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2 Conceptual Issues in the Measurement of Price and Quality Changes

2.1 Introduction

The theory of price measurement is really the theory of output measurement in disguise, because every issue that arises in developing a conceptual basis for measuring price change ultimately hinges on the desired concept of output change.[1] This link between price and output measurement is seen most obviously in the identity that defines an index of real output (Q) as the ratio of an observed value aggregate (V) to a constructed price index (P): $Q \equiv V/P$. The primary purpose of many price indexes, called *deflators,* is to convert changes in observed value aggregates (dV) into changes in that aggregate expressed in the constant prices of some base year (dQ). Price changes themselves would appear to be of independent interest, since the rate of inflation is one of the primary arguments in the observed objective function of most macroeconomic policy authorities. Yet the most important cost of inflation, its effect in eroding the real value of fixed-interest securities (including money), "matters" ultimately because individuals hold these assets in order to purchase output in the future. Thus, the appropriate concept of price change to be used in discussions of the cost of inflation also depends on the desired concept of output change.

The measurement of prices would be straightforward if there were a single, generally accepted index of economic and social welfare that would tell us at a glance how much better or worse off we had become each year. Decisions made in the construction of an aggregate price index would be made entirely with a view to their effect on the aggregate welfare index; for instance, a quality adjustment would be made in the comparison of the prices of two products if one provided more final "welfare" than the other.

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[1] This chapter combines new material with elements of Gordon (1974, 1983). The notation in sec. 2.4 has been altered from that in the 1983 paper to improve the exposition.

As Denison (1971) and others have recognized, however, a single generally acceptable index of welfare cannot be constructed. There is no straightforward way to measure the welfare cost of increased crime, congestion, and pollution of the air and water, or the welfare benefit of improved medical care and of completely new products like the automobile, air conditioning, and home computers. And how are we to compare the present danger of nuclear war with past hazards, some of which are enumerated by Denison:

> Who would now think to consider the danger of attack by hostile Indians? Or the risk of being doused by slops thrown from windows as he walks the city streets? Even the very recent elimination of refrigerator doors that cannot be opened from within, and cost the lives of so many children, is almost forgotten. The annual series for "Persons Lynched" appears in the Census Bureau's *Historical Statistics* but not in its current *Statistical Abstract*. [1971, 5]

Fortunately, many of the issues that complicate the measurement of national welfare lie outside the sphere of the measurement of durable goods prices. We need not concern ourselves with changes in welfare that are unconnected with the development of new types of durable goods, including the changing incidence of crime, discrimination, and other social phenomena. Our task can be circumscribed by adopting four principles to guide our discussion of measurement concepts.

1. The valuation of changes in the characteristics of durable goods depends on the resulting change in the production of goods and services available to final consumers. Changes in well-being not directly attributable to changes in the types and characteristics of durable goods need not be considered.

2. Quality adjustments are to be carried out so as to "credit" manufacturers of durable goods for all changes in the quantity of final consumption goods and services that are caused by changes in the types and characteristics of "new vintage" durable goods. These include changes in the performance characteristics of consumer durables, changes in the quantity of consumer goods and services attributable to innovations in producer durables, changes in available resources attributable to changing fuel efficiency or maintenance requirements of new consumer and producer durables, and external economies and diseconomies, for example, the effect on air quality of smog control devices installed on new durable goods. In principle, then, we are interested in ex ante or "embodied" quality change, that which is designed into the good prior to installation.

3. Users of existing durable goods may also experience ex post changes in performance characteristics, energy efficiency, maintenance requirements, or external effects after the installation date. Possible causes may include changes in relative prices, changes in operating procedures, and environmen-

tal legislation applicable to existing machines. These ex post changes are not attributable to durable goods manufacturers and do not call for quality adjustments. A central measurement problem is to apply the ex ante criterion in practice, since part of the available data on operating performance comes from users rather than manufacturers.

4. It is recognized from the beginning that it is impossible in principle to measure every improvement in consumer welfare attributable to durable goods innovations, because the benefits of new types of activities made possible by totally new goods, for example, the automobile or air conditioning, cannot be quantified. Inevitably, decisions on the definition of product categories must be somewhat arbitrary, for example, whether to consider television a new product or a reduction in the transport cost of seeing baseball games and movies, or whether to compare the price of an electronic calculator at the time of its introduction to that of an old rotary electric calculator, or a slide rule, or neither. Similarly, the environmental and other external effects of changing durable goods characteristics are difficult and sometimes impossible to quantify adequately.

This chapter begins in sections 2.2–2.5 by providing formal definitions for aggregate input and output price indexes, and for the associated quality adjustments that are required when there are shifts in the cost function of producing performance characteristics. In these sections, my debt to Triplett (1983b) is great; the distinction between input and output price indexes and the expression of inputs and outputs in "characteristics space" both lean heavily on his paper. The main contributions of this part of the chapter are to introduce the idea of "nonproportional" quality change, to relate it to the cost function of the industry manufacturing the durable good, and to discuss practical measurement problems within the context of the input and output price index concepts.

Section 2.6 provides an analysis, using the concepts discussed in sections 2.2–2.5, of the debate in the earlier literature between the "resource cost" and "user value" concepts of quality change. This literature review seems necessary in light of previous statements by distinguished writers (e.g., Jaszi 1971, 203) that "most experts subscribe" to the principle that "quality improvements can be quantified only to the extent that they are accompanied by real cost increases." Prior arguments supporting this principle need to be considered carefully, since it appears to rule out the adjustments recommended here for nonproportional quality change.

The more novel part of the chapter, beginning in section 2.7, extends the discussion of changes in performance characteristics to changes in operating characteristics (fuel efficiency and maintenance requirements). A technique is proposed for adjusting capital goods prices for changes in operating efficiency, based on the criterion of improvement in net revenue relative to cost. The last substantive sections 2.9 and 2.10 consider the use of used asset prices as a cross-check on the methodology, and include interpretative comments on the proposed concepts. A summary section 2.11 concludes the chapter.

2.2 The Input Price Index

Durable goods are normally an input into the production of goods and services consumed by final users. Producer durables are an input, along with labor, structures, energy, and materials, in the production of consumer and producer goods. Consumer durables may also be considered an input, producing the services of durable goods. The cost-of-living index literature, including Pollak (1971), Fisher and Shell (1972), and Samuelson and Swamy (1974), treats the CPI as an input price index for consumption. The point of departure for the following analysis is Triplett's (1983b) treatment of the input price index, which is defined as a measure that answers the question, What is the cost change, between two periods, of collections of inputs sufficient to produce some specified output level?

I begin by assuming that the output of final product (y) is produced by a vector of market-purchased input characteristics (x):

$$y = y(x), \quad y_x > 0, \; y_{xx} < 0, \tag{2.1}$$

where y_x represents the partial derivative of y with respect to x. An input characteristic is defined as any attribute of a market-purchased input that has a positive marginal product, including, in the case of durable goods, the horsepower and physical dimensions for a truck, or memory size and calculations per unit of time for a computer. In principle, the vector x also includes labor characteristics (education, experience, training), as well as effective inputs of energy and materials. In Triplett's more precise definition, a quantity is an input characteristic if it reduces the unexplained variation in output, given the explanation contributed by all the other arguments in the production function.

Consideration of energy and materials usage is postponed until section 2.7 of this chapter, and labor input is ignored entirely in order to concentrate on the measurement of the input and output of durable goods. Thus, (2.1) is interpreted as a production function that transforms a vector of a durable good's performance characteristics (x) into final output. By translating the term *quality* into changes in the quantity of performance characteristics, all quality changes are implicitly assumed to be quantifiable. For inventions of totally new consumer durables, this assumption may be overly optimistic.

The durable good is manufactured under competitive supply conditions, according to a cost function that exhibits constant returns in the quantity of goods produced, and diminishing returns in the number of units of the performance characteristic embodied in each physically separate durable good:[2]

$$V(x) = Cc(x), \quad c_x > 0, \; c_{xx} > 0. \tag{2.2}$$

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[2] The assumption of costs that are constant in quantities, but increasing in quality characteristics, has been adopted by most previous papers in this literature, including Parks (1974) and Rosen (1974).

Adopting the convention that lower-case letters represent "real" variables and upper-case letters "nominal" variables (or, later, index numbers for real variables), c represents the real unit cost function, C represents a shift parameter in the cost of producing a given product due to changing profit margins and/or input prices, and V stands for the total value of each unit produced. Both (2.1) and (2.2) are on a "per unit" basis, dividing total output and cost by the number of physically separate durable goods used in the production process.

For any given level of technology, say that obtaining at time t, more inputs are required to produce more output. The input demand function depends on output and on the prices of inputs:

$$x_t = x(y_t, C_t). \tag{2.3}$$

Here, equation (2.3) is a matrix showing the dependence of the demand for each input $(x_{1t}, \ldots, x_{nt})$ on the single output index and on the full set of input prices $(C_{1t}, \ldots, C_{nt})$. When the input demand function from (2.3) is substituted into the cost function of the supplying industry (2.2), we see that there is an indirect dependence of the cost of the good on the output produced by its user:

$$V(x_t) = C_t c[x(y_t, C_t)]. \tag{2.4}$$

The criterion of comparison on which the input price index (P_t^i) is based is that prices are compared holding constant output at a given level, say y^*. The optimal set of input characteristics (x^*) is defined by the demand functions for the characteristics at the given output level (y^*) and the differing input prices, C_t and C_0, respectively:

$$x_t^* = x(y^*, C_t), \quad x_0^* = x(y^*, C_0). \tag{2.5}$$

The input price index can now be calculated as the ratio of the cost (V) of obtaining the optimum (minimum-cost) combinations of the vector of input characteristics sufficient to produce output level y^* in the reference and comparison-period input price regimes. Thus, the input price index is simply the ratio of (2.4) for the two price regimes, evaluated at the constant output level y^*:

$$P_t^i = \frac{V(x_t^*)}{V(x_0^*)} = \frac{C_t c[x(y^*, C_t)]}{C_0 c[x(y^*, C_0)]}. \tag{2.6}$$

Because a change in input prices (C) between regimes can cause substitution in the quantities of the various input characteristics, the input price index allows for such substitution.

In this discussion, the inputs into the production function are the individual characteristics of goods, the vector x, so that a quality change involves a change in the quantity of one or more productive characteristics, which in turn must change the level of output. Since any such quality change would thus violate the criterion of constant output (y^*) on which the input price index is based, price measures must be adjusted "for changes in input characteristics that result in changed output (or reduced cost to the user), and the correct quality adjustment is exactly equal to the cost change or the value of the output change that they induce. In the literature, this is known as the user-value rule" (Triplett 1983b, 286).

2.3 Measuring the Input Price Index When Quality Change Is Nonproportional

Nonproportional technical innovations raise the performance of a good by increasing its built-in quantity of characteristics (x) relative to the resources used by the supplying industry. Thus, such innovations take the form of a downward shift in the real cost of producing a given quantity of characteristics, say computer calculations. The idea of nonproportional quality change can be brought into the measurement of the input price index by introducing a shift term λ_t into the cost function (2.4):

$$V_t = C_t c[x(y_t, C_t), \lambda_t]. \tag{2.7}$$

It is important to note that there is no shift in the using firm's production function (2.1), since a single calculation still produces the same amount of final output (y). Thus, the units of characteristics to be defined as x must be those that directly enter the using firm's production function, for example, a computer's "calculations per second" and not its dimensions. Also, the quality change, although "nonproportional," is not "costless." The reduction in cost must consume managerial and R&D resources, or else it would have occurred long ago. The R&D costs are not treated explicitly, nor is the capital stock in the machine-producing industry. Instead, the shift term λ represents the payoff achieved by the industry incurring those developmental costs. A virtue of our proposed accounting system is that it attributes the benefits of cost-reducing R&D expenditures to the industry that actually performs the R&D, unlike the present system, which often allocates improved productivity to the using rather than the producing industry, for example, to the airlines rather than to the aircraft engine manufacturers.

In this framework, the total change in input cost consists of four terms, obtained by taking the total derivative of (2.7):

$$dV = dC[c + C_t c_x x_C] + C_t(c_x x_y dy + c_\lambda d\lambda). \tag{2.8}$$

These terms represent, respectively, the direct and indirect substitution effect of changing prices of the inputs to the supplying industry, the effect of changing input requirements due to changing input ($x_y dy$), and the effect of

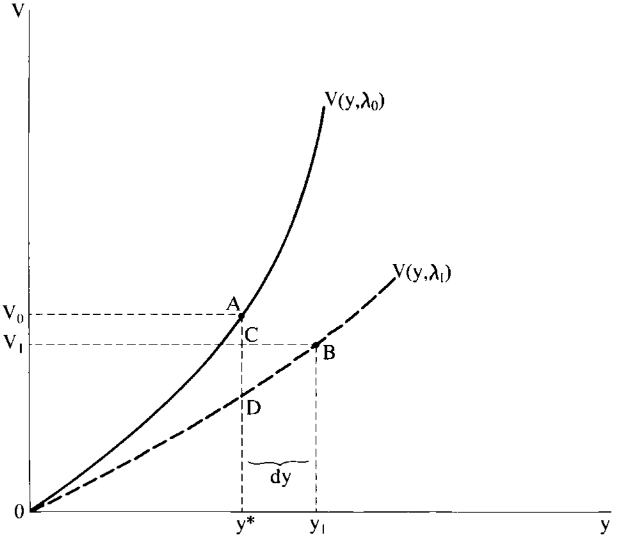

Fig. 2.1 Effect of a technological shift on the unit cost function

technical change in shifting the real cost function ($c_\lambda d\lambda$). Since the input price index (P_t^i) as written in (2.6) holds the output level constant at y^*, the change in P_t^i can be written as the total change in cost from (2.8) minus the contribution to cost of the change in output:

$$(2.9) \qquad \frac{dP^i}{P^i} = \frac{dV - C_t c_x x_y dy}{V(y^*, C_0, \lambda_0)} = \frac{dC[c + C_t c_x x_C] + C_t c_\lambda d\lambda}{V(y^*, C_0, \lambda_0)}.$$

Here, the middle expression indicates that the change in price is measured by adjusting the observed change in the cost of a new model for the change in its quantity of characteristics ($x_y dy$) multiplied by the marginal cost of producing those characteristics ($C_t c_x$). The right-hand expression shows that the price change can be caused either by changes in input prices or profit margins in the supplying industry (dC) or by a technical shift ($d\lambda$). Because the middle expression is used in actual measurement, the technical shift itself ($d\lambda$) does not have to be observed directly.

Figure 2.1 illustrates the measurement of changes in the input price index in the presence of nonproportional quality change. The two upward-sloping lines plot the unit cost function (2.7) for two different values of the technical shift parameter λ. Initially, output level y^* is produced at an input unit cost of V_0 at point A. The technological change represented by the shift from λ_0 to λ_1 improves quality by raising the quantity of input characteristics relative to their cost. This raises the demand for characteristics and the level of output, depicted by y_1 in the diagram. The unit cost of the durable good (V_1) could be either higher or lower than in the initial situation (V_0).

According to equation (2.9), the change in the input price index is equal to the change in unit cost (minus line segment *AC*) minus an adjustment factor equal to the change in output (*CB*) times the marginal cost (*CD*/*CB*) of building extra input characteristics capable of producing the extra output along a new supply schedule. Thus, the change in the input price index is $-AC - CD = -AD$, that is, the vertical downward shift in the supply schedule itself. Note that the change in the real input quantity is measured by the change in output times the marginal cost of producing extra output under the new supply conditions. The change in an index of the real quantity of input characteristics (dQ^i) can be written formally as the proportional change in the number of units of capital (du/u), plus the change in cost per unit (dV/V), minus the input price index:

$$(2.10)\qquad \frac{dQ^i}{Q^i} = \frac{du}{u} + \frac{dV}{V} - \frac{dP^i}{P^i} = \frac{du}{u} + \frac{C_t c_x x_y dy}{V(y^*, C_0, \lambda_0)} .$$

Because it is the marginal cost of producing characteristics that is used to make the actual quality adjustment in (2.9), the much-debated distinction between the "user-value" and "production-cost" criteria for the measurement of quality change is misleading, since both are used in (2.9) and in the corresponding figure 2.1. User value is the criterion used to define x, that is, the choice of calculations rather than dimensions as the characteristic desired by the user of a calculator. And production cost is the criterion used to make the actual quality adjustment. In essence, we have a hybrid criterion in which both the user-value and production-cost criteria are integral parts.

For the purpose of quality adjustment in practice, several alternative methods of estimating the marginal cost (c_x) are available. For instance, if an auto manufacturer were to make automatic transmission standard at no increase in price, and if the BLS had information either on the price of automatic transmission when it was an option or on a manufacturer's estimate of the cost of producing an automatic transmission, then the present BLS pricing methodology would be adequate to measure the marginal cost. Often, when quality change involves continuous rather than discrete change, for example, a change in automobile acceleration and dimensions or in computer performance, it is more convenient to use the hedonic regression technique to estimate the shadow price of a given characteristic, that is, its marginal cost. Clearly, the proper technique to use in each case is independent of whether the nature of the quality change is "cost-increasing" or "nonproportional."

2.4 The Output Price Index

Triplett (1983b) has made Fisher and Shell's (1972) distinction between input and output price indexes the centerpiece of his analysis of quality change. An output price index is used to calculate an aggregate output index by deflation. In the case of a machine that is both an input to a machine-using industry and the output of a machine-producing industry, the input price index should be used in calculating measures of real capital input in the using industry, while the output price index should be used in calculating output and productivity indexes for the machine-producing industry.

The distinction between input and output price indexes creates an obvious problem. The real net investment component of national product is defined as the change in the real capital stock. If the price change of a machine is measured differently by the input and output price indexes, then the resulting change in real capital input will not be compatible with the computed change in net investment. This section demonstrates that, fortunately, both cost-increasing and nonproportional quality changes are treated identically by input and output price index measures. The only justification for a distinction between the two index types arises when output and input change are not identical, as in the addition to a machine of a pollution-control device that does not actually produce output, and thus consumes resources in the machine-producing industry without raising input in the machine-using industry. This and other issues raised by external economies and diseconomies are discussed below.

In contrast to the input price index, the output price index uses a standard that compares prices by holding constant the economy's endowment of productive factors and its production technology. The new output symbol (q) represents a vector of output characteristics. Initially, nonproportional quality change is ignored. A vector of output characteristics (q) is produced in an amount that depends on the quantity of input characteristics (z) and the relative prices of output characteristics (P):

$$q = q(z, P), \quad q_z > 0. \tag{2.11}$$

Triplett defines the output price index P_t^O as the ratio of the revenue (R) obtained from the optimum (maximum-revenue) combination of output characteristics in the reference and comparison-period output price regimes, holding constant both input quantities (z^*) and production functions:

$$P_t^O = \frac{R(q_t^*, P_t)}{R(q_0^*, P_0)} = \frac{P_t q(z^*, P_t)}{P_0 q(z^*, P_0)}. \tag{2.12}$$

Here, P_t and P_0 represent, respectively, the vector of prices of output characteristics in, respectively, the reference and comparison periods. Note that I let z stand for input characteristics in the intermediate goods (i.e., computer-producing) industry, as distinguished from the x vector of inputs in the final goods (computer-using) industry. As we shall see below, output characteristics in the "intermediate" computer industry (the q vector) are the same as input characteristics in the final goods industry (the x vector).

The numerator and denominator of the output price ratio differ both in the price regime (P_t or P_0) and in the quantities of output characteristics (q_t^*) or q_0^*) that are optimal, given the fixed input quantities (z^*) and the fixed production functions that establish the various output combinations that can be produced from those inputs. A quality change now implies an increase in one or more output characteristics.[3] If we assume that the resources devoted to increasing quality are obtained by decreasing the output of some other good, in order to remain on the same production possibility frontier, the output price index must be adjusted for the resource cost of the added output characteristics. "The [quality] adjustment required is equal to the value of the resources required to move the set of output characteristics included in the index back to the same production possibility curve. This is precisely the resource cost quality measurement rule that has been argued in the literature" (Triplett 1983b, 299).

Do the input and output price index concepts give a consistent treatment to an identical technological innovation that was described in figure 2.1 as a cost-saving technological innovation? The nonproportional quality change can be introduced into the discussion of output price indexes by allowing the same shift term (λ) to enter the production function. A vector of output characteristics (q) is now produced in an amount that depends on the quantity of input characteristics (z), the prices of output characteristics (P), and the shift term (λ):

$$(2.13) \qquad q = q(z, P, \lambda), \quad q_z > 0, \; q_\lambda > 0.$$

Following Triplett's usage (1983b, 295), an output characteristic is defined as something that uses resources: "An output is not an output because someone wants it; being useful or desired is the definition of an input."

The output price index, as in (2.12), is now the ratio of revenue in two periods when output prices are allowed to change, holding constant the level of resources (inputs) and production technology:

$$(2.14) \qquad P_t^O = \frac{R(q_t^*, P_t)}{R(q_0^*, P_0)} = \frac{P_t q(z^*, P_t, \lambda^*)}{P_0 q(z^*, P_0, \lambda^*)}.$$

The total change in revenue between the reference and the comparison periods is the total derivative of the revenue function:

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[3] The vector of output characteristics (q) might be imagined to consist of $m - 1$ homogenous goods, plus an mth good that in turn consists of n separate characteristics: $y = (q_1, q_2, \ldots, q_{m-1}, q_{m1}, q_{m2}, \ldots q_{mn})$. Quality change involves an increase in one of the characteristics of the mth good. If resources and technology are fixed, this would in turn require a reduction in the output of one of the $m - 1$ other goods.

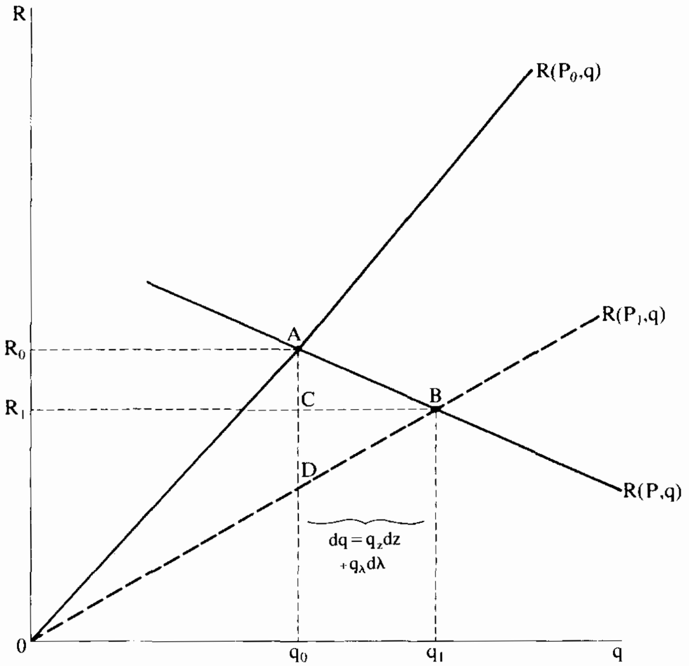

Fig. 2.2 **Effect of a technological shift on the revenue function**

$$\frac{dR}{R} = \frac{dP(q + P_t q_P) + P_t(q_z dz + q_\lambda d\lambda)}{P_0 q(z^*, P_0, \lambda^*)}, \tag{2.15}$$

where the terms represent, respectively, the direct and indirect substitution effects of changes in the output price, the effect on real output of increasing input usage, and the effect on real output of the technological shift itself.

The change in the output price index (2.14) consists of only two of the four terms in (2.15), since both input usage (z^*) and technology (λ^*) are being held constant:

$$\frac{dP^O}{P^O} = \frac{dR - P_t(q_z dz + q_\lambda d\lambda)}{P_0 q(z^*, P_0, \lambda^*)} = \frac{dP(q + P_t q_p)}{P_0 q(z^*, P_0, \lambda^*)}. \tag{2.16}$$

The corresponding quantity index based on the output price index consists of the residual change in revenue:

$$\frac{dQ^O}{Q^O} = \frac{P_t(q_z dz + q_\lambda d\lambda)}{P_0 q(z^*, P_0, \lambda^*)}. \tag{2.17}$$

What is the relation between changes in the output price index in (2.16) and in the input price index defined by (2.9)? Figure 2.2 illustrates the calculation of changes in the output price index and quantity index when there is a technological change represented by a shift from λ_0 to λ_1. The increase in the output that can be produced by the initial resource endowment raises output directly by the term $q_\lambda d\lambda$ in equation (2.17) and indirectly by raising the marginal product of inputs and hence the demand for inputs (the term $q_z dz$). If the higher level of output is to be sold, the output price (P) must drop, as indicated along the appropriate industry demand curve. The downward-sloping total revenue line in figure 2.2 is drawn on the assumption that demand is price inelastic. The upward-sloping lines indicate the revenue that would be obtained from varying levels of output if the price level were fixed. Starting from an initial equilibrium at point A, the innovation-induced increase in output leads to a new equilibrium at point B, where the price level has dropped from P_0 to P_1 and total revenue has declined from R_0 to R_1. According to equation (2.16), the change in the output price index is measured by the change in revenue (minus the line segment AC) minus the new price level (CD/CB) times the change in output (CB), or the distance $-AD$.

Now the connection between figures 2.1 and 2.2 becomes evident. When we consider the output of a capital good, for example, an electronic computer, a technological shift causes a decrease in price measured by the vertical distance AD in figure 2.2. Note that this vertical downward shift AD also appears in figure 2.1 as the change in input prices viewed by the user of the electronic computer. The input and output price index concepts are equivalent in this case and would include in both real GNP and in real capital input technological shifts that raise the output capacity of capital goods relative to their production cost.

The equivalence of the input and output price index concepts can be seen not just in the comparison of figures 2.1 and 2.2, but also in the comparison of equations (2.9) for the input price index and (2.16) for the output price index. First, because the output characteristics produced by the computer industry, the q vector, are identical to the input characteristics purchased by the final-goods industry, the x vector, we can write that in competitive equilibrium per-unit revenue ($R = Pq$) equals per-unit cost ($V = Cc$) in each time period:

$$\begin{aligned} R_0 &= P_0 q_0 = V_0 = C_c c_0 , \\ R_t &= P_t q_t = V_t = C_t c_t . \end{aligned} \tag{2.18}$$

Further, in equilibrium, the price of an output characteristic produced by the computer industry (P) equals the marginal cost of producing a computer input characteristic for use in the final-goods industry:

$$\begin{aligned} P_0 &= C_0 c_z , \\ P_t &= C_t c_z . \end{aligned} \tag{2.19}$$

Comparing (2.9) and (2.16) using the equilibrium conditions in (2.18), the denominator of the former, V_0, is identical to the denominator of the latter ($P_0 q_0$). The first terms in the numerator, respectively, dV and dR, are also identical. The terms subtracted in the middle expression of each equation, respectively, $C_t c_z dz$ and $P_t dq$, are also identical.

The model is applicable not just to "nonproportional" quality change, but also to "resource-using" or "cost-increasing" quality change. Imagine an upward shift in the demand for computers, without any change in technology. The previous equations are appropriate for measuring price and output change if we set the $d\lambda$ terms equal to zero. In figure 2.1, consider an initial equilibrium at point D, where the lower supply curve meets an initial demand curve (not drawn). Then let the demand curve shift upward sufficiently to move the new equilibrium position to point B. The change in unit cost (dV) is exactly offset by the increase in the marginal cost of the additional characteristics, leaving the input price index as measuring shifts in the price of producing a given output; in this case, there has been no such shift. The same conclusion applies to the output price index, which would be measured as unchanged, since the price of utilizing the initial level of resources has remained unchanged.

The previous comparison of equations (2.9) and (2.16) remains valid as well when quality change is resource using. In the case of each equation, the observed change in the value of a computer ($dR = dV$) is adjusted by the marginal cost ($C_t c_z dz$) of additional computer characteristics in the case of the input price index and the price ($P_t q_z dz$) of those characteristics in the case of the output price index.

2.5 The Equivalence of Input and Output Price Indexes

The conclusion of the previous section has been that both input price indexes and output price indexes treat quality change consistently, and that the user-value and resource-cost criteria lead to the same measures of prices of real output. This has always been recognized as true for "resource-using" quality change, where an increase in quality requires an increase in production cost. The novelty here is the demonstration that "nonproportional" quality change is also treated consistently by properly defined input and output indexes. Thus, a technological change that raises the user value of a durable good relative to its production cost will be treated in exactly the same way in input indexes that measure the changes in the real capital input of the using industry, and in output indexes that measure the real output of the producing industry.

This conclusion of equivalence between input and output indexes requires three assumptions for its validity.

1. The basic unit of observation in the theory is the characteristic. This may lead to measurement problems in practice, since we observe market prices in most cases only for physically discrete objects containing different bundles of characteristics.
2. The economy is competitive and in equilibrium, so that the price of characteristics is equal to their marginal cost. This equivalence of the ''demand price'' and ''supply price'' of a characteristic is familiar from the work of Rosen (1974).
3. Characteristics of durable goods must simultaneously make a difference for the output of the user (so that they can be counted as input characteristics for the using industry) and must require resources in their manufacture (so that they can be counted as output characteristics for the producing industry). This requirement may not be satisfied for some goods, for example, pollution-control devices.

If these three conditions are satisfied, the remaining theoretical ambiguity is limited to the usual Laspeyres/Paasche index number problem, for example, the different price indexes that result when base-period and current-period measures of marginal cost are used alternatively in (2.9) to adjust observed changes in the unit value of a durable good. Triplett (1983b) provides a full treatment of index number problems in the context of quality change adjustments and derives the direction of bias in the Laspeyres and Paasche indexes relative to the true input and output price indexes.

In practice, theoretical index number problems are likely to be of less importance than practical measurement issues. How is the marginal cost of an input characteristic, the key ingredient in the input price index formula (2.9), to be measured in practice? Similarly, how is the price of an output characteristic in (2.16) to be measured? Conventional, hedonic, and other measurement methods all involve developing proxies for these unobservables; their advantages and disadvantages are examined in chapter 3.

2.6 Comparison with Previous Approaches to the Quality Adjustment Issue

A complete survey of the large literature on quality change lies outside of the scope of this book. Instead, this section uses the preceding theoretical analysis to interpret the main arguments made by key participants in the debate between the ''resource-cost'' and ''user-value'' approaches to quality change, including Denison (1957, 1972), Gavett (1967), Gilbert (1961), Griliches (1964), and Jaszi (1964).

The analysis in the preceding section takes as its point of departure Triplett's insight that resource cost is the criterion used to define an output characteristic, and that user value is the criterion used to define an input characteristic. It goes beyond Triplett's analysis by making an explicit distinction between the quality-adjustment criterion and the estimator actually used to adjust price indexes for differences in characteristics across models.[4] For an input index, the preferred estimator is the marginal cost of producing an extra characteristic. For an output index, the preferred estimator is the demand price of an extra output characteristic. Both marginal cost and price information may be used to make quality adjustments in practice; the existing BLS quality adjustment procedures request manufacturers to estimate the cost of achieving a reported change in quality, whereas in the hedonic regression technique the dependent variable is the set of observed prices of models containing different quantities of characteristics. Thus, as Jaszi (1964) and some other early authors recognized, the issue of choosing the proper criterion is entirely independent of the practical issues involved in constructing the best possible estimator (e.g., the choice between the conventional and the hedonic methods).

Several authors, notably Denison and Jaszi, have opposed quality adjustments for the types of changes labeled here as *nonproportional,* that is, involving an increase in user value relative to resource cost. In Denison's original treatment of the subject, adjustments for nonproportional quality changes are opposed on grounds of infeasibility, not on the basis of a theoretical principle. Some other authors, however, have stated as a matter of principle that quality adjustments in price indexes are to be limited to cases where increased resources are required to produce an increase in quality.

The basic controversy revolves around the definition of the appropriate unit of measurement, which in this chapter is taken to be the *characteristic* (terminology used by Triplett and Lancaster), and which in some earlier work by myself (1970) and others was called the *quality attribute.* The proponents of the so-called resource cost position can often be described as choosing a more restrictive definition of the unit of measurement.

Another problem is the frequent confusion between movements along cost functions and shifts in those functions. In the computer example, any increase in multiplication speed or memory size raises costs and uses resources for any given technology (represented above by an initial value of the technological shift parameter, say λ_0). Thus, there should be no controversy about the desirability of making quality adjustments in price indexes for computers having different quantities of these resource-using characteristics. Disagreement arises, however, when a computer manufacturer introduces a new model containing twice as many characteristics as before with little or no increase in the computer's price. Here, the ''resource cost'' proponents argue against a quality adjustment, by stating in their terminology that a quality adjustment can be performed only when higher quality requires an increase in cost. Yet this terminology is appropriate only

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[4] Discussions with Triplett in 1979 and 1980 were instrumental in developing this distinction.

when cost functions remain fixed and fails to recognize the decline in the price of characteristics that occurs when there is a downward shift in the cost function, that is, a shift in technology from λ_0 to λ_1. The debate about the appropriate unit was best posed in the often-cited exchange between Griliches (1964) and Jaszi (1964). The question was stated concisely by Griliches (1964, 401–2):

> What should quality change be measured by—"cost" or "value"? The dosage of the new birth control pills (Enovid) has been recently cut in half, reducing thereby the price of this contraceptive method by half. This came about as the result of additional research which showed that half of the previously recommended dose is really enough to achieve the desired result. . . . How we should treat this change depends on our definition of "productivity." I would choose a measure that showed no decline in output, since in this way output would be defined in units comparable to the "market" for it, and such a definition would show a substantial increase in the productivity . . . of this industry. In fact, this is a rare actual example of the "pure-knowledge" no-increase-in-costs type of technological advance which crowds our textbooks.

Assume that before the technical advance two pills per day were required and afterward only one was necessary. Neither the cost of producing a pill nor a price index based on production cost has changed. Yet a price index based on the price of the "desired result," that is, on the ability of pills to produce birth control, has dropped by half. The apparent paradox disappears when we standardize the unit of transaction. While the cost per pill is unchanged, the cost per "desired result" has dropped by half, exactly the same proportion as the price index based on "value." The difference between the two approaches occurs only if the cost method is applied to "pill units" instead of "result units," and there is no conflict if the choice of unit, that is, the adjustment criterion, is based on the evaluation of users. If we observe on the marketplace that prices of pills are not identical but proportional to dosage, then we conclude that the consumer is buying dosage and does not care whether dosage comes in one-pill or two-pill bundles.

In his comment on Griliches's paper, Jaszi recognized that the definition of measurement units was crucial: the durability of automobile tires may be taken as the basic quantity dimension in some studies of transportation. It seems to me that this approach holds more promise than the two outlined before in some specific cases. Nevertheless, Jaszi took a relatively pessimistic attitude regarding the feasibility of measuring quality characteristics: "The difficulties involved in selecting the relevant quality characteristics, in finding good quantity indicators for them, and in assigning appropriate weights to these indicators tend to become unmanageable in most cases even of specific *ad hoc* analysis" (1964, 409).

Later, however, Jaszi shifted toward the view that the "real cost" criterion was desirable as an "underlying concept" rather than on grounds of practicality. Despite the precedent of Chow's (1967) hedonic study estimating the implicit prices of computer characteristics and showing a decline in characteristics prices of 25 percent per year, Jaszi defended his agency's practice of permanently setting the price deflator for computers equal to one by arguing that quality adjustments should not be made when an increase in computer performance relative to cost was made possible by a technological innovation:

> Recognition that we try to implement [the principle that quality changes must be reflected in real cost increases] is relevant in connection with R. J. Gordon's criticism of our assumptions about the prices of electronic computers. . . . The measurements presented in [Chow's] article do not seem to be based on the principle to which OBE [now BEA] and most experts subscribe, vis, that quality improvements can be quantified only to the extent that they are accompanied by real cost increases. [1971, 203]

Denison has contributed the basic theoretical paper (1957) that justifies the real cost criterion and that is cited in virtually every discussion, for example, that of Jaszi quoted in the preceding paragraph, written by those supporting that criterion. Denison distinguishes between a measure of real capital that equates units having the same real cost of production even if their quantity of input characteristics differ (K), a second measure that equates units having the same numbers of input characteristics (J), and a third that uses total output capacity as a proxy for capital input. I shall omit consideration of the latter here and agree with Denison that it is "absurd" because it would count increases in output due to a greater input of labor or land as attributable instead to capital. In Denison's discussion, units of capital goods that in my terminology have the same input characteristics are described as having the same marginal product.

Denison's attempt to distinguish between K and J rests on an arbitrary selection of the transaction unit. Any quality change that requires a higher price and cost of this transaction unit is taken into account in calculating K, but a quality change that leaves price and cost per transaction unit unchanged while reducing price and cost per quality characteristic should not be taken into account. It thus appears that Denison rejects J out of hand. Yet, according to my previous analysis, there should be no distinction between K and J if cost and price are defined in terms of the proper unit, the quality characteristic. Either K is identical to J, or it does not exist as a logically consistent concept.

Denison does not object to J on logical grounds. In fact, he calls it

> coherent and of extreme interest because all changes in real output could be traced to the responsible factor of production or to causes for which the factors were not responsible. Furthermore, it provides a measure of net capital formation which is theoretically meaningful. Zero net capital formation, or keeping capital intact, could be interpreted as that amount of

> capital formation required to maintain the economy's output potential if the supply of all other productive factors were constant . . . and there were no changes in the institutional environment affecting productivity per unit of total input. [1957, 234]

Not only does Denison provide this degree of conceptual support for method 2 (*J*), but he presents two related arguments against the use of his own method 1 (*K*) as the only capital measure. First, he admits that "one aspect of method 1 at first sight appears curious. . . . Quality improvements in product not involving additional costs are usually considered as increases in output for industries producing consumers' goods but, by method 1, are not so considered in the case of durable capital goods." He defends this aspect of method 1 by claiming that capital goods are "instruments of production, not . . . products desired for their own own sake" (226–27). But, as Kuznets remarks in his comment on Denison's paper, this argument, if pushed to its logical conclusion, would cause investment to be excluded from national product altogether.

Second, Denison's own treatment of education in his studies of growth sources amounts to the "*J* approach" applied to people (see, e.g., his 1967 book). An index of quality change for labor is constructed with relative earnings of different education groups as weights on changes in the fraction of the labor force in each group. The weights are not based on the relative costs of educational inputs in each educational group. Thus, Denison's use of the *J* approach to measure labor input is inconsistent with his opposition to this approach for capital; in fact, the *J* approach should be used for both.

Then why does Denison oppose *J* as the appropriate concept? He claims that it simply cannot be measured and presents an example in which an improved variety of machines displaces labor in an industry and in which, he claims, the magnitude of *J* depends on the amount that the displaced labor can produce elsewhere. But the ratio of the quality of the new machines to that of the old depends only on the ratio of their input characteristics in the industries in which they are used and not on conditions in other industries to which displaced workers move. Denison rightly states that the macroeconomic data ordinarily employed by national income accounts will not reveal "the exact role of the change in the capital goods in isolation." But then he incorrectly rejects the use of macro data, for example, evidence on the relative prices of used assets, because the method "requires that buyers and sellers on the secondhand market have information which cannot be known to them . . . like the potential output of displaced workers" (234). The measurement of *J* requires micro data on relative prices, however, because relative prices measure relative marginal products, which are known to or can be estimated by the purchasers of the equipment. The effect of their purchases on conditions in other industries will not affect their price bids and are not relevant to the measurement of *J*.

Denison presents one last argument against *J*, which, even

> if there were no other difficulties, . . . would suffice to prevent [its] acceptance . . . as giving meaningful results. Very often production is increased simply because someone . . . has thought of a better way of organizing it. A more effective way to use a machine may be uncovered, either by change, through the initiative of its operator, as a result of time and motion study or other research project; or through an idea imported from abroad. The new way may involve no change at all in the machine. [233]

The introduction to this chapter, however, explicitly rules out price adjustments for such ex post developments that could apply equally to new or old machines. Events that change the marginal products of all machines by the same proportion do not affect the price or quality change indices defined in equations (2.9) and (2.16) because neither the quantity, nor the implicit prices, nor the marginal costs, of characteristics would change.

Denison has subsequently supported his approach with an additional argument that is conceptual rather than practical. The attempt to measure quality change that raises the ratio of marginal product to cost

> would cause the capital stock in constant prices and hence capital input to rise more over time than the present procedure, and would transfer the gains provided by improved design of capital goods from advances in knowledge to capital. This would eliminate the possibility of a rise in the efficiency of capital and would destroy the possibility of analyzing advances of knowledge as a separate source of growth. [1972, 97]

But, as Rymes (1971) and I (1968) have previously pointed out, Denison's argument goes only halfway if he wants to analyze advances of knowledge as a separate source of growth. Technical advances in knowledge (''process innovations'') that reduce the price of capital goods measured in transactions units, relative to factor costs of inputs in those industries, cause ''the capital stock in constant prices and hence capital input to rise more over time'' than it would in the absence of advances in knowledge, and hence transfer the gains provided by efficiency in the capital-goods-producing industry ''from advances in knowledge to capital.'' Because the Denison (*K*) technique already takes account of this source of growth, that is, productivity improvements in the capital-goods-producing industries, but not the source resulting from ''product innovations'' in those industries, it is a halfway house that is not consistent with either of the two basic purposes of investment statistics, the measurement of the output of real investment goods or the identification of sources of growth. To identify the contribution of advances in knowledge to growth, the proper distinction is to use the *J* concept that attributes to capital goods manufacturers their own advances in knowledge (both ''process innovations'' that raise productivity measured in transactions units and ''product innovations'' that raise the quantity of quality characteristics relative to the number of transactions units) but not those ex post advances achieved by users of capital goods.

Recently Denison (1989, 24–32) has reentered the debate and gone beyond his previous advocacy of method 1 toward an endorsement of what he calls "method 4," the measurement of capital by consumption foregone. This has the effect of eliminating increases in the stock of capital made possible by process innovations, so that increases in GNP made possible by such innovations can be classified as due to advances in knowledge rather than as the result of capital investment. Allyn Young (1989b) provides a rebuttal to Denison's position in the context of defending the BEA's new computer deflators. The debate between Denison and Young does not change our previous conclusion that price deflators should be based on the *J* concept of capital.

Two more extreme positions may be cited. Gilbert presents the strongest statement defending the definition of price and cost in terms of the arbitrary units transacted on the market, rather than in terms of quality characteristics: "Our units of measurement are fixed transactions because they are the only measurable units" (1961, 21). But of course the conventional procedure already goes beyond transaction units, for example, a loaf of bread, and attempts to standardize for the units of a desired attribute, in this case weight per loaf. Once again, the disagreement revolves around an arbitrary and pessimistic presumption that all or most satisfaction-increasing quality changes are unmeasurable.

Gavett confronts an example that is exactly analogous to the case of nonproportional quality change, yet reaches the wrong conclusion:

> Suppose that an improved product can be produced without increasing the cost. If the price tag on the product remains the same, what should we conclude about the quality-adjusted price of this product? Cost considerations alone would suggest that the adjusted price is the same, if costs of the improvement are zero. This answer seems, at first blush, clearly wrong from the viewpoint of utility. After all, the product is better and the price tag the same. . . . Within the context of a pure price index, however, we must conclude that even utility consideration would lead to the conclusion that the quality-adjusted price is the same, not lower. [1967, 18]

The quotation states that the price is unchanged on the basis of both cost and utility considerations. This is wrong for costs, because the unit for measuring costs is wrongly chosen. While the cost of "this product" is indeed unchanged, the cost per unit of quality characteristic has declined. Thus, a properly defined cost measure yields a conclusion that price has declined. Gavett's second conclusion, that price is unchanged even on the utility criterion, is more surprising and equally incorrect. His justification is that the "increase in consumer surplus is not, however, attributable to a change in price but to a change in the quantity of the product purchased. That sort of gain in satisfaction is, however, excluded from a fixed weight index" (18). Yet the consumer's demand curve is exactly analogous to the situation in figure 2.2 above, which is defined with reference to the quality attributes that the consumer values. Thus, the quantity has increased because of the decline in price (and cost) per unit of quality attribute; the supply curve has shifted downward along an unchanged demand curve.

This section concludes, then, that there is no convincing case made in the previous literature that would warrant excluding quality adjustments to price indexes for quality changes that are "nonproportional." The basic Denison position, based on the infeasibility of measuring changes in quality characteristics, was written before Griliches's early work (1961) that demonstrated the feasibility of the hedonic regression technique. While choosing the appropriate unit of measurement may indeed be difficult when genuinely new products are invented, in many cases—like the invention of better-performing computer models—it will be possible to identify appropriate units in a cross section of different models. In these cases where objective evidence is available on the appropriate unit of measurement, there seems to be no articulate justification in the earlier literature for ignoring downward shifts in the cost function generated by reductions in the cost of producing these quality characteristics.

2.7 A Model Incorporating Operating Costs

The analysis to this point has followed the previous literature by analyzing concepts of quality adjustment for changes in performance characteristics, for example, changes in auto horsepower or computer memory. It now turns to a much less familiar topic, quality adjustments for changes in operating characteristics, for example, energy efficiency and maintenance requirements. While Griliches (1971) and others have recognized that fuel economy is a quality attribute that may help to explain some price differences across models, there is no previous theoretical treatment that explicitly integrates adjustments for operating efficiency into the index number literature.

Some research on the production technology of energy use (e.g., Hudson and Jorgenson 1974) assumes that energy (e) enters the production function symmetrically with labor hours (h) and capital input (x):

$$y = y(h, x, e), \quad y_h > 0, y_x > 0, y_e > 0. \tag{2.20}$$

Thus, changing relative prices, in particular the rising relative price of energy observed during the 1970s, can cause substitution both between energy and capital and between energy and labor. Because the price of labor influences the amount of labor used per unit of capital, there is no presumption in this framework that changes in energy efficiency call for adjustments in the prices of capital goods.

Yet failure to do so would prevent the consistent treatment of performance-increasing and energy-saving technological change in the measurement of prices, output, and productivity. The previous sections show why a technological shift in the performance of a capital good per unit of resources used in capital-goods-producing firm A should be treated as an increase in real investment and real GNP. Now let us assume that another capital-goods-producing firm B achieves a technological improvement in one of its products, yielding energy savings having the same value to users as the performance improvement achieved by firm A. Should not the criteria for price measurement be designed to treat both types of technological change symmetrically?

In order to adjust the price of a capital good for changes in energy efficiency, it is necessary to assume that energy usage is "embodied" in capital goods, and that the production function (2.20) can be rewritten in the separable form:

$$y = y[h, k(x, e)], \qquad (2.21)$$

where $k(x, e)$ is a subfunction with two inputs, performance characteristics (x) and energy (e), that produces capital input (k). Berndt and Wood describe the subfunction as follows:

> For example, consider the production of industrial process steam of given specified physical characteristics. In such a context utilized capital services (k) refers to the quantity of steam produced per unit of time using capital . . . and fuel inputs. This assumption of a separable utilized capital subfunction implies that the optimal e/x ratios . . . depend solely on [the prices of x and e] and not on the other input prices or the level of gross output y. [1979, 344; my notation substituted for theirs]

Is this assumption of separability, which is essential to the discussion of price measurement in this paper, a reasonable one? Three arguments can be presented to support the procedures proposed here.

1. Berndt and Wood (1979) have reexamined previous econometric studies in an attempt to reconcile disparate findings regarding the degree of substitution or complementarity between capital and energy. In these reconciliations, "separability has played a prominent role" (350), and their own empirical evidence (1975) appears to support the separability assumption.

2. The study below makes the assumption not only that the production function is separable but that the technology is "putty clay," so that energy usage is "designed in" ex ante when the capital good is built. In some industries, the assumption that energy requirements are embodied in capital goods seems more reasonable than in others. The ability of a user ex post to improve the energy consumption of an automobile, commercial airplane, electricity generating plant, or appliance is relatively minor compared to the latitude available to the manufacturer. My study of the electric generating industry in chapter 5 below provides citations to previous literature, as well

as new evidence, supporting the proposition that energy efficiency is embodied ex ante, at least in that industry.

3. Although users can alter energy consumption even when technology is putty clay, for example, an automobile driver can save gasoline by careful avoidance of sudden starts, the techniques described below involve measuring an energy requirements function that holds constant the characteristics of users, for example, airline utilization or length of hop, and numerous characteristics of electricity generating plants. In addition, performance characteristics are held constant, yielding a function translating energy into performance that can fairly be said to be under the control of the capital-goods manufacturer.

2.8 Adapting the Input Price Index to Incorporate Nonproportional Changes in Net Revenue

The production of output (y) is now assumed not only to require the acquisition of durable goods having productive input characteristics (x), but also to involve a variable operating cost, the consumption of other inputs (e) times their price (S). In the present discussion, e may be taken to represent the yearly consumption of energy of a capital good having performance characteristics x. The energy requirements function is taken as given by the equipment user, reflecting my assumption of a separable putty clay technology:

$$e = e(x, \sigma), \quad e_x > 0,\ e_\sigma < 0, \tag{2.22}$$

where the parameter σ represents a technological shift factor that can alter the energy consumption of a given set of input characteristics. A higher value of σ is assumed to be achieved by R&D expenditures by the equipment manufacturer and to allow a lower consumption of energy for a machine with a given set x of performance characteristics.

The net revenue (N) of the durable good user consists of gross revenue less variable operating cost. Gross revenue is the output price times the production function (eq. [2.1] above), and operating cost is the price of the operating input (S) times the consumption of operating inputs (e) from (2.22):

$$N = Py(x) - Se(x, \sigma). \tag{2.23}$$

Here, to simplify the exposition, labor input is ignored and is implicitly assumed to be a fixed cost of operating capital with performance characteristics x. An expression for real net revenue (n) can be obtained by dividing (2.23) by the output price:

$$n = y(x) - se(x, \sigma), \tag{2.24}$$

where s is the real price of the operating input ($s = S/P$).

Recall that the input price index was previously defined as the ratio for two time periods of the nominal cost of inputs that are capable of producing a given level of output (y^*). A natural extension of this concept in the presence of variable operating costs is to hold constant between the two periods the level of real net revenue (n^*). This criterion reflects the assumption that users of durable goods do not care about gross output but rather about the net revenue that durable goods provide. Thus, a user is assumed to be indifferent between ten units of real net revenue obtained in situation A with fifteen units of real output and five units of real operating cost, and an alternative situation B with sixteen units of real output and six units of real operating cost, holding constant his investment in capital goods (and the assumed fixed complement of labor required to operate the capital).

The introduction of variable operating costs makes the demand for input characteristics depend on real net revenue (n), the vector of prices of input characteristics (C), the real price of operating inputs (s), and the technological shift parameter (σ):

$$(2.25) \qquad x_t = x(n_t, C_t, s_t, \sigma_t), \quad x_n > 0, x_s > 0, x_\sigma < 0.$$

Comparing the arguments here to the previous input demand function in equation (2.3) above, note that real output has been replaced by real net revenue and that the two parameters of variable operating cost have been added (s and σ). The signs of the derivatives of (2.25) assume that the firm is operating in the region in which additional net revenue requires extra energy input and capital performance characteristics to produce more gross output. An increase in operating cost requires an increase in gross output (and hence capital input) to yield any fixed level of net revenue; hence, the derivative is positive with respect to the relative price s and negative with respect to the technological parameter σ.

When the new input demand function in (2.25) is substituted into the input characteristic cost function that allows for technical change (eq. [2.7] above), we obtain an expanded equation for the cost function:

$$(2.26) \qquad V_t = C_t c[x(n_t, C_t, s_t, \sigma_t), \lambda_t].$$

The input price index is defined as the ratio of the cost function in the comparison period to that in the reference period of producing a given real net revenue, holding constant the relative price of operating inputs:

$$(2.27) \qquad P_t^i = \frac{V(n^*, C_t, s_0, \sigma_t, \lambda_t)}{V(n^*, C_0, s_0, \sigma_0, \lambda_0)}.$$

The decision to hold constant the relative price of operating inputs (s) in the numerator and denominator reflects the desire to limit changes in the input price index to factors internal to the firm manufacturing the durable

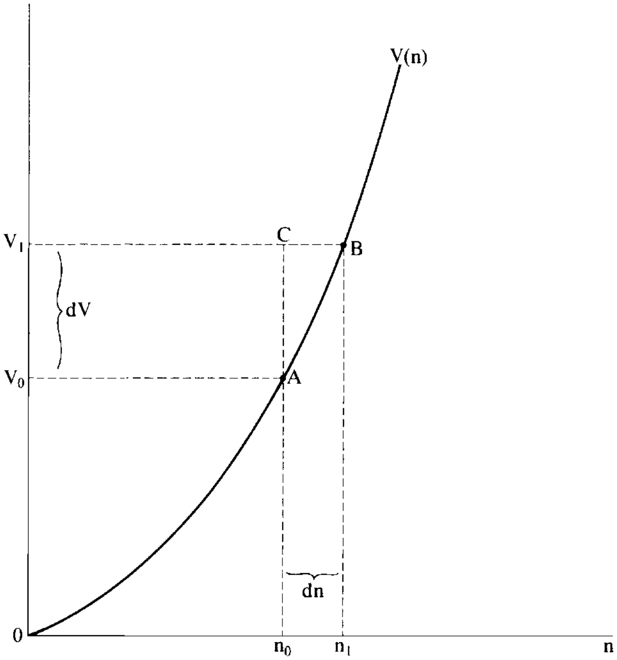

Fig. 2.3 The relation of unit cost for a capital good to its net revenue

good—its input prices and profit margin (C) and the level of technology built into the good (σ, λ). In this way, changes in the relative price of an operating input like energy are not treated as changes in the price of capital input.

The change in the input price index can be written in two equivalent ways:

$$\text{(2.28)} \qquad \frac{dP^i}{P^i} = \frac{dV - C_t c_x(x_n dn + x_s ds)}{V(n^*, C_0, s_0, \sigma_0, \lambda_0)}$$
$$= \frac{dC(c + C_t c_x x_C) + C_t(c_x x_\sigma d\sigma + c_\lambda d\lambda)}{V(n^*, C_0, s_0, \sigma_0, \lambda_0)} .$$

The extended model incorporating operating costs can be illustrated in figure 2.3, which repeats the vertical axis of figure 2.1 and replaces y on the horizontal axis by n. The upward-sloping schedule plots equation (2.26) and shows the increasing unit cost of input characteristics required to generate additional net revenue. The initial equilibrium position, where the quantity of output is chosen to make marginal net revenue equal to marginal cost, is shown at point A.

Consider first the proper treatment in price measurement of an improvement in quality that occurs when an equiproportionate increase in the prices P and S relative to C leads users to demand higher-quality capital goods.

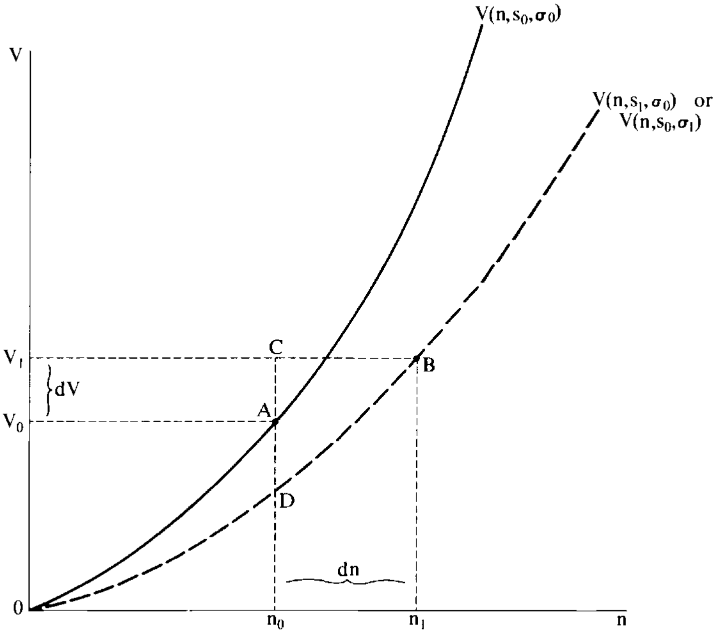

Fig. 2.4 Effect of a reduction in the real price of energy

Because the higher prices P and S shift the nominal marginal net revenue schedule upward, the equilibrium position shifts from A to B. If the manufacturer reports to the BLS that the entire addition to the price of the good from V_0 to V_1 is due to the higher cost (CA) of raising the specification of characteristics embodied in the good, the BLS would correctly conclude that there has been no price change. Note that the manufacturer's cost estimate does not represent simply the effect of higher performance holding constant operating cost, but rather the net extra cost of raising performance while allowing energy consumption to increase along the $e(x, \sigma)$ function. There is no danger that the substitution toward greater operating cost will be misinterpreted as a change in input price as long as the marginal cost (CA/CB) of the extra quantity of input characteristics is correctly measured.

Does the general formula (2.28) for the change in the input price index correctly conclude that there has been no price change? From the change in the cost of the durable good (CA) is to be subtracted the marginal cost (CA/CB) of the extra input characteristics required to raise real net revenue by the actual observed amount (CB). Thus, the observed change in input cost (CA) minus the correction factor (CA) equals zero.

A second case, a reduction in the relative price of energy, is illustrated in figure 2.4. A decrease in the price of energy from S_0 to S_1, while the product price is held constant at P_0, shifts the unit cost schedule rightward, since a smaller nominal operating cost must be deducted from gross revenue for any given quantity of the input characteristic, thus raising net revenue for any given value of *V*. The new equilibrium position is assumed to shift from point *A* to point *B*. The input price index subtracts from the observed change in price (*CA*) the marginal cost (*CD*/*CB*) of the extra input characteristics required to raise real net revenue by the observed amount (*CB*) adjusted for the effect on input cost ($+AD$) of lower real energy prices (ds) when real net revenue is constant. Once again, the observed change in input cost (*CA*) minus the correction factor ($-CD + AD$) equals zero.

As an example of this second case, note that lower relative gasoline prices in the 1950s and 1960s induced firms and consumers to shift to larger automobiles that consumed more fuel.[5] But if an automobile with given horsepower had maintained its previous fuel consumption along a fixed $e(x, \sigma)$ schedule, then no change would be imputed to the price of automobiles as a result of this substitution toward greater fuel consumption. The interesting research on automobiles by Wilcox (1984) describes energy efficiency as a function of performance characteristics and thus provides an estimate for that industry of the $e(x)$ function.

As a third example, let us consider a technological innovation that allows a given quantity of the input characteristic (x) to be used with a smaller consumption of fuel. To simplify the illustration in figure 2.4, it will be assumed that the shift takes the special form of reducing the marginal energy cost of a change in input quantity by the same amount as the decrease in the relative energy price examined in the previous two paragraphs:

$$s_0 e(x, \sigma_1) = s_1 e(x, \sigma_0). \tag{2.29}$$

The lower schedule in figure 2.4 is relabeled to correspond to the new, more efficient energy consumption schedule in which σ_1 replaces σ_0.

In this third case, as in the first two cases, the equilibrium position moves from point *A* to point *B*. But now the input price index registers a decline in price instead of no change in price. From the change in the unit cost of the input characteristic ($dV = CA$) is subtracted the marginal cost (*CD*/*CB*) of the extra input characteristics required to raise real net revenue by the actual observed amount (*CB*). Thus, the observed change in input cost (*CA*) minus the correction factor (*CD*) equals the change in the input price index ($-AD$).

2.9 Implementation of Operating Cost Adjustments

In each of the cases considered in the previous section, the observed change in unit cost of a durable good was adjusted for changes in net

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[5] During the two-decade period 1953–72, the nominal price of gasoline in the CPI increased 34 percent, compared to 56 percent for the all-items CPI, representing a reduction in the relative price of 14.4 percent.

revenue caused by a shift in either an exogenous price or a technological parameter. In each case, the adjustment involved determining the marginal cost of whatever extra quantity of input characteristics would have been required to yield the observed increase in net revenue in the absence of the observed parameter shift. The foregoing discussion implies that, in practice, price changes across different models of a durable good can be measured as the change in unit value relative to the change, if any, in net revenue. The main obstacle to implementation of this idea, as we shall see, is nonlinearity in the function relating unit value to net revenue.

The discussion of measurement can usefully be set in the context of a competitive firm that uses capital goods to produce net revenue. Its user cost of capital multiplies the unit price of a durable good (V) times the interest rate r (representing some combination of borrowing costs and the opportunity cost of the firm's own funds), plus a geometric depreciation rate δ that measures the rate of decay with the asset's age of the stream of services that it provides. The capital market is assumed to set only a single interest rate that each firm takes as given, and the capital gains component of user cost is ignored.[6]

Firms using the durable good are price takers in both input and output markets. They have no influence on the price of the durable assets they purchase (V), on the price of the output they produce (P), or on the price of operating inputs (S) or cost of ownership ($r + \delta$) they must pay. In addition, I assume that the operating efficiency parameter (σ) is fixed by a technical constraint. Firms simply choose the level of output that maximizes yearly profit (π), the difference between nominal net revenue and the user cost of capital:

$$(2.30)\quad \pi = N - (r + \delta)V = Py(x) - Se(x, \sigma) - (r + \delta)V(x).$$

The only choice variable in the simplified structure of (2.30) is the quantity of input characteristics (x). If all producers and users of the durable asset are identical, then there will be a single model produced that embodies enough of the durable input characteristic to equate its real marginal cost of production to the present value of its real marginal net revenue:

$$(2.31)\qquad v_x(x) = \frac{y_x(x) - se_x(x, \sigma)}{r + \delta} = \frac{n_x(x, s, \sigma)}{r + \delta},$$

where $v_x(x) = V_x(x)/P$. The fact that the market usually provides numerous varieties containing different quantities of input characteristics has been

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[6] The depreciation rate should depend both on the built-in durability characteristics of the good and on the user-chosen intensity of repair and maintenance services. In the simple version of the model considered here, with only a single composite operating cost characteristic, the depreciation rate is assumed to be fixed.

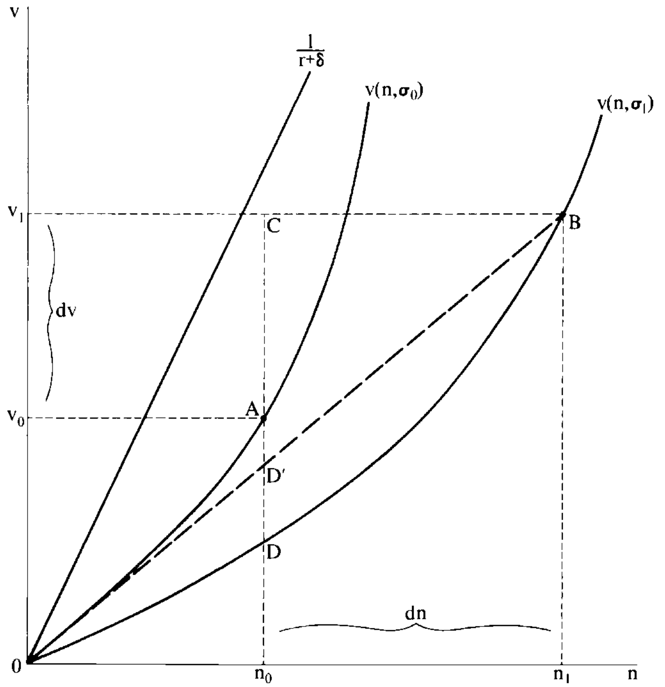

Fig. 2.5 Effect of improved operating efficiency on the real net unit cost function

explained by Rosen (1974) as resulting from the different tastes of consumers and technologies of producers.[7]

Figure 2.5 illustrates the equilibrium described in equation (2.30), with the real unit cost of durable goods on the vertical axis and real net revenue on the horizontal. As in figures 2.3 and 2.4, the purchase of additional input characteristics raises both unit cost (v) and net revenue (n), but the response of net revenue exhibits diminishing returns, both because of diminishing returns in the production function relating output to input characteristics, and because of the increasing marginal cost of producing input characteristics. When the technical level of operating efficiency is represented by σ_0, the initial equilibrium occurs at point A, where the $v(n, \sigma)$ function is tangent to a straight line having the slope $1/(r + \delta)$. The $v(\;)$ function also depends on C/P and x, but these parameters are held constant in the present discussion of adjusting capital input prices for changes in operating efficiency, $d\sigma$.

If the level of operating efficiency were to shift to the improved level represented by σ_1, the firm would move to a new equilibrium position at

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[7] For some qualifications, see Muellbauer (1974).

point B, where the new $v(n, \sigma)$ function again has the slope $1/(r + \delta)$.[8] The change in the input price index, as in figure 2.4, is the observed change in unit cost (dv = line segment CA) minus an adjustment factor equal to the observed change in net revenue ($dn = CB$) times the marginal cost of producing input characteristics capable of providing that amount of net revenue, the slope CD/CB. Although points A and B can be observed, and thus dv and dn can be measured, point D cannot be observed directly. How can the slope CD/CB be calculated in practice in order to compute the quality change adjustment factor AD?

As figure 2.5 illustrates, the problem of estimating point D arises because of the curvature of the $v(n, \sigma)$ function. If the function were a straight line, then the unobservable point D would coincide with point D', which lies along a ray from the origin to point B having the slope v_1/n_1. But as long as there are either diminishing returns in producing net revenue in response to an increase in the quantity of input characteristics or an increasing marginal cost of producing input characteristics, then the curvature of the function will always make point D' lie above point D, and will make the segment AD' an underestimate of the required quality adjustment, segment AD.

Since the exact form of the function is unobservable, and because data are unlikely to be available to estimate it in many cases, the estimation of the quality adjustment factor must inevitably be based on some assumption about the function. Consider, for instance, the particularly simple relation

$$v = \beta n^{\alpha}, \tag{2.32}$$

where the curvature of the function depends on the parameter α. Technological changes that alter the position of the function are represented by shifts in the β parameter.

To use this function in the estimation of changes in input price, first rewrite the basic formula (2.28) for a comparison in which the price of operating inputs (ds) is held constant:

$$\frac{dp^i}{p^i} = \frac{dv - v_n dn}{v_0}, \tag{2.33}$$

where the real unit cost (v) of the capital input replaces the nominal cost (V) appearing in (2.28), and the input price index is now expressed in real (p^i) rather than nominal (P^i) form, on the assumption that the output price can be held constant while comparing the new and old types of durable goods. Converting (2.33) from continuous to discrete changes, we obtain

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[8] Imagine that point B were to lie along an extension of the ray OA. Then the new level of net revenue per dollar of capital ($v_1B/0v_1$) would be the same as before ($v_0A/0v_0$). Since the percentage user cost per dollar of capital ($r + \delta$) is constant, the rate of return on capital would remain constant.

$$(2.34)\qquad \frac{\Delta p^i}{p^i} = \frac{\Delta v - [v(n_1, \sigma_1) - v(n_0, \sigma_1)]}{v(n_0, \sigma_0)} = \frac{v(n_0, \sigma_1)}{v(n_0, \sigma_0)} - 1.$$

When the assumed functional form (2.32) is substituted into the general formula (2.34), the resulting expression depends only on observable variables and the "curvature" parameter:

$$(2.35)\qquad \frac{\Delta p^i}{p^i} = \frac{\beta_1 n_0{}^{\alpha}}{\beta_0 n_0{}^{\alpha}} - 1 = \left[\frac{v_1 n_0}{v_0 n_1}\right]\left[\frac{n_0}{n_1}\right]^{\alpha - 1} - 1.$$

To make sense of the right-hand side of (2.34), imagine first that the $v(n, \sigma)$ function is linear, that is, that $\alpha = 1$, so that the second term in brackets becomes unity. Then the remaining expression states that the "real" price change will be zero if both unit cost and net revenue grow in proportion in the shift to the new model, $(v_1/v_0) = (n_1/n_0)$. This is the case of "resource-using" or "cost-increasing" quality change. A nonproportional quality change, as illustrated in figure 2.5, would raise net revenue relative to cost and would result in an estimated change in the "real" input price index that is less than the observed change in price of models that remain identical.

When the $v(n, \sigma)$ function is strictly convex, then $\alpha > 1$, and the second term in brackets in (2.35) becomes a fraction less than unity, corresponding in figure 2.5 to the fact that the unobservable point D lies below point D'. There seems to be no alternative in the estimation of equation (2.35) to making an arbitrary assumption about the value of the α parameter, or to presenting results for several alternative assumptions regarding the curvature of the $v(n, \sigma)$ function. To make the easy assumption that $\alpha = 1$ would be just as arbitrary as any other choice.

It is important to note that (2.35) is to be used to calculate a quality adjustment when comparing two different models, while holding constant output prices and the prices of operating inputs. Since this means in practice that the net revenue performance of two models must be compared in a particular year when both are in operation, equation (2.35) must be calculated in a way that holds constant any factors that change the cost of manufacturing a given model in the given year of comparison, that is, changes in profit margins and/or the prices of inputs into the manufacturing process. Thus, for practical measurement, equation (2.35), which computes the price change involved in the shift from one model to another, must be combined with an index of changes in the cost of producing identical models. Changes in the nominal input price index, then, are equal to changes in the real input price index plus changes in the cost of producing identical models:

(2.36)
$$\frac{\Delta P^i}{P^i} = \frac{\Delta p^i}{p^i} + \frac{\Delta C[C_t c_x(x^*)]}{C_0 c(x^*)} .$$

Thus, if there is a 10 percent annual increase in the price of identical models, and if all quality change is resource using as in figure 2.3, the quality change adjustment in equation (2.35) will be zero, and the nominal input-cost index in (2.36) will be recorded to increase at a 10 percent annual rate. But if the real quality change adjustment were minus 5 percent, then the increase in the nominal input-cost index would be reduced to a 5 percent annual rate.

2.10 Used Asset Prices and the Accuracy of Quality Adjustments

The above analysis was based on the assumption that firms maximize profits and hence are indifferent between two machines with the same purchase cost and depreciation rate that yield the same net revenue. One of these might have low performance with low operating costs, and the other might have high performance with high operating costs. A corollary to this assumption is that the market for used assets must incorporate the effects of changes in operating costs due to changes either in technological design or in energy prices. Although data on used assets are available for only a relatively small number of durable goods, notably transportation equipment, tractors, and other equipment that is not "bolted down," the study of used asset price data may serve as a useful cross-check on the accuracy of quality adjustments carried out on data for new products.

Let us compare two used assets selling at time t at prices A_{0t} and A_{1t}. The firm is indifferent between the two if they each offer the opportunity to earn the same rate of return, say ρ_t^*. The implications for the relation of used asset prices and net revenue can be seen if we take (2.30), substitute the price of the used asset (A_{it}) for the price of the new asset (V), and divide through by A_{it}:

(2.37)
$$\rho_t^* = \frac{\pi_{0t}}{A_{0t}} = \frac{N_{0t}}{A_{0t}} - (r + \delta),$$
$$\rho_t^* = \frac{\pi_{1t}}{A_{1t}} = \frac{N_{1t}}{A_{1t}} - (r + \delta).$$

Here, assume for convenience that the two assets are different models of the same product, and that the interest rate (r) and depreciation rate (δ) on the two alternative models are identical and constant. If so, then when the upper and lower lines in (2.37) are equated, we obtain:

(2.38)
$$\frac{A_{1t}}{A_{0t}} = \frac{N_{1t}}{N_{0t}} .$$

Given the restrictive assumptions of the previous paragraph, used asset prices of different models for the same product observed at a given moment should be observed to be proportional to their respective ability to earn net revenue. Substituting the definition of nominal net revenue used in the right-hand expression of (2.30), we can relate the ratio of used asset prices to the determinants of net revenue:

$$\frac{A_{1t}}{A_{0t}} = \frac{P_t y(x_1) - S_t e(x_1, \sigma_1)}{P_t y(x_0) - S_t e(x_0, \sigma_0)} = \frac{y(x_1) - s_t e(x_1, \sigma_1)}{y(x_0) - s_t e(x_0, \sigma_0)}. \tag{2.39}$$

Here, it is assumed that the output price (P_t) and energy price (S_t) applicable to the two models are identical and are functions only of time, whereas the performance characteristics (x) and operating efficiency factor (σ) of each model are embodied ex ante and do not change over time.

The expression (2.39), together with the set of assumptions required to derive it, summarize both the benefits and the pitfalls of utilizing used asset price data as a cross-check on quality adjustments for new products. The benefit is that used asset prices should reflect differences in operating efficiency, so that actual observations on used asset prices can be compared with a theoretical calculation of net revenue for the two models based on their ability to generate gross revenue and on their operating costs. A close similarity of the used asset price ratio with the theoretical price ratio would tend to confirm the methodology developed above to perform quality adjustments, and major differences would introduce an important note of caution and qualification.

There are, however, a number of pitfalls.

1. The used asset price comparison cannot shed light on the proper treatment of nonlinearity, discussed above in the context of figure 2.5. If model 1 yields real net revenue n_1 and has a used asset price shown by the vertical distance at B, then a model 0 that yields net revenue n_0 has a used asset price shown by the point D' that lies along the ray OB. Used asset prices can give no information on the unobservable point D, since users care only about net revenue and not about curvature in the production function.

2. Expression (2.37) is overly simplified by assuming that users care about profits only at time t. More realistically, they want to maximize the present value of profits over the expected lifetime of the assets, and correspondingly they care about expected future real energy prices, not just current energy prices. This creates two problems in practice. First, it suggests that quality adjustments for operating efficiency improvements must be based on expected future energy costs, not current energy costs in the year of manufacture. Second, it complicates the task of comparing used asset prices with theoretical calculations of net revenue, since the expected lifetime relevant for expected future energy prices will cover a different interval and

be of a different length for the used asset comparison than for the quality adjustment applied to new equipment.

3. Expressions (2.38) and (2.39) are derived on the assumption that both the more efficient and the less efficient models have the same depreciation rate, and that the depreciation rate is constant. In fact, the depreciation rate on the two models may be different and may (as in the case of gas-guzzling automobiles and commercial aircraft after the 1974 oil price shock) depend on the level of energy prices. A related problem is that the more and less efficient models observed in the used asset market may be of different vintages and may have different expected lifetimes.

Despite all these caveats, comparisons between used asset price ratios and theoretically calculated ratios are of great value, because of their potential for providing verification of the basic approach suggested above, and of the specific assumptions made in quality adjustments for individual products. The qualifications do not seem serious enough to warrant discarding used asset data but rather indicate that their interpretation should be performed with care.[9]

2.11 Interpretation of the Proposed Conceptual Framework

The first part of this chapter explored the concept of nonproportional quality change in performance characteristics, and section 2.6 related this approach to important papers in the previous literature. Sections 2.7 and 2.9 have covered less familiar ground, nonproportional quality change taking the form of changes in operating efficiency. Because there is no significant earlier literature on this topic, it is worthwhile to pause here to consider possible caveats to the proposed treatment.

Triplett (1983a) objects to the proposal in the previous sections that an increase in fuel efficiency calls for a quality adjustment to the prices of fuel-using durable goods. His discussion is framed in terms of a theoretical total input cost index:

> If a fuel-efficiency improvement occurs in the second period, then the cost of the collection of inputs necessary to produce a given level will fall by the decrease in expenditure on fuel. . . . No additional adjustment to the price of aircraft is necessary. . . . the cost of saving from an improvement in fuel efficiency occurs precisely from an adjustment in quantity of fuel required for a fixed amount of output. Therefore, in the total input cost index, adjusting the price of airplanes for fuel savings would double-count

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[9] Diewert (1989b, chap. 5) presents a useful summary of the theory of used asset prices in the context of the measurement of the user cost of capital. His discussion, however, does not treat the problem addressed here: the use of used asset prices to assess quality differences between new and old models.

> the effect of increased fuel efficiency, for that saving already shows up in decreased quantities of fuel purchased by airlines. [1983a, 260]

To consider the implications of Triplett's position, it is best to distinguish (as he does) between a fixed-weight Laspeyres index (L) and a theoretical or exact index number (I). We write L as

$$L = \frac{P_t^F X_0^F + P_t^K X_0^K}{P_0^F X_0^F + P_0^K X_0^K}. \tag{2.40}$$

Here, the superscript F refers to fuel, and K to capital. P is the price of each input, and X is its quantity. In the airline fuel efficiency example, where we assume a constant price of fuel, the Laspeyres input cost index would take the cost of fuel to be unchanged ($P_t^F X_0^F = P_0^F X_0^F$). Thus, the actual decline of input cost would not be reflected unless the price index of capital input (P_t^K) were to decline, as would be accomplished by the procedures suggested above. Triplett does not object to the proposed adjustments in the fixed-weight index case but cautions that "the theory provides no guidance. The theory of index numbers is a theory of the exact or theoretical index" (1983a, 262).

However, it appears that there is no case for objecting to the proposed treatment even for the theoretical input cost index. No double counting is involved. In Triplett's notation, the theoretical index (I) is the ratio of the minimum cost of acquiring inputs sufficient to produce a given output in the reference period relative to the comparison period:[10]

$$I = \frac{P_t^F X_t^F + P_t^K X_t^K}{P_0^F X_0^F + P_0^K X_0^K}. \tag{2.41}$$

The reduction of input cost comes in the reduced quantity of fuel, ($X_t^F < X_0^F$). However, the proposed adjustment to the price index of capital goods does not affect I in (2.41), simply because quantity is measured as nominal expenditure on capital divided by the proposed deflator. Adjustment of the capital goods deflator by any multiplicative constant, say $P_t^{K*} = \gamma P_t^K$, has no effect on the nominal magnitude entering (2.41). Since $X_t^K = P_t^K X_t^K / P_t^K$, it follows that

$$P_t^K X_t^K = P_t^{K*} X_t^{K*} = P_t^K (P_t^K X_t^K / P_t^K). \tag{2.42}$$

Thus the case for including energy efficiency adjustments to capital goods price indexes cannot be opposed on the grounds of double counting, since the "γ adjustment" makes no difference for the total input cost index. Since

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[10] The formula for I comes from eq. (4) in Triplett (1983b), and the formula for L comes from eq. (5).

it makes no difference, Triplett is correct that it is redundant, insofar as the creation of a total input cost index is the sole objective of price measurement. The justification for such adjustments must hinge on other objectives of price measurement, particularly the creation of deflators required to compute time series on real investment, real capital stock, and productivity in particular industries manufacturing durable goods.

Triplett's second major criticism is that the separability assumption written above in equation (2.21), $y = y[h, k(x, e)]$, while plausible, "does not permit forming an index of capital goods prices, independent of energy. . . . the theoretically appropriate subindex is an index for airplanes combined with fuel" (1983a, 261). Triplett is correct that the technology specification in (2.21) does not allow the measurement of real capital input or a price index for capital goods that is independent of the relative price of energy. The connection with that relative price is explicit in the discussion above, particularly in equation (2.39). There it is recognized that quality adjustments must be based on expected future energy costs, and alternative adjustments would be implied by alternative assumptions about the expected energy price regime.

This criticism, while valid, introduces the familiar debate between measures that are "imprecisely right" and those that are "precisely wrong." In the airplane example, it would be incorrect to treat as a price increase rather than a quality increase that portion of the higher sales price of a Boeing 767 relative to a Boeing 727 that can be attributed to improved fuel economy. It is correct in principle to construct the aircraft price index on the basis of an estimate of the value of the fuel savings, and a necessary evil that a range of such adjustments can be calculated on the basis of alternative assumptions about expected fuel prices. This imprecision does not represent a quantum jump from the types of imprecision that have been accepted for years, for example, in the use of hedonic price regressions as the basis for the official residential construction deflator, despite the fact that alternative indexes emerge from the use of different econometric specifications and techniques.

In preference to my approach, which involves introducing quality adjustments for energy efficiency changes into the price indexes for durable goods, Triplett would rather measure the input service price of durable goods as the flow price per unit of time of the combined costs of capital, fuel, and maintenance ("the BLS would be pricing the cost per mile of a constant quality automotive service" [1983a, 262]). This approach would be sensible if the only function of official price measurement were to deflate consumer expenditures on a flow of services. But it would leave us bereft of sensible deflators for the output of producer and consumer durables, and industry output measures that properly allocate productivity gains across industries.

Quality adjustments in durable goods deflators for efficiency changes are necessary for these supplementary purposes of price indexes, while yielding the same results as Triplett's preferred measure. First, in the case of a "proportional" quality change taking the form of an improvement in energy efficiency, neither the service price nor my durable goods price index would register any change. Consider a situation in which a change in relative prices leads a refrigerator producer to add the quality characteristic "energy efficiency" up to the point where its marginal cost equals its value in energy saving to the consumer. There will be no change in the service price of the new-model refrigerator compared to that of an old model in the new energy price regime, since the reduction in the annual value of energy consumption will offset the increase in the annual depreciation and interest cost of the higher-quality refrigerator. In exactly the same way, my own procedure would find that there had been an increase in net revenue measured at constant fuel prices that was proportional to the higher unit price of the equipment, and consequently no quality adjustment would be called for.

Second, consider a "nonproportional" innovation that cut annual expenditures on energy by $20 while increasing the annual capital cost of a refrigerator by only $10. Triplett's service price of refrigerators would register a decline, as would my price index for refrigerators based on a finding that net revenue had increased by more than equipment cost. Either measure of price would be adequate for a study of the demand for refrigerators in a period of constant energy prices and would be far preferable to an index that failed to register any decline in price. In the case of commercial aircraft, a demand study would be highly misleading if it used the official BEA price index.

Consider the following division of annual operating revenue: (*a*) labor cost, (*b*) fuel cost, (*c*) capital cost (interest plus depreciation), and (*d*) profit. Triplett's service price includes *b* plus *c*. A nonproportional improvement in energy efficiency by definition reduces *b* more than it raises *c*, thus reducing the service price. Our "net revenue" is *c* plus *d*. A nonproportional improvement in energy efficiency by my definition raises net revenue (*c* plus *d*) by more than capital cost (*c*) when calculated at fixed prices of output, labor, and fuel. Thus, both criteria give the same answer; the reduction in service price parallels the decline in the equipment price index that results from the method proposed here.

There is an important conceptual distinction between the service price approach and the proposed quality adjustments in durable goods deflators. Measures of service prices will pick up any factors that alter operating efficiency, whether achieved by equipment manufacturers or users. In contrast, my approach requires explicit attention to the distinction between ex ante and ex post improvements. Ideally, quality adjustments using my method should be based on engineering data provided by manufacturers or, as a second best, operating data gathered from a variety of users soon after the introduction of the durable good. Subsequent improvements achieved by users should not be credited to manufacturers.

The discussion of changes in operating efficiency has focused on changes in fuel efficiency. Yet other changes that affect operating costs are equally relevant, including changes in maintenance requirements and in durability achieved by manufacturers. It is likely to be harder to maintain the ex ante versus ex post distinction for maintenance and durability changes, since these are unlikely to be observed until several years after installation.

2.12 Summary and Conclusion

The primary emphasis in this chapter has been on devising methods to make quality adjustments in the computation of price indexes so as to "credit" manufacturers of durable goods for all changes in the quantity of final consumption goods and services that are caused by changes in the types and characteristics of "new vintage" durable goods. The methodology is devised to allow a parallel treatment of technological developments that reduce the cost of purchasing a given quantity of performance characteristics and those that reduce costs of operation, for example, fuel and maintenance.

"Nonproportional" quality changes are those that increase the value of a durable good (specifically, its ability to generate net revenue) relative to its purchase price. These can take the form of higher quantities of performance characteristics provided relative to purchase price, the "price-performance" ratio so often discussed in the example of computers. They can also take the form of improvements in operating efficiency that yield a greater increase in net revenue than in purchase price. Although the literature on quality change adjustments has frequently debated the merits of the "user-value" and "production-cost" criteria for the measurement of quality change, *both* criteria are used in the proposed adjustment procedure. User value is the criterion used to choose the attributes or quality characteristics of each product, whereas production cost is the estimator used to make the actual adjustment. A literature survey finds that much of the past debate has involved disagreements over the choice of attributes.

It is shown that input and output price index concepts give a consistent treatment to a given technological innovation. The only reason to distinguish between the concepts is in cases where manufacturers use resources to produce output characteristics that are not valued by users, for example, antipollution equipment purchased by users of durable goods only as the result of government mandate. In such cases, input and output price indexes can diverge, and explicit accounting is required, as is accomplished by the present procedures that break out the fraction of the capital stock consisting of antipollution equipment.

The last half of the chapter is devoted to quality adjustments for changes in operating efficiency. The basic approach is to estimate the ability of old and new models to generate net revenue ex ante, that is, when calculated with manufacturers' specifications and a constant set of prices for output and fuel input. If the prices of the two models differ in proportion to their ability to generate net revenue, then no quality adjustment is called for. But if net revenue increases relative to the price of the newer model, then a quality adjustment would be performed.

In addition to requiring quality adjustments in price indexes for durable goods, efficiency improvements in new models should also be reflected in relative prices observed in markets for used assets. The main difficulties in achieving actual measures of the recommended quality adjustments include their sensitivity to alternative assumptions about future energy prices and depreciation rates, and problems created by curvature in the production function of durable goods manufacture. Data on used asset prices, while interesting, cannot really resolve the basic ambiguities inherent in this type of measurement.

The quality adjustment procedures proposed in this chapter seem necessary to capture the higher level of net investment and the higher level of aggregate productivity resulting from energy-saving innovations, as well as to allocate correctly the credit for the innovations to the industry achieving them. In the study of commercial aircraft in chapter 4, this involves allocating the credit for improved operating efficiency to the airframe and aircraft engine industries rather than to the airline industry. The importance of a correct allocation is obvious for those who are attempting to trace the current U.S. productivity slowdown to changes in capital and R&D input in particular industries (Griliches 1980).