Hedonic Pricing Models:
A Selective and Applied Review

By

Stephen Malpezzi[†]
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Edited by Kenneth Gibb and Anthony O'Sullivan
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[†]The Center for Urban Land Economics Research
The University of Wisconsin
975 University Avenue
Madison, WI 53706-1323
smalpezzi@bus.wisc.edu
http://www.bus.wisc.edu/realestate

Stephen Malpezzi is associate professor, and Wangard Faculty Scholar, in the Department of Real Estate and Urban Land Economics, and an associate member of the Department of Urban and Regional Planning, of the University of Wisconsin-Madison.

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Introduction

Twenty-five years ago, a few years before his *Housing Economics*, Professor Duncan Maclennan published a seminal paper on "Some Thoughts on the Nature and Purpose of House Price Studies." The pair of publications was well-timed: hedonic price modeling was in the process of moving from a cutting-edge empirical curiosity to a standard method of price index construction that has been used in literally thousands of studies since. [1]

In those two publications and in Maclennan's other papers on the topic, several important themes recur:

(1) The need to put hedonic models on a firm theoretical footing, including, but not limited to, consideration of the consequences of disequilibrium;

(2) To consider whether common specifications are complete, or reasonably so; including, but not limited to, questions of omitted variables, functional form, and the proper definition of a market; and the implications for our work of inevitably imperfect specifications;

(3) The design of the pricing model should fit the purpose at hand.

In this paper we selectively review hedonic price literature (and, briefly, some other related models) with a focus on these questions. The intent is to present ideas that are theoretically sound, so theory will be discussed; but our orientation is more towards the applied economist estimating these models, rather than specialized theorists. In particular, several other recent surveys such as Follain and Jimenez (1985 a) and Sheppard (1999) have discussed certain

[1] In drafting this highly selective review, I have benefited from many previous studies, only some of which are listed below. Even the list of other surveys is incomplete. In my own early work, I greatly benefited from Ball's (1973) classic review of early literature. Among many recent reviews, see especially Follain and Jimenez (1985 a) and Sheppard (1999).

theoretical and econometric issues which I will discuss only briefly below; readers are referred to those excellent reviews, which I am to complement rather than compete with.

What Is An Hedonic Price Index?

The method of hedonic equations is one way expenditures on housing can be decomposed into measurable prices and quantities, so that rents for different dwellings or for identical dwellings in different places can be predicted and compared. At its simplest, an hedonic equation is a regression of expenditures (rents or values) on housing characteristics. The independent variables represent the individual characteristics of the dwelling, and the regression coefficients may be transferred into estimates of the implicit prices of these characteristics.

The Fundamental Hedonic Equation

Hedonic regressions are basically regressions of rent or house value against characteristics of the unit that determine that rent or value. The hedonic regression assumes that we know the determinants of a unit's rent:

$$R = f\,(S, N, L, C, T), \text{ where} \qquad [1]$$

R = rent; (substitute V, value, if estimating hedonic price indexes for, say, homeowners using sales data);

S = structural characteristics;

N = neighborhood characteristics;

L = location within the market; and

C = contract conditions or characteristics, such as whether utilities are included in rent; and

T = the time rent or value is observed.

In this paper, we will refer to a hedonic model more or less along these lines as a "single equation" model or the "first stage" of a "two-stage" model. Two-stage models attempt to go beyond the initial estimation of an hedonic price surface, and in the second stage recover structural supply and demand parameters for individual housing characteristics.

Collapsing the vectors S, N, L. C into a larger vector X for the moment purely for notational convenience, and adopting a common (but sometimes criticized, see below) semi-logrithmic functional form, we re-write [1] compactly as:

$$R = e^{x\beta\varepsilon} \qquad [2]$$

so that

$$\ln R = X\beta + \varepsilon \qquad [3]$$

and we estimate:

$$\ln R = Xb + e \qquad [4]$$

where β and ε are of course the unknown true parameters, and b and e are actual estimates.

Now, by properties of logarithms, we can compute the predicted rent of a unit as $R = e^{xb}$; the price of an individual attribute, X_1, at a given level of X_1, given the level of the *other* m-1 attributes, $X_{i\neq1}$, can be calculated in dollars or pounds as:

$$P = e^{xb} \qquad [5]$$

Notice that with such a logarithmic specification, the dollars or pound price of X_1, or any other single characteristic, varies with the level of X_1, as well as with the level of other X_i;. Prices are nonlinear, an important point to which we return below.

A Potential "Second Stage" of the Hedonic Model: Recovering Structural Parameters

Much of the hedonic literature focuses on the basic hedonic relationship discussed in the preceding paragraphs. However, as papers discussed below by Rosen and others make clear, the hedonic equation discussed above is a reduced form. Under certain maintained hypotheses hedonic equations also admit of a structural interpretation: for example, if the supply of each and all characteristics is perfectly elastic, hedonic coefficients reveal demand for characteristics. But in most real-world contexts such a stringent maintained hypothesis is untenable. A number of papers attempt to recover structural parameters of demand and supply; or at least the demand for characteristics.

Specifically, because dollar or pound prices vary within a sample, if the level of characteristics also varies, we can now make use of this variation to estimate price elasticities for individual coefficients. For example, one specification that has been used in a number of papers is to presume a linear demand model in the second stage, after a first stage logarithmic hedonic. It is not uncommon to place prices of each characteristic on the left hand side, i.e., to assume an inverse demand relation, and to then estimate an equation for each characteristic, of the form:

$$\begin{aligned} P_{1i} &= D_i\alpha_1 + S_i\gamma_1 + \mu_{1i} \\ P_{2i} &= D_i\alpha_2 + S_i\gamma_2 + \mu_{2i} \\ &\vdots \\ P_{mi} &= D_i\alpha_m + S_i\gamma_m + \mu_{mi} \end{aligned} \qquad [6]$$

where $P_{1i} = e^{Xb}$ as before. Note that the money price of each of the m characteristics will vary from one observation to the next (will vary with i) because of the property of joint determination of prices discussed above. Armed with this variation in price, demand estimation can proceed.

Papers such as Follain and Jimenez (1985 b) and Witte, Sumka and Erekson (1979) present estimates of the demand for housing characteristics from such models. Vectors D and Z represent exogenous demand and supply shifters, such as income, or input costs (typically land). Often supply is assumed elastic, so that only demand shifters, like household income or family size, which are more readily available, are included. Thus, prototypical dataset for the first stage would include household level data on some dependent variable like rent or sales price; and on the characteristics S, N, L. and C. The prototypical dataset for the second stage would add information on household/unit level demand and supply shifters. Sometimes neighborhood-level data are appended to household level data[2].

A point now well understood by most experienced practitioners, but only occasionally discussed in the literature, is just how central a role functional form plays in the setup for most two-stage demand for characteristics models. Consider that if the first-stage hedonic regression were linear, there would be no variation in characteristic prices within the sample, and hence no second-stage system to estimate. In fact, it is the *difference* between hedonic functional forms, and second stage demand functional forms, that makes such systems potentially estimable. This point was made clearly by Nelson's (1982) insightful critique of Witte Sumka and Erekson's (1979) otherwise exemplary early study. WSE estimated logarithmic hedonic *and* logarithmic demand functions; Nelson showed that these were not in fact estimable, and Nelson suggests that the fact that WSE did obtain numerical estimates was, paradoxically, due to rounding error. On the other hand, models that involve (say) logarithmic first stage hedonic equations and linear second stage demand equations may be estimable (though subject to remaining problems discussed below).

[2] Some hedonic studies use aggregate data, e.g. average levels of variables over, say, Census tracts; but these have gone out of favor, partly because of aggregation bias (as discussed in Ball 1973) and partly because household/property level data has become more readily available.

Other Pricing Models

In this paper, we focus on hedonic pricing models. In order to place this class of models in context, we briefly discuss another pricing model, namely repeat-sales models, which are, as we shall see, related to hedonic price indices in a certain way.[3]

Repeat Sales Price Indexes

Repeat Sales indexes are estimated by analyzing data where all units have sold at least *twice*. Such data allow us to annualize the percentage growth in sales prices over time.[4] These are time series indexes in their pure form. They do not provide information on the value of individual house characteristics or on price levels. They have the advantage of being based on actual transactions prices, and in principle allow us to sidestep the problem of omitted variable bias. However, units that sell are not necessarily representative of all units. Sometimes it's difficult to tell whether a unit retains the same characteristics across time. For example, remodeling could cause a house's characteristics to change.

One way to motivate the actual technique used to construct the repeat sales index is to start by reconsidering the hedonic model. Consider a simple semi-log hedonic equation

$$\ln P = X\beta + \beta_1 T_1 + \beta_2 T_2 + \beta_3 T_3 + \beta_4 T_4 \qquad [7]$$

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[3] The classic reference on repeat sales is Bailey, Muth and Nourse (1963); while there were early applications such as Nourse (1963), they were greatly popularized by several papers by Case and Shiller, eg. (1987, 1989). Wang and Zorn (1997) provide a thorough review. There are also hybrid models that combine information from both hedonic and repeat sales estimates, see for example Case and Quigley (1991) and Quigley (1995). Green and Malpezzi (2001) presents further discussion of these as well as of simpler "models" such as simple medians of transactions, and Laspeyres, Paasche and Divisia time series indexes, and the very important user cost model of price determination.

[4] Actually, as we will see later in this section, with large samples regression techniques are used, but it amounts to the same thing.

where P is the value or rent for the unit, and where the vector X includes all the relevant characters, including a constant term; and the time dummies T_i represent periods that follow the initial base case period.[5]

The vector X represents a list of housing and neighborhood characteristics that would enter a hedonic equation. The vector T is a series of dummy variables representing the time periods under consideration. These could be months, quarters, or years, depending upon the type of data at hand.

Consider a house "A" that sells in periods 2 and 4 (period 0 is the base year). In period 2:

$$\begin{aligned} \ln P^A{}_2 &= X\beta + \beta_1 T_1 + \beta_2 T_2 + \beta_3 T_3 + \beta_4 T_4 \\ &= X\beta + \beta_2 T_2 \end{aligned} \quad [8]$$

since T_1, T_3, and $T_4 = 0$. And of course, by similar reasoning, in period 4:

$$\ln P^A{}_4 = X\beta + \beta_4 T_4 \quad [9]$$

Then, by subtraction:

$$\begin{aligned} \ln P^A{}_4 - \ln P^A{}_2 &= X\beta + \beta_4 T_4 - X\beta - \beta_2 T_2 \\ &= \beta_4 T_4 - \beta_2 T_2 \end{aligned} \quad [10]$$

This is for a representative housing unit which sells twice. Given a sample of such units, we want, in effect, the "average" β_4 and β_2. Recall that regression is, in effect, estimating a series of *conditional means*. Clearly, by subtraction the characteristics vector drops out, as do the dummy variables for periods in which no transaction takes place. Green and Malpezzi (2002) illustrate with sample data.

[5] For notational simplicity we suppress error terms. Careful consideration of house-specific errors and their "drift"

Another possible refinement is to consider the fact that the variance of these housing prices will generally increase over time. In today's econometric parlance, such prices are not *stationary*. Case and Shiller (1987) suggest a refinement to the Bailey, Muth and Norse model to mitigate such problems. The model we have just described is used as a first stage, and the residuals from this first stage model are used to construct weights which can be used to correct for heteroskedasticity using Generalized Least Squares.

Repeat sales indexes are currently much discussed in the literature because they have a number of advantages. First, no information is required on the characteristics of the unit (other than that an individual unit has not significantly changed its characteristics between sales). Second, the method can be used on data sets which are potentially widely available, at least in the U.S., and collected in a timely manner, with great geographic detail, but do not have detailed housing characteristics. For example, Case and Shiller's original work used data collected by the Society of Real Estate Appraisers. Much of the current U.S. research in this area has been undertaken by Fannie Mae and Freddie Mac, who have the advantage of large data sets with price data from a huge number of transactions nationwide.

The repeat sales method has a number of shortcomings as well.[6] First, while raw data have been widely available in the U.S., data is often harder to come by in other countries; including Britain. Second, even at its best, the method only yields estimates of price *changes*. No information on price levels, or place-to-place price index, is derivable from the repeat sales method. Of course, the repeat sales method can be combined with some other method; i.e., to update earlier estimates of price levels constructed using some other method. Also, because only

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over time is a hallmark of Case and Shiller's (1987) treatment.

[6] In addition to the references on repeat sales above, see Gatzlaff and Haurin (1997) and Gatzlaff, Green and Ling (1997). We also recommend the excellent review of repeat sales issues contained in Wang and Zorn (1997).

a few units transact twice over a given time period, the repeat sales method utilizes only a fraction of potential information on the housing market.

Other potential issues with repeat sales include the following. Units that transact frequently may be systematically different from units representative of the stock as a whole. How big this selection bias is depends partly on the purpose of the index. It certainly would be less of a problem if the purpose of the index were to track the prices of units available on the market.

The method also implicitly assumes that there is no change in the quality or quantity of housing services produced by the unit between periods. Of course, this assumption is always violated to some degree. Those who construct these indexes spend a lot of time weeding out units which have been upgraded using, for example, collateral data on building permits, or the limited structural information that may exist in the data set in use. The method also assumes that the coefficients on the underlying hedonic model remain constant: this is what allows the house characteristics to drop out of the model. But this assumption may also be questioned. For example, as families have gotten smaller, so too has the value of bedrooms, holding all else equal. Thus the hedonic coefficient for bedrooms in 1990 was almost certainly different from the coefficient in 1960, regardless of the particular market.

Hybrid Indexes

Hybrid indexes combine elements of two or more methods into one index. Such methods seek to take advantage of the strengths while minimizing the weakness of the constituent indexes. These could be time series, cross section, or both.

We have already alluded to hybrid models that combine hedonic and repeat sales methods. The essence of most hybrid models is to 'stack' repeat sales and hedonic models, and then to estimate the two models imposing a constraint that estimated price changes over time are equal in both models. In effect, such methods are weighted averages of the hedonic and repeat sales, and have the advantage of making use of all available information.

See Case and Quigley (1991), Quigley (1995), or Hill, Knight and Sirmans (1997) for good examples of hybrid indexes. Knight, Dombrow and Sirmans (1995) use seemingly unrelated regressions as a way to get more efficient coefficient estimates than the coefficient estimates obtained by OLS. But this procedure requires tedious matching of similar observations across years.

Hedonic Prices, and Related Pricing Models: An Abbreviated History

We noted in the Introduction that Professor Maclennan's best-known contributions to hedonic models appeared during the explosive growth in this research some twenty-five or so years ago. But, of course, there were a number of important precursor articles, as well as some notable contemporaneous literature. A full history of hedonic pricing models would be another paper, at least, but it is worthwhile to point out some of the other classics of the literature here.

Two oft-cited predecessors of Maclennan's work (and indeed of most of our work) were classic papers by Kelvin Lancaster (1966) and Sherwin Rosen (1974).[7] Focusing on the demand side of the market, Lancaster developed a sophisticated branch of microeconomic theory in which utility is generated, not by goods *per se*, but by *characteristics* of the goods. The applicability to housing is direct and obvious. I'm happy to be home, not so much to be in anything called a ‘house’, so much as to be in a warm dry place, with a quiet space for a comfortable chair, a functioning toilet or a hot bath should I require them, and some other rooms in the house to store stacks of papers or noisy children.[8] Thus, many hedonic studies cite Lancaster’s work, and justifiably so, for providing microeconomic foundations for analyzing utility-generating characteristics. Lancaster developed this theory using the tools of “activity analysis,” and did not limit his discussion to housing, but applied the concept to topics as diverse as financial assets, the labor-leisure tradeoff, and the demand for money. Perhaps Lancaster’s main contribution was to put center stage the still-slippery question of what exactly is the “good” housing, and how is it related to more fundamental characteristics?

Rosen’s (1974) article is the other oft-cited classic reference. Like Lancaster, Rosen focuses on characteristics, but has less to say about their utility-bearing nature and more about how suppliers and consumers interact within a framework of bids and offers for characteristics. Furthermore, while he did not much discuss functional form explicitly, Rosen’s model naturally leads to a nonlinear hedonic price structure. Many two-stage characteristic demand models, in particular, cite Rosen as their theoretical foundation, although Rosen had little to say about how the estimation of such structural parameters might be carried out.

Of course, there were other early theoretical papers that contributed to the development of this literature. One might point to Sir John Hicks’ (1939, 1978) elaboration of a ‘composite commodity,’ and to Fisher and Shell’s (1971) related ‘repackaging hypothesis,’ anticipating other early work by Triplett (1974) among others.

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[7] Interestingly, a casual perusal through stacks of papers suggest that UK scholars more often cite Lancaster as their fundamental reference, and U.S. authors more readily cite Rosen. Of course, both papers are often cited by writers from any country. See also Lancaster’s later elaboration of his ideas in Lancaster (1971).

[8] My stepsons view the problem somewhat differently, of course; in their childhood they certainly saw their rooms as refuges from noisy parents.

As regards the actual estimation of hedonic price models, the study most often cited as the pioneer was not a housing application at all, but an hedonic price index for automobiles developed by A. T. Court (1939). A later, but still early and influential automobile application was by Griliches (1961). Recently, Goodman (1998) and Colwell and Dilmore (1999) have filled in more of this history, telling us more about Court's early work as well as even earlier efforts by Wallace (1926) and Haas (1922). I have seen less discussion of which two-stage study has pride of place; Witte, Sumka and Erekson (1979) and Awan, Odling-Smee and Whitehead (1982) certainly helped get the ball rolling.

Theoretical Underpinnings of Hedonic Models

In this section, we present an abbreviated discussion of the theoretical underpinnings of hedonic models. Our discussion is short not because such underpinnings are unimportant, but because they have been so well discussed in two recent surveys, Follain and Jimenez (1985a), and Sheppard (1999), as well as several other papers cited in the next few paragraphs.

Bids and Offers

In essence, the hedonic relation arises because of heterogeneity. The model postulates a market containing a heterogeneous housing stock, which can only be modified at some cost, and heterogeneous consumers, some of whom put different valuations on a given bundle of characteristics ("house") than others. In fact, if housing units could, via some Star Trek-inspired machinery, be instantly and costlessly re-formed, then such costless repackaging would imply a linear structure of prices, where the dollar or pound price of each characteristic was simply added up, much as we add different shopping baskets full of groceries at the checkout to obtain their final price (Fisher and Shell 1971, Triplett 1974). It is ultimately the cost of adjustment that gives rise to the nonlinearities we observe empirically in housing prices.

Two Identification Problems

The identification problem – disentangling supply and demand, when faced with data only from their interaction – has bedeviled applied econometrics for years. In addition to the "usual" identification problem, two-stage hedonic analysis of the demand for characteristics faces an additional potential problem. The problem stems from the nonlinearity of the price structure. In garden-variety supply and demand models, individual consumers (and, often, suppliers) are *price-takers*, i.e., the price of the good is exogenous and the consumer chooses a quantity conditional on the reigning price. In nonlinear hedonic models, whether a simple logarithmic model or a more flexible form, prices and quantities are correlated by construction; in effect, consumers choose *both* a quantity of some characteristic and, implicitly, its price. The problem has been well-analyzed by Blomquist and Worley (1982) and Diamond and Smith (1985), and in the Follain and Jimenez (1985a) and Sheppard (1999) surveys; the reader is referred to their more discursive treatment. Suffice it to say that a number of studies have tried to tackle the problems using well-established techniques like instrumental variables. The problem, as ever, is in finding good instruments.

Equilibrium or Disequilibrium Models?

Another ubiquitous feature of housing markets is that their extremely costly adjustment processes make the usual simplifying assumptions that markets are in equilibrium when observed less tenable. In fact, the disequilibrium nature of the housing market is a recurring theme in

Maclennan (1975, 1982) and in many of his other papers. What are the consequences of this disequilibrium, and what can be done about it?

Several possible approaches to issues arising from disequilibrium are possible; in addition to the examples we include here, see also the chapters by Tu (2001) in this volume. One possible approach to the problem of disequilibrium is to estimate hedonic price functions using only observations in or near equilibrium. For example, a switching regression approach could be used, following generally the econometric methods described in, for example, Bowden (1978). Such approaches have been applied generally to the housing market, notably by Fair and Jaffee (1972); but their models are generally studies of the determinants of housing starts, not models of housing prices. An example of a later disequilibrium hedonic model is Anas and Eum (1984).

Several difficulties must be overcome to implement such a switching regression model. First, it is be necessary to specify the nature of the process that distinguishes equilibrium from disequilibrium observations; in a typical cross-section hedonic sample it is not always obvious how this would be done. Second, depending on the purpose of the hedonic index, successfully estimated equilibrium prices may or may not be what it is needed. For example, if one were constructing place-to place price indices to study, say, the cost of living or to set appropriate levels of housing subsidies, presumably one would wish the index to reflect actual prices paid in the market, whether in or out of equilibrium.

An alternative approach is to focus, not on the effects of disequilibrium on the construction of the price index, but rather on the effects of disequilibrium on our analysis of the relationship among the measured process, the amount of disequilibrium in a given sub market or period, and the adjustment process backs to equilibrium. Examples of studies that illustrate the principles include Abraham and Hendershott (1996), Drieman and Follain (2000), and Malpezzi

(1999), each of which studies prices over time. While different in important details, each of these studies essentially proceeds in three steps. First, estimate a time series price index.[9] Second, find some way of differentiating equilibrium prices; in these studies, prices were considered near equilibrium of price *changes* in the next period were near zero. With this subset of equilibrium prices, estimate their fundamental determinants, e.g based on income, recent growth, supply conditions etc.

Now for each period we have the price and index actually realized, and an estimate of the equilibrium price; thus we have an estimate of disequilibrium as well. The third and final phase of these studies is to study the determinants of the disequilibrium, including in these time-series studies the nature of the time path back to equilibrium, once the market has been "shocked out".

Single-Equation Models, or Structural Models?

Taken together, the problems discussed above – especially the identification problems, imperfect specifications, and the general non-robustness of coefficient estimates – suggest that reliable two-stage structural estimation of the demand for characteristics will be difficult. Qualitatively, that is the judgment we reached in the World Bank's housing demand research project, after investing significant resources attempting to develop characteristic demand models that would improve low cost housing project design (Follain and Jimenez 1985, Mayo and Gross 1987, Gross 1985).

That does not mean that there is no hope for developing useful models somewhat along these lines. Models of aggregate housing demand work well enough, despite undoubted problems (see Mayo 1981, Olsen 1987, Whitehead 1999). King (1975) presents an "in-between"

[9] Abraham and Hendershott and Follain use repeat sales indices, while Malpezzi combines hedonic and repeat sales indices. But whether hedonic or repeat sales indices are adopted, the general approach is the same.

model where housing is broken down into three categories – space, quality and location. Possibly further work along these lines would be fruitful.

Specification Issues

In this section, we discuss a number of practical issues such as which variables or functional form to use, or how to define a market. But first, we give a brief overarching comment explaining why these efforts so often seem ad hoc.

What Theory Tells Us About Specification

It is unfortunate, but the answer to "what *does* theory tell us about specification of hedonic models?" is, in brief, "Not much." Papers like Lancaster (1966) and Rosen (1974) elegantly present models of housing characteristics without having much to say about just what those characteristics are, or how exactly they are related to price.

Choice of Dependent Variable

Firstly, the choice of dependent variable is about choosing rent, or value, of the housing unit. Confusion sometimes reigns because of sloppy terminology, especially the common usage among real estate professionals, but also sometimes among housing economists (including the present author frequently enough, *mea culpa*). We often use the term "housing price" loosely as a synonym for "housing value," when of course it is a true "price" only under special conditions. But the usage is so entrenched by now that even housing economists generally relay on context to keep the meaning clear.

Of course it is well known that house rents and house values are related, though only in special cases proportionately so; papers such as Ambrose and Nourse (1993) and Phillips (1988) explore systematic variations in the relationship, or "capitalization rate." Papers that focus on rents must wrestle with problems stemming from the fact that different units have different lease terms or contract conditions. One notable example is the inclusion, or exclusion, of utility payments in rent. One common procedure is to obtain data on such utility charges for units where they are not included, and to add these charges to contract rent to 'gross it up,' so that rents in the sample are for comparable services. Lump sum payments (deposits or "key money") can be annualized with an assumed capitalization rate, and added to rent as in Malpezzi's (1998) study of key money paid for Cairo rent controlled units. Another is to use contract rent as the dependent variable, but to add dummy variables to the right hand side to indicate units with various utilities *included* in rent, so that the estimated coefficients "dummy out" the price of utilities, leaving a rental index net of utilities.

When estimating a hedonic regression on values, several other measurement issues emerge. A number of studies use owner or tenant estimates of the value of the unit. This gives rise to concern over the accuracy of such self-reported appraisals. Several papers have examined the issue with U.S. data, such as Kain and Quigley (1972), Follain and Malpezzi (1981), and Goodman and Ittner (1992). As yet I have found few non-U.S. studies addressing the issue. Early studies such as Kain and Quigley and Follain and Malpezzi suggested that while the *variances* of owner assessments are high, *biases* are modest; given enough data, hedonic models based on owner assessments would be reasonably reliable. But Goodman and Ittner's recent study finds larger biases, and suggests more caution.

Recent sales 'prices' (house values from observed recent transactions) have some obvious advantages as dependent variables. Recent transactions data may present less potential bias, and greater potential precision, than occupants' or owners' self-assessments. But recent sales are not necessarily a random draw from the total housing stock. If the purpose is to index the market of available units, this may not be of great concern, but if the purpose is to index the total stock, we much concern ourselves with possible selection bias. Several papers such as Gatzlaff and Haurin (1997) have tested the presence of such biases. Test statistics often reject the null, but so far most studies have found the magnitude of the bias to be modest.

Some datasets, like the American Housing Survey, truncate housing values; values over $300,000 are reported simply as "Over $300,000." Such dependent variable truncation can cause significant bias in results. Maddala (1983) presents some econometric techniques that attempt to attenuate the effects of such bias, when truncation is an issue.

Selection of Independent Variables

There are literally hundreds of potential housing characteristics that could be included on the right hand side. Butler (1982) and Ozanne and Malpezzi (1985) show that, unfortunately, coefficient estimates are not robust with respect to omitted variables. But interestingly, the same correlation between omitted and included variables that biases individual coefficient estimates can and often does help improved prediction from a "sparse" model. This suggests that hedonic applications that rely on overall predictions – like place-to-place price indexes, or cost-benefit analysis of housing subsidies – can proceed apace, even while papers that rely on interpretation of individual coefficients must be interpreted more cautiously.

While theory is not much of a guide, experience from many studies suggests that, whatever the purpose, a full dataset would include the following:

Rooms, in the aggregate, and by type (bedrooms, bathrooms, etc.)

Floor area of the unit

Structure type (single family, attached or detached, if multifamily the number of units in the structure, number of floors)

Type of heating and cooling systems

Age of the unit

Other structural features, such as presence of basements, fireplaces, garages, etc.

Major categories of structural materials, and quality of finish

Neighborhood variables, perhaps an overall neighborhood rating, quality of schools, socioeconomic characteristics of the neighborhood

Distance to the central business district, and perhaps to sub-centers of employment; access to shopping, schools and other important amenities.

Among characteristics of the tenant that affect prices: length of tenure (especially for renters), whether utilities are included in rent; and possibly racial or ethnic characteristics (if these are hypothesized to affect the price per unit of housing services faced by the occupant)

Date of data collection (especially if the data are collected over a period of months or years).

However this list, while still incomplete, is also general. Hocking (1976), Amemiya (1980) and Leamer (1978) are among useful guides to the actual selection of variables when theory provides little guide.

Functional Form in General

There is no strong theoretical basis for choosing the correct functional form of a hedonic regression (see Halverson and Pollakowski (1981) and Rosen (1974)). Follain and Malpezzi (1980), for example, tested a linear functional form as well as a log-linear (also known as semi-log) specification. But they found the log-linear form had a number of advantages over the linear form, detailed below.

The log-linear form is written:

$$\ln R = \beta_0 + S\beta_1 + + N\beta_2 + L\beta_3 + C\beta_4 + \varepsilon \qquad [11]$$

where ln R is the natural log of imputed rent, S, N, L and C are structural, neighborhood, locational, and contract characteristics of the dwelling,[10] and β_i and ε are the hedonic regression coefficients and error term, respectively.

The log-linear form has five things to recommend it. First, the semi-log model allows for variation in the dollar value of a particular characteristic so that the price of one component depends in part on the house's other characteristics. For example, with the linear model, the value added by a third bathroom to a one-bedroom house is the same as it adds to a five-bedroom house. This seems unlikely. The semi-log model allows the value added to vary proportionally with the size and quality of the home.

Second, the coefficients of a semi-log model have a simple and appealing interpretation. The coefficient can be interpreted as approximately the percentage change in the rent or value given a unit change in the independent variable. For example, if the coefficient of a variable representing central air conditioning is .219, then adding it to a structure adds about 22 percent to

[10] Without loss of generality, we've written one of each, when there will usually be several; or if you like, consider each (S, N, L, and C) as a *vector*.

its value or its rent. Actually, the percentage interpretation is an approximation, and it is not necessarily accurate for dummy variables. Halvorsen and Palmquist (1980) show that a much better approximation of the percentage change is given by e^b-1, where b is the estimated coefficient and e is the base of natural logarithms. So a better approximation is that central air will add exp (.219) – 1 = 24 percent.

Third, the semi-log form often mitigates the common statistical problem known as heteroskedasticity, or changing variance of the error term. Fourth, semi-log models are computationally simple, and so well suited to examples. The one hazard endemic to the semilog form is that the anti-log of the predicted log house price does not give an unbiased estimate of predicted price. This can, however, be fixed with an adjustment (see Goldberger (1968)). Finally, we note that it is possible to build specification flexibility into the right-hand side, using dummy (or indicator) variables, splines and the like (of which more shortly). This allows us a fair amount of flexibility in estimation, even with the semi-log form.

However, some authors have recommended more flexible forms than the semi-log. One common flexible form is the translog functional form, suggested by Christensen, Jorgensen and Lau (1971):

$$\ln R = \beta_0 + \sum_m \beta_m \ln X_m + \frac{1}{2}\sum_m \sum_n \gamma_{mn} \ln X_m \ln X_n \qquad [12]$$

where ln R again represents the log of rent (value can be substituted), and there are m characteristics denoted X. Examples of the translog form can be found in Capozza, Green and Hendershott (1996, 1997).

There is an even more general and flexible class of functions, within which linear, logarithmic and translog functions are subsumed; these flexible forms are carefully analyzed by Box and Cox (1964), and applied to hedonic prices by Halvorsen and Pollakowski (1981):

$$R^{\theta} = \beta_0 + \sum_m \beta_m X_m^{\lambda} + \frac{1}{2}\sum_m \sum_n \gamma_{mn} X_m^{\lambda} X_n^{\lambda} \qquad [13]$$

Such a form is quite flexible, with parameters θ and λ limiting the functional form.[11] For example, when θ and λ are both 1 and γ_{mn} are all identically zero, the Box-Cox form becomes a simple linear model. When θ and λ approach zero and γ_{mn} are all identically zero, the Box-Cox form becomes a logarithmic model. When θ and λ approach zero and but some γ_{mn} are nonzero, the Box-Cox form becomes the translogarithmic model.

This is a good place to reiterate the special role functional form plays in two-stage structural models of characteristics demand and supply. We have already noted this important fact: it is functional form – indeed, differences in functional form between stages – that makes the system of demand (or supply and demand) functions potentially estimable. Thus it is particularly problematic that theory yields little guidance to the functional form of the hedonic relationship, and only tenuous guidance to the functional form for second-stage estimation of the demand for characteristics.

Functional Form and Independent Variables

If data permit it, judicious use of dummy or indicator variables for independent variables can be useful. For example, entering a variable for the number of total rooms in (say) a semi-logarithmic hedonic regression constrains the percentage increase in value from a one unit

[11] As Halvorsen and Pollakowski point out, additional flexibility could be built in by allowing λ_m to vary with each independent variable; for computational convenience and degrees of freedom, all the hedonic applications Halvorsen and Pollakowski cite, and all those I am familiar with, constrain λ to be the same across all independent variables.

addition to a 3 room unit be the same as the percentage increase in value from a one-unit addition to a 6 room unit. If degrees of freedom permit it, at least the most common values can be coded as dummy variables, imparting more flexibility to the form. Malpezzi, Ozanne and Thibodeau (1980) provide additional details, e.g. how to code combinations of dummies and continuous variables. See also the classic review by Harold Watts (1964), and Suits (1984). The special topic of how to interpret dummy variables when the dependent variable is logarithmic is treated in Halverson and Palmquist (1980) and Kennedy (1981).

Of course dummy or indicator variables are not the only method we can use to incorporate flexibility on the right-hand-side. Continuous variables can be entered in quadratic (or cubic or even higher power) form; in fact, as much flexibility as needed can be readily constructed using piecewise spline techniques (Suits, Mason and Chan 1978).

Market, and Submarket, Definition

The definition and testing of submarkets is an important recurring theme in Maclennan's work. Housing markets are local and diverse, and hedonic price estimation requires careful consideration of submarkets.

We can roughly categorize submarket assumptions by threes. The first category comprises papers that define a market as an entire nation, or at least a large region, or perhaps a state. Linneman (1981) and Struyk (1980) fall into the category of national hedonic models, and Mills and Simenauer (1996) present a regional model. The second category, including much of my own work such as Malpezzi, Ozanne and Thibodeau (1980) and Follain and Malpezzi (1980) adopts the metropolitan area as the unit of analysis. Metropolitan areas are usually thought of as labor markets, more or less, and it is certainly appealing to consider housing markets and labor markets as roughly coincident. The third category, including many of Maclennan's own studies as well as papers such as Straszheim (1975) Gabriel (1984), Grigsby, Baratz, Galster and Maclennan (1985), Bourassa *et al*. (1999), Maclenna and Tu (1996), and Rothenberg, Galster, Butler and Pitkin (1991) examine submarkets below the metropolitan level. These may be segmented by location (central city/suburb), or by housing quality level, or by race or income level.

Studies that obtain large datasets and test for the existence of submarkets, usually by segmenting the sample and performing F-tests for equality of hedonic coefficients across sub-samples generally find them: the F-tests usually reject the null. Ohta and Griliches (1975) suggest a more conservative method, that focuses on changes in the standard error of the regression, in effect on how well the segmented model predicts.

Hedonic Specification: Art or Science?

Generally, there is art as well as science in the specification: choice of variables, functional form, and definition of submarket. Whenever sample sizes are small, and especially if the application will involve some prediction out of sample (as with, say, pricing rent controlled or subsidized units) it is often best to stick to a simple parsimonious specification, possibly using the metropolitan area as market definition. But if samples are large and well drawn, and especially if the focus of the hedonic model is a single metropolitan area, more flexible forms, and more careful attention to the delineation of submarkets will generally pay off.

It's somewhat surprising that the literature applying formal specification tests, such as those of Hausman (1978), is modest, since specification is such an issue in hedonic analysis. Burgess and Harmon (1982) is an interesting example that could be replicated further.

Examples of Applications

While there are many important and interesting theoretical issues related to hedonic models, some of which have been discussed above, our main interest ultimately is in understanding real world housing markets, and hence in applications. Space precludes an exhaustive review, but here we mention some examples. We will list a few representative applications mainly by topic; note also that while I know the U.S. literature best and cite it heavily, hedonic models are now truly universally applied. As previously cited work by Maclennan (1982) and Ball (1973) make clear, there is of course a long-standing, large and growing literature focused on the United Kingdom, as well as the rest of Europe and of North America; but in fact hedonic models have been applied in every permanently inhabited region of the globe.[12]

One of the first, and still most important, uses of hedonic models is to make general improvements in housing price indexes, whether time series, place-to-place, or panel data price indexes. Follain and Ozanne (1979), Chowhan and Prud'homme (2000), Englund, Quigley and Redfearn (1998), Follain and Malpezzi (1980), Hoffman and Kurz (2002), Moulton (1995), Malpezzi, Chun and Green (1998) and Tiwari and Hasgawa (2000) are among many examples of studies we could cite that basically aim to improve the precision of housing price benchmarks. Some hedonic studies have been undertaken to construct special-purpose housing price indexes, for example to improve the measurement of poverty thresholds (Short *et al*. 1999)

Hedonic prices have also been examined within cities. In addition to the submarket tests already discussed, many tests of the "standard urban model" of Alonso, Muth and Mills have been carried out. The standard model predicts a generally declining pattern of prices with distance from the center of the city. Competing models based on localized amenities, and models with multiple centers, have other predictions. Adair *et al*. (2000), Follain and Malpezzi (1981), Mozolin (1994), Soderberg and Janssen (2001) are examples of studies that examine intraurban variation in the price of housing using hedonic models. Perhaps unsurprisingly, results for the "standard model" are mixed; while there are some broad tendencies for house prices to fall with distance from CBD, amenities and sub-centers generally play an important role as well.

Hedonic models have also been used to develop measures of environmental quality. One common approach is to examine whether house prices increase when near environmental "goods," or fall when near "bads." Chesire and Sheppard (1995), Freeman (1979), Boyle and Kiel (2001), Des Rosiers and Therieault (1997), Din, Hoesli and Bender (2000), Garrod and Willis (1992 a, b) are among the many examples we could cite of this literature.

Many other interesting studies have been undertaken that focus on interpretations of individual coefficients. We must always be cautious in interpreting individual coefficients in light of the specification issues discussed above. With this caveat, a number of studies have examined racial, ethnic and socioeconomic differences in housing prices. Kain and Quigley (1972, 1975), Follain and Malpezzi (1981), Chambers (1992), Galster (1992) and Vandell (1995) are among many contributions to this strand of literature. Other studies have used hedonic age coefficients to measure depreciation, such as Malpezzi, Ozanne and Thibodeau (1987), Clapp and Giaccotto (1998), Goodman and Thibodeau (1995), and Shilling, Sirmans and Dombrow (1991).

Hedonic prices have been applied to market-rate units and then used to price subsidized or publicly provided units, in order to calculate the costs and benefits of different housing

[12] I hgave yet to find a hedonic suty of Antartica, but that's about the only region as yet unstudied.

subsidy programs. Olsen and Barton (1983), Buchel and Hoesli (1995), De Borger (1986), Quigley 1982), Satsangi (1991), Turner (1997), Gibb and MacKay (2001) and Willis and Cameron (1993) are representative examples. Closely related are studies that undertake regulatory cost benefit, including rent control; for example, Olsen (1972), Malpezzi (1998), Willis and Nicholson (1991).

Another important use of hedonic models is the appraisal of individual housing units. Appraisers and other property market professionals increasingly use hedonic models. They can be used to improve professional practice of appraisers and chartered surveyors (Dubin 1998), or for undertaking mass appraisal for property taxation and other public purposes; see Berry and Bednarz (1975), Lusht (1976), and Pace and Gilley (1990).

Hedonic models are also used to examine the capitalization of a wide range of amenities, as well as costs. One of the earliest literatures along these lines developed to study whether differential local tax rates were capitalized into house prices, following the model of Tiebout (1956), as extended by Oates (1981). After several false starts, papers by Edel and Sclar (1974) and King (1977) clarified the need to include measures of public services as well as taxes paid, and pointed out some important details of the correct functional form for such tests. Many subsequent studies have found such capitalization, on both the benefit and tax side; Zodrow (1983) provides a convenient review.

Despite the problems we've discussed above, many studies have tried to recover demand parameters (and sometimes supply and demand parameters) for individual housing characteristics, or groups of characteristics. Awan, Odling-Smee and Whitehead (1982), Pasha and Butts (1996), Witte, Sumka and Erekson (1982) and Kaufman and Quigley (1987) are among many examples we could cite.

Cutting-Edge Research on Hedonic Models

There is no end of applications that might not be thought of as cutting edge technically, that have not been done, that are potentially terribly useful. Many of these are extensions of the studies listed in the previous section. For example, we still need good benchmark data in many countries. Many housing programs and policies have yet to be submitted to rigorous cost-benefit analysis. Improving systems of mass appraisal remains important; for example, Russia is embarking on the development of a valuation system for all property in the entire country.

However in this section we will briefly indicate some of the cutting-edge areas in the technical sense. First, theoretical work continues apace to understand the foundations of hedonic models, and in particular to attempt to address some of the issues we have raise with two-stage structural models. In addition to the literature cited above, see for example Rouwendal (1992) and Epple (1987).

An alternative way to think about hedonic models is a two stage process of a different sort: samples used for hedonic estimation are not necessarily random draws from the population of houses, but are selected samples (especially when transactions-driven databases are used.) Ermisch Findlay and Gibb (1996), Jud and Seaks (1994) and Clapp, Giaccotto and Tirtiroglu (1991) are examples of studies that address the selection issue.

Another research strand is much less high-tech, but just as fundamental: the collection of more and better data for hedonic estimation (as well as other kinds of housing analyses). Guides to improved housing data collection include Malpezzi and Mayo (1994) and Malpezzi (2000).

In terms of functional form, one of the cutting-edge areas is to eschew parametric forms altogether. Semiparametric and nonparametric approaches can be found in Anglin and Ramazan (1996), Mason and Quigley (1996), Meese and Wallace (1991) and Pace (1993). Another approach is to use Bayesian restrictions on hedonic estimates, as outlined in Gilley and Pace (1995) and Knight, Hill and Sirmans (1992). But perhaps one of the most exciting areas for extending hedonic models is making use of the spatial structure of the data, using the emerging technology of geographic information systems and spatial autocorrelation. Among other recent contributions in this area, see Can (1992), Dubin (1992), Basu and Thibodeau (1998), Gillen, Thibodeau and Wachter (2001), Thibodeau (2002), and Pace and Gilley (1997). Thibodeau (2002), for example, finds a roughly twenty percent improvement in the fit of hedonic models using these techniques. Especially in applications regarding mass appraisal, these techniques are extremely promising.

While we have already cited individual hedonic studies from every continent, there is clearly scope for more and better international comparisons of housing prices. Recently there has been resurgence in cross-country comparisons, partly driven by the United Nations Centre for Human Settlements' Housing and Urban Development Indicators project.[13] Angel (2001) and Malpezzi and Mayo (1997) present data and comparisons, but these are generally based on simple median house prices from selected cities; more careful analysis, including estimating inter-country hedonic models, remains to be done.[14]

[13] Initially the indicators project was a joint World Bank-UNCHS research program, but the World Bank has effectively ceased research in housing and urban development in recent years. See the symposium in Netherlands Journal of Housing Research (e.g. Angel, Mayo and Stephens 1993, Maclennan and Gibb 1993, and Priemus 1993) for critical reviews of the project. See also Flood (1997).

[14] General discussion of cross-country comparisons include Malpezzi (1990), Annez and Wheaton (1984), Malpezzi and Mayo (1987), Maclennan and Gibb (1992), Harsman and Quigley (1991), Strassman (1991), and Boelhouwer and van der Heijden (1993).

Finally, while housing is the bulk of every country's real estate, and in fact typically over half a country's tangible capital, hedonic models have rarely been applied to other forms of real estate. Hedonic applications to commercial real estate will be of interest of their own sake; and the functional interdependence of residential and nonresidential real estate is often underappreciated by those of us focused on housing.

Conclusion

Over the past three decades, hedonic estimation has matured from a new technology to the standard way economists deal with housing's heterogeneity. Duncan Maclennan's own work in this area, and the work of his colleagues and students, has helped push back these frontiers. Despite this progress, many exciting applications and innovations in hedonic technique undoubtedly lie ahead.

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