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The Valuation of Real Capital: A Random Walk down Kungsgatan

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This paper analyzes the temporal pattern of prices for single-family housing. We estimate models of house price dynamics using a repeat sales framework, and we use the results to test for a random walk in asset prices. For eight large samples of housing transactions, representing essentially all house sales in Sweden during a 12-year period, we reject the hypothesis that house prices follow a random walk in favor of a model of first-order serial correlation.

Key Words: housing markets; random walk; hedonic models; repeat sales models; hybrid models.

I. INTRODUCTION

The difficulties in measuring the prices of real capital such as single-family homes, apartments, and office buildings are well known. These difficulties stem, in part, from the heterogeneity of these non-standard assets and the infrequency of observed transactions on individual properties. Nevertheless, the accurate measurement of real estate price trends is important for both practical and theoretical purposes.

Housing, for example, represents more than half of the U.S. private capital stock, or $5.87 trillion (U.S. Department of Commerce, 1997). If, as some have

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proposed, the appreciation of housing were included in measures of national savings, a 2% annual increase in house values would represent an increment of $117 billion in private savings (Case and Shiller, 1987). Thus, the movement of housing prices over time may have important macroeconomic implications (see Meen, 1995).

Housing price trends are of obvious practical importance to market participants. For individual consumers, home equity typically represents the largest component of net worth (U.S. Department of Commerce, 1995). In the U.S., owner-occupied housing also provides security for roughly $3 trillion in mortgage debt. As a result, banks, lending institutions, and the larger investment community have a keen financial interest in the accurate measurement of price movements (Hill *et al.*, 1999). Finally, housing price variations affect the costs of public programs designed to encourage home ownership as well as the calculation of transfer payments and regional cost-of-living indexes (Quigley, 1995).

The accurate measurement of asset price trends is also important for developing and testing many aspects of economic theory. For example, a burgeoning literature in corporate finance analyzes the irreversibility of investment decisions and models the value of delaying such decisions while obtaining additional information. The conclusions of these models are sensitive to the specification of the stochastic process underlying price changes, since it is these changes that measure the opportunity costs of investment (Pindyck, 1991). Applications of this line of research to real estate have tested the efficiency of housing markets by modeling the predictability of investment returns and analyzing the autocorrelation in housing prices and in returns to housing investments (Case and Shiller, 1989). These results are also highly sensitive to the measurement of housing price dynamics (Englund *et al.*, 1999a).

In spite of this widespread interest, methodologies for estimating real estate prices remain underdeveloped. Two general strategies have been employed to make price imputations, “hedonic” methods (as well as extensions to so-called “hybrid” models) and “repeat sales” methods. These latter methods, in particular, underlie most price series currently used in government and commercial applications.

In this paper we extend the repeat sales methodology and test some of its underlying assumptions using a unique body of data on housing sales in Sweden. More specifically, we test the stochastic specification and maintained hypotheses of the model. Following a brief review of methodology in Section II, we describe the unique body of data available to test the model in Section III. Section IV reports the results of these tests, and Section V offers concluding remarks.

II. METHODOLOGICAL ISSUES

The original hedonic regression techniques (e.g., Kain and Quigley, 1970) rely upon cross-sectional or panel data on housing sales to relate the observed prices of houses to their physical attributes, geographical location, neighborhood amenities, and some measure of time. The coefficients in this regression are interpreted as the implicit prices of housing attributes.

To be specific, let P_{it} be the selling price of house i at time t, let V_i be the vintage (i.e., year built) of house i, let D_{it} be the age of house i at year t (i.e., t-V_i), and let $\mathbf{X}_{it}$ be a vector of other house characteristics. Let $\mathbf{T}_{ij}$ be a vector of dummy variables which equal 1 for the period j in which the house is sold, and 0 otherwise. The hedonic model is then

$$\log P_{it} = \beta\,\mathbf{X}_{it} + \beta_{\mathrm{v}} V_i + \beta_{\mathrm{d}}\, D_{it} + \Pi \mathbf{T}_{ij} + \nu_{it}, \tag{1}$$

where ν_{it} is an error term. As noted above, the coefficients β represent the implicit prices of housing attributes. Here, β_{v} is the rate of technical progress in construction vintage, and β_{d} is the depreciation rate. The coefficients Π represent the price index, or the effects of time upon the prices of dwellings after controlling for qualitative and quantitative characteristics. Note that in the absence of a panel of houses, the effects of vintage, depreciation, and time cannot be separately identified. There are other drawbacks to the hedonic approach summarized in Eq. (1). For example, neither the functional form of the relationship nor the variables to be included in the model are known with certainty.

The repeat sales model, on the other hand, attempts to avoid these problems by holding the unit of observation constant and concentrating on multiple sales of the same set of houses. For houses first sold at time τ and later at time t, Eq. (1) implies

$$\log P_{it} - \log P_{i\tau} = \beta(\mathbf{X}_{it} - \mathbf{X}_{i\tau}) + \beta_{\mathrm{d}}(t - \tau) + \Pi\, \mathbf{T}^*_{it\tau} + (\nu_{it} - \nu_{i\tau}), \tag{2}$$

where $\mathbf{T}^*_{it\tau}$ is a vector of dummy variables which equal $+1$ if the second sale occurred in period t, -1 if the first sale occurred in period τ, and zero otherwise. If the characteristics of houses remain unchanged between τ and t (i.e., $\mathbf{X}_{it} = \mathbf{X}_{i\tau}$), the model can be further simplified. The log of the change in housing prices is related to the dates of the two sales and the time interval between sales,

$$\log(P_{it} \,/\, P_{i\tau}) = \beta_{\mathrm{d}}(t - \tau) + \Pi\, \mathbf{T}^*_{it\tau} + \varepsilon_i. \tag{3}$$

A major disadvantage of this model is its restriction to dwellings which have been sold more than once within a sample period. These samples are probably not representative of housing markets in the short or medium run, but there is little systematic evidence on this topic (Gatzlaff and Haurin, 1993; Englund *et al.*, 1999b). Curiously, the repeat sales model summarized in Eq. (3) makes no use of information on single sales of dwellings, and it ignores all information on the physical characteristics of dwellings. This omission seems wasteful of housing market information.

For these reasons, a variety of hybrid models have been proposed (e.g., Case and Quigley, 1991; Quigley, 1995). These hybrid models typically combine both single and repeat sales of dwellings in common statistical analysis. These models are reviewed by Hill *et al.* (1999) and Englund *et al.* (1998).

Appropriate estimation of the repeat sales equation (3) or any hybrid variant depends on the properties of the underlying stochastic errors. In particular, if we assume that the errors in the hedonic model follow an autoregressive process, i.e.,

$$\nu_{it} = \rho \nu_{i,t-1} + \eta_{it}, \tag{4}$$

where

$$\begin{aligned} \mathrm{E}[\eta_{it}] &= 0 \\ \mathrm{E}[\eta_{it}]^2 &= \sigma^2_{\eta i}, \end{aligned} \tag{5}$$

then the properties of the error structure in Eq. (3) are determined. For example, if $\rho = 1$, then

$$\nu_{it} = \nu_{i,t-1} + \eta_{it}, \tag{6}$$

and the errors in the hedonic model follow a random walk. Thus, the errors in the repeat sales model are

$$\varepsilon_i = \nu_{it} - \nu_{i\tau} = \sum_{j=\tau}^{t} \eta_{ij}. \tag{7}$$

From Eq. (5),

$$\begin{aligned} \mathrm{E}[\varepsilon_i] &= 0 \\ \mathrm{E}[\varepsilon_i]^2 &= (t - \tau)\, \sigma^2_{\eta i}. \end{aligned} \tag{8}$$

Alternatively, if $-1 < \rho < 1$, then

$$\begin{aligned} \mathrm{E}[\varepsilon_i] &= 0 \\ \mathrm{E}[\varepsilon_i]^2 &= 2\, \sigma^2_{\eta i}\, (1 - \rho^{t-\tau}) \,/\, (1 - \rho^2). \end{aligned} \tag{9}$$

Recently, Hill *et al.* (1999) proposed a specific test of the null hypothesis that $\rho = 1$ against the alternative hypothesis that $-1 < \rho < 1$. The test is motivated by noting that a transformation of Eq. (3) is

$$\log(P_{it}/P_{i\tau})/(t-\tau)^{1/2} = \beta_{\mathrm{d}}(t-\tau)^{1/2} + \Pi \mathbf{T}^{*}_{it\tau}/(t-\tau)^{1/2} + \varepsilon_i/(t-\tau)^{1/2}. \qquad (10)$$

In this transformed model, the error term has variance

$$\begin{aligned} \mathrm{E}[(\varepsilon_i)^2/(t-\tau)] &= \sigma^2_{\eta i}, \quad \text{if } \rho = 1 \\ &= 2\sigma^2_{\eta i}\,(1-\rho^{(t-\tau)})/[(1-\rho^2)(t-\tau)], \quad \text{if } -1 < \rho < 1. \end{aligned} \qquad (11)$$

If the errors in the hedonic model, Eq. (1), follow a random walk, then the error variances in the transformed repeat sales model, Eq. (3) or Eq. (10), will be unrelated to the time interval between sales. Alternatively, if the hedonic errors follow a first-order autoregressive process, the repeat sales error variance will be inversely related to $(t-\tau)$, the time interval between sales.

In a model of multiplicative heteroskedasticity, for example, the hypothesis test can be formalized as

$$\begin{aligned} \mathrm{var}\,[(\varepsilon_i)/(t-\tau)] &= \sigma^2_{\eta i}\,(t-\tau)^{\gamma} \\ &= \exp\{\gamma_0 + \gamma_1 \log(t-\tau) + \delta \mathbf{Z}_i\}, \end{aligned} \qquad (12)$$

where **Z** is a vector of characteristics of houses which affect the variance of errors in house prices (e.g., unusual features such as size, design, or quality). A test for the presence of a random walk in housing prices is a test of the hypothesis that $\gamma_1 = 0$ against the alternative that $\gamma_1 < 0$. Equations (3) and (12) may be estimated sequentially by generalized least squares or jointly by maximum likelihood techniques as suggested by Hill *et al.* (1999) and as discussed in detail in Judge *et al.* (1988).

III. THE DATA

The random walk assumption is tested using a unique body of data reporting nearly all arm's length sales of single-family detached housing in eight metropolitan regions of Sweden over a 12-year period. The raw data record the date and selling price of each transaction as well as a wide variety of characteristics for each property at the time of sale. (These data are described in more detail in Englund *et al.*, 1998.)

The data set is unique in both its detailed information on each housing unit and its identification of repeat sales. Table I summarizes the sample for this paper. It consists of 136,822 transactions on 63,297 properties. The sample includes all repeat sales for which the observable characteristics of dwellings remained unchanged between sales, or about 68% of all repeat sales. This group was selected through an extensive comparison of the reported characteristics for dwellings sold more than once during the January 1, 1981 to June 30, 1993

TABLE I
Sample Sizes and Sample Definition, House Sales in Regions I–VIII, 1981:I–1993:II

	Region								
	I	II	III	IV	V	VI	VII	VIII	Total
A. Dwellings									
All house sales	59,330	75,193	42,837	70,890	84,697	48,086	18,396	24,534	423,963
Single sales	47,100	59,170	34,013	54,806	67,014	38,440	14,455	19,009	334,007
Repeat sales	12,230	16,023	8,824	16,084	17,683	9,646	3,941	5,525	89,956
Repeat sales of unchanged properties	8,227	11,643	6,373	11,468	12,263	6,849	2,744	3,730	63,297
B. Transactions									
All sales	74,077	94,943	53,527	90,741	106,147	59,821	23,289	31,349	533,894
Single sales	47,100	59,170	34,013	54,806	67,014	38,440	14,455	19,009	334,007
Repeat sales	26,977	35,773	19,514	35,935	39,133	21,381	8,834	12,340	199,887
Repeat sales of unchanged properties	17,712	25,280	13,758	24,768	26,524	14,732	5,959	8,089	136,822

sample period. All dwellings with characteristics that changed between sales (i.e., all dwellings for which $\mathbf{X}_{it} \neq \mathbf{X}_{i\tau}$) were eliminated from the sample This procedure is described further in Englund *et al.* (1999a).

A detailed inspection of the raw data reveals that the fraction of dwellings which remain unchanged between sales declines substantially and systematically with the time interval between sales. Table II describes the distribution of these properties and transactions by the number of observed sales. As indicated in the table, most of the sample is generated from properties that sell twice. However, nearly 14% of the transacting properties that were unchanged between sales sold three or more times, generating 27,932 or about 20% of such transactions.

IV. RESULTS

Equations (3) and (12) can be estimated sequentially by generalized least squares, or jointly by maximum likelihood methods. Tables III and IV report the coefficients from joint estimation of the two equations by the maximum likelihood estimation.[1] Though not reported, the set of coefficients on the 51 dummy variables representing quarter of sale is highly significant.

[1]The maximum likelihood estimator of the coefficients and their asymptotic variance covariance matrix were computed using SHAZAM. Similar results were obtained using a two-step feasible generalized least-squares procedure. This procedure required using asymptotic standard errors for estimators of γ_1 and δ, as described in Judge *et al.* (1988, pp. 366–370). Sample sizes for statistical models in Tables III and IV differ slightly from those reported in Tables I and II.

TABLE II
Sample Sizes and Sample Definition, House Sales in Regions I–VIII, 1981:I–1993:II

	Region								
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Repeat sales of unchanged properties	8,227	11,643	6,373	11,468	12,263	6,849	2,744	3,730	63,297
2	7,154	9,959	5,477	9,856	10,539	5,909	2,353	3,198	54,445
3	916	1,456	789	1,426	1,484	852	332	460	7,715
4	134	174	99	156	210	84	46	54	957
5	20	34	7	27	27	2	8	12	137
6 and above	3	20	1	3	3	2	5	6	43
B. Transactions									
Repeat sales of unchanged properties	17,712	25,280	13,758	24,768	26,524	14,732	5,959	8,089	136,822
2	14,308	19,918	10,954	19,712	21,078	11,818	4,706	6,396	108,890
3	2,748	4,368	2,367	4,278	4,452	2,556	996	1,380	23,145
4	536	696	396	624	840	336	184	216	3,828
5	100	170	35	135	135	10	40	60	685
6 and above	20	128	6	19	19	12	33	37	274

TABLE III
Tests of Random Walk in House Prices, Joint Estimation of Eq. (3) and Eq. (12)

	Region							
	I	II	III	IV	V	VI	VII	VIII
A. Eq. (12)								
γ_0	−4.057	−4.375	−4.154	−3.829	−3.548	−4.231	−4.406	−3.773
	(−81.75)	(−107.40)	(−72.15)	(−94.36)	(−92.05)	(−78.17)	(−53.06)	(−53.94)
γ_1	−0.605	−0.536	−0.560	−0.555	−0.829	−0.510	−0.359	−0.701
	(−25.90)	(−27.69)	(−20.74)	(−28.23)	(−43.83)	(−19.91)	(−8.96)	(−20.82)
B. Eq. (3)								
β_d	0.025	0.025	0.027	0.032	0.027	0.028	0.025	0.025
	(25.05)	(32.92)	(23.23)	(30.93)	(32.45)	(24.33)	(12.98)	(15.52)
Log-likelihood function	10,744.5	16,812.5	8,394.9	12,850.0	15,322.8	8,980.5	3,483.3	4,902.1
Number of observations	8,796	12,879	6,835	12,360	13,261	7,422	3,061	4,227

Note. *t*-ratios appear in parentheses. The coefficients π are not reported.

TABLE IV
Further Tests of Random Walk in House Prices, Joint Estimation of Eq. (3) and Eq. (12)

	Region							
	I	II	III	IV	V	VI	VII	VIII
A. Eq. (12)								
γ_0	−4.471	−4.323	−4.169	−3.452	−3.558	−4.366	−4.407	−3.798
	(−60.83)	(−74.10)	(−51.30)	(−61.07)	(−63.49)	(−56.85)	(−37.05)	(−35.06)
γ_1	−0.611	−0.505	0.541	−0.541	−0.813	−0.494	−0.331	−0.616
	(−26.17)	(−26.09)	(−20.05)	(−27.53)	(−42.95)	(−19.27)	(−8.27)	(−18.30)
δ Living area ('000 m^2)	0.001	−0.004	−0.003	−0.006	−0.003	−0.003	−0.005	−0.008
	(2.73)	(−11.93)	(−7.10)	(−18.78)	(−9.40)	(−6.10)	(−6.35)	(−12.32)
Parcel area ('000 m^2)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
	(16.48)	(25.81)	(16.59)	(19.01)	(25.78)	(19.99)	(14.99)	(25.36)
B. Eq. (3)								
β_d	0.025	0.024	0.025	0.030	0.025	0.026	0.024	0.022
	(25.70)	(33.00)	(22.83)	(30.93)	(32.29)	(24.11)	(13.09)	(16.21)
Log-likelihood function	10,903.7	17,210.7	8,546.5	13,247.9	15,648.6	9,184.4	3,572.9	5,285.7
Number of observations	8,796	12,879	6,835	12,360	13,261	7,422	3,061	4,227

Note. *t*-ratios appear in parentheses. The coefficients π are not reported.

Table III corresponds to the simplest model in which the multiplicative heteroskedasticity is generated only by the time interval between sales. For this model, the coefficient on the time interval in Eq. (12) is precisely estimated and is significantly different from zero, suggesting that the null hypothesis that this coefficient is zero should be rejected. (The *t*-ratios, reported in parentheses, far exceed the critical value of roughly −2.3 for *t* at the 0.01 level for a one-tailed test.)

Table IV tests the hypothesis that the variance in selling prices increases with the size of the properties. There is strong evidence that the variance increases with the lot size or parcel area of the properties, but there is no evidence that the variance in prices is systematically related to the interior size of the dwellings.[2] This evidence suggests strongly that the hypothesis that housing prices follow a random walk can be rejected in favor of the hypothesis of first-order serial correlation.[3]

[2]We also tested the model with the addition of several other variables indicative of higher quality dwellings (e.g., the existence of a fireplace, a sauna, a tile bath, a high-quality kitchen). There is little evidence to suggest that these measures are systematically related to the variance in sale prices.

[3]Somewhat weaker evidence on the same point is presented in the Appendix tables AI and AII. These tables report estimates of models that are analogous to those reported in Tables III and IV but exclude the terms $(t - \tau)$ from Eq. (3), that is, models which do not estimate a depreciation rate for housing. In these models, the coefficient γ_1 is highly significant and negative. We have no reason

As indicated previously, the set of coefficients Π on the time variables in Eqs. (3) and (10) is highly significant. These coefficients form the basis for a repeat sales housing price index during the sample period. Given the logarithmic form of Eq. (1), the index (I_t) at each time t is simply

$$I_t = \exp \Pi_t. \tag{13}$$

Figure 1 presents the estimated price index for Stockholm and the 95% confidence interval for that index. The index is normalized to a value of 1.0 for the first quarter of 1981. Figure 1 provides a qualitative summary of the course of housing price development which is familiar to all Stockholmers, to most Swedes, and to many northern Europeans. Prices were stable and gently rising through 1987. This trend was followed by a sharp run up in price through 1991 and a sudden collapse thereafter. This general pattern is consistent with less volatile price development in other regions of Sweden and in other Nordic countries such as Finland (see Englund *et al.,* 1998 for a discussion).

V. CONCLUSIONS

This research tests one of the important maintained hypotheses in the computation and interpretation of the so-called weighted repeat sales index of real estate prices, namely, the hypothesis that housing prices follow a random walk. If the hypothesis is correct, the procedures followed by government agencies and by private firms in producing indexes of capital prices are vindicated.[4] If the maintained hypothesis is correct, moreover, the basis for several proposed hybrid indexes of property values is undermined. For example, the methods proposed by Quigley (1995) and the methods proposed by Hill *et al.* (1997) are not well defined if prices follow a random walk.

We conduct a rather pure statistical test for a random walk in housing prices against the alternative of first-order serial correlation. The test relies on a sample of dwellings carefully selected from a uniquely rich database to ensure that the characteristics of dwellings in the analysis are unchanged during the interval between sales. When this test is conducted using a sample of transactions on unchanged properties in eight regions of Sweden during the 1981–1993 time period, the random walk in housing prices assumption is rejected by a wide margin.

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to believe that depreciation is zero in housing, however, so we place more credence in the results reported in Table III.

[4]In the United States, real estate price indexes based on the weighted repeat sales model are published quarterly by the Office of Federal Housing Enterprise Oversight. Indexes based upon similar methods are marketed by Case-Shiller-Weiss, Inc., Mortgage Research Analysis Corp., and TRW, Inc., among others.

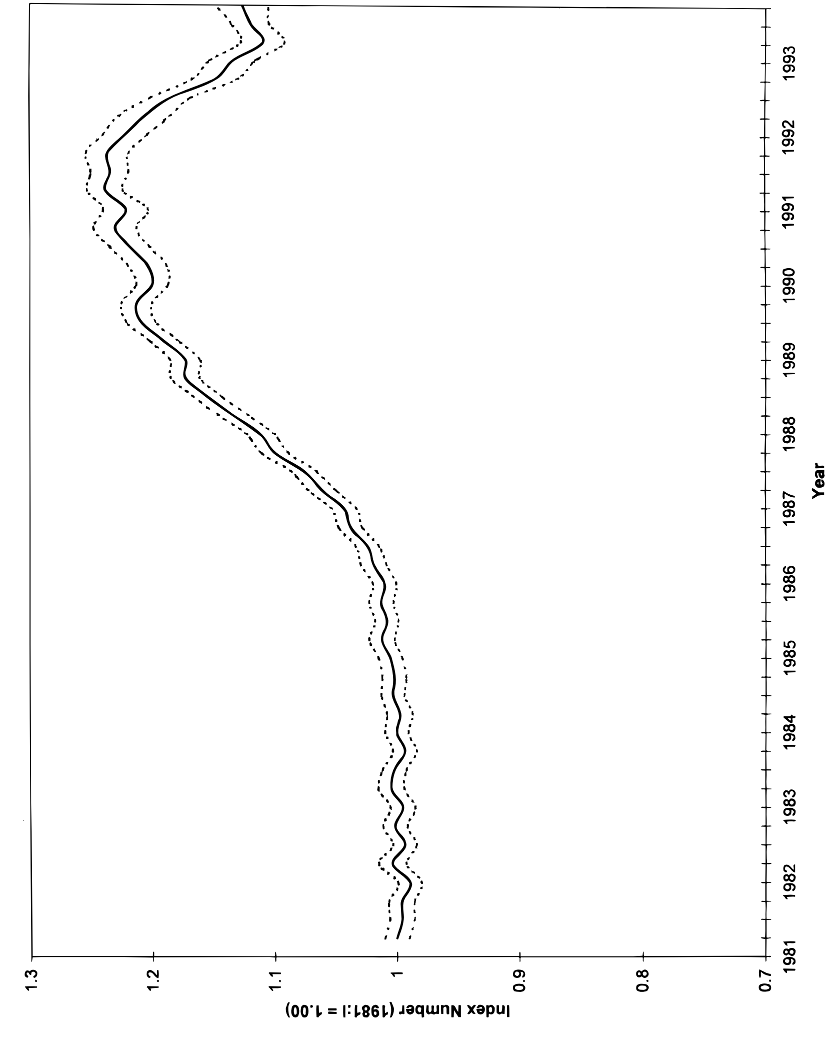

FIG. 1. Quarterly housing price index for Stockholm (solid line) and 95% confidence interval (stippled line).

Rejection of a random walk in housing prices casts doubt on the repeat sales models which underlie most commercial applications. This finding also casts doubt on the validity of government-sponsored regional price indexes such as those recently produced in the United States by the Office of Federal Housing Enterprise Oversight. The evidence further suggests that hybrid models combining both single and repeat sales should be used more prominently in estimating house price indexes.

APPENDIX

TABLE AI
Tests of Random Walk in House Prices, Joint Estimation of Eq. (3) and Eq. (12), Ignoring Depreciation

	Region							
	I	II	III	IV	V	VI	VII	VIII
γ_0	−4.016	−4.288	−4.054	−3.720	−3.501	−4.104	−4.299	−3.672
	(−80.94)	(−105.30)	(−70.42)	(−91.66)	(−90.85)	(−75.83)	(−51.77)	(−52.50)
γ_1	−0.591	−0.539	−0.571	−0.573	−0.814	−0.535	−0.386	−0.724
	(−25.29)	(−27.85)	(−21.18)	(−29.15)	(−43.01)	(−20.89)	(−9.64)	(−21.51)
Log-likelihood function	10,441.7	16,292.4	8,135.3	12,389.7	14,816.5	8,696.3	3,401.5	4,785.3
Number of observations	8,796	12,879	6,835	12,360	13,261	7,422	3,061	4,227

Note. *t*-ratios appear in parentheses. The coefficients π are not reported.

TABLE AII
Further Tests of Random Walk in House Prices, Joint Estimation of Eq. (3) and Eq. (12), Ignoring Depreciation

	Region							
	I	II	III	IV	V	VI	VII	VIII
γ_0	−4.365	−4.187	−4.027	−3.330	−3.469	−4.193	−4.276	−3.684
	(−59.39)	(−71.76)	(−49.55)	(−58.91)	(−61.90)	(−54.61)	(−35.95)	(−34.01)
γ_1	−0.595	−0.510	−0.552	−0.552	−0.792	−0.513	−0.354	−0.637
	(−25.48)	(−26.34)	(−20.46)	(−28.08)	(−41.84)	(−20.00)	(−8.84)	(−18.91)
δ Living area	0.001	−0.005	−0.004	−0.006	−0.004	−0.003	−0.005	−0.008
('000 m^2)	(1.54)	(−12.78)	(−7.96)	(−19.20)	(−10.56)	(−7.13)	(−6.54)	(−12.26)
Parcel area	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
('000 m^2)	(16.33)	(24.97)	(16.57)	(18.23)	(25.14)	(19.64)	(14.44)	(24.63)
Log-likelihood function	10,586.5	16,688.7	8,296.1	12,787.8	15,148.6	8,905.7	3,489.7	5,158.6
Number of observations	8,796	12,879	6,835	12,360	13,261	7,422	3,061	4,227

Note. *t*-ratios appear in parentheses. The coefficients π are not reported.

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