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I. Introduction

It is widely believed that quality characteristics embodied in commodities and services affect consumers' satisfactions and thus the structure of consumers' demands. To the extent that consumer prices indexes attempt to approximate "true" cost-of-living indexes, construction of CPI measures should incorporate quality changes over time into the price index formulae. The practical issue facing the government statistician therefore concerns how quality characteristics might best be incorporated into index number formulae, while the academic economist is likely to be most worried about how the resulting price index formulae relates to the modern theory of consumer demand. This paper focuses on issues of how and under what conditions quality adjustment can be accomplished in a way that is consistent with modern flexible functional form demand analysis.

At the outset, it is worth noting that the issue of quality adjustment in price index construction is an important one. In the late 1930's in the U.S., for example, public policy debates arose over whether General Motors should be required to vary its prices in order to stabilize production volumes and employment levels. As part of its contribution to this debate, in 1938 GM funded a study by A.T. Court of the Automobile Manufacturer's Association to assess the effects of auto price changes on the total volume of auto sales.[1] Court argued that "...Price indexes in gross error have been widely used as the basis for serious, official discussions of policy,"[2] and chastised both the auto manufacturers for failing to cooperate with and provide information to the U.S. Bureau of Labor Statistics,[3] and BLS officials for publishing new automobile price indexes that took no explicit account of changes in physical characteristics (apparently unlike the BLS

practices at that time for constructing price indexes of trucks and farm tractors).[4]

As a practical alternative method for constructing price indexes for goods with frequently changing characteristics and specifications based on "objective usefulness," Court proposed a technique by which, given historical data on auto models over time, price was regressed on time and the characteristics of models (in his case, horsepower, weight and wheelbase length). The coefficient on the time variable was then interpreted as the change in the price index, holding usefulness constant. Invoking utilitarian notions, Court called his procedure the hedonic technique, and summarized its purpose by stating that "...Hedonic price comparisons are those which recognize the potential contribution of any commodity, a motor car in this instance, to the welfare and happiness of its purchasers and the community."[5] He then noted that "...prices per vehicle divided by this index of Hedonic comfort would yield valid comparisons in the face of changing specifications."[6]

Incidentally, it is of interest to note that while the BLS official new car price index rose 45 percent over the 1925-35 time period, Court's proposed quality-adjusted new car price index dropped approximately 55 percent.[7] Not surprisingly, GM officials used these empirical findings along with other data in arguing that auto manufacturers had already been reducing quality-adjusted prices, and that any further price decreases designed to stabilize employment would likely lead the auto manufacturers to the "brink of insolvency," for the required break-even volume would be much larger than the price-induced increase in demand for new cars.[8]

This brief discussion makes clear that issues of quality adjustment in the construction of price indexes are important, and that for some time now, a

body of literature has existed--hedonic price analysis--that attempts to deal with the quality adjustment problem.[9]

Court's suggestions concerning hedonic price analysis received little attention for almost twenty years, and only in the late 1950's did interest in quality adjustment issues re-emerge.[10] Since 1960, however, a very large number of empirical hedonic studies has appeared in the literature, much of it dealing with quality adjustment for durable goods such as autos, houses, trucks, tractors, refrigerators and computers; these and other hedonic studies have been surveyed by Zvi Griliches [1971a].

A potentially related important development of the last fifteen years has been the introduction of "flexible" functional forms (e.g., the generalized Leontief, translog and generalized Box-Cox representations)[11] into empirical studies of commodity or input demand analysis. An attractive feature of these functional forms is that their flexibility has significantly facilitated empirical studies of substitution possibilities among commodities without requiring imposition of prior constraints on substitution elasticities. Moreover, W. Erwin Diewert [1976] has linked the specification of such flexible functional forms to the classic index number literature by demonstrating that there is an equivalence between choice of functional form and choice of index number formula. Hence recent developments in demand theory link the construction of price indexes to the estimation of parameters in demand equations.

Although a very large number of empirical studies of commodity and input demands based on flexible functional forms has been published within the last decade, it is noteworthy that this modern empirical demand analysis has virtually ignored the classic issues of quality adjustment. John Muellbauer, for example, has noted, "...It is a curious feature of the empirical

literature that apparently no one has integrated the hedonic approach into budget studies. Perhaps this is because the practitioners on the two sides have not realized they are speaking the same language."[12] In this paper, I attempt to provide a bridge between the empirical hedonic literature that addresses quality adjustment, and the empirical flexible functional form demand analysis literature that reports estimates of income and price elasticities. Clarification of such links will of course have important implications for empirical research and the construction of price indexes.

One possible way of treating various qualities of commodities is simply to classify them as distinct products. In principle, expansion in the number of commodities to a large number is permitted with flexible functional forms, but in practice such expansion is constrained by finite-sized data bases and the fact that the number of parameters to be estimated increases more rapidly than the number of commodities. Hence there appears to be a trade-off involving detailed specification of commodities and parsimony in parameterization.[13]

Researchers have attacked this trade-off problem in a number of ways. Some, like Giora Hanoch [1978], have urged that simpler and more restrictive functional forms be used, while others, such as Edward Hudson and Dale W. Jorgenson [1974], have partitioned the inputs into separable subsets, and then have estimated each subset separately.

An alternative approach involves attempting to deal with heterogeneous commodities by aggregating them into a single "quality adjusted" measure. For example, following a suggestion of Daniel McFadden [1978, p. 62], Richard H. Spady and Ann F. Friedlaender [1978] have specified a flexible cost function for the trucking industry having only a single output (ton-miles), but have allowed the "quality" of this output to be affected by environmental, network and behavioral variables such as average size of shipment, average load,

average length of haul, and percent of less-than-haul traffic. This reduction of potentially many outputs to a single quality-adjusted measure considerably reduces the number of free parameters to be estimated, and in a number of studies has yielded very satisfying results .[14]

Spady-Friedlaender do not address the issue of how quality adjustment would be done were their output a durable product rather than a flow variable (ton-miles), but their approach is clearly suggestive of novel procedures for quality-adjusting commodities, thereby incorporating additional detail yet not being encumbered with as large an increase in the number of free parameters to be estimated. For example, instead of treating numerous different "diet" and non-diet foods as distinct commodities in the estimation of demand elasticities among food and other commodities, one way of reducing the number of parameters to be estimated would be to develop a procedure by which these commodities could be aggregated into a single commodity called "food," but whose quality would be affected by such nutritional characteristics as, for example, serving size, percent fat, percent protein, caloric and sodium content. The demand estimation would then involve joint estimation of aggregate food and quality parameters. Provided that the number of quality attributes were less than the number of distinct food types, the total number of parameters to be estimated would be reduced. Such an approach has obvious advantages.

In this paper I will attempt to show how such quality adjustment can be incorporated into flexible functional form demand analysis, discuss how such an approach addresses the rich detail-parameter parsimony trade-off, and outline how the suggested procedures could be implemented into much rich new empirical research. Implications for index number construction will also be noted.

The plan of this paper is as follows. In Section II I introduce quality adjustment of non-durable commodities into demand analysis, and relate them to previous literature dealing with the simple and variable repackaging hypotheses. In Section III I extend the analysis to quality adjustment of durable goods, a non-trivial task since the distinction between stock (asset) and rental prices turns out to be an important one. In Section IV I discuss and briefly review hedonic price analysis, emphasizing there the importance of market structure to the interpretation of parameter estimates. Then in Section V I illustrate the potential significance of the synthesis of modern demand with hedonic price analysis by considering empirical implementation using the translog functional form. A number of potential applications are outlined. Finally, in Section VI I present brief concluding remarks.

II. Utility and Expenditure Functions with Quality-Adjusted Non-Durable Commodities

I begin by assuming the existence of a well-behaved continuous and twice-differentiable utility function F,

$$u = F(x;b) \tag{1}$$

relating the consumer's utility level u during a time period to a positive vector x of n commodity flow quantities utilized during the time period, $x = [x_1, x_2,\ldots,x_n]$, and a positive scalar index of quality b for each of the n commodities, $b = [b_1, b_2,\ldots,b_n]$. Let u be monotonically increasing in x and in b. Each scalar element of the vector b is in turn specified to be a function of relevant physical and/or economic

characteristics, e.g., the nutritional content of foods. Denoting these characteristics as z_i, $z_i = [z_{i1}, z_{i2},\ldots,z_{ik}]$, I specify the function

$$(2) \qquad b_i = h_i(z_i), \qquad i = 1,\ldots,n.$$

Note that according to (1), the relationship between u and x depends on the quality of the commodities b. Although initially I will focus here on nondurable commodities, in many cases x_i can be interpreted as the quantity service flow yielded by the stock of a durable good over a given time period; the corresponding price would of course be the rental rather than the asset (stock) price.

Suppose further that the consumer can purchase amounts of the n commodities at fixed positive prices p, $p = [p_1, p_2,\ldots, p_n]$, and that the consumer's "income" or expenditure on the n commodities is denoted by y

where $y = \sum_i p_i x_i$

Define the consumer's dual expenditure function H,

$$(3) \qquad c = H(u; p; b)$$

which indicates the minimum cost c of achieving utility level u given that the consumer faces fixed commodity prices p and commodity qualities b. Note that according to (3), the relationship among c, u and p depends on commodity quality b.

W. Erwin Diewart [1978] has pointed out that while discussions such as that above are couched in the language of consumer demand theory, by redefining y as output, and x, p and b as vectors of input quantity, price and quality, respectively, one can re-interpret the function F in (1) as the

primal production function and the function H in (3) as the dual producer cost function.[15] For most of this paper I will refer to (1) as the utility function and (3) as the expenditure function. It should be noted, however, that results are interpretable in either the utility or production function contexts; indeed, Diewert [1978] invokes a neutral terminology and simply calls (3) the cost function.

The introduction of the quality vector b into the primal (1) and dual function (3) is not new (see Muellbauer [1971b,1974a,b], Robert E. Hall [1968] and Lawrence J. Lau [1982]), but merits special attention. I begin with the special case where the vector b is restricted to $b = [1,1,\ldots,1,b_n]$, i.e. where quality changes affect only the n^{th} commodity, a case which has recently been considered by Lau [1982] in the context of production and cost functions. In this instance the primal function (1) reduces to

$$(4) \qquad u = F(x_1,x_2,\ldots,x_n,b_n)$$

where b_n is the quality index associated with the quantity x_n.
I now provide intuition on the interpretation of the quality index b_n.

Corresponding to each level of b_n, one may solve (4) to obtain the commodity (input) requirement function for x_n:

$$(5) \qquad x_n = f(u,x_1,x_2,\ldots,x_{n-1},b_n) \ .$$

According to (5), x_n is the minimum amount of the commodity (input) required to attain utility (output) level u, given x_1, x_2,...,x_{n-1}, and b_n.
Now compare the different required quantities of x_n corresponding to alternative quality levels b_{no} and b_{n1}:

$$(6) \qquad \frac{x_{n0}}{x_{n1}} = \frac{f(u,x_1,x_2,\ldots,x_{n-1},b_{n0})}{f(u,x_1,x_2,\ldots,x_{n-1},b_{n1})} \ .$$

As Lau has noted, x_{n0}/x_{n1} represents the conversion ratio between two different quality levels of the n^{th} commodity. Note that this conversion ratio in (6) generally depends on u and all of x. As will be seen shortly, specification of quality conversion factors in ratio form (7) has important implications for the multiplicative specification of commodity quality.

Suppose now that one wishes to obtain a quality-adjusted measure of x_n by writing x_{no} in terms of x_{n1}, that is to say, measure x_{no} in units of x_{n1} having quality level b_{n1}. The quantity of x_{no} in terms of its equivalent quantity in x_{n1} units is given by

$$(7) \qquad x^*_{n0} = \left[\frac{f(u,x_1,x_2,\ldots,x_{n-1},b_{n0})}{f(u,x_1,x_2,\ldots,x_{n-1},b_{n1})}\right] \cdot x_{n1} = B_{n0} \cdot x_{n1}$$

where

$$(8) \qquad B_{n0} = \left[\frac{f(u,x_1,x_2,\ldots,x_{n-1},b_{n0})}{f(u,x_1,x_2,\ldots,x_{n-1},b_{n1})}\right] .$$

Note that B_{n0} reflects relative values of b_{n0} and b_{n1}. Next consider the level of u* that could be attained with x^*_{no} units of x_n having quality level B_{n0}, given by

$$(9) \qquad u^* = F(x_1,x_2,\ldots,x^*_{n0},B_{n0}) \ ,$$

and compare this u* with

$$(10) \qquad u' = F(x_1,x_2,\ldots,x_{n1},b_{n1}) \ .$$

Lau [1982, p. 177] has shown that these two levels are precisely equal, i.e. $u^* = u'$. Thus, not only does one have a way of quality-adjusting a commodity (input) in terms of a standard unit that is consistent with demand theory, but these equivalent units can also be inserted into a utility (production) function defined in terms of the standard unit.

Essentially, the task served by the conversion ratios (6) and quality-adjustment (8) is to standardize the various qualities into a common unit of measurement. A non-trivial feature of this quality adjustment is that up to a factor of proportionality the various quality-rated x_n are constructed to be perfect substitutes for one another. Note, however, that the important proportionality factor B_n can vary with elements in the vector of characteristics z_n (see (7) and (2)) and need not be constant. Specifically, from (6) and (7), it is seen that the various types of (x_n,b_n) pairs are convertible into one another by the multiplication of a (not necessarily constant) scalar-valued function of the characteristics z_n. For example, in the context of a nondurable commodity such as energy, if heat values such as Btu's were used to aggregate or quality adjust different fuels, i.e. if $b_n = h(z_n)$ were a function only of Btu thermal conversion ratios, it would implicitly be assumed that up to a factor of proportionality (the heat rate proportions) there is perfect substitution among the fuels in consumption. Hence, the quality measure B_n can be viewed as an aggregate index of commodity quality based on the components z_n.

Any empirical implementation of this quality-quantity approach requires careful specification of the conversion function (8) -- the quality adjustment measures. The simplest case occurs when the conversion function is specified to be independent of u and $x_1,x_2,\ldots,x_{n-1}$, i.e. when the ratio x_{n0}/x_{n1} is independent of u, $x_1,\ldots,x_{n-1}$ for all u, $x_1,x_2,\ldots,x_{n-1}$, b_{n0} and b_n, and depends only on the characteristics

z_n. Lau [1982, p. 178] has shown that this occurs if and only if the derivatives of the logarithm of the commodity requirement function (5)

$$(11) \qquad \frac{\partial \ln f(u,x_1,x_2,\ldots,x_{n-1},b_n)}{\partial u} \quad , \quad \frac{\partial \ln f(u,x_1,x_2,\ldots,x_{n-1},b_n)}{\partial x_i}$$

are independent of b_n, which implies that the commodity requirement function for x_n must have the form

$$(12) \qquad x_n = f(u,x_1,x_2,\ldots,x_{n-1},b_n) = f(u,x_1,x_2,\ldots,x_{n-1},h_n(z_n)),$$

or equivalently, the utility (production) function must have the multiplicative commodity (input) augmentation form

$$(13) \qquad u = F[x_1,x_2,\ldots,x_{n-1},h_n(z_n)x_n] = F[x_1,x_2,\ldots,x_{n-1},b_n \cdot x_n).$$

Moreover, assuming expenditure (cost) minimization, in this case the dual expenditure (cost) function has the form (see Lau [1982, pp. 180-182]):

$$(14) \qquad \begin{aligned} C &= H[u,p_1,p_2,\ldots,p_{n-1},p_n/h_n(z_n)] \\ &= H[u,p_1,p_2,\ldots,p_{n-1},p_n/b_n]. \end{aligned}$$

If improvements in, say, the nutritional content of foods increase food quality b_n, then in (13) the quantity of quality-adjusted foods is augmented, while in (14) the quality-adjusted price of food is reduced. Note also that since the quality-adjusted quantity of food $x_n^* = b_n \cdot x_n$ and

the quality-adjusted price $p_n^* = p_n/b_n$, it follows that $p_n^* \cdot x_n^* = p_n \cdot x_n$, i.e., price times quantity is invariant to quality measurement.

As has been emphasized above, the conversion ratio has been specified to be independent of u and $x_1, x_2, \ldots, x_{n-1}$. In the theory of production, a classic example of this particular conversion function specification is the representation of constant exponential factor augmenting technical change. For example, Harrod-neutral factor augmenting technical change is typically represented by

$$L_t^* = L_t\, h_L(t) = L_t e^{\lambda_L (t-t_0)} \tag{15}$$

where labor in quality-adjusted or augmented units at time t is written as labor in base-period units, L_t, multiplied by an exponential function of time, where t_0 is the base-period point in time and λ_L is the constant rate of factor augmentation for labor. The corresponding dual representation for prices is

$$P_{Lt}^* = P_{Lt} e^{-\lambda_L (t-t_0)} \tag{16}$$

In such cases the conversion ratio $b_L = h_{L(t)}$ is a function only of time. Other specifications of this h_n function are also permissible. For example, in the case of labor input, h_n could be a function of age, sex, educational attainment and experience of the labor force; or, for capital equipment h_n could be a function of the vintage or horsepower capacity, provided of course that h_n always be independent of u and $x_1, \ldots, x_{n-1}$. Note, however, that the traditional Harrod-neutral specification of technical change is simply a special case of the quality adjustment framework presented here.

Following Franklin M. Fisher and Karl Shell [1968], John Muellbauer [1971b, 1972, 1974b, 1975a] has called this case when the conversion or quality aggregation function is independent of u and $x_1, x_2, \ldots, x_{n-1}$ the simple repackaging hypothesis; essentially, quality improvement here implies "more of the same". At the risk of confusing the nomenclature and for reasons that will soon become more obvious, I shall call this type of specification of quality conversion ratios input price-independent quality adjustment.

Having expressed quality adjustment in terms of multiplicative factor augmentation functions, I now relate the quality conversion specification to the widely-used hedonic price equations. Given the conversion functions in (7), (8) and (14), the prices of the different (x_n, b_n) commodities (inputs) must, under the assumption of cost minimization, be in proportion to their marginal utilities (productivities), i.e. the effective price per unit of the standardized quality x_n must be equalized at the margin, so that

$$\frac{p_{n0}}{b_{n0}} = \frac{p_{n1}}{b_{n1}} = p_n^* \tag{17}$$

where p_n^* is, at a given point in time, a "base price" constant reflecting the price of the standardized unit. Taking logarithms of (17), one obtains the familiar hedonic price equation relating quality-unadjusted prices to a vector of characteristics

$$\ln p_{n1} = \ln p_n^* + \ln b_{n1} , \tag{18}$$

which, from (2) becomes

$$\ln p_{n1} = \ln p_n^* + \ln h_{n1}(z_{n1}) . \tag{19}$$

Hence the hedonic price equation (19) corresponding to input price-independent quality adjustment converts the characteristics z_{n1} embodied in x_{n1} into "base price" or effective price units, which can then be inserted into the standardized quality cost function (14).

Suppose that in (19), the quality conversion function $\ln h_{n1}(z_{n1})$ took the log-log form

$$\ln h_{n1}(z_n) = \sum_{k=1}^{K} b_{nk} \ln z_{n1,k}$$

so that (19) could be rewritten as

$$\ln p_{n1} = \ln p_n^* + \sum_{k=1}^{K} b_{nk} \ln z_{n1,k} \tag{20}$$

where the b_{nk} are coefficients on the k^{th} characteristic of the n^{th} commodity. In the classic study by Waugh [1929], for example, prices of vegetables sold at Boston's Fanueil Hall area in the 1920's are related to characteristics such as stem length, coloring, stem diameter, etc. Coefficients on these vegetable characteristics are then interpreted as reflecting the shadow values of the characteristics; in this way vegetable prices are quality-adjusted.

In the context of durable goods, if, for example, a cross-section of rental price and characteristic data were available for a number of alternative models of a durable good such as refrigerators, trucks, or farm tractors, regression estimates of the coefficients b_{nk} could be interpreted as estimates of the shadow values or shadow prices of the characteristics used in converting quality variations into a standardized unit. Moreover, following Robert E. Hall [1971, p. 264], further interpretation of the entire hedonic price equation (20) can be obtained by expressing each of the $z_{n1,k}$

as ratios of the value of this characteristic in the model under consideration (here, model 1) to its value in, say, the j^{th} model, i.e.,

$$(21) \qquad z^*_{n1,k} = \frac{z_{n1,k}}{z_{nj,k}} , \qquad k=1,\ldots,K$$

for all models. This corresponds to B_{n0} in (8) being a relative augmentation index. If parameters in equation (20) were then estimated with the $z^*_{n1,k}$ replacing the $z_{n1,k}$ for all models, the intercept term $\ln p^*_n$ could be interpreted as the price index of the standardized j^{th} model; any other model embodying the same characteristics as that in the j^{th} model would have all $z^*_{nk} = 1$, therefore all $\ln z^*_{nk} = 0$, and hence would have the same effective price as the j^{th} model. Models embodying alternative characteristic combinations would of course have different effective or quality-adjusted price indexes relative to the standardized model.

In the previous paragraphs I have considered the case where the conversion ratio x_{n1}/x_{n0} or characteristic aggregation function is independent of u and $x_1,\ldots,x_{n-1}$.[16] It is desirable to relax this condition, since it is highly restrictive; for example, conversion ratios between two air conditioners with differing energy-efficiency ratios (EER's) but of the same size might well depend on the price of electricity, and such a case is not allowed when the conversion function is of the simple repackaging form, i.e. when the quality-adjustment conversion function (8) is price-independent. So let us now relax the previous assumption, and consider the case in which the conversion ratio for the n^{th} commodity is still independent of u but is a function of commodity level x_{n-1}, i.e. $b_n = h_n(x_{n-1},z_n)$. As will be seen, this has important implications.

Specifically, when the conversion function (8) is independent of u and $x_1, x_2, \ldots, x_{n-2}$, the commodity (input) requirement function must have the form (see Lau [1982], p. 182):

$$(22) \qquad x_n = f(u, x_1, x_2, \ldots x_{n-1}, b_n) = f(u, x_1, x_2, \ldots, x_{n-1}, h_n(z_n, x_{n-1}))$$

which implies that the conversion function is of the form

$$(23) \qquad \frac{x_{n0}}{x_{n1}} = \left[\frac{f(u, x_1, x_2, \ldots, x_{n-1}, b_{n0})}{f(u, x_1, x_2, \ldots, x_{n-1}, b_{n1})}\right] = \left[\frac{h_{no}(x_{n-1}, z_{n0})}{h_{n1}(x_{n-1}, z_{n1})}\right] ,$$

and that the corresponding utility (production) function can be written as

$$(24) \qquad u = F(x_1, x_2, \ldots, x_{n-1}, b_n \cdot x_n)$$

$$= F(x_1, x_2, \ldots, x_{n-1}, h_n(x_{n-1}, z_n) \cdot x_n) .$$

If two quantities of x_n, say x_{n0} and x_{n1}, are both consumed, then the cost minimization assumption requires that

$$(25) \qquad \frac{p_n(b_{n1})}{h_{n1}(x_{n-1}, z_{n1})} = \frac{p_n(b_{n0})}{h_{no}(x_{n-1}, z_{n0})} = p_n^*$$

which implies the generalized hedonic price equation

$$(26) \qquad \ln p_n(b_{n1}) = \ln p_n^* + \ln h_{n1}(x_{n-1}, z_{n1}) .$$

Notice that in (26), the hedonic price conversion function h_{n1} depends not only on the characteristics z_{n1}, but also on the quantity x_{n-1}.[17]

In the context of air conditioners, for example, quality-adjusted rental prices could be regressed on characteristics such as Btu output, noise level, and annual operating costs, where annual operating costs depend on the energy-efficiency ratio and the quantity of electricity consumed.

At this point it is worth noting that Lau [1982, p. 183] has shown that if one assumes cost minimization and specifies an expenditure (cost) function dual to the utility (production) function, the expediture (cost) function will be of the form

$$(27) \qquad C = H[u, p_1, p_2, \ldots, p_{n-1}, p_n / h_n'(p_{n-1}, z_n)]$$

However, in general unless C is homothetic,

$$(28) \qquad h_n'(p_{n-1}, z_n) \neq h_n(x_{n-1}, z_n) \ .$$

Hence, primal and dual conversion factors are not numerically equivalent unless the utility (production) function is homothetic (see Lau [1982], p. 183).

When two or more x_n are utilized at the same set of p_{n-1} as in (27), under cost minimization it must be the case that

$$(29) \qquad h_n'(p_{n-1}, z_n)\, p_n^* = p_n(b_n)$$

so that once more one has an hedonic price equation

$$(30) \qquad \ln p_n(b_n) = \ln p_n^* + \ln h_n(p_{n-1}, z_n)$$

which now depends not only on z_n, but also on p_{n-1}. Again, in the context of air conditioners, by (30) quality-unadjusted prices are regressed on a set of characteristics (Btu output, noise level, etc.) and annual operating costs which are of course a function of p_{n-1}--the price of electricity.

Generalizing slightly the analysis of Fisher-Shell [1968], John Muellbauer [1974b, p. 8] calls this specification of the conversion function the variable repackaging hypothesis.[18] In this more general context, the aggregation of characteristics into a scalar quality index depends on prices of certain commodities or inputs; hence I call it price-dependent quality adjustment.

Note that in the context of a durable such as used autos, price-dependent quality adjustment would permit quality adjustment of two autos to depend not only on their physical characteristics (e.g., horsepower, interior space, weight), but also on the price of fuels (such as gasoline and diesel fuel). This suggests that in any empirical analysis one could test the simple versus the variable repackaging hypothesis by suitable parameter restrictions using classical hypothesis testing procedures, just as others have done in testing for separability of production or cost functions. Such an exercise would however require careful distinction between rental and asset prices of durable goods. Hence I now turn to a discussion of capital stocks and capital service flows, or alternatively, capital asset (stock) prices and capital rental prices.

III. Quality Adjustment: Extension to Durable Commodities or Inputs

In the context of durable goods, it is of course the case that not only do there exist variations among different models of the same age or vintage with varying characteristics, but there also occur significant efficiency differentials among different ages or vintages of the same model. While both these differences can be viewed as variations in quality, the latter have

traditionally been termed deterioration differences, a convention I will follow here.

With durable goods, quality adjustment will standardize assets of different vintages and characteristic combinations into a common unit, i.e. quality adjustment will handle the issue of depreciation. The issue, of course, is what factors affect the quality conversion function. As will be seen, traditional measures based on constant and equal geometric depreciation rates correspond with a special case of the simple repackaging (price independent) hypothesis whereas, for example, energy price-induced economic depreciation of energy-inefficient used autos corresponds with the variable (price dependent) repackaging hypothesis.

Assume that the asset or stock price of the n^{th} capital good of vintage ϕ at time t is equal to the present value of its future services,

$$(31) \qquad q_{n,t,\phi} = \sum_{s=0}^{s=T_n-\phi} \left(\frac{1}{1+r}\right)^s V_{n,t+s,\phi+s}$$

where T_n is the lifetime of the asset, r is the rate of interest (assumed to remain constant over time), and $V_{n,t,\phi}$ is the value (i.e., price times quantity) at time t of the flow of services of the n^{th} capital good of vintage ϕ. Lifetimes and prices are assumed to be fixed and known with certainty.

This value can be decomposed into rental price and quantity flow components in a number of different ways. I begin with the simple repackaging (price independent) type of decomposition, analogous to (17) where $p_{n1} = p_n b_{n1}$ and the b_{n1} are independent of u and $x_1,\ldots,x_{n-1}$. In the present context, consistent with the simple repackaging hypothesis, one can specify fixed conversion ratios both between capital services from different ages of the same model, and

between capital services from different models of a given age, so that deterioration in capital services takes place independently of the year at which the good was produced and of the year in which services are used. Specifically, let the identity be

$$(32) \qquad V_{n,t,\phi} \equiv p_{n,t,\phi} \cdot x_{n,t,\phi} \equiv p^{*}_{n,t} \cdot d_{n,\phi} \cdot b_{n} \cdot x_{n}$$

where $p_{n,t,\phi}$ is the unit rental price of the n^{th} capital service of age ϕ at time t, $x_{n,t,\phi}$ is the number of units of capital services provided by the n^{th} capital good of vintage ϕ at time t, $p^{*}_{n,t}$ is the quality-adjusted, "base" price-index of the n^{th} capital good at time t, $d_{n,\phi}$ is the deterioration index of the services from good n with vintage ϕ relative to, say, age 0 (i.e., it takes the value of unity when the asset is new and declines thereafter), and b_{n} is the quality index of services from good n at age 0 (defined relative to the services of other new goods) reflecting the effects of embodied technical change. For this reason b_{n} is a function of k characteristics $z_{n1},\ldots,z_{nk}$. Also, x_{n} is the number of standardized units of capital services generated by the n^{th} capital good when it was new (i.e., aged zero). The product $d_{n,\phi} \cdot b_{n}$ therefore combines the influence of deterioration (the decline in efficiency as capital ages) and embodied technical progress (increasing quality of more recent vintages).

According to (32), considerable independence exists among the conversion factors $d_{n,\phi}$ and b_{n}. Specifically, deterioration depends on age but not time, and embodied technical change is independent not only of time or age, but also of u and $x_{1},\ldots,x_{n-1}$. Hence (32) represents a highly restrictive specification consistent with the simple repackaging hypothesis (price independent quality adjustment). Note that under the above assumptions, the

product $d_{n,\phi} \cdot b_n$ is a purely technical measure of the relative efficiency or quality of capital services, unaffected by other economic variables.[19] Moreover, in this specification the services of old and new capital goods are perfect substitutes up to a factor of proportionality, and under the assumption of cost-minimization the rental prices of alternative capital goods must stand in fixed proportions reflecting their relative efficiencies (see Robert E. Hall [1971, p. 243]).

A related aspect of (32), however, is that the factorization into the two components $d_{n,\phi}$ and b_n is not unique; this has been shown by Robert E. Hall [1968, 1971]. Essentially, growth in the product of the two indices can be identical yet can correspond to differing growth rates for each of the components; hence an identification problem is present, even in this restrictive simple repackaging (price independent quality adjustment) specification.

One way of eliminating the ambiguity is to adopt a normalization that sets the index of embodied technical change or service quality level equal to well-defined and empirically-based values for two different vintages at the same time t. For example, if the two models were identical except for vintage (i.e., $b_n^0 = b_n^1$, $x_n^0 = x_n^1$), then taking ratios of their rental prices in (32) would result in p_{nt}^* dropping out, leaving only the ratio $d_{n,\phi}^0$ to $d_{n,\phi}^1$. Since $d_{n,\phi}$ is normalized to unity when $\phi = 0$, taking these ratios would yield well-defined estimates of $d_{n,\phi}$. It is worth noting that for certain assets such as lawn mowers, refrigerators or air conditioners, production runs without model changes often occur for two or more years; in such cases use of the above procedure would generate clearly identified estimates of the deterioration parameters.

More generally, when different models and varying vintages are compared, Hall [1971] has suggested employing the hedonic technique to account for quality variations using the procedure described earlier (recall that when two models embodied identical characteristics, use of Hall's ratio procedure (21) ensures equal predicted stock quality indices b_n).

To move from value flows to asset prices, following Muellbauer [1974a] one can substitute (32) into (31) and obtain

$$(33) \qquad q_{n,t,\phi} = b_n \cdot p^*_{n,t} \cdot x_n \cdot \sum_{s=0}^{T_n-\phi} \left(\frac{1}{1+r}\right)^s d_{n,\phi+s} \cdot$$

A natural way of defining an index of depreciation for the n^{th} capital good (the decline in the price of older assets relative to newer ones, observed at the same point in time) is to take the ratio of the appropriately discounted expected stream of service values remaining for the lifetime of the asset to the similarly discounted expected stream of service values were it new, both evaluated at the same point in time:

$$(34) \qquad D_{n,\phi} = \frac{\sum_{s=0}^{T_n-\phi} \left(\frac{1}{1+r}\right)^s d_{n,\phi+s}}{\sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^s d_{n,s}}$$

Note that when $s = 0$, $D_{n,\phi} = 1$. Multiplying both sides of (34) by the right-side denominator and substituting into (33) yields

$$(35) \qquad q_{n,t,\phi} = p^*_{n,t} \cdot x_n \cdot b_n \sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^s d_{n,s} D_{n,\phi} \cdot$$

Since q represents the value product rather than unit price, now divide both sides of (35) by x_n and denote the resulting unit asset price as $u_{n,t,\emptyset}$, i.e.

$$(36) \quad u_{n,t,\emptyset} = \frac{q_{n,t,\emptyset}}{x_n} = p^*_{n,t} \cdot b_n \sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^s \cdot d_{n,s} \cdot D_{n,\emptyset}$$

$$= p^*_{n,t} \cdot b'_n \cdot D_{n,\emptyset}$$

where

$$(37) \quad b'_n = b_n \sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^s d_{n,s} \cdot$$

According to (36), the price of a capital good n of age $\emptyset$ at time t is the product of an efficiency-corrected or quality-adjusted rental price index $p^*_{n,t}$ which depends on the time in which the asset is observed, a depreciation index $D_{n,\emptyset}$ which varies only with the age of the asset (since both r and $\emptyset$ in (35) are assumed to be constant), and an asset or stock quality index b'_n that reflects both durability (the discounted time path of deterioration of the asset) and its quality when new, and which is independent of the year of observation.

The distinction between the <u>service</u> or <u>flow</u> quality-adjusted index b_n and the <u>stock</u> quality-adjusted index b'_n is important, particularly for the interpretation of intercept terms in hedonic price equations. For example, a slightly different grouping of terms in (36) yields an alternative interpretation.

Specifically, following Hall [1971], regroup (36) as follows:

$$(38) \quad u_{n,t,\phi} = p^{*}_{n,t} \sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^{s} d_{n,s} \; b_n \cdot D_{n,\phi}$$

$$= p^{*'}_{n,t} \cdot b_n \cdot D_{n,\phi}$$

Note that b_n appears in (38), while b'_n is in (36). Thus in (38), the first term in brackets ($p'_{n^*,t}$) is the efficiency-corrected stock price of the new n^{th} asset (rather than the rental price), the b_n term is now the service quality (rather than the stock quality), and the depreciation term $D_{n,\phi}$ remains as before. Muellbauer [1974a, pp. 13-14] has argued that if consumers are interested in the services yielded by stocks, then over a group of models in x_n the services should be perfect substitutes, implying that the rental (rather than asset) prices should be in strict fixed proportion to relative service efficiencies. By contrast, to the extent that deterioration time paths and expected lifetimes are different across models, stock prices will behave differently from rental prices, and stock prices may not be in fixed proportion to service efficiencies.

The assumption of proportionality of rental prices to service efficiencies is of course more appealing than the assumption of efficiency-proportionality of stock prices, especially since in utility, production, expenditure or cost functions one is usually interested in service quantity flows and prices, rather than stock quantities and stock prices. Note also that with the service price specifications, the quality concept of relevance is the stock notion b'_n (including both durability and quality when new) rather than the Hall's flow concept b_n. I shall return to this point later.

The hedonic price equations corresponding to (36) and (38) are, since $b_n = h_n(z_{n1}, z_{n2}, \ldots, z_{nk})$,

$$(39) \quad \ln u_{n,t,\phi} = \ln p^*_{n,t} + \ln h'_n(z_{n1}, z_{n2}, \ldots, z_{nk}) + \ln D_{n,\phi}$$

and

$$(40) \quad \ln u_{n,t,\phi} = \ln p^{*'}_{n,t} + \ln h_n(z_{n1}, z_{n2}, \ldots, z_{nk}) + \ln D_{n,\phi} ,$$

respectively. Intercept terms in (39) and (40) should be interpreted as quality-adjusted <u>service</u> prices in (39) or quality-adjusted <u>stock</u> prices in (40). Note also that in (36), the deterioration term $d_{n,s}$ appears in both the depreciation term $D_{n,\phi}$ and b'_n but not in $p^*_{n,t}$, while in (38) the $d_{n,s}$ term appears in $D_{n,\phi}$ and $p^{*'}_{n,t}$ but not in b_n. This implies that if deterioration rates $d_{n,s}$ were assumed to differ among alternate types of x_n (say, different models), consistency would require that in (39) model-specific effects (such as dummy variables) be incorporated in both $\ln D_{n\phi}$ and $\ln h'_n(z_{n1}, \ldots, z_{nk})$ -- but not necessarily in the rental price $\ln p^*_{n,t}$, while in (40) model effects should be incorporated both in $\ln D_{n,\phi}$ and the stock price $\ln p^{*'}_{n,t}$ -- but not necessarily in $\ln h_n(z_{n1}, \ldots, z_{nk})$.

Finally, it is worth noting that when deterioration is geometric at a constant rate of δ_n, the depreciation index $D_{n,\phi}$ also declines geometrically with vintage at the same rate, i.e.

$$(41) \quad D_{n,\phi} = (1 - \delta_n)^{\phi} .$$

(Recall that the depreciation index $D_{n,\emptyset}$ compares retained value proportions of assets identical in all respects except vintage at a given point in time, and not the decline in the value of the asset as it ages between two different points in time; this implies that the difference between $D_{n,\emptyset}$ and $D_{n,\emptyset+s}$ depends only on δ_n, and not on r.) Inserting (41) into (39) then yields the estimable hedonic price equation

$$(42) \quad \ln u_{n,t,\emptyset} = \ln p^{*}_{n,t} + \ln h'_n(z_{n1},\ldots,z_{nk}) + \ln (1 - \delta_n) \cdot \emptyset \ ,$$

an equation relating used asset price to characteristics and age. After adding an independently and identically normally distributed random disturbance term to an equation like (42), Muellbauer [1971a, 1974a] has estimated parameters employing data on prices of used capital goods (farm tractors) observed at different times, plus dummy variables for vintages, models, and time; Hall [1971] added to (42) physical characteristics of Ford and Chevrolet pickup truck models. Tests for the validity of the simple repackaging hypothesis were conducted by Muellbauer by testing whether interaction terms (e.g., model-time, depreciation-time) had estimated coefficients significantly different from zero.

It is worth noting here that the above analysis of durable good quality is based on the simple repackaging (price independent) quality aggregation hypothesis. Hence this framework would not be appropriate for analysis of interesting and important issues such as the determination of whether and to what extent fuel price increases have altered the economic depreciation patterns of various energy-using assets such as autos, refrigerators, or air conditioner models since 1970. To undertake such an analysis would require relaxing the simple repackaging hypothesis (price independent quality

adjustment), and then allowing the conversion ratio b_n' in (36) to depend on prices of other commodities such as gasoline or electicity. Moreover, and this could be very important empirically, since b_n' embodies a stock notion rather than a flow concept [see (37)], it would be necessary to specify that the energy cost variable in the conversion function b_n' reflect discounted lifetime (rather than remaining annual) fuel costs were it new.

Let us now briefly consider extension of this durable good framework to the more general variable repackaging (price independent quality adjustment) hypothesis type of depreciation, using the example of autos and fuel prices. Following the earlier analysis, denote the quantity of, say, gasoline fuel as x_{n-1}, and its price as p_{n-1}. Under the simple repackaging (price independent) hypothesis in (37),

$$(43) \qquad b_n' = h_n'(z_{n1}, z_{n2}, \ldots, z_{nk}) \sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^s d_{n,s}$$

where the $z_{n1}, z_{n2}, \ldots, z_{nk}$ are independent of u and commodity quantities $x_1, x_2, \ldots, x_{n-1}$ or commodity prices $p_1, p_2, \ldots, p_{n-1}$. Note that each of the characteristics in (43) is implicitly assumed to generate services that deteriorate over time at the same rate $d_{n,s}$ (although of course $d_{n,s}$ is permitted to vary with s unless constant geometric deterioration is assumed).

One empirically tractable generalization of (43) consistent with the variable repackaging (price dependent) hypothesis discussed earlier (see equations (22)-(30) above) is to specify that the b_n conversion or quality aggregation function depends not only on $z_{n1}, z_{n2}, \ldots, z_{nk}$, but also on x_{n-1} (or, equivalently, p_{n-1}). In such a case (43) becomes

$$(44) \qquad b_n' = h_n'(z_{n1}, z_{n2}, \ldots, z_{nk}, p_{n-1}) \sum_{s=0}^{T_n} \left(\frac{1}{1+r}\right)^s d_{n,s}$$

and the hedonic price equation (39) becomes

$$(45)\quad \ln u_{n,t,\phi} = \ln p^{*}_{n,t} + \ln h'_{n}(z_{n1}, z_{n2}, \ldots, z_{nk}, p_{n-1}) + \ln D_{n,\phi}$$

While it is again implicitly assumed in (44) that the adverse effects of fuel price increases deteriorate over vintages at the same rate as other characterisitcs, an additional feature of (44) and (45) is that the numerical values of p_{n-1} will vary over time for given models, unlike other engineering characteristics; hence in the variable repackaging input quality case b'_{n} is no longer necessarily constant over time. This is attractive, for it permits quality adjustment between "gas guzzlers" and "gas misers" to vary with the price of gasoline.

It is worthwhile noting, incidentally, that hedonic equations similar to (45) have recently been estimated using second-hand automobile market data by, among others, James Kahn [1982], George Daly and Thomas Mayor [1983] and Zvi Griliches and Makota Ohta [1983]. Their regression results suggest quite clearly that the more general price-dependent (variable repackaging) specification (45) is preferable to that of (39), for not only do automobile prices depend on engineering design and performance characteristics, but they also depend on the price of gasoline.

IV. On the Interpretation of Coefficients in Hedonic Price Equations

In the previous paragraphs I have related quality adjustment for durable and nondurable goods in demand analysis to the well-known hedonic price literature. I now briefly digress to consider conditions under which parameters from hedonic price equations can be interpreted unambiguously as reflecting demand (rather than cost or supply) conditions.

Suppose that for a particular durable or nondurable commodity there existed K detailed engineering, design, performance, or other "quality" characteristics. Denote measures of these k attributes as $z_1, z_2 \ldots, z_K$. Let each model n of vintage v embody a particular configuration of these characteristics. In the hedonic formulation the price of a durable good, u_{nv}, is decomposed into implicit (shadow) prices (denoted $c_1, c_2, \ldots, c_K$) corresponding with the quantity measures $z_1, z_2, \ldots, z_K$ of the attributes, i.e.

$$(46) \qquad u_{nv} = f(c_1, z_1, c_2, z_2, \ldots, c_K, z_K) \ .$$

Recall that under the variable repackaging (price dependent) quality aggregation hypothesis, the list of characteristics in (46) might include quantities (or prices) of commodities related to the engineering characteristics, e.g., fuel prices.

In order empirically to link hedonic price analysis with the modern flexible functional form demand analysis, in principle it is important that coefficients of the hedonic price equations (45) and (46) be properly interpreted as representing demand function parameters. In practice, problems of interpretation arise because in general both supply and demand functions exist for the good/characteristic combinations. Since the hedonic equation (45) or (46) is essentially a reduced form, the existence of varying imperfect market structures may make it impossible in general to retrieve unique structural estimates of demand or supply function parameters using hedonic regression equations based on observed market price, sales and characteristic data.[20]

If the supplying market were composed of identical and perfectly competitive firms and the production of attributes were characterized by constant returns to scale, then the parameters of (46) could be interpreted as representing the average and marginal costs of characteristics. In such cases prices would of course be supply-determined. As Sherwin Rosen [1974] has noted, however, product markets for durable goods are likely to involve non-identical firms selling slightly differentiated new products; others have noted that differentiated markets for durable goods often tend to be oligopolistic in nature.[21] Moreover, for successful new product innovations embodying a novel configuration of characteristic combinations, temporary monopoly profits may exist as rewards to innovation, thereby driving a wedge between marginal costs of production and market price.

On the other hand, if the supply curves of the slightly differentiated products or models (each embodying alternative combinations of characteristics) were perfectly inelastic, then the market demand and supply curves would intersect at different levels for each model (characteristic combination). In such a case the structure of prices would be demand-determined, and the difference in levels among models could be interpreted unambiguously as providing implicit measures of consumers' evaluations of the characteristic combinations, i.e., as well-identified estimates of demand function parameters.

When, however, supply is neither perfectly elastic nor perfectly inelastic, prices are jointly determined by supply and demand. In such cases special care and additional assumptions must be made in order to extract from reduced form hedonic price equations identifiable parameters of the underlying cost and demand functions. The most obvious alternative approach is to estimate jointly structural supply and demand functions, where the supply

function is based on a multi-attribute or multi-product cost function and the demand functions also incorporate these characteristics. Often, however, the required data are not available.

The identification issue in a reduced form hedonic equation was addressed in an important paper by Sherwin Rosen [1974], wherein he proposed a two-step instrumental variable procedure. Recently James N. Brown and Harvey S. Rosen [1982] have qualified some of Rosen's results, suggesting that identification of cost and demand function parameters for new products is not always possible with Rosen's two-step instrumental variable estimator.

While all these authors deal extensively with interpretation of hedonic regression parameters based on new product data, none appear explicitly to have considered the possibility of incorporating into the analysis the fact that second-hand, leasing or rental markets provide additional economic information that can facilitate identification of structural demand or cost function parameters.

Used or secondary markets are of considerable relevance, since supply is almost perfectly inelastic. Once a production run of a particular new car, truck, tractor, or other equipment model is made and sold, durability of the equipment implies that unless it is scrapped, its total quantity is fixed. Each year the owner can be envisaged as making a choice between renting the asset to himself or renting it to someone else. To the extent that scrapping is not empirically significant (which empirically is the case for autos up to about eight years and for farm tractors up to about twelve years), empirical analysis of used asset markets provides reasonably reliable estimates of demand function parameters, for supply is essentially perfectly inelastic.[22]

One other cautionary note in this context involves allowance for interactions between new and used markets. Often a particular piece of equipment

in the used market is considered in isolation from the new market. In such a case an outward shift in the demand curve for, say, used fuel-efficient models is viewed as having no immediate effect in the new market, in spite of the price signal generated by rising relative prices of fuel-efficient used models. If, however, new and used models were at least partial substitutes and if the supply of new fuel-efficient models were rapidly responsive to relative price signals generated in the used market, analysis confined to the used market would no longer contain information only on demand, i.e., used model prices would again be determined jointly by supply and demand. However, such jointness would require rapid responses by durable goods manufacturers, which is somewhat unlikely due to the long lead times often required to introduce new models.

It is clear, therefore, that market structure affects the interpretation of hedonic price equations in a very important manner. Identification of cost or demand function parameters may be difficult even when Rosen's two-step instrumental variable estimator is employed. However, identification of demand parameters can be facilitated when data on used or second-hand markets are exhibited, since in those cases supply may be inelastic and prices will reflect only demand parameters. Note also that if data on used markets are available at different points in time (say, a pooled cross-section, time series data set providing the history of used prices for various models), one could employ the hedonic technique to test whether consumers' preferences and evaluations have changed over time.

A final issue in interpretation of hedonic price equation coefficients concerns the choice of functional form. As noted in the Introduction, it is useful to view hedonic regressions as generating a "quality-adjusted" price index for durable or non-durable goods, which implies that the theoretical

foundations of the hedonic technique should be closely related to the economic theory of index numbers and the "true cost of living indexes". Indeed, the hedonic equations can be viewed as aggregating component characteristics and prices into an aggregate scalar index of quality. In turn, since the theory of index numbers is closely intertwined with the theory of cost, production and utility,[23] it follows that economic theory might imply certain restrictions on the functional form of the hedonic regression equation.

In a series of papers, John Muellbauer [1971a,b; 1972; 1974 a,b; 1975 a,b] has shown that in fact economic theory does place testable parametric restrictions on the functional form of hedonic regression equations when such equations are interpreted as providing input quality-adjusted price indexes. For example, in Muellbauer [1974b] it is shown that a logical contradition occurs when one assumes a semi-logarithmic relationship between prices and characteristics and then also allows the parameters in the relationship to vary from year to year.[24] Also, the hedonic price equation should be homogeneous of degree one in prices of its components. Another problem with the semi-logarithmic form is that with it the identity between value and the multiplicative product of prices and quantities may not be globally preserved. Note, however, that in general it is not required that the hedonic price equation be homogeneous of degree one in the quantities of its components. Thus on the basis of economic theory, either linear-linear, linear-quadratic, log-log linear, or log-log quadratic functional forms are preferable to the semi-logarithmic representation of log price on a linear function of the characteristics, although choice among the set of preferable forms on the basis of theory is not yet clear.

In the previous paragraphs I have digressed briefly to review recent literature on the interpretation of coefficients in hedonic regression

equations, and have emphasized the role of economic theory and second-hand markets in facilitating identification of demand function parameters. I now proceed to illustrate a number of ways in which the hedonic technique can be incorporated into modern flexible functional form empirical demand analysis and price index construction, providing both richness in characteristic detail yet parsimony in parameterization.

V. Towards Empirical Implementation

Earlier I developed an intuition as to what precisely is meant by the term "quality," and how quality aspects for nondurable and durable goods relate to the modern theory of commodity or input demand. In this section I turn to outlining possibilities for implementing empirical research on quality-quantity demand models.

At the outset, it is useful to emphasize again the structural framework that has been developed concerning interpretation of hedonic price equations. Specifically, in this paper I have been concerned primarily with the interpretation of an hedonic equation within the theory of demand; supply and general equilibrium aspects have not been addressed in a detailed manner. The specification of an hedonic price equation has been shown to be equivalent to the specification of quality conversion functions for commodities or inputs. In turn, these quality conversion functions have been specified to be either price-independent (corresponding to the simple repackaging hypothesis) or price-dependent (the variable repackaging hypothesis).

In the case of price-independent quality conversion, the implied hedonic price equation is of the familiar form of quality unadjusted price as a function of characteristics and attributes; the intercept term in such an equation represents price per standardized or quality-adjusted unit. Note

that such a structural equation is of the same form as the numerous "reduced form" hedonic equations surveyed by, for example, Zvi Griliches [1971a,b].

By contrast, when quality conversion is price-dependent, the implied hedonic price equation consistent with this theory of demand relates quality unadjusted price not only to characteristics or attributes, but also to the price (or quantity) of another commodity or input. Hence price is a regressor in this structural hedonic demand equation. Griliches [1971a, p.5] has expressed considerable reservations about having market-determined prices or quantities as regressors in an hedonic price equation, but his vantage is clearly one of reduced form rather than structural analysis.

It is worth noting once again that within the last two years a number of hedonic studies have appeared in the empirical literature with prices as regressors; see, for example, the used auto studies by Kahn [1982], Daly-Mayor [1983] and Griliches-Ohta [1983]. One important empirical implication of this paper is that such structural hedonic equations have a clear and interesting interpretation, for in effect they provide parameter estimates of price-dependent quality conversion equations consistent with the theory of demand.

A second important empirical implication emerging from the previous sections concerns the interpretation of intercept terms in hedonic equations for durable goods. As has been noted earlier by Muellbauer [1974a], if one believes that durable good services rather than durable good stocks are perfect substitutes, then rental rather than asset prices should be proportional to service efficiencies. This implies both that the relevant quality concept is the stock notion b_n' (see (37)) rather than flow concept b_n and that the intercept term refers to the quality-adjusted rental rather than asset price. The discussion to this point has concerned itself primarily

with the interpretation of parameters in structural single-equation hedonic price equations. A more significant empirical implication of the approach presented above, however, concerns the joint efficient estimation of structural demand parameters and quality conversion coefficients in systems of demand equations with testable cross-equation parametric constraints.

To see this, assume the utility function is of the form where only the n^{th} commodity is quality adjusted, i.e.

$$u = F(x_1, x_2, \ldots, x_{n-1}, x_n^*) \quad . \tag{47}$$

and where the budget constraint is $y = \sum_{i=1}^{n-1} p_i \cdot x_i + p_n^* \cdot x_n^*$.

Define the indirect utility function as

$$v = G(p_1, p_2, \ldots, p_{n-1}, p_n^*, y) \quad , \tag{48}$$

where v is the maximum attainable level of utility given the budget constraint y and input prices $p_1, p_2, \ldots, p_n^*$. Denote the normalized prices as P,

$$\begin{aligned} P &= [p_1/y, p_2/y, \ldots, p_{n-1}/y, p_n^*/y] \\ &= [P_1, P_2, \ldots, P_{n-1}, P_n^*] \quad . \end{aligned} \tag{49}$$

Now let the indirect utility function (48) be of the translog form,[25]

$$\ln v = \alpha_0 + \sum_{i=1}^{n^*} \alpha_i \ln P_i + \frac{1}{2} \sum_{j=1}^{n^*} \beta_{ij} \ln P_i \ln P_j \tag{50}$$

where $\beta_{ij} = \beta_{ji}$.

Now specify the quality-adjusted price P_n^* as P_n/b_n, where $P_n=p_n/y$ and $b_n=h_n(z_n)$. Initially, assume that the vector $z_n=[z_{n1},a_{n2},\ldots,z_{nk}]$ contains only characteristics, and no prices or quantities of other commodities; this is consistent with price-independent quality adjustment (in Muellbauer's terminology, the simple repackaging hypothesis). Moreover, in order to be compatible with the logarithmic translog form, next specify that the hedonic price equation be of the log-log form,

$$\ln P_n = \ln P_n^* + \sum_{k=1}^{K} b_{nk} \ln z_{nk} \tag{51}$$

which of course implies

$$\ln P_n^* = \ln P_n - \sum_{k=1}^{K} b_{nk} \ln z_{nk} \tag{52}$$

Now subsitute (52) into (50), and then use Roy's [1943] identity in logarithmic form,

$$\frac{p_i x_i}{y} = \frac{-\partial \ln v}{\partial \ln P_i} \Big/ \frac{\partial \ln v}{\partial \ln y} \quad , \qquad i=1,\ldots n \tag{53}$$

to obtain the optimal budget shares which, after substitution of (52) yields

$$\frac{p_i x_i}{y} = \frac{\alpha_i + \sum_{j=1}^{n^*} \beta_{ij} \ln P_j}{\sum_{j=1}^{n^*} \alpha_j + \sum_{j=1}^{n^*} \sum_{i=1}^{n^*} \beta_{ij} \ln P_i \ln P_j} \quad , \quad i=1,\ldots,n \tag{54}$$

In order that the budget share equations (54) be homogenous of degree zero in the parameters, I adopt the normalization that

$$\sum_{i=1}^{n^*} \alpha_j = -1 \ .$$

Note that when (52) is substituted back into (54), the budget share equations depend not only on the normalized prices P_i, $i=1,\ldots,n$, but also on the characteristics z_{nk}, $k=1,\ldots,K$; moreover, there are testable cross-equation restrictions on the hedonic parameters b_{nk}, which appear in

each of the share equations. Hence when the structural hedonic price (quality-quantity adjustment) framework is integrated with the modern theory of demand, characteristics enter the system of budget share equations with testable cross-equation restraints.

Although these cross-equation constraints are present in rather general formulations, they also occur under more restrictive conditions. Consider, for example, the case when homotheticity (unitary income or expenditure elasticities) is imposed on the translog indirect utility function; this implies the parametric restrictions

$$(55) \qquad \sum_{j=1}^{n^*} \beta_{ij} = 0, \qquad i=1,2,\ldots,n^* .$$

When these homotheticity restrictions are substituted into the budget share equations (54), one obtains the simpler system,

$$(56) \quad \frac{p_i x_i}{y} = -\alpha_i - \sum_{j=1}^{n-1} \beta_{ij} \ln P_j - \beta_{in^*} (\ln P_n - \sum_{k=1}^{K} b_{nk} \ln z_{nk}), \quad i=1,\ldots,n.$$

which makes more clear the presence of characteristics and b_{nk} in each of the share equations, i.e. the existence of testable cross-equation parameter restrictions. Note that when used with, for example, time series data on P_i and z_n, econometric estimation of the structural (β_{ij}, α_i) and hedonic (b_{nk}) parameters.[26] This demonstrates that modern flexible form demand analysis can be integrated with hedonic price analysis in an empirically implementable form with testable cross-equation parameter restrictions.

Suppose, for example, that the n^{th} commodity were food, and that the z_n vector consisted of a set of nutritional variables such as fat, protein, vitamin, sodium, and caloric content. In such a case, these food nutritional

variables would appear in each of the estimable equations with cross-equation constraints. The null hypothesis that "quality" (nutritional content) does not matter would correspond with the joint null hypothesis that $b_{nk}=0$, $k=1,\ldots,k$. Hence such an equation system would reflect two basic premises: (i) if quality is important, it should be evident in quantity or share equations; and (ii) economic theory imposes testable parametric restrictions on the way in which quality enters these quantity or share equations.

The above example of empirical implementation of the quality-quantity demand framework was based on the assumption that the quality adjustment function was price-independent. I now briefly outline generalization to price-dependent quality adjustment.

Suppose, for example, that the n^{th} commodity in the utility function (47) referred to the net services of air conditioners. However, since the net services obtained from a durable good such as air conditioners depend on operating costs such as the costs of electricity, it is reasonable to specify that conversion ratios among air conditioners having differing energy-efficiency ratios (EER's) depend on the price of electricity, and thus that the rental price of air conditioners in the corresponding hedonic price equation be a function both of the characteristic EER and the price of electricity. This corresponds to the case of price-dependent quality adjustment.

Given data on the distribution and levels of air conditioners with differing EER's, assúmptions concerning the constant geometric rate of deterioration δ, the discount rate r and the price of electricity P_{Elec}, one could use (44) to specify a present-valued operating cost variable for air conditioners as

$$(57) \qquad OC = g(P_{Elec}, r, \delta, EER)$$

and then specify an hedonic equation of the form

$$\ln P_n = \ln P_n^* + b_{n0} \ln OC. \tag{58}$$

Solving for $\ln P_n^*$,

$$\ln P_n^* = \ln P_n - b_{n0} \ln OC, \tag{59}$$

one could substitute back into the indirect utility function (50), employ Roy's identity, and then obtain budget share equations for electricity, the services of air conditioners, and all other commodities, each as a function of total expenditure, commodity prices and OC. Again, the parameter b_{n0} would appear in each of the share equations implying testable cross-equation constraints; moreover, whether quality mattered could be tested simply as whether b_{n0} was statistically different from zero.

The above examples illustrate the empirical research potential made possible by the integration of modern demand analysis with hedonic price analysis. This integration also has clear implications for index number construction, provided of course that the resulting index number be interpreted within the context of economic "true" cost of living indexes.[27] As an example, one could incorporate into the price index of meat studies by Christensen-Manser [1976, 1977] a number of nutritional variables; the resulting conditional price indexes for meat (holding u fixed) would then depend explicitly on structural substitution parameters of demand for meat and on the hedonic coefficients of the nutritional variables.

VI. Concluding Remarks

It has been the purpose of this paper to present and discuss a theoretical framework through which durable and nondurable commodities can be quality-adjusted through the integration of hedonic price analysis with modern flexible functional form demand analysis, and quality adjustment thereby be related to the economic theory of index numbers.

The examples presented in this paper have been drawn primarily from the theory of consumer demand. As was noted in Section II, however, this framework is easily transferable to the analysis of producer costs and production. Potential empirical applications of this framework to the factor demand, productivity, and multiple output context have been outlined in Section V of Berndt [1983a]; Berndt [1983b] provides empirical implementation based on the price-independent quality adjustment hypothesis for U.S. manufacturing, 1958-77. It might also be noted that classic empirical studies of production behavior in the U.S. can now be re-interpreted within the integrated hedonic-structural demand approach of this paper; see, for example, Griliches [1970] on the quality of labor as a function of educational attainment.

A number of analytical extensions are also suggested by this research. For example, although this paper has employed the assumption of static optimization, recent work on dynamic factor demand models[28] suggests that generalization to dynamic optimization is feasible and empirically implementable. Specifications of expectations formation, however, will naturally affect the way in which capital quality, quantity, and rental price should be measured. Research on this topic is clearly important.

Another area for fruitful research concerns aggregation over consumers rather than commodities. Specifically, in much recent consumer budget research, individual family units of varying demographic composition have been

re-weighted using family equivalence scales; see, for example, Angus Deaton and John Muellbauer [1980]. The relationship between family equivalence scaling and quality adjustment is not yet clear, and deserves careful attention. If these two notions could be combined, it might be possible to generate quality-adjusted price indexes for various demographic groups as a function of the distribution of expenditures, characteristics, and demographic variables.

Finally, with respect to recent developments in the economic theory of index numbers (see, for example, Diewert [1976, 1981], Pollak [1982] and Triplett [1983]), the framework adopted here involves aggregation of characteristics into a scalar quality measure and thus places separability-type restrictions on the structure of utility functions. These separability restrictions need to be examined more carefully, along with their implications for the construction of index numbers. For example, the price-independent quality adjustment specification could be viewed as placing greater separability restrictions on the functional structure than does price-dependent quality adjustment.[29]

Issues of quality adjustment via hedonic price analysis have a long and distinguished history in the literature on index number construction. In recent years the modern theory of consumer demand has been linked with the economic theory of index numbers. In this paper I have attempted to contribute to both these areas by integrating hedonic price analysis with modern flexible functional form demand analysis. Since the resulting specifications incorporate characteristic data yet still remain relatively parsimonious in parameterization, the potential for new empirical research based on this integration is rich and exciting.

Footnotes

1. S.L. Horner [1939], p. 5.

2. A.T. Court [1939], p. 116.

3. Ibid., footnote 3, p. 101.

4. Ibid., pp. 101-103.

5. Ibid., p. 107.

6. Ibid.

7. Ibid., pp. 101-103, 112. It is not always the case, however, that quality-adjustment reduces the rate of growth of the price index; see M.L. Burstein [1961] and Jack Triplett [1971a,b].

8. See, for example, S.M. Du Brul [1939], pp. 126-130.

9. For an earlier attempt at quality adjustment using regression techniques, see the study on vegetable prices and quality by F.V. Waugh [1929].

10. See, for example, W.M. Gorman [1956] and Richard Stone [1956].

11. See W. Erwin Diewert [1971], Laurits R. Christensen, Dale W. Jorgenson and Lawrence J. Lau [1971], and Ernst R. Berndt and Mohammed S. Khaled [1979]. For a history and brief survey of earlier contributions, see Barry C. Field and Ernst R. Berndt [1981].

12. John Muellbauer [1975b], p. 282. For a theoretical attempt to "rationalize" hedonic equations in the context of new goods, see W. Erwin Diewert [1980], pp. 503-505; also, on the production side, see Makota Ohta [1975].

13. For a discussion of such specification issues, see Melvyn Fuss, Daniel McFadden and Yair Mundlak [1978].

14. See Elizabeth E. Bailey and Ann F. Friedlaender [1982] for a brief survey of econometric studies estimating economies of scale and economies of scope in multi-product firms, including quality adjustment. Also see Richard H. Spady [1979], Ann F. Friedlaender and Richard H. Spady [1981], J.S. Wang Chiang [1981], and J.S. Wang Chiang and Ann F. Friedlaender [1982]. In the context of telecommunications, see Michael Denny et al. [1981a,b].

15. Diewert's presentation does not introduce b explicitly, but these dual relationships are compatible with it. See McFadden [1978].

16. For a discussion of the simple repackaging hypothesis in the context of n (rather than just one) commodities, see John Muellbauer [1974a; 1975a].

17. This treatment of hedonics within an explicit theory of production provides an effective counterexample to the concerns of including market-determined quantities in an hedonic price equation voiced by, in particular, Zvi Griliches [1971a, p.5].

18. In yet a different version of the variable repackaging hypothesis, Muellbauer specifies b_n to be independent of y and $x_1, x_2, \ldots, x_{n-1}$, but dependent on x_n. Under constant returns to scale, however, in this case the simple and variable repackaging hypotheses coincide; see Muellbauer [1975a], fn. 6, p. 42.

19. For a discussion of these assumptions, see Dale W. Jorgenson [1974] and Martin S. Feldstein and Michael Rothschild [1974]. Note also that it would be relatively simple to add disembodied technical change to the above specification; see Hall [1968].

20. The importance of market structure in identifying supply or demand parameters was emphasized already in 1961 by Meyer L. Burstein, discussed briefly by Irma Adelman and Zvi Griliches [1961], yet received very little empirical or theoretical attention until Sherwin Rosen [1974].

21. For an empirical example of hedonic cost function estimation and identification in imperfect markets under a constant mark-up assumption, see Makota Ohta [1975]; also see Makota Ohta and Zvi Griliches [1975].

22. For empirical hedonic studies of used markets under the assumption of inelastic supply, see Phillip Cagan [1965], Robert E. Hall [1971], Charles R. Hulten and Frank C. Wykoff [1981a,b], John Muellbauer [1971a], Makota Ohta and Zvi Griliches [1975], James Kahn [1982], George Daly and Thomas Mayor [1983], and Zvi Griliches and Makota Ohta [1983].

23. See Erwin W. Diewert [1976, 1980, 1981], Robert A. Pollak [1982], Robert E.B. Lucas [1975] and Jack E. Triplett [1976].

24. This is a very common practice. See, for example, the studies surveyed in Zvi Griliches [1971a,b].

25. Other flexible forms are of course available. For an empirical comparison, see Berndt, Darrough and Diewert [1977] and Berndt-Khaled [1979].

26. It would also be possible, of course, to obtain estimates of the hedonic parameters from a different body of data, substitute these into (56), and then estimate only the structural parameters α_j and p_j in (56); the alternative suggested here within a system of equations has the advantage of permitting more efficient estimation.

27. For a survey of the economic theory of index numbers, see W. Erwin Diewert [1981].

28. This literature is surveyed in Ernst R. Berndt, Catherine J. Morrison, and G. Campbell Watkins [1981]; more recent contributions include Catherine J. Morrison [1982] and Robert S. Pindyck and Julio J. Rotemberg [1982].

29. Under price-independent quality adjustment, the functional structure is inherently asymmetric and has been called weakly recursive separability by George Lady and David Nissen [1968]; also see Charles Blackorby, Daniel Primont and R. Robert Russell [1975] and the discussion of groupwise separability by Dale W. Jorgenson and Lawrence J. Lau [1975].

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