum_j \sigma_j$ is greater than $\delta^*\sum_j \phi_j\sigma_j$. On the other hand, we must compare $T_e\cdot\frac{W}{H}$ with $\delta^*\cdot\sum_j \phi_j\cdot\frac{W}{H}$. In this case, as is known, $T_e > \delta^*\cdot\sum_j \phi_j = \delta^*\cdot\sum_j v_j$. Therefore, as a final result, the average cost of in-line process is less than the average cost of serial process. Thus, with respect to the serial process, the in-line arrangement adopted in the factory system takes advantage of the economies of scale.

4.2. In-line production and task balancing

This section illustrates the impact of the organizational factors on in-line- arrangement efficiency. In particular, the relationship between the balancing of tasks and the average cost is analysed. For this purpose, some recent results concerning cost expressions based on the flow-fund analysis,[15] and some ideas drawn from the literature devoted to production management are developed.[16]

The strategic manufacturing theory classifies the different types of the in-line processes through the product-process matrix (Spencer and Cox, 1995). This matrix has two axes: the first one is concerned with the product structure (that is, the volume and the variety of output made per unit of time), while the second one is devoted to the process structure (i.e. the process layout and the pace of production). Three different kinds of in-line processes may be singled out:[17]

1) Batch production. This type of process requires very specialised equipment such as machine-tools.

2) Flow-line, either manual assembly line or transfer lines.[18] The output-in-progress runs through the workstations thanks to a system of transfer. This kind of line is also known as repetitive manufacturing.

3) Continuous output flow (such as fluid or semi-fluid products and bulk raw commodities). A non-stop process is feasible. This type of process uses specialized automated equipment. The main task for employees is constant control to ensure that the production system performs as planned.

The following analysis will examine only the flow-line pattern of in-line production, which consists of a manual assembly line or a transfer line.

Let us assume absence of technical changes and that demand can always absorb the additional output. Moreover, let us ignore other sources of time-saving such as cutting down storage time and reducing the period for consignment of inputs.

An important goal of in-line arrangement is to guarantee equal temporal intervals for every workstation. If the total time required to complete a given intermediate stage in a unit of the product-in-progress is divided as equally as possible among the stations, the output flow will run smoothly and regularly throughout the

[15] See Tani (1986:217-225); Landesmann (1986:299-309); Gaffard (1994:72-77); and Petrocchi and Zedde (1990).
[16] See Heizer and Render (1993:Ch.9); Starr (1989:Ch.10), Vonderembse and White (1991: Ch. 8) and Wild (1972: Ch.3 and 1989: Ch.15). The reference to production management literature does not mean that we intend here to apply the flow-fund model to decision-making problems. Our goal is to provide an analytical description of the in-line process to study the relationship between cost, size and organization of production.
[17] On this point see Wild (1972:3-18) and Miltenburg (1995).
[18] Manual flow-lines are characterised by the use of manual labour both for the transfer and transformation of work-in-progress, while transfer lines are defined as a series of automatic manufacturing tools connected by work-transfer devices. As observed by Wild (1972:44-46), "such lines are normally used for metal (or material) cutting and working, but assembly-type transfer lines are currently being developed. Although early transfer lines relied on the manual movement of the material or product, most contemporary lines utilise automatic movement or transfer methods."

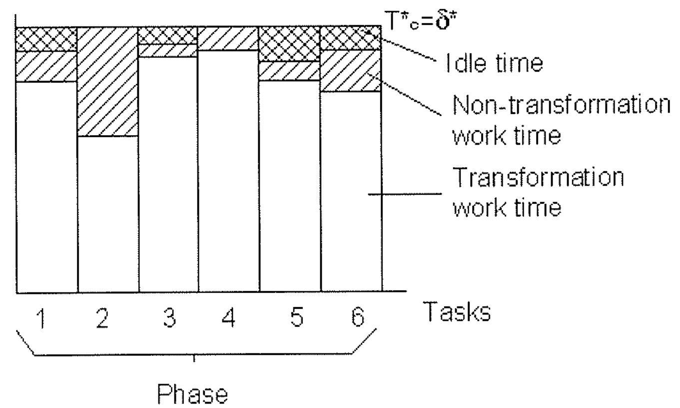
line. In this way, inefficiency is avoided. This optimum temporal length is called the cycle time (T^*_c).[19] The cycle time is composed of the service time and the idle time. The service time includes the transformation time and the non-transformation time. The transformation time is the real time required by funds for performing their task at a given station. Non-transformation time is used in handling and moving tools, checking the items, loading-unloading machines and transferring the product between stations.

At some workstations, idle time must be added when the service time is shorter than the cycle time. The task with the longest service time defines the cycle time and causes intervals of waiting in the remaining tasks. For this reason, the idle time is also called balancing delay.

In the case illustrated in Figure 4.3 below, there is a phase in which different fund elements are activated in six tasks; every one of them with $s_1, ..., s_i, ..., s_6$ intervals of service time. The service time contains the transformation time (p_i) and the non-transformation time (π_i). That is, $s_i = p_i + \pi_i$. The cycle time is $T^*_c = s_i + l_i = p_i + \pi_i + l_i$, where l_i denotes the idle time. As δ^* indicates the temporal interval which allows in-line arrangement of the process, then $T^*_c=\delta^*$. Obviously, for each δ^* length of time, the amount of production will be a unit of output.

For simplicity, the temporal order of tasks or jobs within every single service time is ignored, and the analysis involves a single phase, instead of a whole elementary process consisting of different intermediate stages. The length of a phase is T_p.

Figure 4.3. Tasks balancing



[19] On the assembly line balancing problem, see Starr (1989:492).

Let us assume that:

1) Each task is associated with a particular workstation.

2) The unit of time is one hour (H=1).

Therefore, if δ^* is expressed in terms of the above defined temporal unit, $1/\delta^*$ items every hour will be produced. From the diagram above it is clear that,

$$Tp \text{ (length of the phase)} = n_w \cdot T^*_c = n_w \cdot \delta^*,$$

where n_W is an integer that represents the number of work stations operating in that phase. In our example, n_W=6.

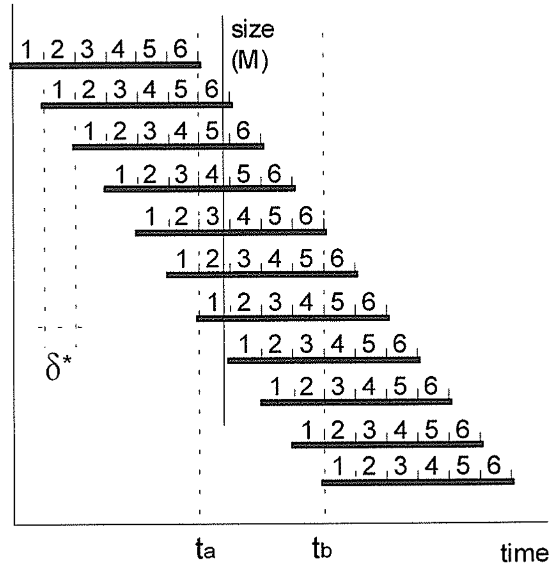
On the basis of these assumptions, what are the effects of an increase in the output per unit of time? In any in-line process, an increase in output may be achieved by stepping up the working pace. Undoubtedly, a temporal interval narrower than δ^*, that is $\delta<\delta^*$, causes a growth in the volume of output obtained. *Ceteris paribus* if the production cadence is $\delta=\delta^*/n$, n>1, the output per hour will be n/δ^*, provided that there are no existing technical constraints or breaks in the supply of parts for assembling (Tani, 1986: 219). If indeed there are none, the quantity of finished elementary processes per unit of time (working day, week, etc.) will rise and an increase in the number of units of funds will be needed. In the following analysis we will answer the following two questions: What will be the number of elementary processes simultaneously required in a given unit of production as a result of the temporal interval reduction? How many units of a specific fund (k_j) which is used in a given work station or task will be required (while $\delta=\delta^*$, $k_j=1$)?

First, we have to define the size (M) of the in-line process. The size of the in-line process corresponds to the number of elementary processes simultaneously processed in a given plant (Scazzieri, 1993:32). That is, $M=T_p/\delta^*$. In other words, the size of the line is the number of times that δ^* is incorporated into T_p. As our model shows, M is equal to the number of workstations.

In Figure 4.4, an intermediate stage begins every δ^* units of time. Since each intermediate stage is composed of six tasks, the size of the line is M=6. That is, the number of elementary processes simultaneously carried on when the line is in full operation-interval $[t_a, t_b]$ (disregarding, the beginning and the end of the line operation). Evidently, as the phase lengthens and/or the temporal interval becomes smaller, the size of the line consequently increases.

Having defined M as the size of the process, the size of the production unit may be settled as M·H. That is, the number of processes carried out in a given plant and time interval.

Figure 4.4. The size of the process-in-line



Therefore, when the line is in operation, the size of the process M and the number of units of a specific fund k_i will be,

$$1)\ M = \frac{T_p}{\delta} = \frac{T_p}{\delta^*/n} = n \cdot n_w, \qquad n>1,$$

$$2)\ k_i = M/n_W = \frac{T_p/\delta}{n_w} = \frac{n \cdot T_p}{\delta^* \cdot n_w} = n, \qquad n>1.$$

As expected, the size of the process-in-line grows in the same proportion as the δ^* falls off. Moreover, the number of funds at every work station (k_i) matches the factor of the temporal interval shrinkage. For instance, if δ is reduced by half, k_i is doubled. Thus, because every workstation will have only finished the first half of its task as the next good is ready to come into operation, the number of funds used in that workstation will have to double. Therefore, all other things being equal, the units of specific task-performing funds will change according to the level of production.

To enlarge the productive capacity of an in-line process, there is another option: the reduction of the cycle time (T^*_c). If we remember that

$$T^*_c = s_i + l_i = p_i + \pi_i + l_i,$$

this goal may be brought about in three ways:

1) Reduction of the transformation time (p_i) by a simple re-arrangement of jobs within the workstations.

2) Reduction of transformation time (p_i) by a complete re-organisation of agents, tasks and materials (such as the decomposition of tasks into very elementary operations, the standardisation of the components to be assembled and the improvement of the tools).

3) Reduction of non-transformation time (π_i) (such as the transfer times between workstations).[20]

A big drop in service time of all workstations will probably cut back on the balancing idle time (I_i) because this interval of time plays a residual role. As the number of work stations remains unchanged, the contraction of T^*_C entails the shortening of δ^* and, in turn, the expansion of the output per hour, despite M and k_i having exactly the same values as before. That is,

$$T_C = \lambda \cdot T^*_C = \lambda \cdot \delta^*, \qquad 0<\lambda<1.$$

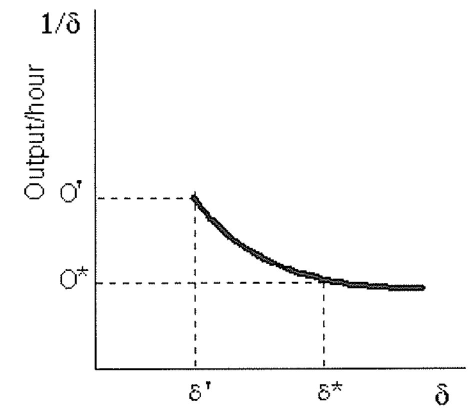
In Figure 4.5 the relationship between the output per unit of time (vertical axis) and the temporal interval values (horizontal axis) is represented.

As has been explained, the production per hour depends exclusively on the temporal interval between consecutive elementary processes. So, the output per hour is equal to $1/\delta$, a value which determines the shape of the curve.

There are therefore two ways to increase production per unit of time. The first one is to directly reduce δ^*, namely $\delta=\delta^*/n$, $n>1$. The second one is to shorten the cycle time: $T_C = \lambda \cdot T^*_C$, $0<\lambda<1$. Both methods give rise to an output expansion. Thus, as shown in the diagram below, the initial level of production (O^* at δ^*) becomes O' when $\delta' = \frac{n}{\lambda} \cdot \frac{1}{\delta^*}$, $n>1$ and $0<\lambda<1$.

[20] For an analysis of the difference between the handicraft production system and the factory system, see Nell (1993).

Figure 4.5. The relationship between the temporal interval and the level of production



In addition, the productivity of work has grown n/λ times. Productivity is increased from

$$(3) \qquad \frac{1}{T^*_c \cdot n_w}, \quad \text{to} \quad \frac{n}{\lambda} \cdot \frac{1}{T^*_c \cdot n_w}.$$

The size of the production is defined as the output per unit of time (an hour) multiplied by H (number of hours of activity per year).

Finally, in Figure 4.5 there is no curve of the output per unit of time above O'. This is due to the fact that the temporal interval reduction and T^*_c have physical limits. Let δ_m indicate the achievable minimum level. That is, $\delta_m \le \delta \le \delta^*$. Of course, if major technical changes modify the capability of funds as well as the methods of production, this restriction might be removed.

An example of an in-line production method developed to achieve higher levels of output per unit of time has been, and still is, the moving assembly line. In such a case, the conveyor belt has caused a large increase in the production rate since work in progress is automatically transferred between the work stations (π_i decline) and workers must follow the chain cadence depending on the belt's speed. Fordism and Taylorism have developed several ways of increasing the pace of the productive line and reducing workers' control over their own activity in order to raise the output level per unit of time and, as a consequence, to reduce the average cost.[21] Labour productivity may vary according to the technical improvements, the increased pace of work or the automation of manual processes.

[21] On Taylorism and Fordism, see Taylor (1967); Coriat (1979 and 1990); and Niebel (1993).

In order to analyse the average cost of in-line production, let us consider a manual assembly-line process with the following characteristics:

1) The process consists in a single phase divided into tasks with specialized funds.

2) Each task is executed by a single worker provided with tools.[22]

For simplicity, the economic impact of the temporal span between payment of the production elements and activation of the process has been disregarded. The average cost (AC) of such a production process is the total cost of funds and inflows divided by the output produced in a given year.[23] That is,

$$AC=\frac{W+A+\sum_k f_k\cdot p_k\cdot H}{\frac{1}{T_c^*}\cdot J\cdot D} \tag{4}$$

where W is the annual payment for labour services, A is the yearly depreciation quota paid for the tools,[24] and $\Sigma_k f_k \cdot p_k \cdot H$ (k=1, 2, ..., K) is the annual cost of the k inflows which is given by the average rate of their quantities coming into the process per hour (f_k), their unitary prices (p_k) and the hours of process activity in a year (H). The total annual hours of activity (H) is, in turn, equal to the length of the working day (J) multiplied by the number of working days in a year (D): H=J·D.[25]

Since H is equal to J·D, the expression above can be rewritten as:

$$AC= T_c^*\left(\alpha+\varpi+\sum_k f_k\cdot p_k\right) \tag{5}$$

where ω is the amount of wages per hour (ω=W/H),[26] and α is the depreciation charge per hour (α=A/H).

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[22] The existence of team production does not change the result of the model.

[23] The model presented here is a development of some elements contained in Petrocchi and Zedde (1990); and Piacentini (1997).

[24] The term Aj is equivalent to $\frac{(1+r)^{n_j}\cdot r\cdot M_j}{(1+r)^{n_j}-1}$, with Mj being the initial value of all tools used in the process, nj the number of years of economic life and r the interest rate. Here, two more assumptions are necessary: the residual value must be zero and the maintenance flow must be included in the other flows.

[25] The number of hours of actual work is disregarded. If we take into account the number of hours of actual work, then we would write $J=\beta\cdot J^*$, $0<\beta\leq 1$.

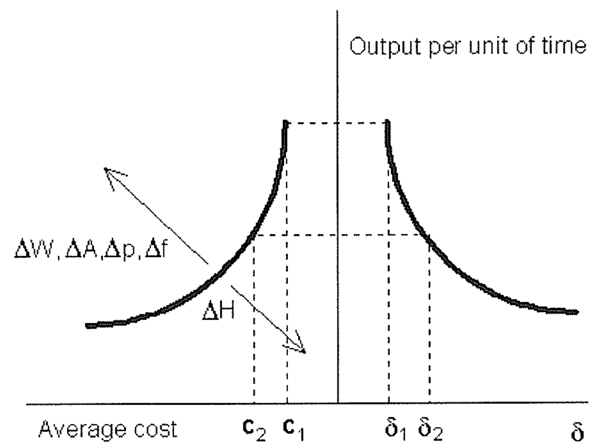
[26] Therefore, the wage per worker and hour is $W/n_w\cdot H$.

In order to increase the production level: i) the cycle time can be reduced by cutting service time (s_i) and by avoiding fund idleness due to balancing delay (l_i); ii) the temporal interval (δ^*) must be curtailed. Taking into account these two points, we obtain from the above expression the following cost function:

$$AC=\frac{\lambda}{n}T_c^*\left(\alpha+\varpi+\sum_k f_k\cdot p_k\right),\quad \text{with } n>1 \text{ and } 0<\lambda<1. \tag{6}$$

This function allows the computation of average cost as production expands. Figure 4.6 illustrates the relationship between level of output per unit of time, average cost and the temporal interval between consecutive elementary processes. In Figure 4.6, the vertical axis refers to the rate of production. The horizontal axis represents, on its right side, measurement of the gap between consecutive elementary processes and, on its left, the cost per unit of production represented in negative values. Changes in the parameters (W,A,H,f_k and p_k) cause shifts of the average cost curve. The position of the average cost curve depends on three types of factors: time, efficiency in using materials and the prices of flows and funds. Average cost may also be affected by the level of output per unit of time.

Figure 4.6. Cost, temporal interval span and the output per unit of time



As far as the time variable is concerned, the temporal efficiency of the process depends on institutional aspects, such as the length of the working day (J), or the total number of annual working days (D), as well as on factors belonging to the internal organisation of the process and fund capacities (δ^* and T^*_c).

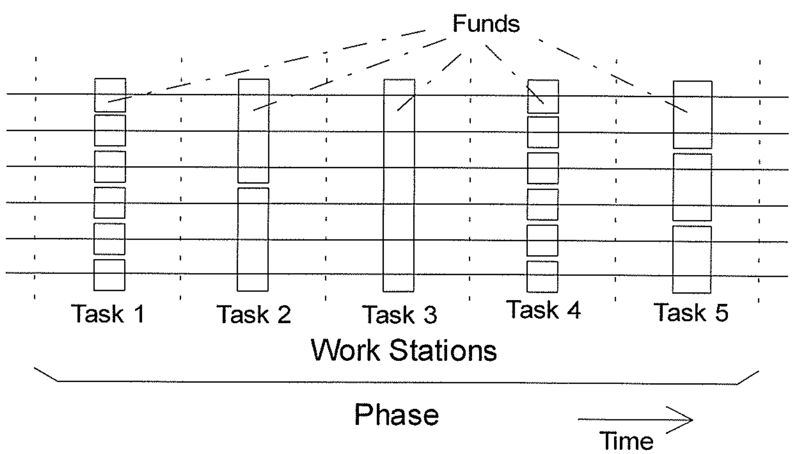
In conclusion, the model presented above highlights the existence of large potential of economies of scale in processes arranged in-line.

4.3. Parallel-in-line process and capacity balancing

In this final section, the assumption that the workstations can produce a single unit of output at any one time is abandoned. Most of the production processes use funds that operate at different productive capacities. This section deals with processes in which funds perform multiple production processes, called parallel-in-line arrangements. As we shall see, parallel-in-line arrangements make further economies of scale possible.

The multiple-work capacity is a characteristic of many funds. There are machines able to produce several units of output simultaneously. This multiple-work capacity is linked to the fund-input indivisibility (a common property of most funds).[27] The multiple production capacity of a fund means there will be an excess of capacity if this fund executes a lesser number of elementary processes than its capacity. Obviously, this implies inefficiency and higher costs. Hence, a general problem of capacity saturation of fixed funds is posed.

Figure 4.7. Capacity saturation of indivisible funds



An example may help illustrate the problem of the capacity saturation. In Figure 4.7 a single phase is composed of five tasks and workstations. There are also funds with specific capacities represented by squares of different sizes. As shown in Figure 4.7, in order to achieve the full utilisation of the funds, six elementary processes should be jointly processed. We therefore have a parallel-in-line process.

[27] Workers and machines are indivisible funds, while land is a divisible fund. On indivisibility, see Landesmann (1986); Morroni (1992:25-6); and Piacentini (1996).

Let $c^*_j \geq 1$ (j=1, 2, ..., J) be the maximum number of elementary processes that a unit of j type fund, in co-ordinated operation with other funds, may simultaneously perform. Then, the coefficient of used capacity (γ_j) is defined as the ratio (Petrocchi and Zedde, 1990:67),

$$\gamma_j = c_j/c^*_j \leq 1,$$

where c_j is the number of real items the fund is operating on in a given process. The coefficient of used capacity (γ_j) approaches the unit as the capacity excess of the fund decreases.

In order to avoid idle capacity, the number of required units of a fund (τ_j) must be equal to the minimum common multiple (mcm) of the c^*_j divided by the j funds' own capacities (Petrocchi and Zedde, 1990:70). That is,

$$\tau_j = mcm/c^*_j.$$

As shown for example, in the case above, $c^*_1=1$, $c^*_2=2$, $c^*_3=3$ and $c^*_4=6$. Thus, the mcm is 6. That means, 6 units of the fund of the first type, 3 of the second, 2 of the third and 1 of the last one.[28] As a consequence, six parallel elementary processes will be deployed. If all fixed-funds were simultaneously operating in all elementary processes, then $\gamma_j=\tau_j=1$ because $c_j = c^*_j = N$ (number of parallel processes).

Returning to the in-line arrangement, the number of elementary processes running at any one time will be:

$$M = T_p/\delta^* \; mcm = n_w \cdot mcm$$

Moreover,

$$\text{output per unit of time} = mcm \cdot 1/\delta^*.$$

In order to determine the single-activation rate of production, the size of the multiple elementary process must be aggregated. A diagram can illustrate this. In Figure 4.8, the horizontal axis refers to δ values, while the vertical axis indicates the units of output per unit of time.

Ceteris paribus, if a process with multi-capacity funds runs in-line, higher levels of production can be achieved as the result of putting into motion a plurality of elementary processes. So, the $1/\delta$ curve moves up, as is shown in the graph in Figure 4.8.

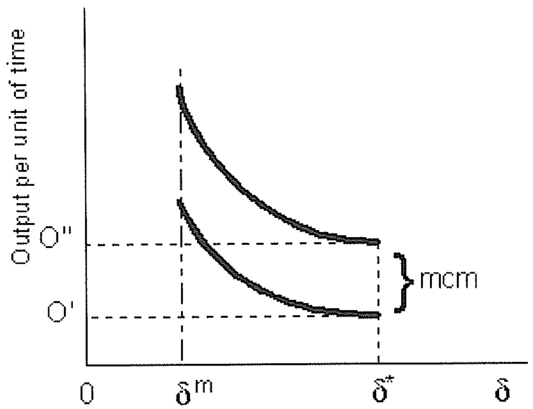
[28] We have assumed that for each task only funds of the same kind are used. However, this supposition is unnecessary if the number of elementary processes guarantees a balance between capacities of funds.

We can collect in a single expression all factors of the output expansion. That is,

$$\text{output per unit of time} = \frac{n}{\lambda} \cdot J \cdot D \cdot mcm \cdot \Lambda \cdot \frac{1}{T_c^*} \quad n>1,\ 0<\lambda<1 \text{ and } mcm>1$$

where n/λ is the shortening of the cycle time caused by Taylorist and Fordist methods, J is the length of the working day, D the number of annual working days per year, mcm is the co-ordination among the different fund capacities that leads to the multiple elementary process, the scalar Λ indicates the number of times that the multiple elementary process is replicated in the unit of production, and finally $1/T^*_c$ denotes the basic level of output per hour without replication.

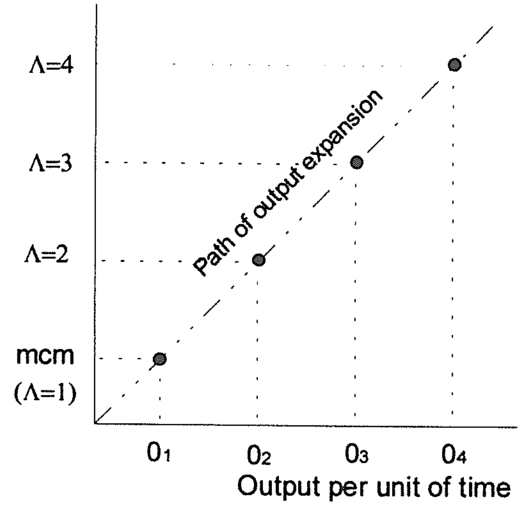
Figure 4.8. Production and multi-capacity funds



Any parallel-in-line process could be replicated in order to raise the production level. Since the multiple elementary process is an efficient arrangement of elementary processes, any other multiple of it will be efficient as well. According to Babbage's Factory Principle: "When the number of processes into which it is most advantageous to divide it, and the number of individuals to be employed in it, are ascertained, then all factories which do not employ a direct multiple of this latter number, will produce the article at a greater cost".[29] Thus, this principle could be included in our model through the Λ parameter.

[29] Babbage (1971:212). The significance of this principle to the theory of production is illustrated by Landesmann (1986:308-9) and Morroni (1992:63-5).

Figure 4.9. Output expansion



As illustrated in Figure 4.9, the level of production increases according to the Λ parameter. Notice that in the diagram, only the points of the path of output expansion have any significance. These points indicate the parallel replication of the multiple elementary process. The different levels of output per unit of time, O_1, O_2,... , have the same level of average cost. Between two consecutive levels of output, the cost per item produced will be higher because of multi-capacity funds working below their full capacity.

Finally, let us include in the cost expression the annual depreciation quota paid for every one type of multiple work-capacity fixed-funds (A_j).The average cost is given by,

$$(7) \quad AC = \frac{\lambda}{n} \cdot \frac{1}{mcm} \cdot T_c^* \left(\alpha + \varpi + \sum_j \alpha_j + \sum_k f_k \cdot p_k \right), \text{ with } n>1,\ mcm>1 \text{ and } 0<\lambda<1,$$

where α_j are the depreciation charges per hour.[30] In this expression, the replication factor (Λ) has been removed because of its simultaneous influence on the total cost and on the production level. Moreover, as can be observed, the greater the work-capacity of the funds, the less the average cost because of the 1/mcm element. This reduction is due to parallel-in-line arrangement. When one or more

[30] We assume the same pattern of depreciation for all j kinds of multi-capacity funds. Since our analysis has been restricted to production activity, the general management expenditures have not been taken into account and, as a consequence, the economies of scale of a managerial type have been neglected.

funds can be partially inactive, because they can execute more elementary processes than they actually do, the parallel spreading of several in-line elementary processes eliminates this excess capacity.

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