By JACK E. TRIPLETT

The Economic Interpretation of Hedonic Methods

Editor's Note—

This article and the one following are parts of a three-part presentation of the new price index for computers incorporated in the revised estimates of the national income and product accounts (NIPA's) released in December 1985. The new index represents a substantial step in coping statistically with what is referred to as the "quality change problem," a problem common to many products to one degree or another but particularly pronounced for computer equipment because of rapid technological change.

The first article provides an introduction to hedonic methods, the econometrically based approach to dealing with quality change that underlies the new price index for computers. The second article, authored by a group from the economics department of the IBM Corporation, describes the results of their work on developing price indexes for computing equipment. Last year, following circulation of a preliminary description of BEA's research on computer prices, IBM offered to make its research available to BEA and to assist in further development of a computer price index. BEA acknowledges the generous contribution made by the authors and IBM.

The third article, which will appear in a forthcoming issue of the SURVEY, *will describe the use of the IBM composite price indexes in the deflation of current-dollar expenditures for computers in the NIPA's. Corrections to the current-dollar estimates of business purchases of computers that were released in December will appear at the same time. Although work on quantifying the error is not yet complete, it is likely that the corrections will raise the estimates of business purchases of computers, producers' durable equipment, and GNP for 1984 by $4 to $5 billion and the estimates for years back to 1978 by smaller amounts.*

Draft versions of portions of the three-part presentation were read by Zvi Griliches of Harvard University and Joel Popkin of Joel Popkin and Company. BEA and the authors appreciate their comments and suggestions.

CONSTRUCTING price indexes for computer equipment is a challenge because these products have exhibited extremely high rates of quality change, and quality change presents one of the most difficult problems encountered in price index construction. Hedonic methods provide an advantageous alternative to conventional price index approaches for situations where quality change is encountered.

The conventional method for controlling for the effects of quality change is designated the "matched-model" method in this article. In this method, only prices for models, or varieties, that are unchanged in specification between the two periods are used in the index. Matching the models assures that any difference between the prices collected for the two periods reflects solely price change, rather than a change in what was bought. Producer Price Indexes, which are used for deflating many components of producers' durable equipment, are constructed with the matched-model method.[1]

For two reasons, price indexes constructed with the matched-model method may not completely avoid errors that are associated with quality change.

One error arises when the price changes observed for *matched* models do not capture the price movement that is taking place for <u>all</u> models. When models embodying an improved technology are introduced, prices of models embodying older technologies are bid down; however, when the older technology cannot successfully compete with the new, it may simply disappear. By following prices of established models until they disappear, the matched-model method misses some of the price change that the new technology engenders, particularly when (as is often the case) the full pattern of discounting is not recorded in the price information used for the index. The potential errors from inferring price change for unmatched models from that observed for matched models, particularly when the matched models become obsolescent, have been discussed in the price index literature for many years.

A second error occurs when models that are not identical are nevertheless matched. Information on some of the specifications of the models, or on aspects of the terms of sale, may not be available, so that some models that appear to be matches actually differ in some respects. Alternatively, the pricing agency may know that two models are not truly identical, but when the differences are small, may conclude that making the match is preferable to dropping the price information from the index. The possibility that unlike models are compared has motivated a good part of the price index literature on quality change. Notice that the stricter the rules for accepting two models as a match, the greater the number of models that will be excluded from the price index. This means that, with the matched-model method, the more one guards against the second error, the more likely the index will contain the first one.[2]

In the BEA price measures for computer equipment, the matched-model method has been supplemented with hedonic methods. Matched-model comparisons are used whenever they are available, and hedonic methods are used to impute missing prices for newly introduced or discontinued models to capture price change that accompanies the turnover of models available in the market. This article introduces hedonic methods and

1. See U.S. Bureau of Labor Statistics, chapter 7, for a description of the methodology for the Producer Price Indexes. (References are at the end of the article.)

2. See Price Statistics Review Committee and Griliches (1971) for a discussion of the quality change problem in economic statistics, and Triplett (1975) for a survey of empirical research.

shows alternative ways for using hedonic methods in price indexes.

I. The Hedonic Function

The hedonic nomenclature is quite old, going back to the late 1930's.[3] The heart of the methodology is a regression equation, referred to as the "hedonic function," in which prices from an array of different models, or varieties, of a product are the dependent variable and the *characteristics* of that product are the independent, or explanatory, variables.

For example, in the IBM study the hedonic functions for computer equipment took the specific form

$$P = A\, M_1^{b_1}\, M_2^{b_2}\, u,$$

where P represents the prices of models of a particular kind of computer equipment, M_1 and M_2 are two characteristics of that item of equipment, and u is an error term. The coefficients A, b_1, and b_2 are estimated by the regression, and from the coefficients one can calculate dollar valuations, or implicit prices, for characteristics.[4]

The number of characteristics in a hedonic function, and accordingly the number of implicit characteristics prices, is a technical matter that depends on the product being investigated. The functional form for the regression has usually been determined empirically. The specific form used in the IBM study is one of three alternatives frequently encountered in hedonic studies.

Interpreting the hedonic function

Hedonic methods were developed, and indeed used in price indexes, long before their conceptual framework was understood. At one time, hedonic methods were regarded as ad hoc adjustments, which could not be related to the conceptual basis for economic measurement nor to the theory of price index numbers and real output measurement.

In the last 10 years or so, an explicit conceptual framework for hedonic methods has been developed. The framework is derived from the idea that production or consumption of heterogeneous goods (or services, for that matter) can be analyzed by disaggregating them into more basic, or elemental, units that better measure the dimensions of what is bought and sold—the characteristics. Several examples may help clarify the meaning of the term "characteristic."

Within the computer equipment industry, it is common to refer to a piece of computer equipment as a "box." Although the sale is conventionally denominated in terms of "box" prices and "box" quantities, meaningful economic units, to both buyers and sellers, are the characteristics in the box—speed, capacity, and other measures, as presented in the IBM study. What it costs to build a box, given a technology, depends on the characteristics the builder puts into the box; from the user's perspective as well, what matters is not the box, but the characteristics in it. For an airline company, the transaction unit is a flight, or an individual ticket purchase for a flight; but a better measure of an airline's output is "passenger miles," so passenger miles could be thought of as one characteristic of airline flights. Although a builder sells houses, housing characteristics (such as square feet of floor space, number of rooms, number of bathrooms, and whether the house has a garage or central air-conditioning) are a more meaningful definition of what the builder produces, as well as what the home buyer purchases.

These examples illustrate three principles that define the term "characteristics." Characteristics are homogeneous economic variables that are building blocks from which heterogeneous goods are, figuratively, assembled—the characteristics are "packaged," or "bundled," into a specific model. Characteristics are valued by both buyers and sellers (indeed, one might say this is what makes them economic variables), a key point in the use of characteristics for measurement purposes.[5] Although the characteristics are generally not priced separately, the price for the model represents the valuation of all the characteristics that are bundled in it—for each characteristic, the quantity of it embodied in the model, valued by its "implicit" price.

A simile clarifies, on the one hand, the relation between the price of a model and the prices of the characteristics embodied in it and, on the other, the role of the hedonic function as a "disaggregator."[6] Suppose that grocers, rather than placing their wares on shelves with unit prices marked on them, loaded various assortments of groceries into grocery carts, attaching prices to each of the preloaded carts. Buyers would select a preloaded cart and pay the specified price for the collection of groceries that it contains. Suppose further that a hedonic function were estimated on the grocery cart data. The dependent variable (which in hedonic regressions is normally the price of models of some product, such as automobiles) in this regression consists of the prices charged for the various preloaded carts of groceries. The independent variables (which in the usual hedonic study are measures of characteristics) are here the quantities of various groceries in the available preloaded carts. Thus, groceries found in the carts may be regarded as characteristics of the "grocery bundle." The estimated regression coefficients provide implicit prices for groceries. One can therefore think of the hedonic function as showing what prices of individual groceries would have been, had they been stocked on the shelves in the customary way. Whether on the shelf or in the carts, prices of individual grocery items will be determined by the forces of supply and demand that always determine prices in a market economy.

A heterogeneous good is a bundle of characteristics, similar to those cart loads of groceries. Once the characteristics in the bundle have been identified and measured, the hedonic function is interpreted as a function that disaggregates the price of the good into the implicit prices and the quantities of the characteristics, and it provides estimates of prices for the characteristics. Because the prices

3. See Court for the first use of the hedonic terminology in the literature.

4. In the hedonic literature, the term "implicit price" is often used to designate the coefficients b_1 and b_2 themselves, as well as to denote the price, expressed in dollars.

5. On the buyer side, the idea that demands for heterogeneous goods could be analyzed through demands for the characteristics embodied in them is developed in Lancaster and Ironmonger, though neither noted that the hedonic function might be used to estimate prices for the characteristics. The extension to modeling the supply of heterogeneous goods, explicitly in a hedonic framework, appears in several places, most notably Rosen and in the empirical work of Spady and Friedlaender.

6. The following passage is adapted from Triplett (1976).

must be estimated, rather than directly observed, they are usually termed "implicit" prices.

Interpreting the implicit prices

Estimated implicit prices for characteristics are the most important empirical results from a hedonic function. Implicit prices have many properties that are similar to those of ordinary prices. As with ordinary prices, an implicit price measures what the seller receives for a characteristic when it is sold as well as what the buyer pays for it. As with ordinary prices, implicit prices for characteristics are proportional to marginal valuations for users, and they are also proportional to marginal costs for producers—but only (as is so well known) when there is competition on the relevant side of the market.[7] The values of implicit prices will reflect the interplay of supply and demand for characteristics, and in the long run competition will push each characteristic price to the cost of producing that characteristic.

Characteristics prices also differ in certain respects from ordinary prices. (1) Because of bundling, the characteristics prices must be estimated with the hedonic function; they can seldom be observed directly, as can ordinary prices. (2) Because the characteristics are purchased as part of a tied sale, in bundled form, relations among the characteristics prices are more complex than what is usually assumed for prices of goods.[8]

Economically meaningful characteristics.—If the characteristics prices estimated from the hedonic function are to be economically meaningful and not just a statistical artifact of a multiple regression, the variables chosen as characteristics must themselves be meaningful. The variables will be meaningful if they represent what a buyer desires in purchasing the product and if they represent what absorbs resources in production.[9] Alternatively, one can say that the variables in the regression are economically meaningful when they represent the inputs used by buyers and the outputs of producers.

Many hedonic studies have departed from the meaningfulness rule, employing variables that are directly interpretable neither as producers' outputs nor as buyers' inputs. For example, early hedonic studies on automobiles employed weight as a variable, even though weight has little to do directly with the usefulness of an automobile or with its production cost.[10] In the automobile studies, weight stood as a proxy for the true characteristics. Use of a proxy variable, however, introduces the possibility of error whenever the relation between the proxy and the true variables changes, and one can never be entirely sure whether such shifts have occurred.

Determining the characteristics of a particular product requires a great deal of technical information, an understanding of what is produced as well as how it is used. It has not always been easy to assemble the technical knowledge. Nevertheless, good design of a hedonic investigation requires that the choice of variables be based on technical considerations about the production and use of the product under investigation.

Resource cost and user value

With hedonic methods, one interprets the variables chosen to represent characteristics both as outputs (which therefore absorb resources) and as inputs (which therefore generate value to the user). What assurance can be obtained that the theoretical interpretation meshes with empirical reality?

Perhaps one can best explore the question by asking: Under what circumstances would either input or output interpretations of characteristics—that is, either resource-cost or user-value interpretations of characteristics prices—be invalid?

A characteristic that represents resource cost, but not user value.—The major cases where a characteristic can only, or primarily, be associated with the cost side of the market involve government regulation. The incorporation of legally mandated smog control devices (as well as analogous noise suppression and safety equipment) would in principle show up in a hedonic function as a characteristic, with a characteristic price (in a competitive situation) approximating its resource cost. In this case, however, the characteristic cannot be interpreted as an input. A smog control device clearly does not provide transportation services.[11] Hence, the device is not an input characteristic when the motor vehicle data are interpreted as investment, or as part of the capital stock, or as consumer durables, even though it is a characteristic of the output of the industries that produce transportation equipment. The implicit characteristic price is interpretable as the resource cost of the output characteristic on the seller side, but as equivalent to a tax on transportation on the buyer side.

A characteristic price can be identified with user valuation, but not resource cost.—Typically, markets are more concentrated on the seller side. If price differentials among models are set by sellers on the basis of their estimates of demand elasticities for characteristics, rather than on the basis of cost, then estimated implicit prices for characteristics will reflect user valuations, but not resource cost.[12]

In this case, unlike the first one, the presumption is that the characteristic itself is both an output and an input. It is only the interpretation of the characteristic *price* that differs from the one presented earlier. Note, however, that the interpretation of the characteristics price under imperfect competition is exactly parallel to standard treatments of goods prices under imperfect competition.

A characteristic price that can be identified with neither user value nor resource cost.—This case is the "false" characteristic, a variable that is correlated with price (and presumably

7. Rosen discusses a competitive equilibrium in which buyers and sellers exchange bundles of characteristics and behave as if characteristics prices represented prices for individual characteristics in the bundle.

8. For example, when the hedonic function is not linear, buyers of different bundles will pay different prices for characteristics, and sellers of different bundles will receive different prices for them, even in competition. See Rosen and Triplett (1976 and 1983, pp. 40–45).

9. This statement may be somewhat too strong in the sense that variables that are related to, or in some way stand for, the true "contents of the box" might also yield acceptable results under some circumstances. See the following paragraph.

10. These studies are listed in the bibliography in Griliches (1971).

11. Some have argued there is a joint product—transportation and clean air—so that the amount of smog control equipment on the vehicle measures its production of clean air.

12. One often hears this conclusion stated backward (and incorrectly): That deviations from competition on the seller side mean that hedonic results do not reflect buyers' marginal valuations.

therefore with the true characteristics), but from the technical point of view can be identified neither with an output of the producing industry nor with an input of the using industry. As an example of such a variable, the number of ice-cube trays provided with a refrigerator was among the statistically best variables in one analysis of refrigerator prices. The number of ice-cube trays was acting as a statistical proxy for the true characteristics of a refrigerator, with which it happened to be correlated. Obviously, use of estimated implicit prices for ice-cube trays (the estimated implicit price of ice-cube trays was far higher than what they sell for when purchased individually) would yield valid economic measurements for refrigerators only by accident. The use of weight as a variable in automobile hedonic studies provides another example that has already been noted. Such variables typically have been introduced into hedonic functions either because the researcher ignored the principle that variables in the hedonic function should have a technical interpretation, did not understand the technology sufficiently to specify it correctly, or perhaps lacked data on the true characteristics. Such results should, however, be regarded more as errors in the application of hedonic methods than as limitations on the resource-cost or user-value interpretation of hedonic results.

Summary

The interpretation of hedonic functions is generated from the idea that heterogeneous goods are a bundle of characteristics. The price of any model of a heterogeneous good can thus be disaggregated into prices and quantities of characteristics. A hedonic function makes this disaggregation explicit, and provides a set of estimated characteristics prices.

The variables representing characteristics in the hedonic function (if they are properly chosen) and the implicit prices estimated for characteristics are—as are any quantities and prices—economic variables that have interpretations on both sides of the market. The characteristics represent the economic units that are being exchanged in the transaction—that is, they are at the same time outputs for the producer and inputs for the buyer. The implicit prices measure value on both sides of the market, as do any prices.

II. Using Hedonic Methods to Calculate Price Indexes

Key data for constructing quality-adjusted price indexes are the estimated implicit prices for characteristics. There are at least four ways to use the information from a hedonic function to construct a price index.

Making an explicit quality adjustment.—Suppose the classic case of quality change: An "old" model is replaced by a "new" one, the two models differ in the characteristics quantities embodied in them, and a comparison of the prices of the new and the old is needed for a price index. For any characteristic, i, the difference in the quantity of the characteristic embodied in "new" (C_{in}) and "old" (C_{io}) models can be valued by the implicit characteristic price, p_i, to yield the "adjustment": $p_i\ (C_{in} - C_{io})$.[13] This adjustment can be added to or subtracted from either the price of the new model or the price of the old one, as appropriate, and the adjusted price is then available for use in a conventional price index constructed by the matched-model method. An example of this application of hedonic functions to a component of the Producer Price Index is Triplett and McDonald.

Imputing a "missing" price.—The hedonic function can be used to impute a price in period t for a model that existed in period s, but not in period t. The imputed price permits a synthetic match, so it is then possible to construct a price index with matched-model methods. In the IBM study, such an index is designated the "composite." An early example of the composite index is the computer processor price index produced by Chow; Fisher, Griliches, and Kaysen perform a similar imputation, although for a different purpose. Imputing a missing price and computing an explicit quality adjustment (the first method) are similar in that the hedonic adjustment or imputation is applied only to models that exhibit quality change, while the remainder of the prices gathered for the price index are handled in the conventional matched-model approach.

Calculating a "characteristics price index."—Because the hedonic function provides estimates of the implicit prices of characteristics, it is natural to think of price index numbers that are defined directly on the characteristics and calculated from characteristics prices and quantities. In the grocery cart simile, for example, once one had estimated the prices of groceries on the shelves, a grocery price index could be constructed from shelf prices, rather than from the prices on the preloaded grocery carts. The first construction of a characteristics price index appears in a study by Griliches (1964), who computed Laspeyres and Paasche price indexes for automobile characteristics, as well as the associated characteristics quantity indexes. Characteristics price indexes for four types of computer equipment are presented in the IBM study. The Price Index of New One-Family Houses Sold is constructed as a characteristics price index that estimates the cost, in the current period, of the base period's quantities of housing characteristics (square footage put in place, and so forth), using characteristics prices from the housing hedonic function. This is the only other hedonic price index used for deflation in the national income and product accounts.

Estimating the price index directly from the regression.—Perhaps the most common hedonic price index in the literature is an index estimated directly from a regression: Year, or period, dummy variables are introduced into a regression on two or more periods' data. The resulting regression coefficient is an estimate of the residual (mean) price change between two periods that cannot be associated with changes in the quantities of characteristics. The implicit prices are in effect used to factor out the value of the change in characteristics quantities from the total change in value. The IBM study presents direct regression indexes for four types of computer equipment.

Sometimes the term "hedonic price index" has been thought to imply that the price index must be calculated by the direct regression method.

13. With some forms of the hedonic function, placing a value on the ratio C_{in}/C_{io} is the appropriate calculation.

However, each of these four calculations provides a hedonic price index in the sense that each uses hedonic methods in the construction of the index. The four calculations are alternatives that have differing practical advantages and usually—but not always—will produce price indexes that show similar patterns of price change.

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Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment

THIS article summarizes IBM's work on developing quality-adjusted price indexes for computer processors and three types of peripheral equipment: Disk drives, printers, and general purpose displays.[1] The first section describes three issues that arise in the application of hedonic regression methods to computing equipment: The level of aggregation, the specification of the characteristics, and the need to modify the hedonic function to deal with the problems of technologically induced disequilibrium.[2] The second section discusses the data; the third, the regression results; and the fourth, the use of the results to construct quality-adjusted price indexes. The article closes with a summary of the findings and their limitations.

I. Issues in the Application of Hedonic Methods to Computers

Level of aggregation

The first issue concerns the level of aggregation at which the analysis should be conducted—complete computing systems or system components. The decision to develop regressions and price indexes at the system component level was based on two considerations. First, with the evolution of system modularity, most purchases are of system components, or "boxes," rather than of complete computing systems. Second, the problems of obtaining appropriate measures of characteristics are more tractable at the box level.

Although working at the box level reduces many of the problems of measurement, it is important to recognize that both the hardware and software of a computing system embody attributes—such as ease of installation, reliability, and ease of use—that are not easily measured. Working at the box level is likely to understate the improvements that have occurred in computing systems over the years.

Specification of characteristics

The second issue concerns the specification of the characteristics of the system components: If the characteristics are not specified and measured correctly, the results of the regressions may be biased. The choice of characteristics for each component was guided by its role in a computing system. The characteristics selected reflect value to users; they also reflect resource cost.

Computer processors, henceforth called processors, execute instructions. They house the central processing unit and main memory. The work described in this article dealt with intermediate- and large-size general purpose digital processors. Small computers are not included; typically, they are packaged with auxiliary storage devices (disk drives or cassettes), and research thus far indicates that their analysis requires a more complicated technique than the one described here.[3]

The two key characteristics of processors are the speed with which instructions are executed and main memory capacity. The unit of measurement of memory capacity is straightforward—megabytes.[4] Manufacturers, however, typically offer several sizes of memory for a given processor. In such cases, both the largest and smallest memory configurations for a given processor were included in the study.

Obtaining an appropriate measure of speed was more difficult. Previous studies have generally used the speed of a single instruction—such as add, or multiply—that can be compared across models. However, the speed of a processor is not adequately represented by the rate of executing a single instruction.[5] A weighted composite of all of the instruction execution rates for a typical job mix (or benchmark) is a better representation. A widely used measure of this

1. Results for processors are from Ellen Dulberger's dissertation in preparation, "The Application of an Hedonic Model to a Quality Adjusted Price Index of Computer Processors" for The City University of New York. Results for disk drives and printers are from two reports in preparation: Y.C. Chen and James H. Hodge, "Using Hedonics to Measure Performance: A Study of Computer Disk Drives" and Joan A. Barquin-Stolleman, "Quality Adjusted Price Indexes for Printers: A Hedonic Approach."

2. The hedonic regression method was so named by Andrew Court (who applied it to automobiles) at General Motors in the 1930's. It has been developed and applied more generally by Zvi Griliches and others. Examples of applications to computers are: Chow; Ratchford and Ford; Stoneman; Archibald and Reece; Michaelis; Fisher, McGowan, and Greenwood; and U.S. Department of Commerce, BEA. (References are at the end of the article.)

NOTE.—The paper has benefited from discussions with David W. Cartwright and Jack E. Triplett of the BEA staff. It has been strengthened by A. J. Karchere's recognition many years ago that work in this area requires a multidisciplinary effort and his establishment of a small group of system performance experts under Y.C. Chen within the IBM economics department.

3. When two or more components are packaged together, other approaches—such as analytic models (which are designed to cope with the queueing aspects of the interactions among the components)—may be more efficient. See Bard and Sauer for a general description of analytic models as well as other types of computing system performance modeling at IBM.

4. For IBM and manufacturers of plug-compatible processors, one byte equals eight bits, and a bit is a binary digit (that is, 0 or 1). For other manufacturers, memory is often expressed in words, where the number of bits per word must be divided by eight to convert to bytes.

5. Two conditions must be met in order for a single instruction execution rate to be adequate: The processors compared must have the same instruction sets and the relative instruction execution rates must not vary across processors. These conditions rarely hold.

In addition to the rate of executing a single instruction, earlier studies also included memory cycle time. Others used only machine cycle time or memory cycle time. See Bloch and Galage for a first-order approximation of the relationship of cycle times to the rates of executing instructions.

kind is MIPS—millions of instruction executions per second, in which each instruction is weighted by its frequency of use in a specific job mix. Two types of problems, however, arise with respect to the use of this measure. The first problem concerns comparability. If two processors have different instruction formats or different logic designs, the MIPS ratings are not comparable. They can, however, be made comparable. Assume the MIPS rating of a given processor equals $MIPS_1$ and that N_1 equals the number of instruction executions in processing the job mix. If some other processor has a rating of $MIPS_2$ and its number of instruction executions equals N_2 for the same job mix, then the "equivalent MIPS" rating equals $MIPS_2(N_1/N_2)$. The second problem relates to the choice of the job mix. It arises because of the difficulty of defining a truly representative benchmark. The advantage of equivalent MIPS as a measure of processor speed is realized only if the specified job mix is representative of the jobs expected to be performed by the processors being compared.

Estimates of equivalent MIPS ratings, expressed in terms of IBM 370-equivalent MIPS, are publicly available for IBM and plug-compatible processors. MIPS ratings published for the processors of other manufacturers may not be expressed in the same terms. To be assured of a consistent and comparable measure of speed, the work described here is based on IBM and plug-compatible processors.

Disk drives—technically, direct access storage devices (DASD)—are devices that write, store, and retrieve data. They are now the dominant auxiliary storage device. Basically, they consist of stacks of records or disks, centered on a spindle, on which data can be written or from which data can be read. A disk drive may possess one or more spindles. The component that does the actual reading and writing of data is known as the read/write head; until recently, there was one set of heads per spindle. Disk drives are random access devices—that is, they have the ability to move the head to any point on the disk so that the stored data are directly accessible. Data stored on tapes—the main competing storage medium—can be accessed only sequentially.[6] The work described here covered large and intermediate single-density drives that do not possess explicit control functions.

The two key characteristics for disk drives are capacity and the speed with which data can be transferred between the device and main memory. Unlike processors, the measurement of both these characteristics is relatively straightforward. Capacity can be measured by the number of megabytes that can be stored in a device.

The measure of speed, in units of kilobytes per second, consists of three elements. (1) Average seek time (*ast*) is the average time for the read/write head to locate and arrive at the correct track of the disk. (2) Average rotation delay (*arotd*) is the time for the disk to rotate so that the read/write head is lined up at the correct point on the track. (3) The transfer rate (*tr*) is the time it takes to transfer the data, once the correct position on the disk has been located, between the drive and main memory. The total time to transfer a kilobyte of data is the sum of these three elements. The calculations are made under the assumption that the average amount of data transferred at one time is two kilobytes. Under this assumption, speed per set of read/write heads is measured as the inverse of the time it takes to transfer two kilobytes, or as:

$$\text{Speed} = 2\,/\,(ast + arotd + 2/tr).$$

If there is more than one set of heads per device, the speed of the device is measured as the speed per set times the number of sets.

Printers record the system's output on paper. There are two broad categories of printers: Impact and nonimpact. There are two classes of impact printers: System line printers, which can print an entire line of characters at once, and serial printers, which print one character at a time. Serial printers are used with personal computers and other workstations. They may use daisywheel (for letter-quality print) or dot matrix mechanisms. There are also two classes of nonimpact printers: Page printers, which are based on laser electrophotographic technology, and ink jet printers.[7] The study covered all of these classes of printers.

The three key characteristics for printers are speed, resolution, and the number of fonts available on-line to permit automatic variation of type size, style, and boldness. Speed is measured as characters per second. Resolution is measured by the number of dots per character.[8]

General purpose displays, or terminals, are input-output devices that allow communication between the processor and a user. They possess no data processing capability. A unit consists of a keyboard and a monitor—the former to enter data, the latter to display data. Two types of monitors are available: Cathode ray tube (CRT) and gas panel. The study covered only CRT displays.

The four key characteristics for displays are screen capacity, resolution, the number of colors that can be displayed, and the number of programmable function keys. Screen capacity is measured as the number of characters that can be displayed. Resolution is measured as the number of picture elements per character. Displays also differ in various ergonomic attributes, such as the feel and shape of the keys or tilt positions of the monitor; these are difficult to quantify and are assumed to be uncorrelated with the measured characteristics. In contrast with processors and the other peripheral equipment, speed is not a characteristic for displays. The speed with which information is exchanged between the display and the host processor can be considered essentially independent of the type of display used. The main determinants of speed, as perceived by the user, are characteristics of other components of the system.

Modification of the hedonic function

The use of hedonic regressions is based on the premise that differences in the prices of goods offered in the same market at the same time mainly reflect differences in the characteristics of the goods. When the market

6. See Harker et al.; Engh; and Mulvany and Thompson for detailed descriptions of disk drives.

7. See Nickel and Kania and Elzinga et al. for detailed descriptions of printing mechanisms and technology.

8. Resolution measures were not published for some printers and were imputed using data from a reference printer. In other cases, the published measures were in terms of dots per square inch. Data from the reference printer were used to convert dots per square inch to dots per character. See Barquin-Stolleman for a detailed description of the estimating and conversion procedures used in these cases.

Table 1.—Processor and Disk Drive Technologies, 1972–84

Processors					Large and intermediate disk drives				
Class code	Memory type	Memory chip density (kilobits per chip)	Years: In sample	Years: "Best"	Class code	Type	Areal density[1] (kilobytes per square inch)	Years: In sample	Years: "Best"
1	Magnetic core	[2] 0.0025	1972	.....	1	Removable disk pack	220	1972	.....
2	Semiconductor, bipolar	.128	1972	1972	2	Removable disk pack	776	1972–77	1972–73
3	Semiconductor, bipolar	1	1973–74	.....	3[3]	Removable head/disk pack	1,591	1974–77	1974–75
4	Semiconductor, field effect transistor	1	1973, 1976–79	1973	4[1]	Fixed disk	2,694–2,706	1976–81	.....
5	Semiconductor, field effect transistor	2	1974–83	1974	5	Fixed disk	3,071–3,084	1976–82	1976
6	Semiconductor, field effect transistor	4	1975–82	1975–78	6	Fixed disk	4,191	1977–82	1977–79
7	Semiconductor, field effect transistor	16	1981–84	.....	7[3]	Fixed disk	7,706	1980–84	1980
8	Semiconductor, field effect transistor	64	1979–84	1979–84	8	Fixed disk	9,707	1981–84	.....
					9	Fixed disk	12,192–12,939	1981–84	1981–84

1 Single density only (see footnote 11 in text).
2 Estimated using relative volume/megabyte from Pugh et al., table 1.
3 Intermediate drives.

u er study is not in long-run equilibrium, and when the forces creating the disequilibrium are correlated with the characteristics, a statistical analysis that fails to treat the issue explicitly risks producing biased estimates.[9]

The market for computing equipment is characterized by disequilibrium caused by rapid technological change. Existing products are leapfrogged by products embodying improved technology and manufactured using improved processes. The introduction of the new products induces market disequilibrium. An important aspect of the disequilibrium is that there is a period of time when two sets of prices coexist for products possessing the same characteristics—one price for the products based on the old technology and one for the products based on the new. In this study, the hedonic function was expanded to take this aspect of disequilibrium into account for processors and disk drives by introducing measures of embodied technology into the regressions. The measures serve as proxies for technology-associated differences in production costs and for the attractiveness of technologically superior substitutes. The measures of technology are described next; the ways in which they are introduced into the hedonic regressions are described in the third section. (For printers and displays, it was not feasible to allow for disequilibrium.)

The measures used to represent technology are based on density—that is, the amount of information that can be stored on a given surface area. Semiconductor memory chip density was used for processors, and the recording, or areal density, was used for disk drives.

Semiconductor memory chip density was used for processors because much of the improvement of processors has come from advances in semiconductor technology. Greater speed and memory capacity have been achieved by packaging increased numbers of circuits closer together. With increased densities, the distance electrons travel is shortened; not only can more information be stored, but also instruction execution time is reduced. Improvements in packaging at higher levels (cards and boards) have enabled improvements in computer manufacturing (and reductions in costs) to parallel improvements in chip densities.[10] The use of memory chip density to represent logic technology (its proprietary nature precludes direct comparison) is appropriate only to the extent that logic design is also improved by advances in semiconductor technology. The unit of measurement of memory chip density is kilobits per chip.

By reference to density, the study established eight classes of technology for processors, shown in table 1. The first class is magnetic core, the storage material in use before the shift to semiconductors during the early 1970's. Semiconductors, although initially expensive, reduced by a factor of 50 the space required to store a given amount of information. This new material provided the potential for future improvements in densities. The first semiconductors covered in the sample were bipolar. Of these, there are two classes: The first, introduced in 1972, had a density of 0.128 kilobits per chip; the second had a density of 1 kilobit per chip. They were replaced by field effect transistor (FET) semiconductors, which were produced at substantially lower costs. Of these, there are five classes, over which densities increased from 1 to 64 kilobits per chip.

For disk drives, manufacturers have improved speed and capacity in three ways: By decreasing the distance from the read/write head to the disk, by decreasing the head-gap length (that is, the distance between the reading and writing elements on the read/write head), and by decreasing the thickness of the recording medium on the disk. Each of these improvements makes it possible for the head to read information from a smaller area on the disk. The unit of measurement of areal density is the number of kilobytes per square inch.

The first two of the nine technology classes for disk drives consist of those designed to handle disk packs that could be removed (table 1). The first, introduced in the mid-1960's, had an areal density of 220 kilobytes per square inch; the second, introduced in 1972, had a density of 776.[11] In the mid-1970's, separate technologies were

9. See Rosen and Fisher, McGowan, and Greenwood for discussions of the conditions under which it is appropriate to employ the traditional hedonic approach.

10. See Seraphim and Feinberg and Bloch and Galage for discussions of the interrelationships between improvements in semiconductor technology and the design and manufacture of computers.

11. As noted earlier, the study only included single-density drives. However, classes 1, 2, and 4 also contain products known as double-density drives. A double-density drive is one in which the manufacturer has made changes that lead to a doubling of the product's areal density, but has not changed other pertinent parameters that affect the device's overall performance. These drives were not included in the study because they do not represent the same technological improvement as the introduction of a new generation of devices for which all of the technical parameters have been changed.

introduced for intermediate and large disk drives. The first intermediate drives had a density of 1,691 kilobytes per square inch. This type was called the "Winchester," and it had disks and read/write heads that were packaged together in a removable unit. Other intermediate drives, as well as large drives, had fixed disks—that is, they could not be removed. The first of the large drives, introduced in the mid-1970's, had areal densities in excess of 3,000 kilobytes per square inch. The current generation of large disk drives, introduced in the early 1980's, has areal densities in excess of 12,000 kilobytes per square inch—densities 55 times greater than the densities of the devices introduced in the mid-1960's.

II. The Data

The samples for all four system components contain annual data for 1972-84. Each sample contains information on prices and characteristics for each model used in the regressions. Prices for IBM models in the samples were taken from IBM sales manuals. In general, prices for non-IBM models and information on characteristics for all models were drawn from trade and general press sources, as indicated in the descriptions of the sample data that follow.[12]

The processor sample consists of 67 different models from 4 manufacturers. Prices refer to the central electronic complex, which includes—in addition to the central processing unit and main memory—the minimum required gear, such as standard channels, the console, and the power supply unit. For non-IBM processors, prices, main memory sizes, and information on the minimum required gear came from the trade and general press. MIPS ratings for all models appearing prior to 1981 are from "Tracking Those Elusive KOPS," in *Datamation* of November 1980; ratings for models introduced after 1980 are from the annual "Hardware Roundup," in *Computerworld* of July 1981 and August 1982, 1983, and 1984.

Average annual prices for processors were obtained by weighting the different prices prevailing within a year by their respective durations. For non-IBM processors, dates of price change were taken from the press; when no reports of change were located, prices were assumed unchanged.

The sample for disk drives consists of 30 devices marketed by 10 vendors. Characteristics and prices were compiled from a number of sources. The main ones were the series of annual reports for 1973-85 published by Datapro Research Corporation and *Disk Trend Reports* for 1976-84 published by J. Porter.

The printer sample consists of 480 models from 126 vendors. Characteristics and prices are from reports published by Datapro Research Corporation for 1972-84 and from *Electronic Printer Industry Services*, a series of reports published by Dataquest, Inc., for 1983 and 1984. The display sample consists of 772 models from 115 vendors. Characteristics and prices are from Datapro's series of annual reports, "All About Alphanumeric Display Terminals," 1973-84.

It was necessary to devise rules to determine how long a model appears in the sample. In principle, a model should appear as long as it is being produced. For IBM models, it was possible to determine this directly; other models were a problem. For non-IBM processors, a model was entered the first year it appeared in the annual tabulations of the stock of installed computers in the United States prepared by the International Data Corporation and published in *EDP Industry Reports*, and it was deleted the year after the stock peaked. A non-IBM disk drive model was entered in the sample in the year in which it was first shipped and deleted the second year after a new generation of technology was introduced. Non-IBM printer and display models were carried in the sample as long as they appeared in annual Datapro reports.

The price data have serious limitations. First, they are list prices for a quantity of one. Because discounting is a widespread practice in the industry, particularly on multiple-unit sales, the prices do not represent transaction prices. Second, prices for non-IBM peripherals refer to a point in time rather than the full year. Point-in-time prices may distort estimates of year-to-year change because any price change occurring after the survey date will not be reflected until the following year.

III. Regression Results

The authors had strong views with respect to the variables to be included in the hedonic regressions and weaker notions with regard to the functional form. A double-log form was tried first, and Box-Cox transformations were used to test alternatives. The results indicated that, for all product types, the double-log form is preferred to the semilog and linear forms.

Regressions were estimated for time periods of varying lengths, including single years, groups of adjacent years, and the entire 1972-84 period. For the sake of simplicity and ease of exposition, only the results for the regressions estimated for the entire 1972-84 period are shown in table 2.

Results denoted "I" refer to a traditional hedonic regression of price as a function of characteristics and year dummies. The estimated coefficients from these regressions suggest that speed is more important than main memory capacity for processors, but that capacity is somewhat more important than speed for disk drives. Speed is the most important characteristic for printers, followed by resolution and the number of on-line fonts. The number of colors and resolution are almost equally important for displays; capacity and the number of programmable function keys are much less important.

Modified regressions for processors and disk drives

The information on technology in table 1 was used in the hedonic regressions in two alternative ways. In table 2, the results of these regressions are denoted "II" and "III." In II, technology is represented by a set of dummy variables for each year for the technology classes described earlier. For example, a processor with memory using 4 kilobit ("4K") chips was coded as belonging to technology class 6 by entering "1" for that class and "0" for the other classes.

In III, technology is represented by a set of three technology variables: Embodied, or "own," technology; "best" technology; and age of own technology. (1) The own technology variable is measured directly. For example, the value of the variable for a processor with memory using 4K chips was "4" in each year. The own technology variable is an indicator of

12. The availability of a package of data and a detailed listing of the data sources will be announced in the SURVEY OF CURRENT BUSINESS.

Table 2.—Regression Coefficients for 1972–84 Pooled Regressions

	Processors				Disk Drives				Printers	Displays[1]
	I	II	II'	III	I	II	III	III'	I	I
Characteristics:										
Speed	0.80 (35.1)	0.78 (39.0)	0.78 (41.7)	0.76 (23.1)	0.41 (3.3)	0.33 (0.9)	0.33 (2.7)	0.33 (2.8)	0.76 (26.4)	....
Capacity	.17 (6.6)	.22 (10.0)	.22 (10.2)	.14 (3.1)	.46 (5.8)	.82 (2.4)	.73 (7.9)	.73 (8.0)	....	....
Resolution	....	....	....	....	....	....	....	....	....	0.09 (2.7)
Number of Colors	....	....	....	....	....	....	....	....	.306 (5.7)	.39 (14.9)
Function keys	....	....	....	....	....	....	....	....	....	.40 (22.5)
Fonts on-line	....	....	....	....	....	....	....	....	.09 (2.2)	.07 (7.6)
Technology variables:										
Own technology	....	....	....	−.12 (−4.5)	....	....	−.53 (−4.6)	−.58 (−9.9)	....	....
"Best" technology	....	....	....	−.39 (−9.5)	....	....	.01 (.1)	....	....	....
Age of own technology	....	....	....	−.06 (−3.8)	....	....	−.08 (3.0)	−.08 (−6.0)	....	....
Intercept	7.58 (94.1)	7.94 (79.1)	7.94 (79.8)	7.88 (95.1)	6.36 (22.0)	4.96 (9.2)	8.83 (23.4)	8.88 (24.0)	3.94 (10.4)	5.81 (23.5)
Dummies:										
Portable storage	....	....	....	....	....	....	.25 (2.2)	.25 (2.2)	....	....
Technology dummies	*	....	....	....	*	....	....	....	....	*
Technology class by year	....	*	*	....	....	*	....	....	....	....
Product class by year	....	....	....	....	....	....	....	....	*	....
Addenda:										
R^2	.968	.973	.973	.900	.844	.910	.870	.870	.918	.427
Standard error of estimate	.062	.039	.039	.129	.051	.050	.038	.038	.273	.181
Number of observations	296	296	296	296	91	91	91	91	813	2,023

NOTE.—Dependent and independent variables, except age of own technology and dummies, are in natural logarithms. An asterisk denotes a set of dummies included in regressions. Technology classes are based on memory density for processors and on areal density for disk drives. Printer categories are line, daisywheel, dot matrix, ink jet, and page. The t statistics are in parentheses.

1. Regression for displays is estimated for 1973–84.

the sophistication of the technology employed in manufacturing a given processor or disk drive. Because employment of more advanced technologies permits the same characteristics to be produced at lower costs, this variable can be considered as an exogenous "supply shifter." (2) The "best" technology is a variable that takes the value of the greatest density available in each year. It has the same value for all processors within any year. (In years during the transition to a new technology, the value of the "best" technology variable was taken as an average of the current year and the preceding 2 years.) This variable represents the competitive pressure to lower prices that is exerted by technologically superior substitutes. (3) The age of own technology variable is defined as the number of years since introduction of the technology. In any year, it has the same value for all models embodying the same technology. Age is expected to be important for at least two reasons. One is that lower costs and cheaper prices are achieved with the efficiency in production that comes with experience. The second reason is expected obsolescence on the demand side. The older a technology, the less buyers will be willing to pay because the probability increases that new products based on cheaper technology will soon become available.

In addition, for disk drives, another variable was added—a portable drive dummy. It was assigned a value of "1" when the product has a removable disk and a value of "0" when it has a fixed disk. Including this variable permits the intercept of the regression equations to be different for drives with removable disks and fixed disks.

Comparison of equations II and III with equation I shows that the technology information, in one specification or another, can substantially reduce the standard error of the traditional hedonic equation. For processors, the information on technology in the form of technology class by year dummies yields better results than in the form of the set of technology variables: The standard error is reduced from 0.062 in equation I to 0.039 in equation II; it is doubled to 0.129 in equation III. In contrast, for disk drives, the information on technology in the form of the set of technology variables yields better results: The standard error is reduced from 0.051 in equation I to 0.038 in equation III; it is marginally reduced to 0.050 in equation II. A likely explanation of these differences is that areal density is a better measure of technology for disk drives than memory chip density is for processors. Improvements in logic technology, though highly related to memory chip density, may not be well measured by increases in densities.[13] Although significant for processors, the "best" technology variable was insignificant for disk drives. The results without this variable for disk drives are denoted equation III'.

For disk drives, although not for processors, the inclusion of technology variables in both specifications has a marked effect on the estimated coefficients for speed and capacity. The effect is to raise the estimated importance of capacity relative to speed. The inclusion of the technology variables gives more plausible results; one would expect capacity to be more important than speed for large- and intermediate-size storage devices.

Table 3 shows the estimated coefficients for the technology class by year dummies for processors for equation II. The coefficients in the first column are estimates of the logarithm of ratio of the price of the products embodying the "best" technology in 1972. These coefficients can be converted to index numbers, with 1972 = 100, by taking the antilog of each year's value and multiplying by 100. For example, the coefficient −0.746 in 1975 means that the price index for processors embodying the "best" technology equals 47.4 after allowing for differences in speed and storage capacity.

The coefficients in each row to the right of the double line are the estimates of the logarithm of ratio of the price of each "nonbest" technology to the price of the "best" technology in the same year. For any given year, the coefficients can be stated relative to the price of the "best" technology in that year by taking the antilog of the coefficients and multiplying by 100. For example, the coefficient 0.524 on technology class 5 for 1975 means that the price of products in this class

13. The results may also reflect the fact that by improved packaging, manufacturers may increase the effective capabilities of memory chips. For example, 2K chips have been packaged to have the effective capabilities of 16K chips.

was 168.9 percent of the "best" in 1975 after allowing for differences in speed and storage capacity. In most cases, the coefficients indicate that prices tend to be higher for "nonbest" (and usually older) technologies than for the "best." Moreover, the t statistics indicate that 16 out of 24 of these price differentials are significantly different from zero.

Comparisons across technology classes within a given year show cases where the coefficient for a "nonbest" technology is not statistically different from the coefficient of the "best" technology, of another "nonbest" technology, or of both. Formal tests of the equivalence of regression coefficients lead to a simplified version of equation II, denoted equation II', for which results are shown in the lower panel of the table. It involves two kinds of restrictions: (1) Coefficients are set equal to zero if not statistically different from zero (for example, class 4 in 1976) and (2) coefficients within a given year were constrained to be equal if they did not differ significantly from one another (for example, classes 4 and 5 in 1977).[14] The results of equation II' similarly indicate the existence of multiple prices.[15]

The only "nonbest" technology that sold for less was magnetic core memory in 1972. The shift to semiconductor memory took place during this period, and—because it was clear that further improvements were much more likely to come from semiconductors—core was considered obsolete.

For disk drives, all except one of the estimated coefficients for the technology class by year dummies in equation II, shown in table 4, are positive and are larger the older is the

14. Because the insignificance of individual t statistics is not sufficient to permit the set of restrictions involved in equation II', additional tests were necessary to support the use of equation II'. An F test indicates that one cannot reject the hypothesis that the set of restrictions is valid. A second F test was necessary to justify pooling the cross-sections into one sample. Single-year regressions of price on characteristics and the same restricted technology class by year dummies as in equation II' were calculated. By the standard F test (the Chow test), one cannot reject the null hypothesis that all the single-year regression coefficients are the same.

15. Other studies of processors have shared the underlying thread of coexisting multiple prices: Stoneman; Fisher, McGowan, and Greenwood; and U.S. Department of Commerce, BEA. The BEA study stratifies observations by whether the model number is new or has existed in the sample previously. The BEA coefficients for new models and the IBM coefficients for new technologies for 1975 and 1979, years in which new models also embody new technology, show similar price differentials for new products.

Table 3.—Regression Coefficients on Technology Class by Year Dummies for Processors

Year	"Best"	Technology class[1]: 1	2	3	4[2]	5	6	7	8
					Equation II				
1972		−0.554 (−4.4)	*						
1973	−.239 (−1.8)			0.296 (2.5)	*				
1974	−.196 (−1.6)			.284 (2.3)		*			
1975	−.744 (−4.3)					0.524 (3.3)	*		
1976	−.798 (−4.6)				0.160 (1.8)	.567 (3.5)	*		
1977	−1.008 (−7.5)				.318 (2.4)	.383 (3.0)	*		
1978	−1.248 (−9.3)				.379 (2.9)	−.084 (−.7)	*		
1979	−2.288 (−13.1)				1.181 (6.0)	.877 (5.4)	0.838 (5.3)		*
1980	−2.257 (−16.7)					.537 (4.0)	.544 (5.3)		*
1981	−2.167 (−17.7)					.282 (2.7)	−.338 (−.4)	0.327 (3.7)	*
1982	−2.298 (−19.0)					.147 (1.0)	.142 (1.6)	.281 (3.7)	*
1983	−2.392 (−20.3)					.173 (1.2)		.032 (.4)	*
1984	−2.564 (−21.0)							−.360 (−.8)	*
					Equation II'				
1972		−.554 (−4.4)	*						
1973	−.236 (−1.8)			.298 (2.3)	*				
1974	−.192 (−1.6)			.282 (2.3)		*			
1975	−.748 (−4.3)					.524 (3.8)	*		
1976	−.715 (−5.1)				0	.477 (4.0)	*		
1977	−.999 (−7.5)				.350 (3.3)	.350 (3.3)	*		
1978	−1.282 (−10.7)				.420 (3.6)	0	*		
1979	−2.277 (−13.1)				1.180 (6.0)	.851 (5.7)	.851 (5.7)		*
1980	−2.250 (−16.8)					.539 (5.7)	.539 (5.7)		*
1981	−2.172 (−18.5)					.271 (3.0)	0	.338 (4.1)	*
1982	−2.248 (−19.3)					0	0	.243 (3.4)	*
1983	−2.273 (−20.6)					0		0	*
1984	−2.564 (−21.8)							0	*

NOTE.—The t statistics are in parentheses. An asterisk indicates "best" technology class.

1. See table 1.

2. Technology class 4, the 1K field effect transistor chip, first appeared in 1973 and was replaced after only 1 year by the 2K chip embodied in 1974 shipments of the same processor models. The 1K chip was reintroduced in 1976 in new processors.

Table 4.—Regression Coefficients on Technology Class by Year Dummies for Disk Drives, Equation II

Year	"Best"	Technology class[1]: 1	2	3	4	5	6	7	8	9
1972		0.351 (1.20)	*							
1973	0.006 (.04)		*							
1974	−.336 (−1.18)		0.123 (.43)	*						
1975	−.387 (−1.36)		.076 (.26)	*						
1976	−1.033 (−2.36)		.651 (1.53)	0.457 (.79)	0.127 (.40)	*				
1977	−1.567 (−3.53)		1.422 (3.14)	.981 (1.70)	.661 (2.07)	0.520 (1.89)	*			
1978	−1.567 (−3.58)				.559 (2.02)	.500 (1.81)	*			
1979	−.567 (−3.53)				.353 (1.27)	.219 (.80)	*			
1980	−1.659 (−4.36)				.308 (1.09)	.169 (.59)	−0.131 (−.40)	*		
1981	−2.015 (−3.61)				.563 (2.01)	.528 (1.66)	.225 (.65)	0.455 (1.19)	0.282 (.88)	*
1982	−1.986 (−3.56)					.534 (1.67)	.387 (1.11)	.465 (1.21)	.282 (.89)	*
1983	−2.063 (−4.20)							.458 (1.47)	.229 (.84)	*
1984	−2.228 (−4.26)							.624 (1.87)	.396 (1.39)	*

NOTE.—The t statistics are in parentheses. An asterisk indicates "best" technology class.

1. See table 1.

technology. However, the t statistics indicate that only four of the estimated coefficients are statistically significant. Similar but stronger results are provided by the estimated coefficients of the set of technology variables in equation III′ of table 2, which suggest that multiple prices exist and that—because coefficients are negative—older technologies sell for more than newer ones. The hypothesis of multiple prices was further tested by an alternative equation containing both the technology variables and year dummies. The appropriate F tests indicate that one cannot reject the hypothesis that the coefficients on the technology variables are 0 when the year dummies are included. Thus, there is cross-sectional variation in the sample beyond that captured by speed and capacity measures, and the technology variables capture it.

In table 5, the information from the lower panel of table 3 and from table 4 is recast into the form of price indexes having the 1972 "best" = 100. This presentation makes it easy to see the course of the price changes of a given technology class. As seen by the pattern of generally declining prices reading down the columns, older technology classes have continually and rapidly falling prices in response to competitive pressure from newer technology classes.

In summary, the introduction of products embodying new technology leads initially to multiple prices, with the products based on "nonbest" technologies selling for more. The prices for older products decline rapidly, until they either match the quality-adjusted price of products based on new technology or the products disappear. The claim that improved technology leads to reduced costs and, hence, to a lower quality-adjusted price is consistent with a competitive marketplace in which only one quality-adjusted price (the "best") ultimately prevails. It was found that in many cases price reductions permit an older technology to compete with a newer one for a limited time, but as the new technology becomes diffused, its own age-related cost and price reductions eventually drive the older technology out of production. The evidence presented here suggests that prices reflect this process of adjustment and that equilibrium is not reached within a period as short as 1 year.

Table 5.—Price Indexes by Technology Class for Processors and Disk Drives

[1972 "Best" = 100]

Year	"Best"	Technology class[1]								
		1	2	3	4	5	6	7	8	9
		Processors								
1972	100.0	57.6	*100.0*							
1973	79.0			108.0	*79.0*					
1974	82.5			109.4		*82.5*				
1975	47.6					30.3	*47.6*			
1976	48.9				48.9	78.8	*48.9*			
1977	36.9				52.3	52.3	*36.9*			
1978	27.7				42.2	27.7	*27.7*			
1979	10.2				33.4	24.0	24.0		*10.2*	
1980	10.5					18.1	18.1		*10.5*	
1981	11.4					15.0	11.4	16.0	*11.4*	
1982	10.8					10.6	10.6	13.5	*10.8*	
1983	10.3					10.3		10.3	*10.3*	
1984	7.7							7.7	*7.7*	
		Disk Drives								
1972	100.0	142.0	*100.0*							
1973	100.5		*100.5*							
1974	71.5		90.8	*71.5*						
1975	67.9		73.3	*67.9*						
1976	35.6		68.2	56.2	40.4	*35.6*				
1977	20.9		86.6	56.2	40.4	35.1	*20.9*			
1978	20.9				36.5	34.4	*20.9*			
1979	20.9				29.7	26.0	*20.5*			
1980	19.0				25.8	22.5	18.7	*19.0*		
1981	13.3				25.8	22.6	18.7	21.8	17.7	*13.3*
1982	13.7					23.4	20.2	21.8	18.2	*13.7*
1983	12.7							20.1	16.0	*12.7*
1984	10.8							20.1	14.0	*10.8*

NOTE.—In the columns for technology classes, the index for the "best" is repeated (in italics) from the first column.
1. See table 1.

Prices for characteristics of processors and disk drives

The hedonic equations can be used to derive estimates of implicit prices for characteristics. Such prices are shown in table 6 for processors and disk drives. Each estimate is a marginal price, or price for an incremental unit, of capacity and speed. (The specific formula is presented in the footnote to the table.)

The estimated characteristics prices fell sharply between 1972 and 1984.

Table 6.—Estimated Characteristics Prices

[Thousand dollars per unit]

Year	Processors		Disk drives	
	Speed, in MIPS	Capacity, in megabytes	Speed, in kilobytes per second	Capacity, in megabytes
1972	1,884	501	75	189
1973	2,298	404	80	178
1974	1,908	332	59	150
1975	1,827	289	52	133
1976	1,922	285	52	90
1977	1,385	154	58	80
1978	771	97	62	50
1979	561	80	50	38
1980	419	41	40	34
1981	394	24	40	34
1982	288	28	43	38
1983	264	25	37	23
1984	220	26	35	21

NOTE.—The estimates use multiyear (1972-84) equation II′ for processors and equation III′ for disk drives. Because the formulations are multiplicative, the price of the ith characteristic in year t ($\hat{P}_{it}$) is estimated as

$$\hat{P}_{it} = \frac{\partial P_t}{\partial z_i} = b_i \sum_m \left(\frac{\overline{P_{mt}}}{z_{im}}\right) s_{mt}\ ,$$

where the overbar denotes the arithmetic mean; P_{mt} denotes the price of the jth model of the mth technology class in year t; z_{im} denotes the quantity of the ith characteristic in the jth model; s_{mt} denotes the share of characteristics from the mth technology class shipped in year t; and b_i denotes the regression coefficient for the ith characteristic.

The most dramatic drops occurred in prices of capacity. In 1984, the price of one megabyte of main memory was less than one-twentieth the 1972 price. The price of one megabyte of auxiliary storage (in the disk drive) was about one-ninth the 1972 price. Main memory was almost twice as expensive as auxiliary storage until processors embodying the 64K memory chip were introduced in 1979. After that year, the price of data storage was essentially the same, whether in main memory or in auxiliary storage.

The estimated prices of speed fell less rapidly. In 1984, the price of executing one million instructions per second was about one-ninth the 1972 price. The price of transferring one kilobyte of data per second from the disk was about one-half the 1972 price.

Homogeneity

Further tests of the hedonic equations were conducted. The hypothesis that the characteristics coefficients sum to one could not be rejected for any of the four types of equipment. The finding that the implicit characteristics prices for these products are probably homogeneous to the first degree is appealing. Homogeneity implies that the valuation of characteristics quantities equals the observed price of the product.

IV. The Price Indexes

The price index used as a deflator to convert current-dollar values to constant-dollar values is a Paasche formula index,

$$(1) \quad I_{t,0} = \frac{\Sigma P_{it} Q_{it}}{\Sigma P_{i0} Q_{it}}$$

where, for model i, P_{it} and P_{i0} denote prices in the current and base periods, respectively, and Q_{it} denotes the quantity purchased in the current period. The problem encountered in constructing such an index for products experiencing rapid change is that models purchased in the current period may not have existed in the base period.

Matched-model index

The most frequently used approach for dealing with the problem uses observations only for the models that exist in both period t *and* in period 0. Models that exist only in the current period are ignored. Such an index may be referred to as a "matched-model" index.

Because computing equipment changes so rapidly, it was not possible to calculate a matched-model index using equation (1). Instead, matched models for 2 adjacent years were used to calculate an index where the base period is the first of the 2 years (that is, $t-1$):

$$(2) \quad I_{t-1,t} = \frac{\Sigma P_{it} Q_{it}}{\Sigma P_{i,t-1} Q_{it}}$$

An index for the entire period is calculated as a multiplicative "chain" of the adjacent-year indexes:

$$(3) \quad I_{0,t} = I_{01} \times I_{12} \times \ldots \times I_{t-1,t}.$$

This index is referred to as a "chain index of matched models."

The assumption underlying the matched-model procedure is that the mean price change associated with the introduction of new models (or the discontinuance of old ones) equals the mean price change observed for models that are common to both periods. In terms of the analysis of technological disequilibrium presented earlier in this article, one can state this assumption in an alternative and illuminating way: Use of the matched-model procedure assumes that prices of models embodying old technology adjust instantaneously, so that their quality-adjusted prices are equal to those of the models embodying improved technology. If the assumption holds, the price change in the matched models equals the unobserved price change implicit in the introduction of new models (or the discontinuance of old ones).

Three hedonic indexes

Use of hedonic methods does not require the assumption that the observed price change in the matched models equals the unobserved price change. Hedonic methods make use of all the price information. They can be employed in a number of ways. The present study explored three alternatives.

The composite index.—The "composite" index uses prices from the matched-model approach whenever models exist in both current and base periods and hypothetical prices for the models that did not exist in the base period from hedonic equations. If an "overlap" model (one that exists in both periods) is designated "i" and a model present in period t but not in period 0 is designated "j," then the composite index is:

$$(4) \quad I_{\alpha} = \frac{\sum_i P_{it} Q_{it} + \sum_j P_{jt} Q_{jt}}{\sum_i P_{i0} Q_{it} + \sum_j \hat{P}_{j0} Q_{jt}}$$

In this formula, $\hat{P}_{j0}$ denotes the estimate, taken from the hedonic equation, of the hypothetical price that the "missing" model would have commanded in the base period. Note that when 1982 is the base (as it is for all the present calculations) and a year subsequent to 1982 is "year t," then $\hat{P}_{j0}$ is the hypothetical price for a new model. When a year earlier than 1982 (such as 1977) is "year t," then $\hat{P}_{j0}$ is the hypothetical price for a discontinued model.

When there are multiple prices in the base period, some convention must be adopted in estimating $\hat{P}_{j0}$ because there is more than one price prevailing for any specified set of characteristics. In this study, the dominant technology—that is, the technology embodied by the majority of models shipped in the base period (1982)—was used to determine the hypothetical price $\hat{P}_{j0}$. In 1982, for processors, the majority of models shipped were from technology class 8; for disk drives, the majority were from technology class 4.

The characteristics price index.—In hedonic studies, one can identify more than one kind of price. The conventional concept is that of the price of the model. A second concept is that of the prices of the "characteristics." One can use the estimated characteristics prices—such as those shown in table 6—to construct a price index.

Given the formulation of the hedonic functions, the implicit dollar price of the kth characteristic possessed by the ith model of the mth technology class would be:

$$(5) \quad \hat{P}_{ikmt} = b_k \frac{P_{imt}}{x_{ikm}},$$

where b_k is the regression coefficient for the kth characteristic (estimated as constant for all years of the study), x_{ikm} denotes the quantity of the kth characteristic possessed by model i, and P_{imt} is the price for model i, of technology class m, at time t.

The characteristics price index is:

$$(6) \quad I_{\alpha} = \frac{\sum_k \sum_m \sum_i (\hat{P}_{ikmt})(x_{ikm} Q_{imt})}{\sum_k \sum_m \sum_i (\hat{P}_{ikm0})(x_{ikm} Q_{imt})},$$

where $x_{ikm} Q_{imt}$ denotes the quantity of the kth characteristic possessed by model i of the mth technology class in period t.

The regression index.—The regression index was created from the year dummies in the regressions. The price index number formula for the regression index is based on the expression for the regression coefficients for the year dummies.

Regression indexes may produce indexes that differ from alternative indexes that use hedonic methods.[16] (In the present case, for example, the regression index is unweighted, whereas the composite and characteristics price indexes employ shipments weights.) Several econometric shortcomings of the regression index have been pointed out.[17] However, because the regression index is so frequently encountered in other hedonic studies (including those for computing equip-

16. See Triplett and McDonald.
17. See Griliches.

ment), it was calculated in this study for purposes of comparison.

The four price indexes

In calculating the three hedonic indexes, the results from equation II' were employed for processors and the results from equation I for printers and displays. For disk drives, results from equation III' were used for the composite and characteristics price indexes; the regression index was based on equation II results. It was necessary to develop estimates of quantities shipped for the products in which models were distinguished by class. F processors, the quantity shipped o. .ach model was approximated from the annual tabulations of the stock of installed computers prepared by the International Data Corporation. For .sk drives, no information on shipments by model was available. Estimates of shipments by technology class were developed from information from International Data Corporation's studies and from *Disk Trend Reports*, published by J. Porter, for 1976-84. For printers, estimates were developed by class from information published by Dataquest, Inc. Except for processors where shipments were available by model, the prices for models within a class were averaged to obtain the estimated price for the class.

Table 7 shows the four price indexes calculated for each of the four products. The matched-model indexes decline much less than the three hedonic indexes. For processors, the matched-model index declines at an annual rate of 8.5 percent from 1972 1984, compared with declines in the hedonic indexes ranging from 17.6 percent to 19.2 percent. For disk drives, the matched-model index declines at an annual rate of 6.9 percent, compared with declines ranging from 12.6 percent to 16.9 percent. For printers and displays, the matched-model indexes decline much less than one-half as much as the hedonic indexes.

In the case of processors, the matched-model index does not reflect the introduction of semiconductor technology nor its subsequent rapid price declines. It also continued to miss the price declines associated with major improvements in the semiconductor technology during the 1978-80 period. All four indexes move roughly together in 1983-84, when no new technologies were being introduced. In the case of disk drives, the matched-models index does not reflect the adjustment to new technologies in 1975-78 and 1982-84. All four indexes move similarly during 1972-75 and 1978-82. In the case of printers, the four indexes move together through 1982. From 1982 to 1984, however, the hedonic indexes dropped 70 to 80 percent and the matched-model index only 10 percent. The latter misses the surge of the low-priced serial printers, the majority of which were imports. The matched-model index for displays shows little movement over the entire period.[18]

Table 7.—Price Indexes

[1982 = 100]

Year	Matched model	Hedonic: Composite	Hedonic: Characteristics	Hedonic: Regression	Matched model	Hedonic: Composite	Hedonic: Characteristics	Hedonic: Regression
	Processors				**Disk drives**			
1972	214.1	855.8	816.9	990.1	201.7	324.0	321.9	[illegible]
1973	214.6	865.8	924.5	1,647.5	200.9	313.4	328.6	[illegible]
1974	219.9	788.6	780.0	814.8	154.5	237.3	272.1	[illegible]
1975	228.9	703.7	721.0	792.1	143.4	222.0	260.2	[illegible]
1976	223.6	665.3	711.8	778.2	134.0	176.6	197.8	[illegible]
1977	183.5	473.6	505.3	499.0	133.5	144.3	156.7	[illegible]
1978	147.3	242.0	283.3	262.4	131.1	133.7	140.4	147.8
1979	136.4	204.9	242.8	242.6	107.7	108.4	111.7	111.4
1980	115.4	147.2	168.0	177.2	91.0	92.2	93.9	96.2
1981	111.1	119.8	125.4	112.9	92.9	92.6	94.1	96.6
1982	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1983	89.7	98.9	92.7	90.1	86.5	74.4	70.4	54.3
1984	73.7	80.8	80.8	77.2	85.1	54.4	53.6	46.5
Average annual rate of change:								
1972-77	-3.0	-11.2	-9.2	-12.8	-7.9	-14.9	-13.4	-18.9
1977-84	-12.2	-22.3	-23.1	-23.4	-6.2	-20.9	-12.1	-15.5
1972-84	-8.5	-17.8	-17.6	-19.2	-6.9	-12.6	-12.8	-16.9
	Printers				**Displays**			
1972	138.3	158.5	139.9	156.6	106.7	176.6	204.8	195.1
1973	139.0	152.8	136.2	158.9	105.9	175.9	206.3	196.1
1974	141.4	157.1	144.6	156.9	104.8	171.6	208.3	188.4
1975	140.1	142.9	129.0	134.0	105.0	158.5	198.7	173.2
1976	130.8	124.2	111.3	121.4	105.1	144.7	181.9	182.7
1977	121.4	116.4	111.8	119.7	103.6	148.3	174.8	159.6
1978	117.3	118.4	120.9	128.3	102.0	127.5	157.0	142.5
1979	107.1	109.5	106.8	103.6	101.4	111.0	124.1	122.0
1980	108.6	108.1	109.2	102.4	100.2	98.5	107.8	106.3
1981	101.9	102.6	98.6	98.5	99.6	94.7	102.0	100.6
1982	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1983	94.2	33.0	44.6	27.1	97.5	96.2	[illegible]	91.8
1984	90.3	27.0	37.8	20.6	[illegible]	77.4	78.7	78.6
Average annual rate of change:								
1972-77	-2.6	-6.0	-4.4	-5.1	-0.4	-4.1	-8.1	-4.0
1977-84	-4.1	-18.8	-14.4	-22.3	-2.0	-9.6	-10.8	-9.6
1972-84	-3.6	-13.7	-10.4	-15.6	-1.3	[illegible]	-7.7	[illegible]

18. Only price observations for three display models were available for 1972. All four price indexes, therefore, use the price relatives for these models to move the index from 1972 to 1973.

V. Conclusion

Although there may be widespread agreement that the present procedure for deflating expenditures on computing equipment is inadequate, a completely satisfactory alternative is not readily devised. Such a claim is certainly not made for the present study. Rather, it is more in the nature of a first step.

One deficiency of the study, and there are several, relates to its scope. Price indexes for personal computers and small disk drives were not produced. While work is underway on these products, the results are too tentative to report at this time. Another deficiency, and one less easily corrected, relates to the use of list rather than transaction prices. Ideally, a price index requires transaction prices. In particular, a thoroughly convincing case for the presence or absence of multiple prices requires the use of transaction prices.

The study demonstrated the inappropriateness of a matched-model index for computers. Even where there are no major technological shifts, such as for printers or displays, the matched-model index understated movements in prices. This understatement occurs because the matched-model index misses the replacement of old, higher priced models by new models, manufactured by improved methods and introduced at lower quality-adjusted prices.

In the authors' view, hedonic methods—applied at the system-component level, employing appropriate measures of characteristics, and expanded to deal with the problem of technologically induced disequilibrium—are useful for constructing quality-adjusted price indexes and represent an improvement over the present procedure for deflating expenditures on computing equipment.

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Abstracts of 4 papers on

hedonic price indexes

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PRICE AND TECHNOLOGICAL CHANGE IN A CAPITAL GOOD

A SURVEY OF RESEARCH ON COMPUTERS

By

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Abstract

The first commercial computers appeared around 1953-54. Three decades later, computer prices had fallen to one tenth of one percent of their introductory price level. The basis for this estimate is a review of nearly 30 separate hedonic, or quasi-hedonic, studies of computer processors and peripheral equipment. The studies use a variety of different data bases, cover various periods, and apply hedonic methodology in somewhat different ways. They offer a unique opportunity to assess the robustness of hedonic methods.

In the empirical portions of this survey, I first review the hedonic functions that were estimated by researchers. The assessment makes use of the economic theory of hedonic functions (summarized in the paper) and a rudimentary technological model of the production and use of computers. I then present price indexes covering 1953-84 and subperiods for computer processors, for peripheral equipment, and for computer "systems." These indexes are interpreted in the light of the theory of hedonic price indexes, also summarized in the paper.

This paper is forthcoming in Dale W. Jorgenson and Ralph Landau, eds., Technology and Capital Formation

Table of Contents

5 Concepts of Quality in Input and Output Price Measures: A Resolution of the User-Value Resource-Cost Debate

Jack E. Triplett

5.1 Introduction

The appropriate treatment of quality change is a very old issue in the analysis of productivity, the measurement of capital, and in many other areas of economic measurement.

Many economists have advocated a "user-value" criterion. Under this concept, a new computer which does more calculations would be taken as a higher quality machine (provided this aspect of performance is valuable to the computer user). Price indexes would be adjusted for the value to the user of the performance difference, regardless of what it cost to produce the new computer. Because the performance difference has been removed from the price measure, it shows up in quantity measures. Despite the wide acceptance of the user-value criterion (based on my own informal poll), to my knowledge no explicit theoretical justification has ever appeared.

The alternative "production-cost" criterion is associated with Edward Denison[1] and accepted in the national accounts. This concept requires that quality differences among various computer models be evaluated using data on the resource cost of building computers, regardless of their relative performance in use.

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Erwin Diewert, Edward Denison, Robert Gillingham, Dale Jorgenson, and Robert Pollak commented on an earlier draft of this paper, which was read at the Summer 1979 meetings of the Econometric Society in Montreal. Their helpful contributions are greatly appreciated, as are valuable conversations with colleagues B. K. Atrostic and Richard J. McDonald. The paper also benefited substantially from seminar presentations at the University of Michigan, Michigan State University, University of Oregon, University of Wisconsin, University of Washington, and Washington University. Views expressed are not intended as official policy statements of the Bureau of Labor Statistics.

One might suppose the conceptual issue to be of small practical importance. In equilibrium the two methods should yield similar numbers; and whether at equilibrium or not, most practical quality adjustment proposals make use of market price information (hedonic methods and traditional "linking" methods share this property). Prices reflect, obviously, both value and cost, rendering a distinction between them inoperative.

Yet counterexamples abound. Griliches (1964) and Jaszi (1964) discussed an example (birth-control pills) for which resource cost and user-value treatment of a technical change gave different measures. More recently, a controversy over the appropriate price index treatment of legally mandated smog control and safety devices again showed that the conceptual treatment of quality change has a perceptible impact on economic measurements, and that resolving the conceptual and theoretical issues has clear practical importance. Such examples provide the motivation for the present paper.

The approach followed combines theoretical specifications that have been developed for input price indexes (among which are closely related theories of the "true cost-of-living index" and the "true input cost index") and for output price indexes (sometimes known as "true output deflators") with previous work of the author (Triplett 1971*b*, 1973, 1976). The latter argues that "quality," in economics, can best be understood by shifting the analysis from goods space to characteristics space, along lines proposed by Lancaster (1971). The results show that the Denison–Bureau of Economic Analysis production-cost criterion is correct if what is wanted is a measure of the output of capital goods (as the numerator, e.g., in a productivity measure for a machinery-producing industry). However, the user-value criterion is correct if one wants to construct an input measure—for example, a measure of capital services for incorporation into a production function.

The plan of the paper provides separate treatments for input and output price indexes. The distinction between the two is made in the first section, along with some discussion that sets the stage. Section 5.3 sets out the input price index case, with output price indexes discussed in Section 5.4. Each of these two central sections is organized along parallel lines—a first subsection which sets out the basic theory of input and output price indexes (these sections could be skipped by readers who are familiar with the technical index number literature), followed by a second section which explains the concept of characteristics (done separately for input and output price indexes because the characteristics concepts differ according to their use). Subsections 5.3.3 and 5.4.3 contain the core of the paper—the statements of input and output price index theory in characteristics space and the demonstration that theory leads to two different treatments of quality change. Section 5.5 concerns two arguments the protagonists of alternative approaches have made against each other's positions; the characteristics-space price index theory developed in this paper shows that both are false, thus illustrating its utility for clearing up many of the murky disputes that have so long dominated the literature on quality change. The final Section 5.6 contains an overall perspective on the paper and its conclusions.

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Hedonic Functions and Hedonic Indexes

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Abstract

This paper summarizes the economic theory of hedonic functions and of the "constant-quality" price indexes that are computed from them. It is forthcoming in the New Palgrave Dictionary of Economic Theory.

ASSESSING THE QUALITY ERROR IN OUTPUT MEASURES: THE CASE OF REFRIGERATORS*

BY JACK E. TRIPLETT AND RICHARD J. MCDONALD

U.S. Bureau of Labor Statistics

This paper computes new indexes of output for refrigerators, using hedonic methods to adjust for quality change. The hedonic technique is applied in a new way (it is used to make quality adjustments to prices before they are used in the index), and the results are compared with those from methods used in previous hedonic investigations.

There are three major findings. (1) Overall (1960–1972), our hedonic deflated output series rise more rapidly than conventional measures, because the price indexes used for deflation rise more slowly. (2) The output measures fluctuate more than do output measures produced by conventional methods, because adding hedonic quality adjustments to WPI indexes moves them up in some years and down in others, and the resulting adjustments to the output series were positively correlated with changes in output. (3) Applying methods used in previous studies produces larger adjustments to the published indexes, suggesting that some of the differences noted in previous studies between hedonic indexes and official published indexes are related to computational methods, not to quality adjustment.

I. INTRODUCTION

Economists are accustomed to using output measures as if they corresponded to the physical quantities dealt with in the theory of production. However, most output data in the National Accounts and in other economic measurements are not based on physical quantities, but rather are derived from value data (such as value of shipments) through deflation by appropriate price indexes.

Under the deflation method for calculating real output, any error in the price indexes causes an equivalent error (of opposite sign) in the output measures. Quality change has long been acknowledged as a major potential source of price index error,[1] and may therefore bias measures of real output. The present paper was stimulated, in part, by the U.S. Productivity Commission's interest in determining whether official measures of output per employee hour were biased because of quality error in the output figures.

We chose to examine output, output per employee hour, and price measures for the major household appliances industry, partly because it is an important

*The research for this paper was supported, in part, by the U.S. Productivity Commission. We wish to acknowledge the contributions of David C. Lund and Dale A. Smith, who participated in the research, research assistance by Mary Burns and Susan G. Sammarco, and helpful comments from Zvi Griliches and Owen Sauerlender. The project could not have been completed without advice and guidance on construction of the original data series from the staffs of the BLS Office of Productivity and Technology and Office of Prices and Living Conditions. Views expressed are those of the authors and do not reflect official positions by the U.S. Bureau of Labor Statistics or the U.S. Productivity Commission.

[1]There is an extensive literature on this subject. See the bibliography in Griliches, ed. (1971), and also the survey by Triplett (1975).

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