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MEASURING CAPITAL DEPRECIATION

By

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44(E)

July, 1991

We would like to thank Mr. Aldo Diaz and Mr. René Durand for their very useful comments and revisions.

1. Introduction

The purpose of this study is to determine the best method to measure capital depreciation for purposes of the empirical calculation of multifactor productivity indices for Canadian industries.

Given the complexity of the relationship between physical depreciation and economic depreciation, and the lack of a single definition of economic depreciation, the first stage will involve defining these two terms and demonstrating the relationship that exists between these two concepts (Chapter 2).

Once this relationship has been established, we will examine the practical problems posed by the assessment of economic depreciation. Thus, we will discuss the perpetual inventory method and the main methods that make it possible to estimate efficiency functions (Chapters 3 and 4). Subsequently, we will discuss various criticisms of the perpetual inventory method (Chapter 5). Finally, after summarizing and comparing the main empirical studies (Chapter 6), we will recommend the physical depreciation model that we feel is the most appropriate one within the framework of multifactor analysis (Chapter 7).

2. Definitions: Physical Depreciation and Economic Depreciation.

All businesses need various kinds of equipment, machines, and buildings for the purposes of production, all of which have more or less limited lives. This lifetime is a function, for example, of the type of capital and the intensity with which it is used. Capital stock is consumed in the production process; its production capacity and monetary value diminish with time.

Depreciation is a physical concept reflecting the loss of production capacity of a given capital stock. We also speak of its loss of efficiency or mortality. Physical depreciation is measured by the relative loss of the marginal productivity of an asset over a period of time t, so that: $(\phi_s - \phi_{s+t})$, where ϕ_s represents the ratio of the marginal productivities of a used good of age s, to those of a new good (we will return to this in the next section). Physical depreciation leads to the need for replacement, in order for productivity to remain at its initial level. Thus, we can also say that physical depreciation represents that portion of an investment that must be replaced over a given period of time, in order to maintain production at its initial level.

In this document, the term economic depreciation will be used to refer to both the loss of monetary value of a durable capital good associated with physical depreciation or loss of efficiency, and that associated with the loss of anticipated service: the loss of value associated with physical depreciation should be distinguished from that associated with aging; because, even though the aging of an asset implies a loss of value, it does not necessarily imply a loss of efficiency. For example, a lightbulb may lose a major part of its value over its first year of use, without losing any of its efficiency; that is, without depreciating.

Thus, the assessment of physical depreciation makes it possible to measure the quantity of capital input; that is, the portion of capital rendered nonproductive, while economic depreciation measures the loss of value of the capital, that is, the value of capital input.

In the context of this study, the term economic depreciation will be used to refer to loss of capital value. We will reserve the term physical depreciation solely for the loss of physical efficiency: the distinction between physical depreciation and economic depreciation is very important; because, in general, the two measurements are not comparable. In French, the terms "amortissement" and "dépréciation" are used to refer to economic depreciation and physical depreciation respectively.

Economic depreciation can be measured in current or constant dollars because inflation has no effect on its definition. However, we should always maintain consistency and use an economic depreciation measurement that is compatible with the measurement of capital value. Economic depreciation is independent of maintenance, repair, and obsolescence costs; that is, the loss of value caused by technological aging.

While we have defined economic depreciation as reflecting the loss of value associated with the loss of efficiency and the aging of a durable capital good, we must emphasize that not all economists agree on a single definition. Young and Musgrave feel that the various concepts can be condensed into two. They refer to the first as that used in the national income and expenditures accounts, and the second as that of the estimated value of future services.

According to the first approach, economic depreciation is defined as the cost of a capital good distributed over its lifetime, estimated as a function of the service provided in each period. The services are not discounted and are net of maintenance and repair costs. Obsolescence is charged when the good is retired, as it has no effect on service but only on the length of the service lifetime of the asset: "The charge for obsolescence at retirement writes off the remainder of the asset as a component of capital

consumption and in effect replaces the physical life with the economic service life"[1].

According to Young and Musgrave, this definition results from a vision of economic depreciation as a production expense, representing the difference between the gross national product and the net national product, and not a past or present anticipation of future income. According to Young and Musgrave, this approach is consistent with the practice of national income and expenditures accounts, which measure the flow of goods and services, on the basis of production and productivity. However, this method has the disadvantage of not allowing the economic depreciation function to be determined: "Given the available information, the depreciation curve that best implements the definition cannot be determined precisely"[2]. Thus, the shape of the curve is determined arbitrarily: most often, we assume a straight line.

According to the second approach, economic depreciation is the decline in services estimated at the present time. The estimated services are net of maintenance, repair, and obsolescence costs, that is, of technological aging: "The effect of obsolescence is best viewed as occurring at a constant rate"[3]. In addition to the loss of efficiency that affects the sum of estimated services, the capital stock ages each year and loses one of its remaining years. However, since this is the last year and it is farther into the future, because of the actualization factor, its value is lower than that of the other years. Even in the absence of physical depreciation, over a given period of time t, a production asset will have an increasing economic depreciation rate resulting from its aging and from the fact that the actualization of its services will assign a lower value to the later years.

In our opinion, the difference between the two approaches is actually much more than just a simple question of measuring. For example Thomas K. Rymes, in a comment on Young and Musgrave's paper, emphasizes how his point of view differs from that of the authors by insisting on the importance of remaining as close to market values as possible:

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[1] Musgrave, J.C. and Young, A.H., "Estimation of Capital Stock in the United States" in Usher, Dan, *The Measurement of Capital*, Edited by Dan Usher, The University of Chicago Press, 1980, p. 33.

[2] Musgrave, J.C. and Young, A.H., "Estimation of Capital Stock in the United States", op. cit., p. 32.

[3] Idem, p. 33.

"The time pattern of the value of the net stock of the asset generated by the discounted value definition, with its corresponding different pattern of depreciation, would be that generated by the market value of the asset...That, it seems to me, is what we want and so I strongly support the discounted value definition"[4].

The cost approach does not make it possible to measure the form of economic depreciation, while the discounted service value approach allows us to infer the shape of the physical or economic depreciation curve by using the relationship that exists between an asset's marginal productivity and its rental cost, in a situation of competition and equilibrium. More generally, this relationship allows us to establish the ratio between value and productivity, or between economic and physical depreciation. Thus, we prefer the discounted value approach, precisely because of the relationship it allows us to establish between economic and physical depreciation. However, we must still discuss, in detail, the nature of this relationship.

2.1 Relationship Between Economic and Physical Depreciation

Elsewhere, we defined economic depreciation as reflecting the monetary loss of an asset attributable to the loss of its estimated service as the result of physical depreciation and aging, net of maintenance, repair and obsolescence costs. Despite the apparent simplicity of this definition, however, the relationship between physical depreciation, economic depreciation, and estimated services is not direct. In fact, it is the result of a series of intermediate relationships that will be listed here, and will subsequently be discussed in detail:

- the relationship between capital goods and the production function;
- the relationship between the ratio of marginal productivities and relative efficiencies ϕ;
- the relationship between purchase price and rental price;
- the relationship between the ratio of rental prices and the ratio of marginal productivities;

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[4] Rymes, Thomas, comment on a paper by Musgrave, J.C. and Young, A.H., "Estimation of Capital Stock in the United States" in Usher, Dan, *The Measurement of Capital*, edited by Dan Usher, The University of Chicago Press, 1980, p. 58.

- the relationship between the ratio of rental prices and relative efficiencies ϕ;

- the relationship between purchase price, efficiency, and estimated services; and finally,

- the relationship between economic depreciation, physical depreciation, and estimated services.

a) The relationship between capital goods and the production function

The relationship between capital goods and the production function has been developed by Léontief (1947)[5], Solow (1960)[6], and Fisher (1965)[7]. The main question involves the required conditions that allow different vintages of capital and technologies to be aggregated within the same production function.

In the case of **homogenous goods**, we first assume that each vintage of capital can be combined with homogenous labour and produce homogenous goods (that can be added). The problem of aggregation involves being able to write our production function in the following form:

$$Q_t^* = F(\tau_t, K(I_t, \ldots, I_{t-T})) \tag{1}$$

where $\tau_t = \sum_v \tau_{t,v}$, that is, the quantity of labour used by each vintage of capital v in time t; Q_t^* is the maximum quantity of output that can be produced assuming that the labour is optimally distributed between the various vintages of capital. The necessary and sufficient conditions for the aggregation of homogenous capital goods are given by Léontief's Theorem: the marginal substitution rates between each vintage of capital should be independent of the quantity of other inputs such as labour:

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5 Léontief, W.W., "A Note on the Interrelation of Subsets of Independent Variables of a Continuous First Derivatives", Bulletin of the American Mathematical Society, 53, pp. 343-350.

6 Robert M., "Investment and Technical ProSolow, Rgress", in K. Arrow, S. Karlin, and P. Suppes., "Mathematical Methods in the Social Sciences", Stanford University Press, 1959.

7 Fisher, Franklin, "Embodied Technical Change and the Existence of an Aggregate Capital Stock," Review of Economic Studies 32, pp. 263-268.

(2) $$\frac{\partial}{\partial \tau_t}\left(\frac{\partial Q^*/\partial I_{v,t}}{\partial Q^*/\partial I_{s,t}}\right)=0,\ \forall v,s \leq t \wedge \forall t.$$

$I_{v,t}$ and $I_{s,t}$ represent two different vintages of capital used at time t.

When we wish to aggregate **heterogenous goods**, for example when we wish to aggregate goods belonging to the same sector of activity, we must first, as in the case of homogenous goods, assume that each vintage of capital may be combined with homogenous labour and produce homogenous goods (that may be added). The problem of aggregation involves writing our production function in the following form:

(3) $$Q_t^* = F(\tau_t, K(K_t^1, \ldots, K_{t-T}^N)),$$

where each K^i is itself an aggregate of different vintages of a homogenous good i which comply with the aggregation conditions mentioned above. In addition to these conditions, the marginal substitution rate between each type of capital good must also be independent of the quantity of labour used:

(4) $$\frac{\partial}{\partial \tau_t}\left(\frac{\partial Q/\partial K_t^i}{\partial Q/\partial K_t^j}\right)=0,\ i,j=1,\ldots N, i\neq j$$

where each K^i represents a given category of good. Thus, this condition, known as *weak separability*, requires that the changes coming from the labour side (or from any input other than capital) will not affect the possible substitution between the various types of capital goods used:

> "Suppose labour is ten, and the two capital substitutions possible are, say, three v,d) to one x2 and two x1 to three x2, both combinations yielding one hundred units of output. Now let the labor increase to twenty, which combined with the same capital ratios, yields two hundred units of output. In this case the Léontief condition holds"[8].

This restriction implies that the aggregation function K ( ) determines the nature of the capital aggregation, and measuring

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[8] Brown, Murray, "The Measurement of Capital Aggregates: A Postreswitching Problem" in Usher, Dan, *The Measurement of Capital*, edited by Dan Usher, The University of Chicago Press, 1980, p. 388.

aggregate capital thus becomes the problem of determining the form of this function. This can be done by direct estimation of F ( ) and K ( ), which makes it possible to avoid having to construct capital aggregates, or by deriving Divisia indices.

The Divisia indices are constructed by weighting the growth rate of each category of capital by their share of the total capital income,

(5) $$s_t^i = p_t^{k_i} k_t^i / \sum p_t^{k_i} K_t^i$$

and, by adding the result

(6) $$\frac{\dot{K}_t}{K_t} = \sum s_t^i \frac{\dot{K}_t^i}{k_t^i}$$

b) The relationship between the ratio of marginal productivities and relative efficiencies ϕ

Fisher (1965) showed that, assuming constant return, the condition of weak separability implies that the technology should be such that the ratio between the marginal productivity of the old capital I_v and that of new capital I_t is expressed by a fixed constant ϕ, known as relative efficiency, which depends solely upon the vintage under consideration[9]:

> "Recalling that the weak separability condition (...) is both necessary and sufficient for the existence of a group capital index, Fisher proceeds to draw the implication of this condition for the form of the original firm production functions (...). He finds that, under the assumption of strictly diminishing returns to labour, a necessary and sufficient condition for capital aggregation is that every firm's production satisfy a partial differential equation in the form
>
> $$(F^j_{0j,0j}/F^1_{1j}F^j_{0j,0j}) = g(F^j_{0j}),$$
>
> where g is the same function for all firms. Further, assuming constant returns to scale, capital augmentation technical differences turns out to be the only case under constant returns in which a capital exists. This means that each firm's production could be written as $F^j(x_{0j}, x_{ij}) = F^1(x_{0j}, b_j x_{1j})$, where the b_j are positive constants".

[9] Brown, Murray, "The Measurement of Capital Aggregates: A Postreswitching Problem", op. cit., p. 394.

In the case of a homogenous good, for example, this implies that:

$$\frac{\partial Q^*/\partial I_v}{\partial Q^*/\partial I_t}=\phi_{t-v} \quad v=t,t-1,... \tag{7}$$

The old capital enters into the production function as a fraction of the new capital. Thus, this means that the capital stock must be aggregated by weighting each investment as a function of its relative marginal productivity. Thus, the result is a measurement of the net productive capital stock that is consistent with the use of the production functions; that is, that in order to comply with the conditions of weak separability, the capital stock $K(I_t,...I_{t-T})$ must be aggregated in the following form:

$$k_t=\sum \phi_{t-v}I_v, \quad v=t,t-1,...t-T. \tag{8}$$

The gross stock is simply expressed by the following relationship:

$$k_t=\sum I_{t-v}, \quad v=t,t-1,...t-T. \tag{9}$$

The measurement of net productive stock (stock before physical and not economic deprecation) and gross stock will, exceptionally, be equivalent, in cases where there is no physical depreciation; that is, when the service provided by the capital stock remains constant throughout its life (one-horse-shay).

c) The relationship between purchase and rental prices

In a situation of competition and equilibrium, the production cost of a capital good is equal to its purchase price, which in turn is equal to the discounted value of the income produced over the life of this good. If we consider goods of different vintages, the value of one vintage of age s is equal to the remaining value of the discounted gross annual incomes, which are equal to the rental price:

$$P_{t,s}=\sum_{\tau=0}^{T-s-1} \frac{L_{t+\tau,s+\tau}}{(1+r)^{\tau+1}}, s=1,2,3,... \tag{10}$$

$P_{t,s}$ is the equilibrium price of an asset at time t, s being the age of this vintage, T the life of this asset, and T-s-1 its residual

life[10]. $L_{t+\tau,s+\tau}$ is the anticipated gross annual income (equal to the rental price) of an asset from vintage $s+\tau$ years (in the year $t+\tau$), and r is the nominal interest rate (which is assumed to be constant for simplicity's sake).

d) The relationship between the ratio of rental prices and the ratio of marginal productivities

When there are rental markets for all the cohorts of goods and we are in a position of equilibrium in a perfect competitive market, since the supply of capital goods belonging to various vintages is inelastic, cost minimization implies that the capital of each vintage will be rented until the value of its marginal productivity for a given period is equal to its rental price for the same period. Thus, the marginal substitution rate between the vintage of year v (v=t-s) and the new capital is equal to the corresponding ratio of the rental prices:

$$(11) \qquad \frac{L_{t,s}}{L_{t,0}}=\frac{\partial Q/\partial I_v}{\partial Q/\partial I_t}, \quad s=(t-v)=1,2,...$$

$L_{t,s}$ is the rental price of a capital good of age s at time t. This price corresponds to the investment belonging to vintage v, I_v. $L_{t,s}$ is the rental price of a new capital good at time t corresponding to a new investment, I_t.

e) The relationship between the ratio of rental prices and relative efficiencies

We have shown that old capital should be expressed as a fraction of new capital, thus we obtain (4) and (8):

$$(12) \qquad \frac{L_{t,s}}{L_{t,0}}=\frac{\partial Q/\partial I_v}{\partial Q/\partial I_t}=\phi_s, \quad s=(t-v)=1,2,...$$

The ratio between the rental price of a used good and the rental price of a new good is equal to the relative efficiency (ϕ).

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[10] The length of a vintage depends in part on the decision to retire it: an asset is retired when the expected revenues drop below the disposal value.

Jorgenson (1973)[11] suggested using this relationship to infer the relative efficiencies (ϕ), and named the sequence of these relative efficiencies (equation (6), the *efficiency function*. Thus, the relative efficiencies represent the ratios of rental prices, which are also equal to the ratios of marginal productivities.

f) The relationship between purchase price, efficiency, and estimated services

Using this relationship, we can also write the price of an asset in terms of the relative efficiency sequence and the rental price of new units:

$$(13) \qquad P_{t,s} = \sum_{\tau=0}^{T-s-1} \frac{\phi_{s+\tau} \; L_{t+\tau,0}}{(1+r)^{\tau+1}} \qquad s=(t-v)=1,2,\ldots$$

Thus, this expression links the current value of an asset to its efficiency and the estimated services of this asset: the purchase price of an asset of vintage s at time t is equal to the current value of the sum of the incomes derived from a new good multiplied by the relative efficiencies applicable each year. It was derived for the case where there is a rental market, but it is also valid when the capital is used by its owner, because it is possible to reorganize equation (11) to express the rental price or quasi-rental as a function of the other variables, ϕ, r, and p.

Using the definition of economic depreciation given by Hicks[12] (1946); that is, the sum of money that must be set aside to maintain the value of the capital in real terms, using our notation we can express this definition of economic depreciation by $[P_{t,s}-P_{t,s+1}]$: thus, this is the difference between the price of an asset belonging to vintage s and the price of the same asset (we must recall that these are identical assets, and that the only difference between assets is their productivity) belonging to vintage s+1; that is, the same asset one year later, with this difference in value being measured in dollars of year t. It can also be expressed by $\delta_{t,s}\, P_{t,s}$, where $\delta_{t,s}$ is the economic depreciation rate of the price of the asset at age s:

The economic depreciation rate δ of an asset over a given period of time is equal to the relative drop in the price of that asset.

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[11] Jorgenson, Dale W., "The Economic Theory of Replacement and Depreciation," in W. Sellykaerts ed., *Econometrics and Economic Theory*, New York: MacMillan, 1973.

[12] Hicks, J.R. "Value and Capital," Oxford, Oxford University Press, 1946.

(14) $$\delta_{t,s} = -\left[\frac{P_{t,s+1}}{P_{t,s}} - 1\right]$$

g) The relationship between economic depreciation, physical depreciation, and estimated services

Thus, as Jorgenson (1973) did, equation (12) can be used to establish a link between economic depreciation and the decline in efficiency:

(15) $$\delta_{t,s}\, P_{t,s} = [P_{t,s} - P_{t,s+1}] = \sum_{\tau=0}^{T-s-1} \frac{(\phi_{s+\tau} - \phi_{s+\tau+1})\, L_{t+\tau,0}}{(1+r)^{\tau+1}}$$

This expression indicates that economic depreciation, or the loss of value of an asset of vintage s, is the present value of the initial rental income $L_{t+\tau,0}$ lost over the course of a given period of time as the result of the depreciation ($\phi_{s+\tau}$ - $\phi_{s+\tau+1}$) of this asset between each of the periods that has gone by, as well as future ones (τ=0,1,2,...T-s-1):

> "The depreciation (economic) reflects both the current decline in efficiency and the present value of future declines in efficiency"[13].

Or, as Hulten says:

> "...depreciation (economic) occurs because the efficiency pattern is shifted one year for every year the asset ages. It is the shift in the entire efficiency pattern which leads to a decline in asset value"[14].

Thus, as we have already said, economic depreciation is the reflection of the monetary loss of an asset attributable to its physical depreciation and to the loss in estimated service as the result of aging. Even though we have considered the case of economic depreciation in constant dollars, the reasoning remains similar in the presence of inflation; however, the equation is more complex, since we have to measure the difference between two vintages of different price levels.

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13 Dale W. Jorgenson, "Capital as a Factor of Production", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989, p. 5.

14 Hulten, Charles R., "The Measurement of Capital," University of Maryland and The National Bureau of Economic Research, April, 1988, p. 18.

(16) $$[P_{t,s}-P_{t+1,s+1}] = \frac{(\phi_s-\phi_{s+1})\,L_{t,0}}{(1+r)} + \sum_{\tau=1}^{T-s-1} \frac{(\phi_{s+\tau}-\phi_{s+\tau+1})\,L_{t+\tau,1}}{(1+r)^{\tau+1}}$$

While equations (15) and (16) demonstrate that the concepts of physical and economic depreciation are not independent, they also show that the economic and physical depreciation curves will not necessarily have the same shape.

Economic depreciation is different from the replacement cost made necessary by the physical depreciation undergone in a year; that is: $[P_{t,s} - P_{t,s+1}] \neq (\phi_s - \phi_{s+1})\, P_{t,0}$ because $P_{t,0}$ is not equal to $[P_{t,s}/\phi_s]$ unless the physical depreciation is geometric[15]. In other words, $\delta_{t,s}\, P_{t,s} \neq (\phi_s - \phi_{s+1})\, P_{t,0}$: because: $P_{t,0} \neq [P_{t,s}/\phi_s]$.

In the case where $P_{t,0} = [P_{t,s}/\phi_s]$, then $\delta_{t,s}\, P_{t,s} = (\phi_s - \phi_{s+1})\, P_{t,s}/\phi_s$ and $\delta_{t,s} = (\phi_s - \phi_{s+1})/\phi_s$; that is, the rate of economic depreciation is equal to the rate of physical depreciation.

We should also remember that in cases where the two rates are equal, the rate is geometric, and, as a result, the curves are convex. It is only in this case that we obtain equality between economic depreciation and the replacement cost of lost efficiency.

We can understand intuitively that, in general, the cost to replace efficiency lost over a period of time t is different from the loss of value of the capital measured in real terms over the course of the same period; let us consider the following example: Let us assume that the asset has one-horse-shay depreciation and a service life of 10 years. Even though, for example, there was no loss of efficiency between the first and ninth years, and the cost of replacing lost efficiency will be zero, there is still a loss of value of the asset (since there has been some economic depreciation) because, as the result of aging, the sum of the discounted rental incomes has decreased.

2.2 Measuring Economic Depreciation

Let us remember that Hicks[16] defined economic depreciation as the sum of money, in constant dollars, that must be set aside to maintain the value of the capital stock in real terms. This sum is obviously the loss of value suffered by the capital stock. As we

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[15] Thus, linear physical depreciation implies a convex non-geometric economic depreciation curve and, conversely, a convex non-geometric physical depreciation curve implies linear economic depreciation.

[16] Hicks, J.R. "Value and Capital," Oxford, Oxford University Press, 1946).

have already mentioned, this loss is attributable to the physical depreciation and to the decline in estimated service resulting from aging.

More practically, the problem posed by the measurement of the economic depreciation of capital can be reduced, as D. Usher[17] points out, to determining what proportion of the capital produced in one year will still be available t years later. Usher, however, points out that there are four problems with this point of view: (1) some assets have been retired; (2) some assets have deteriorated; their marginal productivity is not as high, or their maintenance costs have increased; (3) the capital stock is older, and thus it has fewer estimated service years left; (4) the stock has become obsolete; its marginal productivity has dropped because of changes in tastes, the availability of more productive capital, or an increase in the price of complementary production factors.

According to Hulten and Wykoff, problems related to aging (the third problem raised by Usher) form part of the deterioration problems (the second problem raised by Usher). According to them, the central problem of the economic depreciation theory consists of determining how the prices of a cohort of identical assets change with age:

> "The older assets in the collection should be less valuable than the newer for two reasons: (1) the age of "optimal" retirement from service is nearer for the older assets and (2) older assets may be less profitable because they either produce less output or because they require more input (ie maintenance) to operate"[18].

Thus, they define the economic depreciation of a durable good as the decline in value of an asset as a function of age: the estimated services and physical depreciation being a function of the age of the asset. They also distinguish between the problem of deterioration and the problem of obsolescence related to technological aging: obsolescence is attributable to altogether different factors: "A given car usually loses value as it ages for an entirely different reason based on technological change and

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[17] Usher, Dan, "The Measurement of Capital," edited by Dan Usher, The University of Chicago Press, 1980, p. 6.

[18] Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from capital*, The Urban Institute press, Washington D.C., 1981, edited by Charles Hulten, p. 84.

vintage"[19]. In their model, they add a time variable, in order to take into account inflation and obsolescence (see Section 6.1).

Finally, regardless of the approach taken, the first stage in the measurement of the economic depreciation of the capital stock involves measuring the capital stock. However, a problem arises immediately: What type of unit should be used?

Measuring Capital Stock by Type of Asset

Even in an economy composed of only one type of asset, automobiles for example, we could not simply add the assets to obtain the capital stock. In fact, even if automobiles formed a homogenous category of goods, apart from their age, they also have other characteristics that account for differences between them. At present, the solution used to deal with this difficulty involves weighting these assets by their relative marginal productivity; that is, the ratio of their marginal productivity to that of an equivalent new good. This allows us to compare indirectly two assets by first comparing each of them to a common unit. The sum of these ratios, known as the productive capital stock, represents the number of efficient units. But now, how do we determine the relative marginal productivity of an asset?

While the marginal productivity of a capital good is not directly observable, we know that, in a situation of competition and equilibrium, it should be equal to the rental price. Thus, the solution consists of adding the number of capital units pre-multiplied by their relative rental cost. Two other problems then arise: the number of capital units is not directly observable, and not all the goods are rented. The perpetual inventory method, which we will examine in the next section, allows us to solve these problems and aggregate various vintages of capital.

After the capital stock has been measured for each type of asset, it must also be aggregated by category; this problem of aggregation was already raised in Section 2.1 and lies outside the scope of the question of measuring capital depreciation, which is more related to the aggregation of various vintages of assets belonging to the same category.

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19 Wykoff, Economic Depreciation and Business-Leased Automobiles", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge Massachussetts, London, England, 1989, p. 261.

3. Measuring Capital Stock: Perpetual Inventory

If all the capital were consumed immediately, or if the capital were rented, we would be able to determine the service cost of the capital directly. However, since capital is a production factor that may be used for several years after its initial purchase, and is used by its owner, it is necessary to estimate the cost and flow of capital service. The perpetual inventory method is a very popular method to estimate capital service indirectly; it is used by almost all national statistics agencies. The perpetual inventory method makes it possible to estimate either the productive capital stock (stock before depreciation) or the gross value of the capital stock. Then, we must estimate the flow of the service provided by this capital stock.

Since existing capital stock is not directly observable, we proceed indirectly by adding, for each category of assets; that is, for each cohort of assets that are considered to be identical, the amount of new capital I (in constant dollars) added each year. However, we must take into account both the fact that part of the old capital has been retired, and the fact that the old capital may be less productive. Thus, this represents a weighted addition of previous gross investments in constant dollars, where each investment is weighted by the relative efficiency ϕ; that is, the ratio of the marginal productivities or rental prices that take the loss of capital efficiency into account (see equation 10). Thus, this is a measurement of the productive stock or depreciated capital stock, which, according to equation (8) is expressed as follows:

$$(8)\quad K_t = \phi_0 I_t + \phi_1 I_{t-1} + \ldots\ldots + \phi_T I_{t-T} \qquad 0 < \phi_i < 1 \text{ et } i = 1 \ldots T$$

where K_t is the net capital stock for a category of assets, $\phi_0=1$ (the relative efficiencies for each new addition of capital are standardized), and t-T is the age of the oldest vintage[20] still in existence. Since the weights correspond to the relative efficiencies of capital goods of various ages, the weighted components of capital stock have the same efficiency. The productive stock represents the amount of investment that would be required over a period of time t to produce a capital service equivalent to that provided by the current stock. The productive stock model was developed by Robert E. Hall(1968)[21] and was used

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20 The term "*vintage*" is used to represent the capital assets produced over the course of a year.

21 Hall, Robert E., "Technical Change and Capital From the Point of View the Dual," Review of Economic Studies, 35, 1968, pp. 34-36.

empirically for the first time by Laurits R. Christensen and Dale W. Jorgenson (1969)[22]

Since the average lifetime is not the same for all the various types of assets, apart from estimates of relative efficiency, we must also have information on the lives of various assets.

In order to take into account the fact that the retirement of assets belonging to the same vintage does not correspond exactly to their average lifetime, in the more recent studies we use a retirement curve; that is a distribution of retirements around their average lifetime. Thus, the investments are also weighted by a survival probability function and a retirement probability function, in order to obtain a realistic measurement of the productive stock.

In addition to the efficiency function it is necessary to have information available on gross investments of capital in constant dollars, in order to be able to aggregate the productive capital stock. Also, since the data on capital formation are in current prices, we must have a price index to deflate the nominal values of the investments in real values. Finally, since not all assets are affected by inflation in the same way, we must construct a deflation index for each category of assets. Hulten emphasizes two potential sources of error in this operation: the use of a single deflator for heterogenous goods, and the adjustment for changes in quality. One of the problems that arises, for example, is that of the introduction of new goods.

How is it possible to construct a price index when new goods are constantly being introduced? Computers, for example, due to the importance of their market share in the economy and their phenomenal increases in power, represent a particular problem for the design of a price deflation index. Non-residential structures are a second major problem, because of their very high heterogeneity. The problem is not, however, specific to the perpetual inventory method, as it is part of all aggregation processes.

Once the productive capital stock for each type of asset has been evaluated, the second stage in the design of a multifactor productivity measurement involves calculating the capital input in each of the economic sectors under consideration: "Capital services represent the quantity of capital input, just as labour services

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[22] Christensen, Laurits R. and Jorgenson, Dale W., "The Measurement of U.S. Real Capital Input, 1929-1967", Review of Income and Wealth, Vol. 15, 1969. pp. 292-320.

represent the quantity of labour input"[23]. Up to this point, we have considered capital stock; how should we convert the stock into flow? The solution used within the framework of the perpetual inventory method is called the "minimalist" solution. It consists of assuming that the total quantity of current service is proportional to the productive stock:

> "This assumption implies that the services derived from equipment assets that bought during different periods are perfect substitutes in production. In time, this substitutability leads to the proportionality of services derived from each equipment asset and capital stock corresponding to the sum of the total past capital expenditures"[24].

Another method of converting the gross capital stock into flow involves multiplying the capital stock by an estimate of capital utilisation. However, this method converts to the problem of measuring capital service to one of estimating the use of capital, and measuring use is very problematical:

> "Ambiguity about the exact nature of capital services is at the centre of the problem. What, exactly, is a capital "service"? Is a chair in "service" when occupied?...is an office building utilized only during business hours?"[25].

Thus, the "minimalist" solution is generally used. We are aware, however, that this relationship is not a strict one, especially because of variations attributable to economic cycles.

Once the quantity of service has been determined, we must determine the price associated with that service:

> "Rental rates for capital services provide the basis for property compensation, just as wages provide the basis for labour compensation"[26].

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[23] Jorgenson, Dale W., "Productivity and Economic Growth", Harvard Institute of Economic Research, Harvard University, Discussion Paper No. 1487, June 1990, p. 31.

[24] Fixed Capital Flows and Stocks: Methodology, National Wealth and Capital Stock Section, Investment and Capital Stock Division, May 1990, p. 3.

[25] Hulten, Charles, "The Measurement of Capital", op. cit., p. 29.

[26] Jorgenson, Dale W., "Productivity and Economic Growth", Harvard Institute of Economic Research, Harvard University, Discussion Paper No. 1487, June 1990, p. 31.

While various rental cost formulations are used, the most important component of this cost is capital depreciation. Obviously, for simple reasons of consistency, the depreciation rates used in the implicit calculation of rental rates are the same as those used in the evaluation of capital stock:

> "The first and most important criterion for internal consistency of a measure of capital input is that the same patterns of relative efficiency must underlie both the estimates of capital stock A(T) and the estimates of rental prices $p_K(T)$ for each class of assets"[27].

This logic is also based on the relationship between the economic and physical depreciation curves: entire studies have been invalidated because they have not followed this logic:

> "Our overall conclusion is that none of Denison's measures of capital input satisfies the criterion that the same pattern of relative efficiency must be employed in estimates of capital stock and of rental price of capital services"[28].

Thus, an estimate of the sequence of relative efficiencies or relative marginal productivities $[\phi_0, \phi_1, \ldots, \phi_T]$ allows us to meet two objectives: the evaluation of capital stock and the measurement of capital input. Unfortunately, there are no simple methods for estimating these relative efficiencies directly. Thus, we must use indirect methods to infer them.

4. Relative Efficiencies

Four types of curves are often used in the literature to describe the sequence of relative efficiencies ϕ: one-horse-shay, the straight (45 degree) line, the convex curve, and the concave curve.

One-horse-shay describes the case of an asset that keeps all of its efficiency until the end of its service life. A common example is a lightbulb, which continues to produce light until it burns out completely. Thus, the problem is strictly one of evaluating the life of the asset, since the efficiencies are equal from period to period.

$$\phi_0 = \phi_1 = \ldots = \phi_{T-1} = 1, \quad \phi_{T+\alpha} = 0 \quad \alpha = 0,1,2,\ldots$$

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27 Jorgenson, Dale W., "Productivity and Economic Growth", op. cit., p. 43.

28 Dale W. Jorgenson, "Capital as a Factor of Production", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge Massachussetts, London, England, 1989, p. 26.

The (45 degree) straight line illustrates the same loss of service each year, the capacity decreases by a constant **amount**, and thus the **rate** of depreciation is thus **increasing**. As with one-horse-shay, the problem consists of evaluating the asset's lifetime. Its great popularity springs from its use in accounting.

$$\phi_0 = 1,\ \phi_1 = 1 - 1/T,\ \phi_2 = 1 - 2/T...,\ \phi_{T-1} = 1-(T-1)/T$$

$$\phi_{T+\alpha} = 0 \quad \alpha = 0,1,2,...$$

Geometric depreciation (convex curve) represents an asset whose productive capacity decreases at a constant **rate**. Thus, this is the only type of depreciation that can be described by a single depreciation rate δ.

$$(\phi_{T-1} - \phi_t)/\phi_{t-1} = \delta, \text{ which implies that}$$

$$\phi_0 = 1,\ \phi_1 = (1 - \delta),\ \phi_2 = (1 - \delta)^2,...,\ \phi_T = 1-(1-\delta)^t$$

Deferred depreciation (concave curve) shows a slow loss at the beginning but a faster loss toward the end of the capital asset's lifetime.

Since it is not possible to measure relative efficiencies directly, there are two methods that can be used to estimate them. The first method simply involves choosing intuitively a sequence of relative efficiencies. The second method involves measuring the physical or economic depreciation of the capital stock through the observation of the decline in the sale or rental prices of the assets in question. Thus, we will first discuss these two approaches, and will then describe two alternative approaches: the retirement approach, and the investment approach.

4.1 Intuitive Choice of an Efficiency Curve

The first solution to the problem of determining a sequence of relative efficiencies is to assume, either intuitively or by referring to previous studies, that the efficiency sequence follows a given shape, as a function of the capital's lifetime. The apparent ease of choosing a curve on the basis of intuition may, however, lead to error. Similarly, applying conclusions drawn from estimating individual cases to cohorts may be very deceiving: the cohort may in fact follow a depreciation curve that is very different from that of a single asset. What type of curve, for example, would fit a cohort of assets each of which was characterized by one-horse-shay? Wykoff has this to say on this subject: "Even a cohort of lightbulbs, or one-horse-shays, will, due to heterogeneity, typically depreciate in a convex, or

accelerated, pattern"[29]. Let us also remember that, except for geometric curves, as we pointed out before, economic and physical depreciation curves will assume different shapes.

4.2 Estimating the Efficiency Sequence by Observing Prices

The observation of market prices is the most frequently used method to study physical depreciation. The first, and most direct, method consists of observing the rental prices of assets of various ages. The second method consists of estimating physical depreciation indirectly by analyzing the sale prices of used assets using the relationship that exists between physical and economic depreciation.

Rental Prices

Estimating the "age-rental cost" function is interesting because of the direct relationship that exists between the ratio of rental prices and the determination of relative efficiency. Malzpezzi, Ozasme and Thibodeau (1987)[30] used this method to study the rental prices of residential buildings. Taubman and Rasche[31] used it in 1967 to study the prices of commercial buildings.

This method also has the advantage of ignoring the problem of "lemons" found in the analysis of used assets: as Hulten (1980) mentions, no rental business will be interested in renting "lemons".

However the approach has its own problems. It seems, for example, that, as a result of the often stable rental prices, we obtain a bias toward one-horse-shay depreciation. A second problem is related to the inventory a rental business must maintain: the rental price of an asset must be determined in such a way as to take into account capital on the shelves. In this sense, long-term rental prices are more representative of the real cost, because they make it possible to restrict the inventory. Finally, there is

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29 Wykoff, F.C., "Economic Depreciation and Business-Leased Automobiles", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989, p. 265.

30 Malzpezzi, Stephen, Larry Ozasme, and Thomas G. Thibodeau, "Housing Depreciation", Land Economics, November 1987, Vol. 63, No. 4, pp.372-386.

31 Taubman, Paul, and Robert Rasche, "Economic and tax depreciation of office buildings," National Tax Journal, September 1969, pp. 334-346.

no rental market for all the assets, and it seems that few efforts have been made to collect existing data.

Observing the Prices of Used Assets

Since we know that the relative efficiencies represent the physical depreciation of capital, and we know the relationship that exists between physical and economic depreciation, it is possible to estimate the efficiency curves by observing the prices of used assets. First, we estimate the age-price curve using empirical data on the prices of used assets; these data are then corrected to take into account assets that have been retired[32], and finally we postulate a relationship between the efficiency of a used good and its market price relative to a new good.

This is the method most commonly used in depreciation studies. It was used for the first time by Terborgh (1954)[33], and was used again for the study of automobile prices by Ackerman (1973)[34], Cagan (1965)[35], Chow (1957, 1960)[36], Ohta and Griliches (1976)[37], Ramm (1970)[38], and Wykoff (1970)[39]. Griliches (1960)[40] used it for the

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[32] This very important correction was not made until 1981, by Hulten and Wykoff. The method is discussed in Section 6.1 of this paper.

[33] Terborgh, George, "Realistic Depreciation Policy, Machinery and Allied Products Institute", 1954.

[34] Ackerman, Susan Rose, "Used Cars as a Depreciating Asset", Western Economic Journal, December 1973, pp. 463-473.

[35] Cagan, Phillips, "Measuring Quality Change and the Purchasing Power of Money: An Exploratory Study of Automobiles" in Zvi Griliches, ed. Prices Index and Quality Change, Cambridge, MA: Harvard University Press, 1971.

[36] Chow, Gregory, "The demand for Automobiles in the United States", Amsterdam: North Holland, 1957.

[37] Ohta, Makoto and Griliches, Zvi, "Automobile Prices Revisited: Extension of the Hedonic Price Hypothesis" National Bureau of Economic Research, Studies in Income and Wealth, Vol. 40, pp. 325-390.

[38] Ramm, Wolfhard, "Measuring the services of household durables: The case of automobiles", in *Proceedings of the business and economics statistics section of the American Statistical Association* (Washington, D.C.), 1970, pp. 149-158.

[39] Wykoff, Frank C., "Capital depreciation in the postwar period: Automobiles", Restat 52, May 1970, pp. 168-172.

study of tractor prices, Hall (1973)[41] for that of pick-up trucks, Beidleman (1976)[42] for that of machine tools, Lee (1978)[43] for boats, and Chinloy (1977)[44] for residential dwellings. The most important studies of this type were carried out by Hulten and Wykoff (1981a, b),[45] firs in a study of residential and commercial buildings, and then for the cohort of goods studied by national income and expenditures accounts.

However not all authors have considered the used assets market to be an ideal source of data. For example, some authors believe that it does not reflect the value of the cohort of assets because of the over-representation of low quality assets, or "lemons". Good cars, for example, are not found on the used market, because this market offers much lower prices due to the high numbers of lower quality assets. Other authors, on the other hand, respond to this criticism by saying that the used goods market is dominated by specialists who are used to buying and selling, and know how to recognize the quality of used goods and set the correct price. The question here, as Hulten points out, is to know whether or not we should reject the information provided by the market at the expense of depreciation functions chosen on the basis of ideas about the depreciation of assets that are largely subjective.

Still other authors, such as Keith A. Shriver[46], feel that the price of a used good may vary as a function of several factors other than

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40 Griliches, Zvi, "The demand for a durable input: Us farm tractors, 1921-1957," in Arnold Harberberg, ed, *The demand for durable goods*, Chicago, Il, 1970.

41 Hall, Robert, "The measurement of quality change from vintage price data" in Zvi Griliches, ed., *Price indexes and quality change*, (Cambridge, MA), 1973.

42 Beidleman, Carl R., "Economic Depreciation in a Capital Goods Industry", National Tax Journal, Vol. 29, No. 4, December, pp. 379-390.

43 Lee, Bun Song, "Measurement of economic depreciation within the Japanese fishing fleet", Review of Economic Statistics, May, 1978, pp. 253-273.

44 Chinloy, Peter T., "Sources of Quality Change in Labour Input," American Economic Review, Vol. 70, No. 1, March 1970, pp. 108-119.

45 a) Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from Capital*, The Urban Institute Press, Washington D.C., 1981, edited by Charles Hulten, pp. 80-130.

b) Hulten and Wykoff, The Estimation of Depreciation Using Vintage Asset Prices, Journal of Econometrics 15 (1981), pp. 367-394.

46 Shriver, Keith A., "The Valuation of Used Capital Assets During Time Periods Exhibiting Alternative Degrees of demand for Industrial Machinery and Equipment," Journal of Economics and Social Measurement 14 289-310 (1986).

age, such as interests rates, for example, or the scarcity of the asset. Beidleman (1973)[47] feels that the most important variable is the current price of an equivalent new good. Taubman and Rasche (1971)[48], and Feldstein and Rothschild (1974)[49] have also pointed out that the prices of used assets are a function of taxes, interest rates, and other variables that are subject to change over time. Hulten and Wykoff (1981), however, looked at these theories, and found no statistical evidence allowing these hypotheses to be confirmed. On the contrary, their study shows that depreciation rates remained virtually constant over the period under consideration: "We found almost no statistical evidence that parameters changed over time."[50]

4.3 Other Approaches

Several approaches based neither on the rental price nor on the price of used assets have been used to determine the form of the efficiency function. We will discuss two of the more commonly used ones, the retirement approach and the investment approach.

The Retirement Approach

The first alternative that can be used to estimate physical depreciation is the study of retirement. We begin by estimating a distribution of retired assets for each type of asset under consideration either directly, or indirectly, through the analysis of account books or changes in capital stocks. This distribution is then used to separate each asset vintage into sub-cohorts, each identified by their retirement date. For example, a vintage of $100 assets with a lifetime of 4 years, a quarter of which will be retired over the course of the first year, and three quarters of which will be retired by the end of the fifth year, will be separated into two sub-cohorts: one with a lifetime of one year,

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47 Beidleman, Carl, "Valuation of Used Capital Assets", Sarasota Florida: American Accounting Association, 1973.

48 Taubman, Paul, and Robert Rasche, "Economic and Tax Depreciation of Office Buildings," National Tax Journal, September 1969, pp. 334-346.

49 Feldstein, Martin, and Michael Rothschild, "Towards an Economic Theory of Economic Replacement," Econometrica 42, May, 1974.

50 Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from Capital*, The Urban Institute Press, Washington D.C., 1981, edited by Charles Hulten, p. 99.

and the other with a lifetime of five years. An arbitrarily chosen depreciation function is then applied to each of the sub-cohorts; generally, a straight line or decreasing balance function is chosen. Faucet[51] and the Bureau of Economic Analysis use this approach.

While this method seems to provide interesting results, until now estimates of retirement distribution have been based on Winfrey's[52] studies, which are now over 50 years old; or indirectly, from the study of account books, which lack precision. Furthermore, the depreciation rate of each sub-cohort is chosen arbitrarily.

While none of the authors consulted raised this point, we feel that another problem arises from the use of this method, because the estimated depreciation is, in fact, the depreciation of the entire cohort and not the aggregate depreciation of the individual assets: depreciation is entered into the accounts only when a cohort of assets has been retired. As a result, we feel that, because of the normal distribution of the life of the cohort of assets, a downward bias is introduced for the first years, and an upward bias is introduced toward the average lifetime of the asset under consideration. For example, if no assets are retired over the course of the first year, the depreciation of the cohort will be zero, despite the fact that we know that the efficiency of the entire cohort of capital assets has diminished, since each of the assets has undergone some degree of depreciation over this period.

The Investment Study Approach

A second alternative that can be used to estimate efficiency consists of analyzing what form of depreciation best explains investment in the context of a neo-classical investment model. This approach was introduced by Meyer and Kuh (1957), and used by

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51 Faucett, Jack G., "Development of Capital Stock Series By Industries Sector", U.S. Office of Emergency Preparedness, Washington, D.C.

52 Winfrey, R., "Statistical Analyses of Industrial Property Retirements", Iowa: Engineering Department Station, Bulletin 125.

Eisner (1972)[53], Feldstein and Foot (1974)[54] and Robert Coen (1976, 1980)[55].

However, there is a problem with the neo-classical investment model, and that is establishing a distinction between replacement investment and new investment. As J.G. Loranger[56] points out, the demand for replacement capital may be determined by the same factors as new capital. On the other hand, we know that replacement demand cannot be considered to be a constant fraction of total investment.

5. Criticism of Perpetual Inventory

Despite the fact that it is in general use, various criticisms, often shared by several authors, have been raised against the perpetual inventory method. Two main types of criticisms have been raised: the first involves the choice between productive stock and stock measured by its costs, and the second concerns the limitations of the method themselves.

5.1 Productive Stock or Stock Value

The first criticism is not directly aimed at the method used, but rather at the measurement of productive stock itself. While several authors believe that productive stock represents the ideal stock in the study of productivity: "It is this measure of capital

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[53] Eisner, Robert, "Components of Capital Expenditures: Replacement and Modernization", Review of Economics and Statistics, Vol. 54, No. 3, August, pp. 297-305.

[54] Feldstein, Martin S., and David K. Foot, "The Other Half of Gross Investment: Replacement and Modernization Expenditures", Review of Economics and Statistics, Vol. 56, No.1, February, pp. 49-58.

[55] Coen, Robert, "Investment Behaviour, the Measurement of Depreciation, and Tax Policy," American Economic Review, Vol. 65, No. 1 March 1975, pp. 59-74.

------------ "Depreciation, Profits, and Rates of Return in Manufacturing Industries," in Dan Usher, *The Measurement of Capital*, Chicago, University of Chicago Press, (1980), pp. 121-152.

[56] Loranger, Jean Guy, "La Théorie Néo-Classique de la Demande de Capital: Problèmes Théoriques de Spécifications", L'actualité économique, May 1975, p. 359.

stock which is directly associated with productivity"[57], not all authors share this opinion.

Some authors, including Young and Musgrave or Denison, feel that gross capital stock measured by costs in real terms is the stock that should be used to calculate productivity: "Capital measured on this basis (by its cost) is useful in the measurement of productivity"[58]. According to Denison, capital stock should be measured in terms of cost, not production capacity:

> "The value, in base-periods prices, of the stock of durable goods (before allowance for capital consumption) measures the amount it would have cost in the base period to produce the actual stock of capital goods existing in the given year (not its equivalent in ability to contribute to production)"[59].

For goods not produced during the base year, it is necessary to evaluate the price that it would have cost to produce them if they had been known:

> "This method is statistically feasible within reasonable limits. Computers apart, it is the only one for which estimates exist, because of the nature of the price indexes used for deflation"[60].

According to Denison, measuring capital stock by marginal productivities is inappropriate. First, taking into account information currently available, and the problem posed by the lack of a unit of measurement in the evaluation of the relative marginal productivity of new capital assets, this method cannot be used to measure capital stock. Second, he adds, even if the method were practical, it could not provide interesting estimates of growth sources:

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57 "Trends in Multifactor Productivity", 1948-81, U.S. Department of Labour Statistics, September 1983, Bulletin 2178, note 14, p. 40.

58 Musgrave, J.C. and Young, A.H., "Estimation of Capital Stock in the United States", in Usher, Dan, *The Measurement of Capital*, edited by Dan Usher, The University of Chicago Press, 1980, p.30.

59 Denison, Edward F., Estimates of Productivity Change by Industry: "An Evaluation and Alternative" the Brookinks Institute, Washington, D.C., 1989, p. 26.

60 Idem, p.26.

"It would ascribe output gains made possible by advances in knowledge, not saving and investment, to the increase in capital"[61].

The first stage, described below, and used to measure gross capital stocks, is identical in the case of the method proposed by Denison and in that based on productive stock. The investments that constitute the capital stock are evaluated in constant dollars, and the total gross stock measures the value (before economic depreciation) of what it would have cost to produce the actual capital stock in the base period. For goods not produced during the base year, it is necessary to evaluate what it would have cost to produce them, if they had been known. Only changes in quality associated with a change in price, and thus indirectly with a change of quantity, are included. This is the measurement proposed by Denison.

The productive stock method uses the results obtained from this first stage and then weights each investment using a relative efficiency, in order to obtain the depreciated capital stock or productive stock. Generally assets depreciate, and thus this measurement is lower than that obtained in the first stage.

The two methods measure what it would have cost to produce the capital stock in the base year; in the first case, the **gross** capital stock; and in the second, the **net** productive capital stock. In the first case, the difference between two subsequent years, before adding new investments, gives us the measurement of economic depreciation; and in the second, the measurement of physical depreciation. Thus, we can obtain the curve of the economic depreciation function with the first method; and the curve of the physical depreciation function with the second.

Using the second method, capital input is measured directly. When using the method proposed by Denison it is not necessary to determine the value of the remaining sum of estimated services at the current time to determine the shape of the depreciation curve and obtain the capital input. Nevertheless, the form of the depreciation function must be determined somehow. Denison chose to allocate the service cost in proportion to the lifetime of the capital:

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[61] Denison, Edward F., Estimates of Productivity Change by Industry: "An Evaluation and an Alternative" The Brookinks Institute, Washington, D.C., 1989, p. 29.

"Within the framework for the measurement of capital input presented above, Denison's concept of depreciation is based on the notion of allocating the cost of an asset over its lifetime in proportion to the relative efficiencies $\{d_t\}$ of capital goods of different ages"[62].

Thus, this question is related to the definition of physical depreciation we have adopted, and discussed in Section 2. We have already explained that physical depreciation is not proportional to economic depreciation, except in the particular case when depreciation is geometric.

Finally, contrary to what Denison says, it is possible to measure productive stock (we will return to this subject in Section 5), as Hulten and Wykoff, or even Koumanakos and Hwang have shown. Furthermore, we believe that it is preferable to use the little information available than to rely on arbitrary estimates of the shape of the efficiency curve. As for the criticism that, since the new capital has new properties, it cannot be considered, we should simply remember that the problem is similar to what we must face when estimating gross capital stocks when deflating prices. Thus, it seems clear to us that productive capital stock, or stock before physical depreciation (and not stock before economic depreciation) will provide us with the most useful measurement of capital service.

5.2 Limitations of the Perpetual Inventory Method

We must remember that the perpetual inventory method provides only an approximation of the capital stock, and, as such, is not perfect: there are limitations to how precise it can be in regards to the measurement of capital stock.

While Hulten (1988) himself used the perpetual inventory method, he remained quite aware of its limitations. He was also aware of Feldstein and Rothschild's (1974)[63] criticism concerning the perpetual inventory method: businesses are not free to retire their capital as economic conditions may dictate, since only the average lifetime of the type of capital is considered; maintenance and repair costs do not affect the relative efficiencies (ϕ), because they take into account services before maintenance; and, since we do not take into account the rate of use of the capital, it is

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62 Dale W. Jorgenson, "Capital as a Factor of Production", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989, p. 27.

63 Feldstein, Martin, and Michael Rothschild, "Towards an economic theory of economic replacement", Econometrica 42, May, 1974.

simply assumed that the flow of capital service is proportional to the capital stock.

Hulten (1988) also noted that there are few reasons to believe that technologies in the real world show the separability required by Léontief's Theorem of capital aggregation. Even if aggregation were possible, nothing guarantees that this aggregate production function will be valid for an industry or industrial sector as a whole. In reality, other conditions are necessary for aggregation between establishments within a given industry. These are Gorman's[64] conditions, and they are very restrictive. Briefly, these conditions require that:

- marginal substitution rates between different production factors be identical for all businesses;

- the expansion paths of all the businesses be parallel lines passing through their own origin;

- the optimal ratios be identical for all businesses.

Finally, Hulten added that the perpetual inventory method does not take technical improvements into consideration. Fisher's aggregation function requires that all differences in new technology be representable by a fixed relative efficiency: any difference in quality between the capital goods must be expressed by increased productivity in order to be included. Hall[65] has also shown that there is a fundamental indeterminacy separating the effects of loss of efficiency, the use of new technologies in new goods, and the overall relative loss of existing goods due to new technical refinements. The problem is similar on the price side when we try to separate the effects of physical depreciation, obsolescence, and inflation.

Edward Miller[66] has also criticized the perpetual inventory method. First, he points out that the usual solution to the problem of lack of data on retired capital is to assume that it is proportional to the stock or is simply a function of its age. This approach is incorrect because, according to Miller, replacement and

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64 See Murray Brown in "The measurement of Capital Aggregates: A Postreswitching Problem" in Usher, Dan, *The Measurement of Capital*, edited by Dan Usher, The University of Chicago Press, 1980, p. 396, for a discussion of Gorman's aggregation conditions.

65 Hall, Robert E., "The Measurement of Quality Change From Vintage Price Data", in Zvi Griliches, ed. Prices Index and Quality Change, Cambridge, MA: Harvard University Press, 1971.

66 Edward Miller, "Can a Perpetual Inventory: Capital Stock be Used for Production Function Parameter Estimation?", Review of Income and Wealth Series 36, Number 1, March 1990, pp. 67-82.

modernization go together, and a high rate of investment is often accompanied by a high capital replacement rate. Thus, we should, for example, ask ourselves what happens to an old machine once a new one has been purchased. According to the author, even though the errors in the perpetual inventory method are very small, and the series may be used for some purposes, this does not mean that they can be used to estimate parameters such as the elasticity of substitution or productivity growth rates. The fact that we cannot distinguish replacement investment from modernization investment creates identification problems. Thus, the fundamental question is not the size of the error in absolute terms, but rather knowing to what extent the error is correlated with the independent variables that must be estimated:

> "Experiments with plausible parameter values of covariance between variables and the errors in a perpetual inventory capital stock can lead to large errors in estimating production function parameters"[67].

For Miller, as for many other authors, the worst error, however, is the exclusion of economic cycles from most empirical studies: during the slack periods in the economic cycle, inputs of capital, energy, and labour are low, but nothing, however, implies that these declines are proportional.

Finally, according to Miller, the perpetual inventory method systematically over-evaluates the capital stock, because it does not take into account assets retired due to the introduction of new goods with new technologies. Michael F. Mohr answers this criticism of Miller's, however, by saying that this is an extreme case, and that often these assets are not discarded, but rather sold to other businesses in the same sector:

> "...it seems apparent, a priori that the likelihood that any particular type of vintage of capital will be affected so drastically by technical obsolescence so as to cause it to be scrapped is that of a random event"[68].

For other authors such as Musgrave and Young or Michael Jaffey, a perpetual inventory does not make it possible to correctly evaluate the lifetime of assets:

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67 Edward Miller, idem, p. 76.

68 Mohr, F., Michael, "The Theory and Measurement of the Rental Price of Capital in Industry-Specific Productivity Analysis: A Vintage Rental Price Model", in *Measurement Issues and Behaviour of Productivity Variables*, edited by Ali Dogramaci, Kluwer Nijhoff Publishing, Boston, 1969, p. 135.

"The success of the perpetual inventory method in measuring the stock of fixed capital depends, to a large extent, on the accuracy of the service lives assigned to different types of assets. Unfortunately, only fragmentary information is available on the actual or economic service lives of assets"[69].

"The imprecise practice of assuming a constant life is perhaps explained by the difficulty of the PIM approach in measuring life directly"[70].

Thus, we can see that the perpetual inventory method is not perfect. At best, it provides an approximation of reality. In the absence of alternative methods, however, it remains quite useful. It is always possible to improve the precision of the measurements provided by this method. Some authors, for example, suggest that the perpetual inventory method could be improved by periodic surveys that would make it possible to check, on site, the quantity of capital stock:

"Since the perpetual inventory method requires such a large number of hypotheses and data that do not correspond to all the uses to which they are put, it would be useful to carry out periodic reference surveys of assets, on site, at a specific time"[71].

In 1982 Statistics Canada, the Bank of Canada, the Economic Council of Canada, and the Department of Finance launched a project to survey capital stocks. In 1985-86, the survey was expanded to include the following elements;

- capital expenditures (acquisition of new goods and adaption, revision, or refurbishing of assets in place);

- the expected lifetime of new goods;

- the initial cost and age of assets;

- sales and purchases of used assets;

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69 Musgrave, J.C. and Young, A.H., "Estimation of Capital Stock in the United States", in Usher, Dan, *The Measurement of Capital*, edited by Dan Usher, The University of Chicago Press, 1980, p. 41.

70 Michael Jaffey, "The Measurement of Capital Through a Fixed Asset Accounting Simulation Model," Review of Income and Wealth, Series 36, Number 1, March 1990.

71 Fixed Capital Flows and Stocks: Methodology, National Wealth and Capital Stock Section, Investment and Capital Stock Division, May 1990, p. 4.

- the reasons for capital expenditures and retirements;

- automation expenses;

- the value of work in progress at the end of the year;

- the value of capital expenditures; that is, the accumulated capital cost (gross book value) and the accumulated economic depreciation, starting in 1987.

The data were collected annually for the period 1985-87. They were categorized into 30 classes of assets classified into 45 branches of activity.

Thus, this was a major survey that greatly increased the precision of the estimates produced using the perpetual inventory method, especially in terms of the lifetimes and economic depreciation of capital.

6. Summary and Comparisons of Empirical Studies

As we have shown, various approaches, the two main ones being the rental price approach and the used asset price approach, have been used to measure physical depreciation. These various approaches can, however, be classified as a function of the type of physical or economic depreciation that they adopt or measure.

6.1 Studies That Favour Geometric Economic Depreciation

While geometric economic depreciation is supported by several empirical studies, Hulten and Wykoff[72] (1981a) point out that the use of a single (geometric) economic depreciation rate by Jorgenson and his collaborators has been the subject of considerable debate. Feldstein and Foot (1971), Eisner (1972), and Feldstein and Rothschild (1974)[73] believed that this theory was untenable and inconsistent with the McGraw-Hill surveys of anticipated replacement investment. We should also emphasize that some people feel it is very unrealistic, because of how fast the losses are in the early years. However, the fact of accepting a physical depreciation rate that is a function of the age of the capital considerably complicates the empirical analysis, and makes it

[72] Hulten and Wykoff, "The Estimation of Depreciation Using Vintage Asset Prices", Journal of Econometrics 15 (1981), p. 367.

[73] Feldstein, Martin, and Michael Rothschild, "Towards an Economic Theory of Economic Replacement", Econometrica 42, May, 1974.

necessary to determine the endogenous variables of physical depreciation.

Hulten and Wykoff have produced several empirical studies on the economic depreciation of capital. In 1976 they published an estimate of economic depreciation of non-residential structures. In 1981, they applied the Box-Cox transformation function to a sample of prices of used commercial and industrial buildings to estimate the rate and form of the economic depreciation. In a subsequent study carried out the same year, Hulten and Wykoff expanded the number of types of assets to all the categories of assets studied by the American national accounts system:

> "Although only a quarter of the asset categories are accounted for by this approach, these categories included 55 percent of 1977 NIPA (National Income and Product Accounts) investment expenditures on producers' durable equipment and 42 percent of 1977 NIPA investment in non-residential structures"[74].

Finally, in 1989 Wykoff studied the economic depreciation of rental cars.

While none of Hulten and Wykoff's studies was statistically significant, they observed that the shape of the economic depreciation curve was often geometric for all asset categories, except for the last study, where economic depreciation was even more accelerated:

> "The approximately geometric form of the age-price profiles ranging from buildings to machine tools to construction equipment is the most significant finding of our research"[75].

In general, the Box-Cox transformation function was chosen for all the studies because of its flexibility. In this model, concave, convex, linear, or rectangular (one-horse-shay) curves are only specific cases. The model assigns two parameters to each variable, and the function makes it possible to estimate jointly the parameters that determine the form of the function and those that determine the slope and the ordinate at the origin of the equation.

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74 Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from Capital*, The Urban Institute Press, Washington D.C., 1981, edited by Charles Hulten, p. 94.

75 Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from Capital*, The Urban Institute Press, Washington D.C., 1981, edited by Charles Hulten, p. 94.

The Box-Cox transformation function is applied to an equation expressed as follows:

$$q_i = \alpha + \beta s_i + \gamma t_i + u_i \qquad i = 1,\ldots,N$$

where

$$q_i^* = \frac{q_i^{\theta_1} - 1}{\theta_1}, \quad s_i^* = \frac{s_i^{\theta_2} - 1}{\theta_2}, \quad t_i^* = \frac{t_i^{\theta_3} - 1}{\theta_3}$$

where q_i is the sale price of a used good, s_i is the age of the good, t_i is the year, and i represents observations 1 through N. Variable t makes it possible to take into account shifts in the age-price curve because of inflation or obsolescence. Parameters θ_1, θ_2, and θ_3 determine the form of the function, and parameters α, β and θ determine the ordinate at the origin, and the slopes of the model.

In comparison to previous studies of the price of used assets, Hulten and Wykoff's studies (1981 a,b) brought something new to the field, by taking into account assets that had been retired: since the price of retired assets equals zero, if we forget to take retired assets into account we introduce an upwards censored sample bias in the estimated value of our capital stock. In order to correct for this bias, Hulten and Wykoff (1981) multiplied the price of surviving used assets by the probability of survival expressed as a function of age. For some types of assets, these probabilities are based on the Bureau of Economic Analysis lifetime estimates, and for others on the distribution of service lives used by Winfrey. The study also demonstrated the importance of taking retired assets into account.

The economic depreciation rates obtained from Hulten and Wykoff's (1981 a, b) studies were used in several other studies. Jorgenson, Gallop, Fraumeni (1987)[76], Fraumeni and Jorgenson (1986)[77], Boskin, Robinson, and Huber (1987)[78], Boskin, Robinson and Roberts (1987)[79],

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[76] Jorgenson, Dale W., Frank M. Gallop, and Barbara M. Fraumeni, "Productivity and U.S. Economic Growth", Cambridge, Harvard University Press, 1987.

[77] Fraumeni, Barbara M. and Dale W. Jorgenson, "The Role of Capital in U.S. Economic Growth, 1948-1979," in Ali Dogramaci ed., *Measurement Issues and Behaviour of Productivity Variables*, Boston, Martinus Nijhoff, 1986, pp. 161-244.

[78] Boskin, Michael J., Marc S. Robinson, and Alan Huber, "Government Saving, Capital Formation and Wealth," paper presented at the Conference on Research in Income and Wealth, Baltimore, Maryland, March 27 and 28, 1987.

Hulten, Robertson and Wykoff (1989)[80], and, most recently, Jorgenson (1990)[81] have used efficiency functions derived from the economic depreciation rates estimated by Hulten and Wykoff (1981 a, b).

Coen chose to study the decline in efficiency through the analysis of replacement investment behaviour. He obtained different forms of depreciation. After reviewing these results, however, Hulten and Wykoff concluded that "The weight of Coen's study is evidently on the side of geometric and near geometric forms of depreciation"[82].

While Koumanakos and Hwang considered that the type of economic depreciation was a function of the category of asset under consideration, they nevertheless observed that the economic depreciation rates were on the whole rather geometric: "It appears that depreciation patterns are close to geometric form for the manufacturing sector and accelerated vis-à-vis straight line for the non manufacturing sector"[83].

Following Hulten and Wykoff's example, Koumanakos and Hwang applied the Box-Cox transformation function to a sample of used good prices. Due to the limited amount of data, however, they used a simplified version of the Box-Cox transformation function that does not include the time variable. Thus, in the absence of the time variable, the model used cannot take into account shifts in the age-price curve that are the result of inflation or technological obsolescence, and we have to use existing price indexes to deflate the prices.

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79 Boskin, Michael J., Marc S. Robinson, and John M. Roberts, "New Estimates of Federal Government Tangible Capital and Net Investment," in Robert E. Lipsey and Helen Stone Tice, eds., *The Measurement of Savings, Investment, and Wealth*, in Income and Wealth, Vol. 52, New York, National Bureau of Economic Research, 1987.

80 Wykoff, Frank C., James W. Robertson, and Charles R. Hulten, "Energy Obsolescence and the Productivity Slowdown", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989.

81 Jorgenson, Dale W., "Productivity and Economic Growth", Harvard Institute of Economic Research, Harvard University, Discussion Paper no. 1487, June 1990.

82 Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from Capital*, The Urban Institute Press, Washington D.C., 1981, edited by Charles Hulten, p. 110.

83 Koumanakos, P., Hwang, J.C., "The Forms and Rates of Economic Depreciation, The Canadian Experience", Science, Technology, and Capital Stock Division, Statistics Canada, February 1988, p. 15.

One of the weak points of this study is that we cannot count upon the capital units being well defined. We do not know the prices for different assets, we only know those of various categories of assets:

> "Unlike other recent studies of economic studies of economic depreciation, we do not have well defined physical units and market transaction prices. Instead, in our revised capital and repair expenditures survey, we collect selling price, accumulated cost and age data for 100 different types of assets"[84].

Finally, it is regrettable that the amount of available data was so limited: "Availability of data has been a limiting factor in this study..."[85]. Only 3,892 observations were available: 1,701 in the manufacturing sector, and 2,192 in the non-manufacturing sector. For comparison, Hulten and Wykoff used 8,066 observations of non-residential structure transactions collected by the Office of Industrial Economics. They used data collected by Bieldman for machine equipment transactions, and used various sources including the Forke Brothers Bluebook, the Ward Automotive Yearbooks, the Kelly Bluebooks, and the General Services Administration reports for construction equipment, cars, and office equipment. As a result, we have to admit that, despite the fact that Koumanakos and Hwang's study is interesting, their results are based on much less information than those obtained by Hulten and Wykoff.

In its estimates of capital flow and stocks for 1990, Statistics Canada[86] used the sale prices and age characteristics reported during the course of the capital stock survey to estimate the form of the economic depreciation: the estimates of form and economic depreciation rates are the work of Koumanakos and Hwang[87].

Like the Hulten and Wykoff study, the 1990 Statistics Canada study entitled *Fixed Capital Flows and Stocks* uses a retirement function. The shape of this distribution is a normal truncated bell whose lower and upper limits correspond to 50 and 150 percent of the average lifetime. Contrary to almost all other countries, which

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[84] Koumanakos, P., Hwang, J.C., "The Forms and Rates of Economic Depreciation, The Canadian Experience", Science, Technology, and Capital Stock Division, Statistics Canada, February 1988, p. 15.

[85] Koumanakos, P., and Hwang, J.C., op. cit., page 15.

[86] Fixed Capital Flows and Stocks: Methodology, National Wealth and Capital Stock Section, Investment and Capital Stock Division, May 1990, p. 11.

[87] Koumanakos, P., Hwang, J.C., "The Forms and Rates of Economic Depreciation, The Canadian Experience," Science, Technology and Capital Stock Division, Statistics Canada, February 1988.

assume a constant average lifetime for assets, Statistics Canada adopted a geometrically decreasing lifetime based on the old lifetime and the estimated lifetime reported in the annual surveys:

> "The hypothesis that is the basis for the calculation of these estimations is that, since 1947; which is to say, since the post-War period, the age at which assets are retired has been lower than during the previous year[88]".

It is also important to emphasize that Statistics Canada believes that it has been the first to collect annual data on anticipated lifetimes.

Thus, we find that the widespread use of geometric economic and physical depreciation rates is based on vast surveys and serious empirical studies. Even though no studies have been able to show that a geometric physical depreciation rate is statistically significant, most of the studies have shown that the economic depreciation rate is, in general, rather geometric.

6.2 Studies in Favour of a Concave Shape of Depreciation

The Bureau of Labour Statistics (BLS) decided to use a concave shape of depreciation, taking into account that the efficiency of many capital assets does not tend to decrease quickly over the course of the first few years[89]. The BLS also engaged in consultations with businesses represented by the Bureau of Labour Statistics Business Research Advisory Council. They decided to use a concave hyperbolic function and to determine its exact shape on the basis of data provided by the Hulten and Wykoff survey of used asset prices.

More specifically, the mathematical form of the age-efficiency relationship is represented by the following hyperbolic function:

$$s_t = (L-t)/(L-\beta_t) \qquad 0<t<L$$
$$s_t = 0 \qquad t>L$$

where: s_t is the relative efficiency of an asset of age t;
L is the lifetime;
t is the age of the asset;
β is the parameter allowing the shape of the curve to vary.

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[88] Fixed Capital Flows and Stocks: Methodology, Op. cit., p. 31.

[89] Capital Stocks for Input-Output Industries: Methods and Data, Bulletin 2034 (Bureau of Labour Statistics, 1979).

Since each type of asset under consideration represents a wide variety of assets, the authors of the BLS study used an "overall" efficiency function, which is a weighted mean of the efficiency functions. The weights are determined by a retirement function. This function represents a normal distribution function of retired assets. They chose a function with a normal distribution varying between 0.02 and 1.98 times the average lifetime.

Finally, the following equation was used to generate the dual price functions for different values of β:

$$p_t = \frac{\sum_{\tau=t}^{\infty} s^*_\tau (1-r)^{\tau-1}}{\sum_{\tau=0}^{\infty} s^*_\tau (1-r)^{\tau}} \qquad (17)$$

where p_t is the price of an asset t years old compared to a new asset, s_t^* is the efficiency function, and r is the interest rate. Five price functions were generated, corresponding to the five values of β chosen, or 0.0 (straight line), 0.25, 0.5, 0.75, and 1.0 (one-horse-shay). The three intermediate values of β correspond to increasing degrees of concavity.

Finally, the price functions generated for each β were compared with price functions estimated using the Hulten and Wykoff Box-Cox transformation function, and the β values with the greatest similarity between the two functions were kept.

This procedure was repeated for four types of structures and one type of equipment. For the structures, one-horse-shay was chosen in two cases, while the values 0.5 and 0.75 were chosen for the two others. Two comparisons were done for the equipment, a direct comparison of the efficiency functions found in the U.S. Census Bureau "Truck Inventory and Use Survey (1977)", while the comparison for the tractors was done by comparing price functions, as previously. One-horse-shay was chosen for the tractors, while the values 0.75 and 0.25 were chosen for light and heavy trucks respectively.

Even though the number of asset categories was very limited, this study is still very interesting, because it explores the possibility of using non-geometric depreciation curves while remaining consistent with the chosen forms of economic depreciation.

6.3 Straight Line (45 degree)

The Bureau of Economic Analysis used a linear depreciation in its net and gross capital stock estimates: according to them, it gives the best approximation. The properties of the straight line for a single asset are as follows:

a) If service is constant over the lifetime and there is no obsolescence, the straight line is the correct measurement.

b) If service decreases and there is no obsolescence, the depreciation is too high in the early years and not high enough in the later years.

c) If service is constant but there is obsolescence, the depreciation will be too high for all years, but not as much for the later years.

d) If service decreases and there is obsolescence, **the two errors combined tend to balance out**, depending upon the decline in service and obsolescence. Thus, the use of the straight line is justified.

Since cohorts of capital follow a different type of depreciation from that of single assets, we find that the above considerations are, unfortunately, without interest. This is the reason why we must be able to refer to empirical studies.

Denison (1967, 1974) and Kendrick (1973) used linear depreciation based on estimates of net and gross capital stock estimates produced by the Bureau of Economic Analysis. However, these two studies are not consistent, because the authors chose economic depreciation rates that are incompatible with the chosen physical depreciation rates:

> "In estimating capital stocks Denison uses three alternative linearly declining patterns of relative efficiency. None of these patters results in a straight-line depreciation method, as Denison assumes"[90].

After a short review of various studies, Young and Musgrave concluded that straight line economic depreciation is a reasonable approximation for each of the two approaches for large aggregates. This conclusion was based on the fact that in both cases the errors committed are compensated for by the use of the straight line:

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[90] **Dale W. Jorgenson, "Capital as a Factor of Production", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989, p. 27.**

"For the discounted value definition, straight-line depreciation may provide too slow a write-off for certain types of equipment. However, such understatement tends to be offset by the use of straight line depreciation for buildings. For the NIPA definition, errors arising from use of straight-line depreciation for types of equipment where services decline over the service life tend to be offset by errors arising from the treatment of obsolescence"[91].

We cannot agree with the assessment that errors tend to compensate for each other instead of piling up. Thus, in sum, the studies that have used linear economic or physical depreciation models have not produced very interesting results.

6.4 Multiple Choices

Even though we have classified the preceding studies according to a given type of economic or physical depreciation, we must emphasize that, in most cases, the authors point out that economic or physical depreciation is a function of the type of asset and that, in reality, in order to be accurate, various economic or physical depreciation functions should be used. For practical reasons, we are limited to one or several types of functions, and for the same reason we have classified the studies according to one or the other of these choices.

- For example, Young and Musgrave note that there is no single answer, but that the shape of the economic depreciation curve is a function of the type of asset under consideration:

  "It seems reasonable to conclude that for some types of equipment the effect of maintenance and repair coupled with obsolescence outweighs the effect of discounting, and consequently the decline in the value of the estimated future services is more rapid than straight-line depreciation in the early years of the service life (Such findings should not be extrapolated, however, to all types of equipment..."[92].

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91 Young, Allan, and John C. Musgrave, "The Measurement of Capital", The University of Chicago Press, p. 36.

92 Young, Allan, and John C. Musgrave, "The Measurement of Capital", The University of Chicago Press, p. 37.

- The Bureau of Labour Statistics study (1983) used various physical depreciation functions, although they were all concave hyperbolic functions in various degrees.

- Despite its preference for geometric economic depreciation, Statistics Canada uses three types of economic depreciation to evaluate capital stocks: linear, geometric (convex), and deferred (concave). The three types of economic depreciation do not apply to three categories of assets, but to three estimates of capital stock in order to meet specific applications:

  > "...there must be capital stock measurements for various applications in the field of economic analysis and business analysis and...there is no single measurement that meets all these needs"[93].

Thus, in general, from a theoretical point of view, we must agree with the use of various functions when the data require it. This is why, for example, we prefer using the Box-Cox transformation function, which allows great flexibility when choosing the appropriate function. However, from a practical point of view, we should add that the use of several non-geometric economic depreciation functions considerably complicates the study, since the economic depreciation rate is different for each year.

7. Choosing a Depreciation Measurement

> "From Karl Marx to the Cambridge Controversies, there has been an ongoing disagreement among economists as to what capital is and how it should be measured"[94].

It is important to remember that the purpose of this study is to determine the most appropriate method to measure capital depreciation for the purposes of the empirical calculation of multifactor productivity indices in Canadian industries.

As we have shown, the study of capital stock depreciation is not limited to the intuitive choice of a shape of curve. The study of depreciation is an integral part of the problem of capital, which is undoubtedly one of the most complex in economic theory. The difficulty of defining and measuring capital has lead to a multiplicity of methods and approaches. With the numerous theoretical and empirical studies dealing with capital, and the

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[93] Fixed Capital Flows and Stocks: Methodology, op. cit. p.11.

[94] Hulten, Charles R., "The Measurement of Capital", op. cit., p.1.

discussions that they have generated, and also thanks in large measure to new sources of data, measurements of depreciation and capital stock have evolved significantly over the past twenty years. However many questions remain to be answered. Thus, this shortage of answers, and the choices they allow are left to the discretion of researchers. The study has, nevertheless, allowed us to make certain choices in the determination of measurements of capital stock depreciation. In the context of the study of multifactor productivity, the measurement of capital depreciation allows us to determine capital service. Since service flow is, itself, proportional to the capital stock, we must have a measurement of capital stock. Thus, the measurement of capital input cannot be obtained until a number of stages have been completed.

The first stage involves determining the capital stock, which can only be achieved after having determined the depreciation function, which, in turn, cannot be obtained until we have chosen a model that allows us to determine this function. Thus, choices arise at each of these steps, and we will discuss the choices we recommend in the same order: a productive capital stock measurement derived from the study of used asset prices using a geometric depreciation function.

7.1 Measuring Productive Capital Stock

We have shown that the cost approach proposed by Denison does not make it possible to measure the form of the economic depreciation function, while the method based on the value of the estimated service allows us to derive the shape of either the economic or the physical depreciation curve using the relationship that exists between the marginal productivity of an asset and its rental price, in a situation of competition and equilibrium. We have also shown that the measurement of stock within the framework of the aggregation of production functions is the measurement of the productive stock.

Despite the many possible criticisms that could be raised against the perpetual inventory method, which we have summarized here, it is still the most commonly used and most appropriate method for measuring capital stock. In the absence of data on capital prices and quantities, and the current level of development of new approaches such as Michael Jaffey's[95], we feel that there is no alternative method.

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[95] Michael Jaffey, "The Measurement of Capital Through a Fixed Asset Accounting Simulation Model", Review of Income and Wealth, Series 36, Number 1, March 1990.

Nevertheless, we believe that the evaluation of capital stock should, as Hulten and Edward Miller have pointed out, be accompanied by regular surveys that can be used as a reference for estimating assets in place at a specific time:

> "It therefore seems appropriate to end this survey with a renewed call for a national capital benchmark"[96].

> "Despite the very substantial effort and ingenuity of economists and statisticians at BEA, BLS, Census, and other agencies, much remains to be accomplished. And, in my judgement, real progress must await the development of new data sources"[97].

In Canada, the new capital flow and stock estimates based on the results of the capital stock survey are a privileged source of information. The perpetual inventory should also take into account retired assets, since Hulten and Wykoff have shown the importance of this procedure.

7.2 Choosing a Model

We have discussed four models that make it possible to estimate the depreciation function. The first uses rental prices, the second the prices of used assets, the third retirements, and the last the investment approach. We have discussed the advantages and weak points of each.

In terms of studies that use rental prices, we found, unfortunately, that too few efforts have been made to collect the necessary data. Since so few studies have been carried out, and the data collection methods used are likely to lead to error, we also have to reject the retirement approach.

We feel that the investment approach deserves more serious examination; however, for the moment, we find that it is much less secure than the used assets approach, because of the distinction that has to be made between replacement and new investment.

Thus, we believe that, for the moment, depreciation estimates derived from the study of used assets based on the studies of Hulten and Wykoff, such as those of Koumanakos and Hwang, clearly represent the most interesting model. Furthermore, despite its limitations, the study of depreciation through the price of used

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96 Hulten, Charles, "The Measurement of Capital", op. cit., p. 45.

97 Idem, p. 45.

assets has been the most popular choice in recent years. The Hulten and Wykoff (1981 b) study, for example, represents the most comprehensive empirical study of used assets carried out to date:

> "The most intensive empirical study of used asset prices done to date is by Hulten and Wykoff"[98].

> "The most well-known and, we believe, thorough attempt to implant the used asset price approach in the private sector is that of Hulten and Wykoff (1981). While not perfect, we feel that the Hulten and Wykoff approach is the best available..."[99].

Finally, as M.J. Boskin, M.S. Robinson, and J.M. Roberts (1989) point out, the used asset price approach has the advantage of being based on market prices: "It is our view that the price approach is preferable, because it attempts to take into account market data"[100].

7.3 Choosing a Curve

Despite the support for geometric economic depreciation in various studies, different results have been obtained for the shapes of the economic and physical depreciation curves. Furthermore, even the largest empirical study carried out to date was unable to find a statistically acceptable shape of curve: "We found that, in general, none of these alternatives (geometric, linear, or one-horse-shay) is statistically acceptable"[101]. Finally, according to the Bureau of Labour Statistics, given the lack of knowledge, there is to date no empirical basis for choosing between a hyperbolic and a geometric shape: "The choice is then up to the researcher, and,

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98 "Trends in Multifactor Productivity" 1948-81, U.S. Department of Labour Statistics, September 1983, Bulletin 2178, p. 42.

99 M.J. Boskin, M.S. Robinson, and J.M. Roberts, "New Estimates of Federal Government Tangible Capital", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989, p. 458.

100 M.J. Boskin, M.S. Robinson, and J.M. Roberts, "New Estimates of Federal Government Tangible Capital", in *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau, MIT Press, Cambridge, Massachussetts, London, England, 1989, p. 458.

101 Hulten, Charles, and Wykoff, Frank, "The Measurement of Economic Depreciation", in *Depreciation, Inflation, and the Taxation of Income from Capital*, The Urban Institute Press, Washington D.C., 1981, edited by Charles Hulten, p. 110.

clearly, different researchers have different preferences"[102]. Should we then assume that there is no way to choose a depreciation function?

Given the diversity of capital assets and the many factors that influence capital depreciation, it is not surprising to find that it cannot be represented by a simple mathematical function, the reverse would simply lead to random choice. Under such circumstances we can only choose the best approximation. According to Hulten and Wykoff, the geometric form is the best approximation:

> "The important conclusion that emerges from this analysis is that *a constant rate of depreciation can serve as a reasonable statistical approximation to the underlying Box-Cox rates even though the latter are not geometric* (their italics)"[103].

Using a non-geometric depreciation rate also complicates the empirical analysis:

> "... the cost of finding the depreciation function is probably proportional to the complexity of the function, and a single geometric rate depreciation function is probably the simplest depreciation function that exists which gives the best approximation"[104].

Nevertheless this was the route chosen by the Bureau of Labour Statistics, which constructed an age-efficiency function to calculate the economic depreciation rate necessary for the calculation of rental prices. The choice of a geometric form also has the advantage of simplifying the job, not only because of the duality between economic and physical depreciation, but because it allows us to use a single rate to describe the curve:

> "If, on the other hand, geometric depreciation can be shown to provide a reasonable approximation to actual depreciation patterns, then the researchers can continue to characterize depreciation as a single rate and thus achieve a considerable degree of simplification"[105].

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[102] "Trends in Multifactor Productivity" 1948-81, U.S. Department of Labour Statistics, September 1983, Bulletin 2178, p. 42.

[103] Koumanakos, P., and J.C. Hwang, op. cit., p. 15.

[104] Koumanakos, P. and J. C. Hwaang, op. cit. p. 15

[105] Hulten and Wykoff, "The Estimation of Depreciation Using Vintage Asset Prices", Journal of Econometrics 15 (1981), p. 368.

This being said, we must not forget that, obviously, different types of capital do not follow the same depreciation forms. Thus, since we cannot choose one or another depreciation form a priori, we must use a flexible method, in order to make it possible to represent this diversity. This is another advantage of the Hulten and Wykoff study: the Box-Cox transformation function makes it possible to obtain a convex, concave, linear, or rectangular (one-horse-shay) form, depending upon the set of data used.

Thus, from a theoretical point of view, the ideal approach would be to use a Box-Cox transformation function, and determine the most appropriate curve shape for each category of assets. Then, like the Bureau of Labour Statistics, we would use an economic and a physical depreciation curve for each type of asset that did not follow a geometric economic depreciation curve.

From a practical point of view, we can ask whether the difference in the evaluation of capital stock and the measurement of capital input is large enough to take such an approach. This question is discussed in the last section.

Finally, since the choice of a curve cannot be made arbitrarily, this implies that we have available data that would allow us to make a choice. Thus, we must first decide whether we wish to carry out a new survey of the prices of used assets, or whether we would simply prefer to use existing data. Assuming that we wish to use existing data, we feel that the choice is between the economic depreciation rates estimated by Hulten and Wykoff and those obtained by Koumanakos and Hwang.

By choosing the rates estimated by Hulten and Wykoff, we would ensure that the rates have been evaluated on the basis of a larger number of data, and with greater precision, because of a better definition of the capital categories. Another point to consider is that all the rates evaluated by Koumanakos do not correspond to constant rates, and that evaluation of productive stock in this case is more difficult[106]. The sole advantage of the Koumanakos study is thus that it was based on Canadian statistics.

Thus, the problem is to determine to what extent Canadian depreciation rates differ from American ones, and to judge whether this difference is worth the sacrifice in terms of precision. Undoubtedly, the difference between American and Canadian assets and the types of production used by the two countries are not different enough to justify sacrificing greater precision. As a

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106 Although it would, of course, be possible to follow the Bureau of Labour Statistics' example and define a hyperbolic age-efficiency function for asset categories that do not have a geometric depreciation rate, and determine its form using the age-price function.

result, we recommend the use of the depreciation rates estimated by Hulten and Wykoff (1981 b).

7.4 Sensitivity of the Measurement of Multifactor Productivity

Since the purpose of this study was to determine the most appropriate depreciation measurement, it was important to know the effect that choosing a depreciation function would have on the measurement of multifactor productivity. The following table shows some of the results of a BLS analysis on the sensitivity of multifactor productivity to various hypotheses respecting the form of depreciation.

TABLE 1

Sensitivity of the measurement of multifactor productivity for the business sector to hypotheses respecting efficiency: changes in percentage[107]

Period	BLS (hyperbolic)	Hulten/Wykoff (geometric)	Horizontal line (one-horse-shay)	Straight line
1966	1.9	2.0	2.2	1.8
1980	-2.2	-2.2	-2.3	-2.2
1981	1.1	1.1	1.0	1.1
1948-65	2.2	2.3	2.3	2.2
1973-81	0.1	0.2	0.1	0.2
1948-81	1.5	1.6	1.5	1.5

The largest difference between the various annual growth rates calculated in accordance with the various hypotheses was found in 1966, when it was 0.4 percent. The difference was 0.1 percent for the longer periods. The Bureau of Labour Statistics concluded that the form used was of little importance:

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[107] Taken from Table C-11 in the study "Trends in Multifactor Productivity", op. cit.

"It is evident that the method selected has little effect on the final measure of multifactor productivity"[108].

We can see that, in the long term, the method used has little effect, since the growth rates of gross and net capital stock should be equal. Thus, it is not surprising to find that the growth rates for the longer periods are independent of the depreciation method adopted. It is surprising, however, that there is so much similarity in the growth rates of the annual periods, however. Undoubtedly, one of the explanations is that the capital share of total inputs represents only about 35 percent of the total.

While this estimate of the sensitivity of productivity to various hypotheses respecting depreciation does not favour any form of depreciation over another, it confirms that the choice of the Hulten Wykoff model and a geometric form is reasonable within the framework of multifactor analysis.

In addition to ensuring a certain amount of security in our approach and making our task easier, the choice of a known model and a geometric economic depreciation rate will also make it possible to establish interesting comparisons between our results and those of other studies that have used a similar model.

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108 "Trends in Multifactor Productivity", 1948-81, U.S. Department of Labour Statistics, September 1983, Bulletin 2178, note number 14, p. 53.

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