Grant-in-Aid for Scientific Research（S）

Real Estate Markets, Financial Crisis, and Economic Growth

: An Integrated Economic Approach

Working Paper Series No.44

Structure Depreciation and the Production of Real Estate Services

Jiro Yoshida

March, 2016

HIT-REFINED PROJECT
Institute of Economic Research, Hitotsubashi University
Naka 2-1, Kunitachi-city, Tokyo 186-8603, JAPAN
Tel: +81-42-580-9145
E-mail: hit-refined-sec@ier.hit-u.ac.jp
http://www.ier.hit-u.ac.jp/hit-refined/

Structure Depreciation and the Production of Real Estate Services*

Jiro Yoshida†

March 12, 2016

Abstract

This study simultaneously analyzes the real estate production function and economic depreciation of structures by using data from Japan and the U.S. The estimated share of structure value is used to infer returns to scale, the land-structure substitution, and the structure depreciation rate. Real estate exhibits approximately constant returns in Japan, but decreasing returns in the U.S. Land and structures are substitutes in both countries. The land value ratio is 10% in Centre County, PA, but 60%-70% in Japan, reflecting the scarcity of land. The property depreciation rate is larger for newer and denser properties located further away from the downtown area in a smaller city. The property depreciation rate is smaller than the structure depreciation rate due to the effect of land and a survivorship bias. The bias-corrected structure depreciation rates significantly vary by property type and country: approximately 7% for residential properties and 10% for commercial properties in Japan in contrast with 1% for residential structures in the U.S. The median life-span of structures is 30-35 years for residential and 20-30 years for commercial properties in Japan.

JEL Classification: R32; D24; E23

Keywords: capital consumption, returns to scale, elasticity of substitution, housing, commercial real estate, hedonic analysis, survivorship bias, demolition, Japan, USA

*I thank Chris Mayer, Iichiro Uesugi, Brent Ambrose, Marcus Berliant, David Geltner, Liang Peng, Maisy Wong, Dana Buntrock, and seminar participants at Columbia and Penn State for their helpful comments and suggestions. I also gratefully acknowledge research assistance from Conor Doyle. This paper is financially supported by the JSPS KAKENHI #25220502.

†Smeal College of Business, The Pennsylvania State University, 368 Business Building, University Park, PA 16802, jiro@psu.edu.

I. Introduction

Real estate provides shelter to economic activities in cities. Since economic agglomerations of cities require increasing returns in the aggregate production activities (Fujita and Thisse, 2002), it is natural to ask whether increasing returns also characterize the real estate service production. Furthermore, the elasticity of substitution between land and structure is a key parameter that determines the urban spatial structure. When analyzing the real estate service production, one needs to simultaneously analyze the economic depreciation of structures because it implies that the quality-adjusted scale of the property changes over time.

The economic depreciation of structures is important in its own right in a wide range of economic analysis and decision making. First, in macroeconomics, depreciation rates are a key parameter in models of economic growth and dynamic stochastic general equilibrium (e.g., Greenwood and Hercowitz, 1991; Davis and Heathcote, 2005; Davis and Nieuwerburgh, 2015). For example, the measurement of depreciation rates is central to understanding Japan's high saving rate (Hayashi, 1986, 1989, 1991; Hayashi, Ito, and Slemrod, 1987; Dekle and Summers, 1991; Hayashi and Prescott, 2002; Imrohoroglu, Imrohoroglu, and Chen, 2006). Depreciation rates are also a key input to macroeconomic statistics such as gross domestic product and inflation rates, which influence monetary and other macroeconomic policies (e.g., Ambrose, Coulson, and Yoshida, 2015).

Second, in real estate investments, a large depreciation rate implies small appreciation returns and large income returns.[1] Thus, the component returns can significantly vary simply due to variations in depreciation rates by country, city, urban location, building age, and property type. Because investors choose portfolios by taking into account the proportions of income and appreciation returns for the purpose of liquidity management, investor asset allocations are influenced by the cross-sectional variation in depreciation rate.

Third, in housing economics, the depreciation rate of housing affects consumer choice, welfare, and the environmental sustainability. For example, a large depreciation rate increases the user cost and rental cost of housing. Since housing services are complementary to other goods (Davidoff and Yoshida, 2013), a large depreciation increases the expenditure share of housing. Frequent

[1] The equilibrium rent R equals the user cost of real estate: $R = P\left(r + m - g + d^P\right)$, where P is property price, r is the after-tax cost of capital, m is the rate of operating expenses including property tax, g is the market-wide appreciation rate, and d^P is the property depreciation rate. Rearranging this equation gives $(R - Pm)/P = r - g + d^P$, which shows a positive direct effect of depreciation rate on the income return.

demolitions of structures due to a large depreciation rate also have an environmental consequence because a large fraction of CO_2 emissions are associated with the operation and construction of real estate. In countries where buildings are frequently demolished, slow depreciation has a positive effect on the reduction of CO_2 emissions and the initial asset value (Yoshida and Sugiura, 2015).

This study has three objectives. First, I develop a model of the real estate service production and show how the parameters in the production function determine returns to scale, depreciation rate, and the ratio of structure value to the total property value. By using a function of the constant elasticity of substitution (CES) form that allows non-constant returns to scale, I demonstrate that (1) the degree of homogeneity determines the share of land and structure values in the property value and (2) the elasticity of substitution between land and structure affects the dynamics of the structure value ratio and the property depreciation rates.

By using data for the U.S. residential properties (Centre County, PA) and the Japanese residential and commercial properties, I estimate a flexible function for property values. The estimated share of structure value is used to infer returns to scale, the land-structure substitution, and the structure depreciation rate. The real estate production function exhibits approximately constant returns to scale in Japan but decreasing returns to scale in the U.S. The land and structure are gross substitutes in both countries; the unit elasticity of substitution is rejected. The structure value ratio is generally smaller in Japan (30%-40% at median ages) than in the U.S. (50%-70%) whereas the land value ratio is larger in Japan (60%-70%) than in the U.S. (10%). The larger proportion of land value probably reflects the scarcity of habitable land in Japan.[2] That the sum of land and structure values does not explain the entire property value in the U.S. also implies the existence of other factors in the property value. I discuss several possibilities based on the access to infrastructure and a limited competition for differentiated goods.

The second objective is to demonstrate significant cross-sectional variations in the structure value ratio and the property-level depreciation rate. The urban economic theory predicts that the structure value ratio, and thus the property depreciation rate, are affected by the city size, the location within a city, the building age, the density of a property, and other factors (e.g., Alonso, 1964; Muth, 1969; Mills, 1967; Fujita, 1989; Duranton and Puga, 2015). The estimated variations

[2]The habitable area is only approximately 30% of the national land; large part is forest, mountains, and waters. Therefore, population density is 50 times larger in Japan than in the United States.

are consistent with the theory for both countries; i.e., the property depreciation rate is larger for newer and denser properties located away from the Central Business District (CBD) in a smaller city. These variations are economically significant (up to 3.5% per year). Since depreciation rates have a direct impact on the proportions of income and appreciation returns, this result provides a new insight into the variation in real estate returns.

The third objective is to develop and empirically demonstrate new methods of correcting for biases in the estimation of structure depreciation rates. In particular, survivorship biases need to be addressed in both the price analysis and the demolition data analysis. The proposed methods have several advantages. First, they do not require data on both surviving and demolished buildings unlike standard methods such as the Cox proportional hazard rate model, the Kaplan-Meier estimator, and Heckman's two-step procedure. Second, the methods improve the one proposed by Hulten and Wykoff (1981b). They implicitly assume that the depreciation rate for demolished structures is zero by treating the value of demolished structures being zero. In contrast, I incorporate large depreciation rates for demolished buildings based on a distributional assumption.

The early empirical literature on the housing production function is reviewed by McDonald (1981) with a particular focus on the elasticity of substitution between land and structure. Most of these early studies use the assessed land value and obtain small values of the elasticity of land-structure substitution in new construction, typically ranging between 0.4 and 0.6. However, more recent studies report the elasticity greater than unity by correcting for attenuation biases and using transaction prices (e.g., McDonald, 1979; Clapp, 1980; Epple, Gordon, and Sieg, 2010; Ahlfeldt and McMillen, 2014; Combes, Duranton, and Gobillon, 2015).

Regarding returns to scale, most studies assume constant returns to scale (e.g., Epple, Gordon, and Sieg, 2010; Ahlfeldt and McMillen, 2014). An exception is Combes, Duranton, and Gobillon (2015) who estimate returns to scale by applying the CES and translog functions to French housing data. They obtain approximately constant, but slightly decreasing, returns to scale. This result is consistent with the result for Japan in this study. They also estimate that the land value ratio is approximately 20%, which is close to the ratio for Centre County.

The estimated structure depreciation rates also vary widely by country and the estimation method. The structure depreciation rate based on the price data is 6.4%-7.0% for residential properties and 9.1%-10.2% for commercial properties in Japan whereas it is 1.5% for residential properties in the U.S. These rates are consistent with those based on the demolition data in Japan. The bias corrected median life span of structures in Japan is 30-35 years for residential and 20-30 years for commercial properties. The property-type specific depreciation rate for commercial properties in Japan is 7.8% for industrial, 9.9% for office, 14.6% for hotel, and 12.6% for retail properties. Since researchers have not reached a consensus regarding the level of aggregate structure depreciation rates, the estimated rate serves as an important input for macroeconomic models.

The large depreciation rates in Japan could be caused by cultural, historical, and institutional factors. For example, a lack of reliable information about building inspections can be causing adverse selection and moral hazard. In such a bad equilibrium, depreciation rates are necessarily large. Cultural and behavioral biases can be another cause. People's perceptions about building life spans were formed when wooden structures easily collapsed from earthquakes and were often burned down by fire. Although modern structures are significantly more robust to these risks, people's perceptions have not changed very much. Given that approximately 20% of large earthquakes on earth occur in and around Japan (Cabinet Office of Japan, 2013), technological progress in earthquake resistance was particularly large over the past half century. The earthquake resistance standard in the national building code was repeatedly revised in 1950 (after Fukui earthquake), 1971 (after Tokachi earthquake), 1981 (after Miyagi earthquake), and 2000 (after Hanshin-Awaji earthquake). The proportion of directly damaged structures was not large in the national stock of structures. However, the existing buildings became obsolete relatively quickly due to the rapid progress in building technologies. Moreover, many existing buildings became out of compliance after revisions to the national building code.

In both Japan and the United States, the extant studies report a wide range of the estimated rate of depreciation. In Japan, depreciation rates for residential structures range from as low as 1%-2% (Seko, 1998) to 15% (Yoshida and Ha, 2001). Based on the National Accounts of Japan, the depreciation rate is 8.5%-9.9% when data between 1970 and 1989 is used (Hayashi, 1991) but the rate is 4.7% and 5.4% when newer data are used (Economic and Social Research Institute, 2011).[3] For non-residential (commercial) structures, a few available estimates based on the National Accounts are 5.7%-7.2% (Hayashi, 1991; Economic and Social Research Institute, 2011).

[3]The depreciation rate also varies by prefecture, property type, whether a property is for rental or not, and whether a property is a green building or not (Yoshida and Ha, 2001; Yoshida, Yamazaki, and Lee, 2009; Yamazaki and Sadayuki, 2010; Yoshida and Sugiura, 2015)

In the United States, the estimated depreciation rates for residential structures fall within a relatively narrow range; they are 1.36% (Leigh, 1980), 1.89% (Knight and Sirmans, 1996), and 1.94% (Harding, Rosenthal, and Sirmans, 2007) based on asset prices.[4] Based on the National Accounts, the rate is 1.57% between 1948 and 2001 (Davis and Heathcote, 2005). Depreciation rates for commercial structures are larger and exhibit some variations; they are 2.0% for retail, 2.5% for office, 2.7% for warehouse, and 3.6% for factory based on asset prices (Hulten and Wykoff, 1981b) but 5.2%-7.2% based on the implicit rate in the National Accounts published by the Buerau of Economic Analysis (Hulten and Wykoff, 1981a; Hayashi, 1991). In a recent study that uses asset prices, the rate is approximately 3% for all commercial real estate and 3.3%-4.0% for apartments (Fisher, Smith, Stern, and Webb, 2005; Geltner and Bokhari, 2015).

There are several major methods to estimate depreciation rates. The first method utilizes time-series or cross-sectional variations in asset prices (e.g., Hulten and Wykoff, 1981a; Coulson and McMillen, 2008; Yoshida and Sugiura, 2015; Geltner and Bokhari, 2015). A cross-sectional hedonic regression is often used because of better data availability. The second method combines the flow investment data and the real estate stock data, typically in the National Accounts (e.g., Hulten and Wykoff, 1981a; Hayashi, 1991; Yoshida and Ha, 2001; Economic and Social Research Institute, 2011). The implicit depreciation rate in the accumulation equation is estimated. The third method utilizes the data on demolished buildings. Structure depreciation rates are estimated by the building life at the time of demolition. This is more common in engineering studies.

When using cross-sectional data of transaction prices to estimate the hedonic coefficient on age, a researcher needs to adjust for the following biases. First, the depreciation rate is different between structures and the property, which includes non-depreciable land value. For example, the depreciation rate that Knight and Sirmans (1996) estimate is the property depreciation rate. This concept is relevant for measuring investment returns but does not correspond to the depreciation rate in the national income account and macroeconomic models. To estimate the structure depreciation rate, econometricians need to adjust for the ratio of structure value to the total property value, which varies by location and over time. Second, there is a survivorship bias because econometricians only observe buildings that were not demolished by the time of observation (Hulten and

[4] However, the effect of aging on residential rents is significanlty smaller at 0.11% to 0.36% (Lane, Randolph, and Berenson, 1988).

Wykoff, 1981b). On the other hand, when using demolition data, econometricians face the reverse survivorship bias because they only observe demolished buildings. Since standard methods of controlling for a survivorship bias require data for both surviving and demolished buildings at the same time, a new method is needed. Thrid, the effects of time, age, and vintage cannot be disentangled in many applications because two out of three factors become collinear. In order to estimate all three effects, econometricians need to either impose some restriction on functional form or use long time-series of cross sectional data (Coulson and McMillen, 2008). Fourth, there is a possibility of adverse selection and moral hazard because the building quality information is asymmetric between buyers and sellers. The observed transactions in the resale market may overrepresent low quality buildings. In this study, I address the first two biases. Regarding the effects of time and vintage, I only control for transaction year and quarter by assuming that the time effect is stronger than the vintage effect. The adverse selection issue is partially mitigated because I use samples of traded properties.

The remaining sections proceed as follows. In Section II, I develop a model of real estate production and present two methods of bias correction. Section III discusses the data and summary statistics, and Section IV outlines the empirical strategy. Sections V, VI, and VII present the empirical results regarding returns to scale, cross-sectional variations, and the bias-corrected depreciation rates, respectively. Section VIII concludes.

II. Model

Existing real estate can be considered a service-generating asset that the current owner has produced by combining land and the existing structure. The value $V_{t,u}$ of a property of age u is determined in the real estate asset market at time t. The property value is the product of the unit price and quantity: $V_{t,u} = P_t^H H_u$, where P_t^H is the price for one unit of property and H_u is the effective quantity of a property. The effective quantity of an asset can be considered the discounted sum of the expected future service flows. In the data, $V_{t,u}$ is observed but P_t^H and H_u are latent variables as in Epple, Gordon, and Sieg (2010) and Combes, Duranton, and Gobillon (2015). I consider the production function that takes the form of generalized constant elasticity of substitution:

$$H_u = \left[\alpha(E_u S)^{\frac{\theta-1}{\theta}} + (1-\alpha)L^{\frac{\theta-1}{\theta}}\right]^{\frac{\eta\theta}{\theta-1}}, \tag{1}$$

where E_u is the effectiveness of structure, S is the quantity of structure (i.e., square footage of floor area), L is the quantity of land (i.e., square footage of land area).[5] Variables S and L are observed in data but E_u is not.[6] The economic depreciation, defined as the rate of decrease in asset value with age (Hulten and Wykoff, 1981b), occurs due to the decreasing effectiveness (or obsolescence) of structures. However, the effectiveness of an old asset may rather increase with age possibly due to increasing historic qualities or the increasing value of an option to renovate. Thus, the change in the effectiveness of structure (dE_u/du) is the sum of economic depreciation and the factors that augment effectiveness. To disentangle these factors, the econometrician will need to additionally estimate the option and historic values. The parameters α, θ, and η are the relative weight of structure, the elasticity of substitution between structure and land, and returns to scale, respectively (See Appendix A). This function nests the Cobb-Douglas production function when $\theta = \eta = 1$.

Although the objective of this study is to estimate the factor prices, there is no actual market for the existing structure and land. Thus, I formulate a hypothetical internal factor market (within a household) to analyze the shadow prices of the effective structure (P_t^{ES}) and land (P_t^L). On one hand, the owner's optimality condition characterizes the implicit factor demand at the time of transaction. On the other hand, these factors are inelastically supplied based on the existing stock of the effective structure and land. The shadow factor prices are determined such that the demand equals the supply. This method is better grounded on the economic theory than the ad-hoc decomposition of the property value into the replacement cost of new structure and the residual land value.

The property owner's hypothetical problem is to solve the following equation by taking all prices as given:

$$\max_{S,L} \Pi \equiv V_{t,u} - P_t^{ES} E_u S - P_t^L L. \tag{2}$$

The demand for the effective structure and land is characterized by the following optimality con-

[5] I subsume the effectiveness of land into the factor price because it is not the primary focus of this study.

[6] In this theoretical model, the land and structure of the same age are homogeneous, but in the empirical analysis, I will control for both observed and unobserved heterogeneity by hedonic regressions with fixed effects.

ditions derived from the first order conditions:

$$\frac{\eta\alpha\left(E_u S\right)^{\left(1-\frac{1}{\theta}\right)}}{\alpha\left(E_u S\right)^{\left(1-\frac{1}{\theta}\right)}+(1-\alpha)L^{\left(1-\frac{1}{\theta}\right)}} = \frac{P_t^{ES} E_u S}{V_{t,u}} \left(\equiv s_{t,u}\right), \tag{3}$$

$$\frac{\eta(1-\alpha)L^{\left(1-\frac{1}{\theta}\right)}}{\alpha\left(E_u S\right)^{\left(1-\frac{1}{\theta}\right)}+(1-\alpha)L^{\left(1-\frac{1}{\theta}\right)}} = \frac{P_t^{L} L}{V_{t,u}} \left(\equiv l_{t,u}\right). \tag{4}$$

The variables on the right hand side are the ratio of structure value to the property value (henceforth the structure value ratio denoted by $s_{t,u}$) and the ratio of land value to the property value (henceforth the land value ratio denoted by $l_{t,u}$), respectively. Using these ratios, the property value can be decomposed as:

$$V_{t,u} = s_{t,u}V_{t,u} + l_{t,u}V_{t,u} + \Pi_{t,u}. \tag{5}$$

By adding equations (3) and (4), I obtain the following proposition regarding returns to scale.

Proposition 1: *The value share of structure and land equals the homogeneity parameter of the real estate production function:* $s_{t,u} + l_{t,u} = \eta$.

When the production function exhibits constant returns to scale ($\eta = 1$), then $s_{t,u} = \alpha, l_{t,u} = 1-\alpha$, and $\Pi_{t,u} = 0$. In contrast, if the production function exhibits decreasing returns to scale ($\eta < 1$), then $s_{t,u} + l_{t,u} < 1$ and $\Pi_{t,u} > 0$.

The property depreciation rate can be derived by using equations (1) and (3):

$$-\frac{\partial \ln V_{t,u}}{\partial u} = \delta_u s_{t,u}, \tag{6}$$

where $\delta_u = d\ln E_u\,/du$ denotes the instantaneous depreciation rate of structures. Since the structure value ratio $s_{t,u}$ is less than one, the property depreciation rate is always smaller in absolute value than the structure depreciation rate. When property value appreciates with age (after removing the inflation effect), then the effectiveness of structure increases (a negative δ_u) possibly due to increasing historical values.

The structure value ratio equals a constant $\eta\alpha$ when the elasticity of substitution equals unity ($\theta = 1$). Otherwise, it causes the property depreciation rate to change with building age.[7] By

[7]Equation (6) does not depend on a specific production function. As shown in Appendix B, the same equation can be derived from the log-linearization of equation (5).

taking the partial derivative of equation (3) with respect to u, I derive the change in the structure value ratio:

$$\frac{\partial s_{t,u}}{\partial u} = \frac{(1-\theta)\,\delta_u s_{t,u} l_{t,u}}{\theta\eta}. \tag{7}$$

The sign of $\partial s_{t,u}/\partial u$ depends on the elasticity of substitution and the depreciation rate. Under the normal assumption of $\delta_u > 0$, when $\theta > 1$ (i.e., two factors are substitutes), the structure value ratio decreases with age. In contrast, when $\theta < 1$ (i.e., two factors are complements), the structure value ratio increases with age. The next proposition summarizes this result.

Proposition 2: *The direction of changes in the structure value ratio is determined by the elasticity of substitution: i.e.,* $sgn\,(\partial s_{t,u}/\partial u) = sgn\,((1-\theta)\delta_u)$.

The possibility of an increasing structure value ratio may be counterintuitive when structures continuously deteriorate. Actually, the structure value ratio would always decrease in partial equilibrium where the factor prices are fixed. However, the equilibrium factor prices are determined by equations (3) and (4). When structure and land are complements, the structure value ratio increases with age because the relative price of the effective structure significantly increases. This proposition shows that the conventional belief of a decreasing structure value ratio is based on an implicit assumption that structure and land are substitutes.

When estimating depreciation rates and the structure value ratio using the actual data, an econometrician can only observe the nominal value of a property and the quantities of structure and land. By defining the nominal price of (non-quality adjusted) structure as $P^S_{t,u} \equiv P^{ES}_t E_u$, I rewrite equation (5) as:

$$V_{t,u} = P^S_{t,u} S + P^L_t L + \Pi_{t,u}. \tag{8}$$

Consider the elasticity of property value with respect to the quantities of structure and land:

$$\frac{\partial \ln V_{t,u}}{\partial \ln S} = \frac{\partial V_{t,u}}{\partial S}\frac{S}{V_{t,u}} = \frac{P^S_{t,u} S}{V_{t,u}} = s_{t,u}, \tag{9}$$

$$\frac{\partial \ln V_{t,u}}{\partial \ln L} = \frac{\partial V_{t,u}}{\partial L}\frac{L}{V_{t,u}} = \frac{P^L_{t,u} L}{V_{t,u}} = l_{t,u}. \tag{10}$$

These elasticities correspond to the structure and land value ratios. Thus, in my empirical analysis, I estimate these elasticities to test Propositions 1 and 2. I also use these elasticities to estimate a bias-corrected structure depreciation rate.

This method has an advantage over another popular method of estimating the structure value ratio. For example, Yoshida, Yamazaki, and Lee (2009) and Geltner and Bokhari (2015) estimate the land value ratio by taking the ratio of the value of old properties to the value of new properties, and subtract the land value ratio from one. There are several implicit assumptions in this method. First, the structure value must be approximately zero for old properties. This may not be the case when historical values are attached to structures. Second, the structure value ratio must equal one minus the land value ratio. As I show in Proposition 1, this may not be the case when the real estate production function exhibits non-constant returns to scale.

In the next three sections, I analyze how the structure value ratio varies by location (II.A) and how to correct for biases in estimating the structure depreciation rate from price data (II.B) and from demolition data (II.C).

A. Cross-Sectional Variation in Property Depreciation Rates

The structure ratio varies by location in the urban economic theory. In particular, the monocentric city model of urban land use predicts that the structure ratio varies by city size (e.g., population) and urban location (e.g., distance to the CBD) for several reasons. For example, Duranton and Puga (2015) summarize the following predictions of the basic monocentric city model. First, for newly developed properties, land prices decline as one moves away from the CBD. Since the unit cost of structures is by and large constant within a city, the property value also exhibits a declining price gradient. Second, the density of construction declines as one moves away from the CBD. Since the physical land ratio increases and the land price decreases with distance, whether the land value ratio decreases with distance depends on these competing effects. In spatial equilibrium, the land value ratio equals the ratio of the percentage decline in the property price to the percentage decline in the land price with distance. Third, the differential land price between the CBD and the edge of the city should be proportional to the city population and the unit commuting cost.

Since the structure value ratio impacts the property depreciation rate in equation (6), the above results imply that the property depreciation rate also varies by (1) building age, (2) city size, (3) unit commuting cost in a city, (4) distance to the CBD, and (5) physical density. Furthermore, the proportions of income and appreciation returns will also vary by these factors. This study empirically analyzes (1), (2), (4), and (5).

B. Bias Corrections: Case of Price Data

The structure depreciation rate that is estimated from the average of property depreciation rate for the observed properties of age u is by equation (6):

$$\bar{\delta_u} = -\frac{\partial \ln V_{t,u}}{\partial u}\frac{1}{s_{t,u}}. \tag{11}$$

However, this estimate is biased due to survivorship when structures are heterogeneous and demolished in the descending order of depreciation rates. The observed structures that remain in the market have small depreciation rates. To crystallize the idea, assume that the depreciation rate for building i, δ^i, is constant and uniformly distributed on $\left[\delta^L, \delta^H\right]$ at the time of construction. The initial mean depreciation rate δ equals $\left(\delta^H + \delta^L\right)/2$. Assume further that building i is demolished when the structure value $P^{Si}_{t,u}S$ becomes smaller than a scrap value: $\ln P^{Si}_{t,u}S - \ln P^{Si}_{t,0}S \leq \zeta$, where $\zeta < 0$ is the natural logarithm of the scrap value relative to the new structure value. The age of a demolished structure is: $u^i = -\zeta/\delta^i \in \left(-\zeta/\delta^H, -\zeta/\delta^L\right)$. Thus, the proportion of surviving buildings (survival ratio) of age u is:

$$r_u = \begin{cases} 1 & \text{if } u < -\frac{\zeta}{\delta^H} \\ \dfrac{-\frac{\zeta}{u} - \delta^L}{\delta^H - \delta^L} & \text{if } u \in \left(-\frac{\zeta}{\delta^H}, -\frac{\zeta}{\delta^L}\right) \end{cases} \tag{12}$$

The mean depreciation rate for the surviving structures is:

$$\bar{\delta_u} = \begin{cases} \dfrac{\delta^H + \delta^L}{2} & \text{if } u < -\frac{\zeta}{\delta^H} \\ \dfrac{-\frac{\zeta}{u} + \delta^L}{2} & \text{if } u \in \left(-\frac{\zeta}{\delta^H}, -\frac{\zeta}{\delta^L}\right) \end{cases} \tag{13}$$

Although the structure depreciation rate does not change over time, the mean depreciation rate of the structures that remain in the market decreases from $\left(\delta^H + \delta^L\right)/2$ to δ^L. On the other hand, the mean depreciation rate of the structures that were already demolished but would be u years old is $\left(-\zeta/u + \delta^H\right)/2$ for $u \geq -\zeta/\delta^H$. Thus, the original mean structure depreciation rate is recovered by the weighted average rate for the surviging and demolished structures:

$$\delta = r_u \bar{\delta_u} + (1 - r_u)\frac{-\frac{\zeta}{u} + \delta^H}{2}. \tag{14}$$

A benefit of this method over other standard methods of dealing with survivorship biases (e.g., the Cox proportional hazard rate model, the Kaplan-Meier estimator, and Heckman's two-step procedure) is that it does not require the detailed information on the demolished structures. It is common that data are available only for the surviving structures. The proposed method does not need those data by imposing a structure in the distribution of depreciation rates. However, the specific formulas (12), (13), and (14) depend on the distributional assumption.

The proposed method is somewhat similar to the method proposed by Hulten and Wykoff (1981b) in that both methods take a weighted average for the surviving and demolished structures, there is an important difference. They take the weighted average of structure values by assuming that the value of demolished structures is always zero. Thus, they implicitly assume that the change in the value of demolished structures is zero. In contrast, I recover the mean depreciation rate if all structures existed by taking the weighted average of depreciation rates. In other words, the method in this study incorporates large depreciation rates of demolished structures.

C. Bias Corrections: Case of Demolition Data

Consider the model characterized by equations (12) and (13). There is a one-to-one relationship between a depreciation rate δ^i and the age at demolition u^i (i.e., building life): $u^i = -\zeta / \delta^i$. Suppose the initial depreciation rate is drawn from a continuous probability density function $f(\delta^i)$ on the support $[\delta^L, \delta^H]$. Then the corresponding life span is distributed on $[-\zeta / \delta^H, -\zeta / \delta^L]$. At any time t, a full range of depreciation rates (and life spans) are observed in the sample of demolished structures.

However, since structures with a short life (i.e., a large depreciation rate) are frequently demolished, the demolition sample overrepresents these short-lived structures. If the market is in a steady state in the sense that the total amout of structures is constant over time, the frequency of demolition is inversely proportional to life span and directly proportional to depreciation rate. This causes the selection bias in the observed rate of depreciation in the demolition sample. This bias can be corrected by multiplying the probability density function of observed depreciation rate $g(\delta)$ by $u(\delta)$ and normalize it so that its integral equals unity:

$$g^*(\delta) \equiv \frac{g(\delta)u(\delta)}{\int_{\delta^L}^{\delta^H} g(\theta)u(\theta)d\theta}. \tag{15}$$

When the construction volume changes over time, let C_u denote the construction volume for age u. Then, in the time t sample of demolished structures, the frequency of age u is proportional to C_u. This causes the second bias in the observed depreciation rate in a demolition sample. This bias can be corrected by multiplying the probability density function and normalizing it. Thus, the density function corrected for both biases is:

$$g^{**}(\delta) \equiv \frac{g(\delta)u(\delta)C^{-1}_{u(\delta)}}{\int_{\delta^L}^{\delta^H} g(\theta)u(\theta)C^{-1}_{u(\theta)}d\theta}. \tag{16}$$

III. Data

This study uses three different data sets. The first data set contains transactions of single-family housing in Centre County, PA in the United States. The data is taken from the Multiple Lisiting Service (MLS) data between 1996 and 2015. Centre County comprises the State College Metropolitan Statistical Area where the Pennsylvania State University's main campus is located. The population was 153,990 in the 2010 Census. Although it is a college town, it has a well-balanced industry structure, which approximately represents the national average. For example, the largest value of location quotient is only 1.33 for real estate, rental and leasing.[8]

Table I shows the descriptive statistics. The average home price is \$215,723, which approximately equals the national average during the sample period. The average characteristics of houses are 30 years old, 2,000 square feet of floor area, 36,000 square feet of lot size, and 6.5 miles from the CBD. Houses typically have 2 stories, a parking structure, a fireplace, Vinyl exterior, and a basement.

The second data set contains transactions of the Japanese residential and commercial properties between 2005 and 2007 compiled by Yoshida, Yamazaki, and Lee (2009). The original source is the

[8]The location quotient is the ratio of an industrys share of regional employment to its share of national employment. See `www.bls.gov/cew/cewlq.htm`.

Transaction Price Information Service (TPIS) obtained from the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT). The MLIT generates its data by combining three data sources. First, the registry data are obtained from the Ministry of Justice (MOJ) on transactions of raw land, built property, and condominiums. The MOJs registry information includes location, plot number, land use type, area, dates of receipt and contract, and the name and address of the new owner. Second, property buyers fill out the MLIT survey on the transaction price, property size, and reason for the transaction. Third, real estate appraisers conduct a field survey on each property to record the information necessary to perform an appraisal, such as building height, frontal road, distance from the nearest railway station, site shape, and land use. The TPIS is the only source of transaction price data and is regarded as the most reliable price data by real estate appraisers. Since the data set contains a rich set of real estate characteristics, hedonic models have a significant explanatory power.

Table II shows the descriptive statistics of major variables used in the empirical analysis. I divide the sample to Tokyo and Non-Tokyo to characterize large and small cities. I removed outliers in terms of the number of stories, sales price, price per floor area, floor area, lot size, age, and the distance to the CBD. The number of residential transactions is 12,624 and 53,938 for Tokyo and elsewhere, respectively. The number of commercial transactions is 2,184 and 7,413, respectively. The average transaction price for residential real estate is 66 million yen for Tokyo and 32 million yen for outside Tokyo. The average price is significantly larger for commercial real estate: 345 million yen for Tokyo and 213 million yen for outside Tokyo. The average age of structures is 10-13 years for residential and 21-22 years for commercial real estate. The average floor area is approximately 127 m^2 for residential and 550 m^2 for commercial real estate. Residential properties typically have one- or two-story wooden structures and are located in a residential zoning area with low floor-to-area ratio (FAR). Commercial properties typically have non-wooden structures of 4-story or higher and are located in a commercial zoning area with a large FAR near a train station. Most sites have a regular shape and face public roads.

The third data set is the demolition statistics constructed from two data sources. The first data source is the Annual Survey on Capital Expenditures and Disposals of Private Enterprises in the system of National Accounts of Japan. This survey is conducted by the Cabinet Office of Japan since 2005 and considered one of a few reliable statistics of asset demolition. In the most recent survey, 13,524 firms reported their actual capital expenditures and disposals. The statistics include the number of demolished structures by ten age groups for single-family housing, apartment, factory, warehouse, office, hotel, restaurant, and retail. I use surveys between 2005 and 2014, which contain 1,351 residential, 15,782 industrial, 8,531 office, 383 hotel, and 6,141 retail properties. The second data source is buildings construction started (construction starts) from the Annual Survey on Construction Statistics conducted by the MLIT. This survey is based on the mandated construction registration information and goes back to 1951. The construction volume in the past is used to correct for estimation biases.

IV. Empirical Strategy

I analyze five samples for (1) residential properties in Centre County, PA, USA, (2) residential properties in Tokyo, (3) residential properties outside Tokyo in Japan, (4) commercial properties in Tokyo, and (5) commercial properties outside Tokyo in Japan. For each sample, I estimate the following hedonic model:

$$\begin{aligned}\ln V_{ijt} =& a_0 + f(A_i, \ln S_i, \ln L_i, D_i) \\ &+ a_2 \ln S_i + a_3 (\ln S_i)^2 + a_4 \ln L_i + a_5 (\ln L_i)^2 + a_6 D_i + a_7 D_i^2 + a_8 D_i^3 \\ &+ a_9 \ln S_i \times \ln L_i + a_{10} \ln S_i \times D_i + a_{11} \ln L_i \times D_i \\ &+ X_i b + N_j + Q_t + \epsilon_{it}, \end{aligned} \tag{17}$$

where V_{ijt} denotes the price of property i located in district j traded in time t, $\ln S_i$ denotes the log floor area, L_i denotes the log lot size, D_i denotes the distance, $f(A_i, \ln S_i, \ln L_i, D_i)$ denotes a function of building age A_i and its interaction terms with the above variables, and ϵ_{it} denotes the error term. The location fixed effects N_j are school districts for Centre County, wards and cities for Tokyo, and prefectures for the other part of Japan. The time fixed effects Q_t are years for Centre County and quarters for Japan.[9] The vector X_i includes a rich set of property characteristics: For Centre County, the number of bathrooms, building style, parking, heating system, exterior finish, and basement; for Japan, the site shape, street type, rental or non-rental, structure type,

[9] The coefficients on Q_t form a hedonic price index (e.g., Ito and Hirono, 1993; Yoshida, Yamazaki, and Lee, 2009), but it is not a focus of the present study.

the number of stories, zoning, the FAR restriction, the building coverage ratio restriction for Japan. Tables I and II show the descriptive statistics of major variables.

The translog function with respect to land and structure provides flexibility in estimating the production parameters (See Rosen, 1978). The marginal effects of the log floor area ($\partial \ln V_{ijt} / \partial \ln S_i$) and the log lot size ($\partial \ln V_{ijt} / \partial \ln L_i$) represent the structure value ratio and the land value ratio, respectively (equations (9) and (10)). I use these ratios to estimate the returns to scale of real estate production (Proposition 1) and the elasticity of substitution between land and structures (Proposition 2). These ratios are also used to estimate the structure depreciation rate (equation (11)).

The property depreciation rate is measured by the marginal effect of building age ($\partial f / \partial A_i$). I first estimate the non-parametric function $f(A_i)$ without interaction terms. To include interaction terms, I use a step function of age groups as a parametric counterpart of this function. Specifically, I estimate:

$$f(A_i, \ln S_i, \ln L_i, D_i) = \sum_g a_{1,g}\mathbb{I}_g + a_{1,g,s}\mathbb{I}_g \times \ln S_i + a_{1,g,l}\mathbb{I}_g \times \ln L_i + a_{1,g,d}\mathbb{I}_g \times D_i, \qquad (18)$$

where $\mathbb{I}_g$ is an indicator function for the 5-year or 10-year age group g. I also estimate the following parametric models to directly obtain the annual depreciation rate:

$$f(A_i) = a_1 A_i, \qquad (19)$$

$$f(A_i, \ln S_i, \ln L_i, D_i) = \sum_g a_{1,g} A_i \mathbb{I}_g + a_{1,s} A_i \ln S_i + a_{1,l} A_i \ln L_i + a_{1,d} A_i D_i. \qquad (20)$$

In particular, the additional interaction term with distance can be important because of a correlation between distance and building age. The new houses were actively developed around the city center a century ago but at more distant locations in later years as the city size grew. Figure 11 in Appendix C depicts how the active development areas changed over time.

V. Returns to Scale and the Elasticity of Substitution

Figure 1 depicts the sum of the elasticity of value with respect to floor area and the elasticity of value with respect to lot size. These elasticities are evaluated at the mean value of other variables. For most ages, the estimates are significantly smaller than unity. The estimate is 0.81 for new properties and decreases to 0.52 until 40 years old.

This result can be interpreted in several ways. First, this sum of elasticities represents the homogeneity parameter η in the real estate production function (Proposition 1). Thus, a small estimated value indicates decreasing returns to scale in land and structure. Returns to scale are relatively close to unity for new and old properties but very small for 40 year old properties with the average characteristics. The homogeneity of 0.52 implies that a property with a 1% larger scale has a 0.52% larger effective quantity of real estate.

Second, this sum of elasticities represents the ratio of structure and land values to the property value (equations (9) and (10)). With this interpretation, 48% of the value of a 40-year old residential property is derived from factors other than land or structure in Centre County. Although what constitutes this "dark matter" is not entirely clear, it could be the value of the access to energy, utilities, infrastructure, and other puclic services. For example, Quigley (1984) include operating inputs (e.g., energy and utility) as a factor of housing service production. In the present study, however, neither the current owner's past energy expenditures nor the future energy expenditures can explain the current property price. Instead, the access to street, gas, electricity, water, sewage, cable TV, and other public services is valuable for all existing properties regardless of scale. Thus, the value of access to these factors may constitute a fixed component of property value.

Third, this result can be considered as evidence of profits from housing production; i.e., the property value exceeds factor payments (equation (5)). In models with increasing returns (e.g., in urban economics, endogenous growth, and international trade), the intermediate good sector is often characterized by constant returns and monopolistic competition. These models typically assume free entry of intermediate good producers to ensure zero profits. However, if there are some entry barriers, then positive profits will be observed in the intermediate good sector. This interpretation is not unreasonable for commercial real estate, which is a factor of production (e.g., Ambrose, Diop, and Yoshida, 2016). However, single family housing in Centre County is not an intermediate good but a final consumption good. Thus, although large profits for aged houses are likely to be associated with some sort of limited competition for a differentiated good, a monopolistic competition model does not seem best suited for this market.

Figure 1 also depicts the change in the land and structure value ratios with building age. Consistent with the estimate by Epple, Gordon, and Sieg (2010), the land value ratio is almost constant around 10% for most building ages. The area between the bold line and the dashed line represents the structure value ratio. It decreases until 40 yeas old but increases thereafter. A decreasing structure ratio until 40 years indicates that the elasticity of substitution between land and structure is greater than unity. An increasing structure value ratio after 40 years indicates $(1-\theta)\delta_u > 0$ (Proposition 1). The question is whether θ becomes less than unity or δ_u becomes negative. If θ changes and δ_u remains positive, then property values must depreciate in value by equation (6). However, the average property value appreciates after 40 years old. Thus, the elasticity of substitution must be consistently greater than unity (i.e, two production factors are substitutes), and the structure depreciation rates changes from positive values to negative values around 40 years old. The increasing structure value ratio with age for old properties is consistent with the gradually increasing value of options to renovate. I will discuss the value appreciation for relatively old properties in the next section.

Figure 2 depicts the estimated structure and land value ratios for Japan. Unlike the estimate for the U.S., the estimates are approximately unity and constant across ages for all four samples. Specifically, the null hypothesis that the homogeneity parameter equals unity is not rejected for commercial properties at the 5% level. This hypothesis is rejected for residential properties but the point estimates are within a range of 0.88 and 1.12. Thus, the real estate production function exhibits approximately constant returns to scale in Japan.

The structure value ratio steadily decreases with age and the land value ratio steadily increases with age. This result indicates that land and structures are substitutes; i.e., the elasticity of substitution is greater than one. Since the estimates for Japan are until 50 years, this result is consistent with those for the U.S. Unfortunately, it is difficult to obtain estimates beyond 50 years because of a small number of observations.

VI. The Cross-Sectional Variation in Property Depreciation Rates

A. Centre County, U.S.A.

Table III and Figures 1 and 3 summarize the estimation result for Centre County. Figure 3a shows the relative prices of properties of various ages based on the nonparametric estimation of the age function. Property prices continuously depreciate until 50 years old and then level off around 75% of the new property price. They depreciate again after 70 years old although standard errors become larger due to a smaller number of observations. The estimated annual depreciation rate is shown in Table III. Based on the linear age funciton in equation (19), the average property depreciation rate is 0.4% per year. However, the property depreciation rate decreases with age when the pairwise linear function in equation (20) is estimated (column 2). The annual depreciation rate is 1.2% for properties newer than 10 years old but 0.2% for properties older than 71 years old.

Figure 3b shows the variation in depreciation rate by the distance to the CBD. This figure depicts the marginal effect of age group dummies evaluated at the mean values of other variables based on the step function (18). The exponential of the marginal effect represents the relative property price. Properties located farther away from the CBD (24.93 miles) significantly depreciate in value. For example, the marginal effect of -0.62 for 61-70 years old corresponds to a 46% depreciation in value. In contrast, properties located near the CBD (0.56 miles) depreciate less. This variation is summarized in column 1 of Table V. On the basis of the marginal effect for 40 year-old properties, the average annual log depreciation rate is 0.56% for the CBD and 1.06% for the distant location. This result indicates that the appreciation return to a residential property is larger (and the income return is smaller) for the central location by 0.50% than for the 25-mile distant location.

Figure 3c shows the variation by the log floor area when other variables are fixed at the mean values. Thus, this variation is caused by the physical density of properties. Properties with a low density (1 percentile in the floor area) depreciate at a significantly smaller rate than properties with a high density (99 percentile in the floor area) until 60 years old. The difference is insignificant after 60 years old. Moreover, the depreciation profiles are very different by the physical density. For low density properties, the depreciation is not statistically significant until 40 years old and becomes significant thereafter. In contrast, for high density properties, the initial depreciation is very large until 40 years old; the property value after 40 years is approximately 60% of the new property value. The difference in the annual depreciation rate is close to 1.16% between a high-density property and a low-density property (Table V). However, prices somewhat recover after 40 years.

As I discussed in the previous section, this price recovery is caused by the appreciation in the structure value (i.e., $\partial P^S_{t,u}/\partial u > 0$) after 40 years old.[10] In particular, based on figures 3b and 3c, the property value appreciation after 40 years old is mainly driven by the high-density properties located relatively close to the CBD. Other types of properties constantly depreciate in value with age. On the basis of the theoretical model, the value appreciation for old properties can be caused either by increasing prices of the effective structure (P^{ES}) or the increasing effectiveness of structure (E_u). However, it is not plausible that the price of deteriorated structures significantly increases only for high-density properties in downtown areas. Rather, it seems more natural that the effectiveness of structure gradually increases after 40 years due to the increasing value of renovation options or historic qualities particularly for high-density properties located in the downtown area. However, separating out these appreciating factors is not possible from the data of this study.

Figure 3d shows the variation by the log lot size. This variation is negatively associated with the physical density, but the variation is insignificant. This is because the land value ratio is approximately 10% in Centre County, PA.

B. Japan

Figures 4 through 7 depict the estimated depreciation profiles for residential and commercial properties in Japan. Panel (a) shows the nonparametric estimate of relative prices for different ages. The graph is truncated at 50 years old because the number of older properties is small and standard errors are very large. The depreciation profile in Japan exhibits both similarities and differences compared with that for the United States. First, the functional form is generally similar until 50 years old. In particular, property values level off by 50 years old. However, unlike in the U.S., the depreciation rate is very small for the first few years before it increases and remains high for the subsequent 15 years. Overall, the total depreciation is much larger in Japan. For residential

[10]Note that better locations for older properties are not the cause because the correlation between building age and distance is controlled for.

properties, the property values depreciate by half in Tokyo and 55% in smaller cities whereas values depreciate only by a quarter in Centre County. Commercial property values depreciate by 40% after 30 years in Tokyo and by 50% after 35 years outside Tokyo.

Table IV shows the estimated annual depreciation rate based on a linear and pairwise linear functions for building ages (equations 19 and 20). The average depreciation rate is 1.6% in Tokyo and 2.3% outside Tokyo for residential properties (columns 1 and 5) whereas it is 1.1% in Tokyo and 1.6% outside Tokyo for commercial properties (columns 3 and 7). Based on the pairwise linear function, the property depreciation rate gradually decreases. For example, for residential properties in Tokyo (column 2), the rate is 3.1% for the first 5 years but 1.1% between 46 and 50 years. The initial depreciation rate is even larger for commercial properties in Tokyo: 5.3% for the first 5 years.

Depreciation rates are larger for residential properties and properties outside Tokyo than for commercial properties and properties in Tokyo. A major cause is the variation in the structure value ratio. As shown in equation (6), the property depreciation rate is porportional to the structure value ratio. In Figure 2, the estimated structure value ratio is represented by the area between the bold line and the dashed line. The structure ratio is larger for residential properties than for commercial properties, and larger for porperties outside Tokyo than for those in Tokyo. This variation in structure ratio explains the variation in property depreciation rates.

The cross-sectional variations in depreciation by distance and the physical density are significant and consistent with variations in the United States. Table V and Figures 4 through 7 summarize the results. Panel (b) of these figures shows the variation by the distance to the nearest station.[11] The variation by distance is qualitatively similar to that for Centre County; property value depreciates less significantly at the central locations. Property values at the central locations even exhibit appreciation after 40 years outside Tokyo (5b and 7b). Qualitatively, for residential properties in Tokyo (4b), the relative price is 59.5% of the new value after 40 years if distance is 140 meters but 39.4% if distance is 3500 meters. The implied annual depreciation rate is 1.30% for the close location but 2.33% for the distant location; the difference is 1.03 percentage points (column 2 of

[11] The distance to the nearest station is a relevant measure in Japan. In Tokyo, train and subway stations serve as local commercial centers and commuting hubs connected to multiple city centers. The network of railways and subways is so dense that the median distance to the nearest station is only 830 meters for residential properties and 320 meters for commercial properties. Outside Tokyo, although train stations are not necessarily located at CBD, alternative commercial centers are often formed around stations. The errors in the distance variable may be attenuating the estimated coefficients and decreasing the statistical significance.

Table V).[12] This result explains why real estate agents in Japan conjecture that property values tend to be sustained at a better location near a station. It is because the depreciating component is small at a good location if it is not the only reason.

Panels (c) and (d) depict the variation by the physical density of properties. A large density is represented by a large log floor area and a small log lot size. The variation is significant and consistent with that in Centre County. A high-density property with a large floor area or a small lot size significantly depreciates in value, ceteris paribus. (See also Table IV.) In contrast, the economic depreciation is small for a low-density property. Remarkably, for both residential and commercial properties in Tokyo, there is no significant depreciation over 50 years for a property at the 99 percentile in the lot size (4d and 6d). The implied annual depreciation rate over 40 years for residential properties in Tokyo is 2.83% and -0.70% for the 1 and 99 percentiles in the lot size, respectively (Column 2 of Table V). The difference of 3.53% in depreciation rates will make a large impact on investment returns. The variation in floor area also creates a similarly large variation in depreciation rate. For example, the average annual depreciation rates over 40 years are 0.79% and 3.34% for the 1 and 99 percentiles in the floor area, respectively, for residential properties in Tokyo. The result for residential properties outside Tokyo (5c and 5d), commercial properties in Tokyo (6c and 6d), and commercial properties outside Tokyo (7c and 7d) are qualitatively the same. The differences in depreciation rates between 1 and 99 pecerntiles in floor area and lot size are all economically and statistically significant (Columns 3, 4, and 5 of Table V).

VII. Bias-Corrected Rates of Structure Depreciation

This section empirically demonstrates two bias adjustment methods that I propose. The first method (Section II.B) is applied to the property depreciation rate estimated by hedonic regressions of traded real estate prices. The second method (Section II.C) is applied to the demolition statistics.

A. Asset Price Approach

I estimate the bias-corrected rate of structure depreciation by using equations 11 and 14. The data for this exercise are summarized in Tables VI and VII. For the annual property depreciation

[12] The same result is confirmed in column 1 of Table IV by a negative and statistically significant coefficient on the interaction term between age and distance.

rate, I use the estimate of the pairwise linear function (20) (Tables III and IV). The structure value ratio is taken from the result depicted in Figures 1 and 2. To calculate survival ratio, I set the lower bound of structure depreciation rate as half of the initial depreciation rate. For Japan, I set the the lower and upper bounds such that the implied survival rates approximately match the demolition data (column 5 of Table VII). Note that these upper and lower bounds affect the variances but not the mean depreciation rate. The scrap value of structure is 20% of the original value: $\zeta = \ln 0.2$.

Figure 8 depicts the estimation result. Downward-sloping dashed lines are property depreciation rates estimated by hedonic regressions whereas the thick solid lines are the bias corrected structure depreciation rates for each age group. The property depreciation rates are smaller than the structure depreciation rates due to both the effect of structure value ratio and a survivorship bias. In the United States, the structure depreciation rate is small and decreasing with age; the initial depreciation rate is 1.8%, but the rate for old buildings is 0.3%. Because the building life is relatively long, the survivorship bias is not large. Furthermore, since the structure value ratio is large in Centre County, PA, its effect is also small.

In contrast, the structure depreciation rate is much larger in Japan. For residential properties, the initial depreciation rate is 5.8% in Tokyo and 6.7% outside Tokyo. These rates tend to increase with age and become 7.7% in Tokyo and 7.3% outside Tokyo. For commercial properties, the initial depreciation rate is 10.8% in Tokyo and 9.8% outside Tokyo. These rates do not change much with age and become 10.0% and 9.1%, respectively, after 50 years. The median age group is 26-35 years for residential properties and 16-25 years for commercial properties. At the median age, the bias-corrected aggregate structure depreciation rate is 6.4% for residential properties in Tokyo, 7.0% for residential properties outside Tokyo, 10.2% for commercial properties in Tokyo, and 9.1% for commercial properties outside Tokyo. These rates fall in the range of the lowest estimate by Seko (1998) and the highest estimate by Yoshida and Ha (2001). These rates are also significantly larger than those in the United States.

B. Demolition Approach

The sample of demolished structures is another source of information for depreciation rates. Since the life span of a structure is directly associated with its depreciation rate, one can infer the depreciation rate by measuring the building age at the time of demolition. However, there are obvious biases because the sample of demolished structures do not represent the entire population of structures. The first is a selection bias that fast depreciating structures are more frequently observed in the sample of demolished structures. The second bias is that historical changes in construction volume affect the age distribution of demolished buildings. For example, a construction boom that occurred several decades ago would naturally increases the frequency of the corresponding ages in the current demolition sample.

Figure 9 depicts the cumulative distribution of building age at demolition. The ten age groups in the data are on the horizontal axis. Panel (a) shows unadjusted distributions by property type. Residential real estate has the longest life and retail real estate has the shortest life. The observed median life is quite short: 30-40 years for residential, 20-25 years for industrial, 15-20 years for office, 10-15 years for hotel, and 5-10 years for retail. However, by adjusting for frequency and construction volume, the cumulative distribution function tends to be shifted to the right (Panels b and c). The median life corrected for both biases (Panel c) is 40-50 years for residential, 25-30 years for industrial and office, 15-20 years for hotel, and 20-25 years for retail.

Figure 10 depicts the probability mass function for depreciation rates. The discrete depreciation rates on the horizontal axis correspond to ten age groups. Panels (a), (b), and (c) are discrete analogues of density functions $g(\delta)$, $g^{*}(\delta)$, and $g^{**}(\delta)$, respectively. By comparing Panel (a) with Panel (c), it is clear that probability masses are shifted toward smaller depreciation rates. The shift is most clearly seen for residential and retail. The residential distribution is extremely skewed to the right after correcting for biases. The unadjusted retail distribution is skewed to the left but the adjusted distribution is more symmetrical.

Table VIII presents the mean and median depreciation rate with and without bias corrections by Equation (16). Since these rates depend on the assumption of scrap value, I examine three cases of scrap value. First, bias corrections are significant in magnitude. For example, when the scrap value equals 0.15, the unadjusted mean depreciation rate for residential real estate is 9.64% whereas the bias-corrected rate is 6.20%. The unadjuted rates are unreasonably large; e.g., 28.82% for retail. Second, the bias-corrected mean depreciation rate is consistent with the rate estimated by the asset price approach when the scrap value equals 0.15 or 0.2. For example, when the scrap value is 0.15, the mean rate is 6.2% for residential and 9.2-17.2% for commercial real estate. Although there are no reliable statistics for scrap values, this scrap value seems reasonable.

VIII. Conclusion

This study takes a unique approach to simultaneously estimating the real estate production function and the structure depreciation rate. The outcome of this study has important implications in at least three areas. First, returns to scale and the elasticity of substitution between land and structures have important implications on the urban and regional economics. Second, the cross-sectional variation in the property depreciation rate has an important implication on real estate investments and the housing economics. Third, the bias corrected structure depreciation rate serves as an important input to macroeconomics models.

The result is qualitatively summarized as follows. Real estate exhibits constant returns in Japan, but decreasing returns in the U.S. Land and structures are substitutes in both countries. The property depreciation rate decreases with age and is always smaller than the structure depreciation rate due to the effect of the non-depreciating land component and a survivorship bias. The property depreciation rate is larger for newer and denser properties located away from the CBD in a smaller city. The structure depreciation rate is larger in Japan than in the U.S. and larger for commercial properties than for residential properties.

References

Ahlfeldt, Gabriel, and Daniel McMillen, 2014, New Estimates of the Elasticity of Substitution of Land for Capital, ERSA conference papers ersa14p108 European Regional Science Association.

Alonso, William, 1964, *Location and Land Use; Toward a General Theory of Land Rent* (Harvard University Press: Cambridge, MA).

Ambrose, Brent W., N. Edward Coulson, and Jiro Yoshida, 2015, The repeat rent index, *Review of Economics and Statistics.*

Ambrose, Brent W., Moussa Diop, and Jiro Yoshida, 2016, Product market competition and corporate real estate investment under demand uncertainty, *Real Estate Economics* pp. n/a–n/a.

Cabinet Office of Japan, 2013, White paper on disaster management, Discussion paper.

Clapp, John M., 1980, The elasticity of substitution for land: The effects of measurement errors, *Journal of Urban Economics* 8, 255 – 263.

Combes, Pierre-Philippe, Gilles Duranton, and Laurent Gobillon, 2015, The production function for housing: Evidence from france, Working paper University of Pennsylvania.

Coulson, N. Edward, and Daniel P. McMillen, 2008, Estimating time, age and vintage effects in housing prices, *Journal of Housing Economics* 17, 138 – 151.

Davidoff, Thomas, and Jiro Yoshida, 2013, Estimating consumption substitution between housing and non-housing goods using macro data, Working paper.

Davis, Morris, and Jonathan Heathcote, 2005, Housing and the business cycle, *International Economic Review* 46, 751–784.

Davis, Morris A., and Stijn Van Nieuwerburgh, 2015, Chapter 12 - housing, finance, and the macroeconomy, in J. Vernon Henderson Gilles Duranton, and William C. Strange, ed.: *Handbook of Regional and Urban Economics*, vol. 5 of *Handbook of Regional and Urban Economics* . pp. 753 – 811 (Elsevier).

Dekle, Robert, and Lawrence H. Summers, 1991, Japan's High Saving Rate Reaffirmed, NBER Working Papers 3690 National Bureau of Economic Research, Inc.

Duranton, Gilles, and Diego Puga, 2015, Chapter 8 - urban land use, in J. Vernon Henderson Gilles Duranton, and William C. Strange, ed.: *Handbook of Regional and Urban Economics*, vol. 5 of *Handbook of Regional and Urban Economics* . pp. 467 – 560 (Elsevier).

Economic and Social Research Institute, 2011, Outline of the 2005 revision to the national account (in japanese), Discussion paper Cabinet Office of Japan.

Epple, Dennis, Brett Gordon, and Holger Sieg, 2010, A new approach to estimating the production function for housing, *American Economic Review* 100, 905–24.

Fisher, Jeffrey D., Brent C Smith, Jerrold J. Stern, and R. Brian Webb, 2005, Analysis of Economic Depreciation for Multi-Family Property, *Journal of Real Estate Research* 27, 355–370.

Fujita, Masahisa, 1989, *Urban Economic Theory* . No. 9780521346627 in Cambridge Books (Cambridge University Press).

Fujita, M., and J.F. Thisse, 2002, *Economics of Agglomeration: Cities, Industrial Location, and Regional Growth* (Cambridge University Press).

Geltner, D., and S. Bokhari, 2015, The nature and magnitude of commercial buildings capital consumption in the united states, Working paper MIT Center for Real Estate.

Greenwood, Jeremy, and Zvi Hercowitz, 1991, The Allocation of Capital and Time over the Business Cycle, *Journal of Political Economy* 99, 1188–214.

Harding, John P., Stuart S. Rosenthal, and C.F. Sirmans, 2007, Depreciation of housing capital, maintenance, and house price inflation: Estimates from a repeat sales model, *Journal of Urban Economics* 61, 193 – 217.

Hayashi, Fumio, 1986, Why Is Japan's Saving Rate So Apparently High?, in *NBER Macroeconomics Annual 1986, Volume 1* NBER Chapters . pp. 147–234 (National Bureau of Economic Research, Inc).

——— , 1989, Japan's Saving Rate: New Data and Reflections, NBER Working Papers 3205 National Bureau of Economic Research, Inc.

——— , 1991, Measuring Depreciation For Japan: Rejoinder to Dekle and Summers, NBER Working Papers 3836 National Bureau of Economic Research, Inc.

——— , Takatoshi Ito, and Joel Slemrod, 1987, Housing Finance Imperfections and Private Saving: A Comparative Simulation Analysis of the U.S. and Japan, NBER Working Papers 2272 National Bureau of Economic Research, Inc.

Hayashi, Fumio, and Edward C. Prescott, 2002, The 1990s in Japan: A Lost Decade, *Review of Economic Dynamics* 5, 206–235.

Hulten, Charles, and Frank C. Wykoff, 1981a, The Measurement of Economic Depreciation, in Charles Hulten, ed.: *Depreciation, Inflation, and the Taxation of Income from Capital* . pp. 81–125 (The Urban Institute, Washington, D.C.).

Hulten, Charles R., and Frank C. Wykoff, 1981b, The estimation of economic depreciation using vintage asset prices, *Journal of Econometrics* 15, 367 – 396.

Imrohoroglu, Selahattin, Ayse Imrohoroglu, and Kaiji Chen, 2006, The Japanese Saving Rate, *American Economic Review* 96, 1850–1858.

Ito, Takatoshi, and Keiko Nosse Hirono, 1993, Efficiency of the Tokyo Housing Market, *Monetary and Economic Studies* 11, 1–32.

Knight, John R., and C.F. Sirmans, 1996, Depreciation, maintenance, and housing prices, *Journal of Housing Economics* 5, 369 – 389.

Lane, Walter F., William C. Randolph, and Stephen A. Berenson, 1988, Adjusting the cpi shelter index to compensate for effect of depreciation, *Monthly Labor Review* pp. 34–37.

Leigh, Wilhelmina A., 1980, Economic depreciation of the residential housing stock of the united states, 1950-1970, *The Review of Economics and Statistics* 62, 200–206.

McDonald, J.F., 1979, *Economic analysis of an urban housing market* . Perspectives in Immunology (Academic Press).

McDonald, John F., 1981, Capital-land substitution in urban housing: A survey of empirical estimates, *Journal of Urban Economics* 9, 190–211.

Mills, Edwin S., 1967, An aggregative model of resource allocation in a metropolitan area, *The American Economic Review* 57, 197–210.

Muth, Richard F., 1969, *Cities and housing; the spatial pattern of urban residential land use* (niversity of Chicago Press: Chicago, IL).

Quigley, John M., 1984, The Production of Housing Services and the Derived Demand for Residential Energy, *RAND Journal of Economics* 15, 555–567.

Rosen, Harvey S., 1978, Estimating Inter-city Differences in the Price of Housing Services, *Urban Studies* 15, 351–355.

Seko, Miki, 1998, *Tochi to jutaku no keizai bunseki* (Sobunsha: Tokyo, Japan).

Yamazaki, F., and T. Sadayuki, 2010, An estimation of collective action cost in condominium reconstruction: The case of japanese condominium law, Working Paper REAL 12-T-05 The Regional Economics Applications Laboratory, University of Illinois.

Yoshida, Atsushi, and Chun Ha, 2001, Todofuken betsu jutaku stokku no suikei, *Kikan Jutaku Tochi Keizai* 39, pp. 18–27.

Yoshida, Jiro, and Ayako Sugiura, 2015, The effects of multiple green factors on condominium prices, *The Journal of Real Estate Finance and Economics* 50, 412–437.

Yoshida, J., R. Yamazaki, and J. E. Lee, 2009, Real estate transaction prices in japan: New findings of time-series and cross-sectional characteristics, *AsRES-AREUEA Conference Proceedings*.

	$N = 13,803$			
SELECTED VARIABLES	Mean	SD	Min	Max
Price	215,723	106,719	20,000	875,000
Log Price	12.17	0.482	9.903	13.68
Building Age	29.82	23.63	0	100
# of Bedrooms	3.448	0.723	1	10
# of Bathrooms	1.984	0.747	1	6
Floor Area (sq.ft.)	2,008	694.3	792	4,552
Log Floor Area	7.548	0.338	6.675	8.423
Lot Size (sq.ft.)	36,246	77,124	3,920	871,200
Log Lot Size	9.867	0.900	8.274	13.68
Style: 2 Stories	0.385	0.487	0	1
Style: Ranch	0.300	0.458	0	1
Parking: Yes	0.886	0.318	0	1
Parking: Attached	0.557	0.497	0	1
Parking: Detached	0.109	0.311	0	1
Heating: Forced Air Heating	0.342	0.474	0	1
Heating: Baseboard	0.252	0.434	0	1
Heating: Heat Pump	0.180	0.384	0	1
Heating: Hot Water	0.171	0.376	0	1
Fireplace: Yes	0.786	0.410	0	1
Fireplace: Wood	0.306	0.461	0	1
Exterior: Vinyl	0.549	0.498	0	1
Exterior: Brick	0.343	0.475	0	1
Exterior: Aluminum	0.164	0.371	0	1
Basement: Full	0.671	0.470	0	1
Basement: Partial	0.131	0.337	0	1
City: State College	0.648	0.478	0	1
City: Bald Eagle	0.0477	0.213	0	1
City: Bellefonte	0.191	0.393	0	1
City: Penns Valley	0.0501	0.218	0	1
City: Philipsburg-Osceola	0.0324	0.177	0	1
Direction: North	0.628	0.483	0	1
Direction: East	0.511	0.500	0	1
Distance to CBD	6.534	5.996	0.335	29.97
Year of Transaction	2,007	5.064	1,996	2,015

Table I: Descriptive Statistics (Centre County, PA, USA)

SELECTED VARIABLES	Tokyo Residential N = 12,624 Mean	S.D.	Tokyo Commercial N = 2,184 Mean	S.D.	Outside Tokyo Residential N = 53,938 Mean	S.D.	Outside Tokyo Commercial N = 7,413 Mean	S.D.
Property Value (million yen)	66.3	96.8	345.4	747.1	31.7	37.4	213.3	499.8
Log Property Value	17.70	0.711	18.83	1.257	17.01	0.742	18.24	1.317
Building Age	10.47	13.38	21.77	13.54	13.19	13.67	22.17	12.95
Floor Area (sq. meter)	126.6	117.4	549.6	666.5	127.2	92.71	583.3	779.9
Log Floor Area	4.667	0.495	5.764	1.032	4.724	0.429	5.795	1.035
Lot Size (sq. meter)	116.9	85.89	166.6	157.5	179.1	133.4	302.1	393.8
Log Lot Size	4.600	0.521	4.811	0.745	5.005	0.579	5.222	0.930
Distance to Station (meter)	996.2	685.6	419.0	347.2	1,591	1,087	829.2	1,028
Site Width (meter)	7.622	6.318	9.882	6.050	10.50	8.175	12.95	10.41
Rectangular shaped site	0.31	0.46	0.32	0.47	0.34	0.47	0.33	0.47
Private road	0.31	0.46	0.05	0.21	0.18	0.38	0.02	0.15
Number of Stories	2.390	0.649	4.633	2.464	2.127	0.546	3.955	2.415
Wooden structure	0.83	0.37	0.19	0.39	0.82	0.38	0.23	0.42
Regulation: Coverage Ratio (%)	56.22	9.283	78.70	5.180	57.42	9.090	76.05	8.026
Regulation: Floor Area Ratio (%)	178.0	84.65	472.7	156.3	166.8	66.61	393.8	168.2

Table II: Descriptive Statistics (Japan)

Dependent Variable: Log transaction price	(1) Linear	(2) Pairwise linear with interactions
Building Age	-0.004***	
	(0.000)	
$\times \mathbb{I}(1-10 \text{ years})$		-0.012***
		(0.001)
$\times \mathbb{I}(11-20 \text{ years})$		-0.010***
		(0.000)
$\times \mathbb{I}(21-30 \text{ years})$		-0.007***
		(0.000)
$\times \mathbb{I}(31-40 \text{ years})$		-0.006***
		(0.000)
$\times \mathbb{I}(41-50 \text{ years})$		-0.005***
		(0.000)
$\times \mathbb{I}(51-60 \text{ years})$		-0.004***
		(0.000)
$\times \mathbb{I}(61-70 \text{ years})$		-0.003***
		(0.000)
$\times \mathbb{I}(71-80 \text{ years})$		-0.002***
		(0.000)
$\times \mathbb{I}(81-90 \text{ years})$		-0.002***
		(0.000)
$\times \mathbb{I}(91-100 \text{ years})$		-0.002***
		(0.000)
$\times$ Log Floor Area (demeaned)		-0.000
		(0.000)
$\times$ Log Lot Size (demeaned)		-0.000
		(0.000)
$\times$ Distance		-0.000***
		(0.000)
Other variables	Yes	Yes
Location fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	13,803	13,803
Adjusted R-Squared	0.841	0.852

Table III: Regression Result (Cenre County, PA)

This table presents the key estimation result of equation (17) for Centre County with age functions (19) (column 1) and (20) (column 2). $\mathbb{I}(\cdot)$ denotes an indicator variable for each age group. White's heteroskedasticity-robust standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Dependent Variable:	Tokyo				Outside Tokyo			
Log transaction price	Residential		Commerical		Residential		Commerical	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Building age	-0.016***		-0.011***		-0.023***		-0.016***	
	(0.000)		(0.001)		(0.000)		(0.001)	
$\times\mathbb{I}(1-5$ years$)$		-0.031***		-0.053***		-0.044***		-0.048***
		(0.004)		(0.013)		(0.002)		(0.010)
$\times\mathbb{I}(6-10$ years$)$		-0.021***		-0.036***		-0.036***		-0.028***
		(0.001)		(0.008)		(0.001)		(0.004)
$\times\mathbb{I}(11-15$ years$)$		-0.020***		-0.031***		-0.033***		-0.029***
		(0.001)		(0.003)		(0.001)		(0.002)
$\times\mathbb{I}(16-20$ years$)$		-0.019***		-0.022***		-0.029***		-0.025***
		(0.001)		(0.002)		(0.000)		(0.001)
$\times\mathbb{I}(21-25$ years$)$		-0.016***		-0.021***		-0.025***		-0.024***
		(0.001)		(0.002)		(0.000)		(0.001)
$\times\mathbb{I}(26-30$ years$)$		-0.014***		-0.019***		-0.024***		-0.023***
		(0.001)		(0.002)		(0.000)		(0.001)
$\times\mathbb{I}(31-35$ years$)$		-0.014***		-0.016***		-0.021***		-0.020***
		(0.001)		(0.002)		(0.000)		(0.001)
$\times\mathbb{I}(36-40$ years$)$		-0.013***		-0.010***		-0.018***		-0.016***
		(0.001)		(0.002)		(0.000)		(0.001)
$\times\mathbb{I}(41-45$ years$)$		-0.013***		-0.009***		-0.016***		-0.015***
		(0.001)		(0.002)		(0.000)		(0.001)
$\times\mathbb{I}(46-50$ years$)$		-0.011***		-0.008***		-0.014***		-0.012***
		(0.001)		(0.002)		(0.001)		(0.001)
× Log Floor Area (demeaned)		-0.008***		-0.005***		-0.009***		-0.004***
		(0.001)		(0.002)		(0.001)		(0.001)
× Log Lot Size (demeaned)		0.012***		0.008***		0.008***		0.003***
		(0.001)		(0.002)		(0.000)		(0.001)
× Distance		-0.000***		-0.000***		-0.000***		-0.000***
		(0.000)		(0.000)		(0.000)		(0.000)
Other variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-quarter fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,624	12,624	2,184	2,184	53,938	53,938	7,413	7,413
Adjusted R-squared	0.816	0.826	0.836	0.844	0.679	0.698	0.795	0.800

Table IV: Regression Result (Japan)

This table presents the key estimation result of equation (17) for Tokyo (columns 1-4) and outside Tokyo (columns 5-8), for both residential (columns 1,2,5,6) and commerical (columns 3,4,7,8) with age functions (19) (columns 1, 3, 5, 7) and (20) (columns 2, 4, 6, 8). $\mathbb{I}(\cdot)$ denotes an indicator variable for each age group. White's heteroskedasticity-robust standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

		Residential		Commerical	
	Centre County	Tokyo	Outside Tokyo	Tokyo	Outside Tokyo
	(1)	(2)	(3)	(4)	(5)
Distance Measure					
1 percentile	0.0056	0.0130	0.0180	0.0103	0.0163
	(0.0004)	(0.0009)	(0.0005)	(0.0019)	(0.0011)
99 percentile	0.0106	0.0233	0.0260	0.0285	0.0255
	(0.001)	(0.0025)	(0.0011)	(0.0054)	(0.0039)
Difference	0.0050	0.0103	0.0081	0.0183	0.0092
Floor Area					
1 percentile	0.0012	0.0079	0.0123	-0.0012	0.0122
	(0.0007)	(0.0011)	(0.0006)	(0.0037)	(0.0023)
99 percentile	0.0128	0.0334	0.0370	0.0334	0.0251
	(0.0006)	(0.0026)	(0.0014)	(0.0052)	(0.0032)
Difference	0.0116	0.0255	0.0247	0.0347	0.0128
Lot Size					
1 percentile	0.0075	0.0283	0.0304	0.0268	0.0195
	(0.0005)	(0.0015)	(0.0009)	(0.004)	(0.0026)
99 percentile	0.0053	-0.0070	0.0064	-0.0050	0.0150
	(0.0012)	(0.0019)	(0.001)	(0.0057)	(0.0039)
Difference	-0.0021	-0.0353	-0.0240	-0.0318	-0.0045

Table V: Variation in the Implied Annual Depreciation Rate

This table presents the average annual log depreciation rate over 40 years that is implied by Figures 3 and 4. The depreciation rates are contrasted between the 1 percentile and 99 percentile in distance, floor area, and lot size. In parentheses are White's heteroskedasticity-robust standard errors computed by the delta method.

Age Group	Property Depreciation Rate	Structure Value Ratio	Structure Depreciation Rate without Correction (Eq. 11)	Survival Rate (Eq. 12)	Structure Depreciation Rate with Correction (Eq. 14)
10	0.012	0.699	0.018	1.000	0.018
20	0.010	0.607	0.016	1.000	0.016
30	0.007	0.476	0.015	1.000	0.015
40	0.006	0.433	0.014	1.000	0.014
50	0.005	0.478	0.010	1.000	0.010
60	0.004	0.560	0.007	1.000	0.007
70	0.003	0.725	0.004	1.000	0.004
80	0.002	0.866	0.002	1.000	0.002
90	0.002	0.783	0.003	1.000	0.003
100	0.002	0.733	0.002	0.948	0.003

Table VI: Bias-Corrected Rate of Structure Depreciation (Centre County, PA)

This table presents the bias correction in the estimation of the structure depreciation rate based on equations 11 and 14. Assumptions are: $\zeta = \ln 0.2$, $\delta^L = 0.009$, $\delta^H = 0.027$

Age Group	Property Depreciation Rate	Structure Value Ratio	Structure Depreciation Rate without Correction (Eq. 11)	Survival Rate (Eq. 12)	Structure Depreciation Rate with Correction (Eq. 14)
(a) Residential Properties, Tokyo. Assumptions: $\zeta = \ln 0.2, \delta^L = 0.005, \delta^H = 0.111$					
5	0.031	0.519	0.058	1.000	0.058
10	0.021	0.476	0.049	1.000	0.049
15	0.020	0.433	0.056	1.000	0.056
20	0.019	0.390	0.045	0.866	0.052
25	0.016	0.347	0.042	0.674	0.058
30	0.014	0.304	0.045	0.551	0.063
35	0.014	0.261	0.047	0.466	0.065
40	0.013	0.218	0.062	0.404	0.071
45	0.013	0.175	0.050	0.357	0.066
50	0.011	0.132	0.086	0.319	0.077
(b) Residential Properties, Outside Tokyo. Assumptions: $\zeta = \ln 0.2, \delta^L = 0.005, \delta^H = 0.130$					
5	0.044	0.718	0.067	1.000	0.067
10	0.036	0.671	0.054	1.000	0.054
15	0.033	0.625	0.055	1.000	0.055
20	0.029	0.579	0.044	0.738	0.061
25	0.025	0.532	0.046	0.574	0.069
30	0.024	0.486	0.044	0.469	0.071
35	0.021	0.440	0.042	0.397	0.071
40	0.018	0.393	0.049	0.344	0.074
45	0.016	0.347	0.054	0.304	0.075
50	0.014	0.301	0.049	0.272	0.073
(c) Commerical Properties, Outside Tokyo. Assumptions: $\zeta = \ln 0.2, \delta^L = 0.02, \delta^H = 0.197$					
5	0.053	0.429	0.108	1.000	0.108
10	0.036	0.403	0.129	1.000	0.129
15	0.031	0.377	0.086	0.728	0.107
20	0.022	0.351	0.062	0.520	0.102
25	0.021	0.324	0.052	0.405	0.101
30	0.019	0.298	0.062	0.331	0.106
35	0.016	0.272	0.059	0.280	0.105
40	0.010	0.245	0.061	0.243	0.105
45	0.009	0.219	0.041	0.214	0.101
50	0.008	0.193	0.034	0.192	0.100
(d) Commerical Properties, Outside Tokyo. Assumptions: $\zeta = \ln 0.2, \delta^L = 0.02, \delta^H = 0.176$					
5	0.048	0.477	0.098	1.000	0.098
10	0.028	0.456	0.058	1.000	0.058
15	0.029	0.436	0.071	0.824	0.086
20	0.025	0.415	0.058	0.589	0.089
25	0.024	0.395	0.054	0.458	0.092
30	0.023	0.375	0.056	0.375	0.094
35	0.020	0.354	0.066	0.317	0.098
40	0.016	0.334	0.047	0.275	0.092
45	0.015	0.313	0.049	0.243	0.093
50	0.012	0.293	0.042	0.217	0.091

Table VII: Bias-Corrected Rate of Structure Depreciation (Japan)

This table presents the bias correction in the estimation of the structure depreciation rate based on equations 11 and 14.

	Scrap Value: 0.1		Scrap Value: 0.15		Scrap Value: 0.2	
	Mean	Median	Mean	Median	Mean	Median
Bias-Corrected Rate						
Residential	0.0753	0.0512	0.0620	0.0422	0.0526	0.0358
Industrial	0.1117	0.0837	0.0920	0.0690	0.0781	0.0585
Office	0.1422	0.0837	0.1171	0.0690	0.0994	0.0585
Hotel	0.2092	0.1316	0.1724	0.1084	0.1462	0.0920
Retail	0.1797	0.1023	0.1481	0.0843	0.1256	0.0715
Unadjusted Rate						
Residential	0.1170	0.0658	0.0964	0.0542	0.0818	0.0460
Industrial	0.1766	0.1023	0.1455	0.0843	0.1234	0.0715
Office	0.2408	0.1316	0.1984	0.1084	0.1683	0.0920
Hotel	0.2531	0.1842	0.2085	0.1518	0.1769	0.1288
Retail	0.3498	0.1842	0.2882	0.1518	0.2445	0.1288

Table VIII: Demolition-Based Estimate of Structure Depreciation Rate

This table presents the mean and median rate of structure depreciation that is estimated from demolition statistics. The frequency and construction volume biases are corrected.

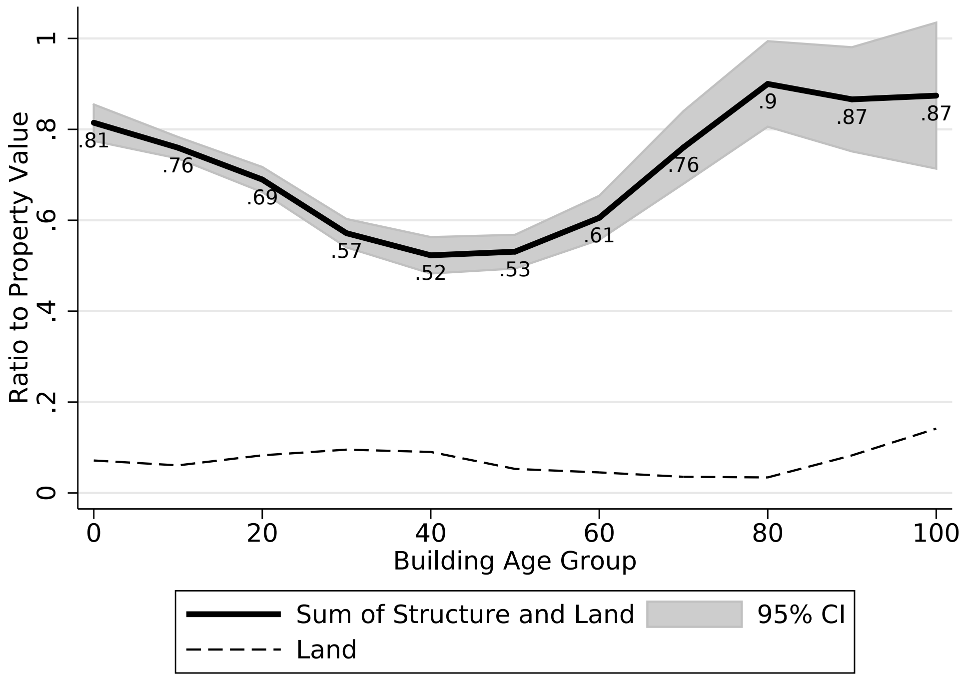
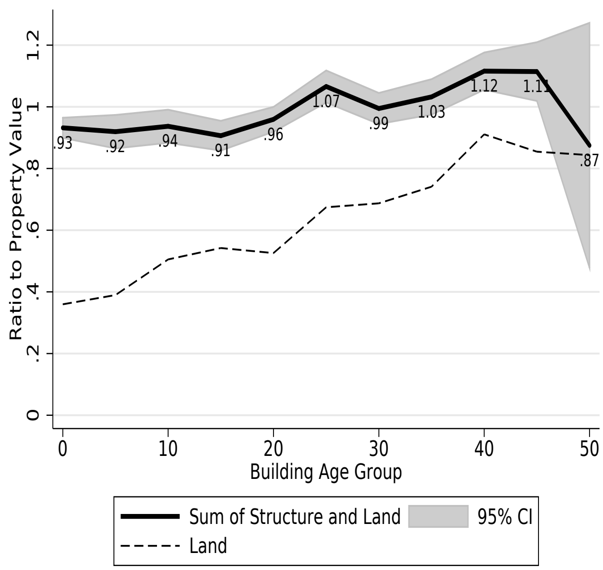
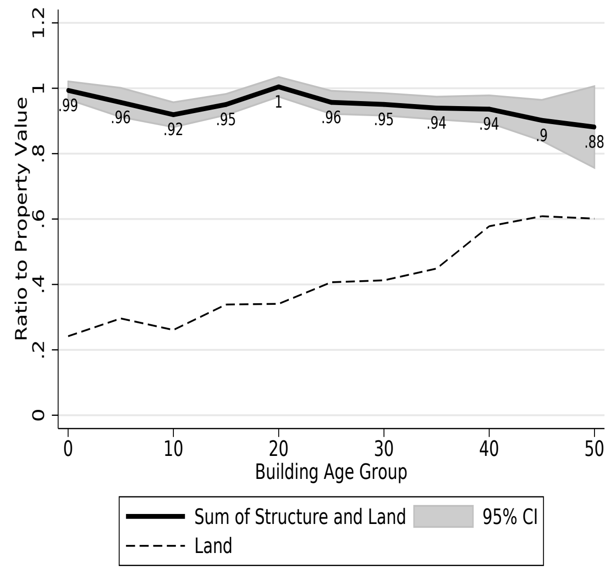


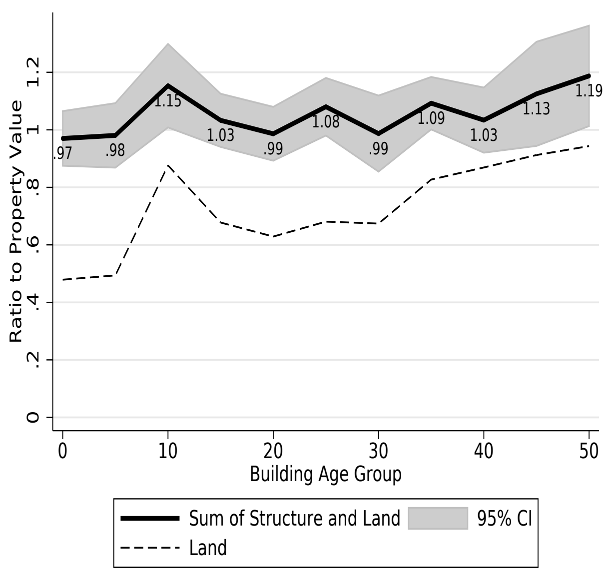
Figure 1: Structure and Land Value Ratios for Centre County (By Age)



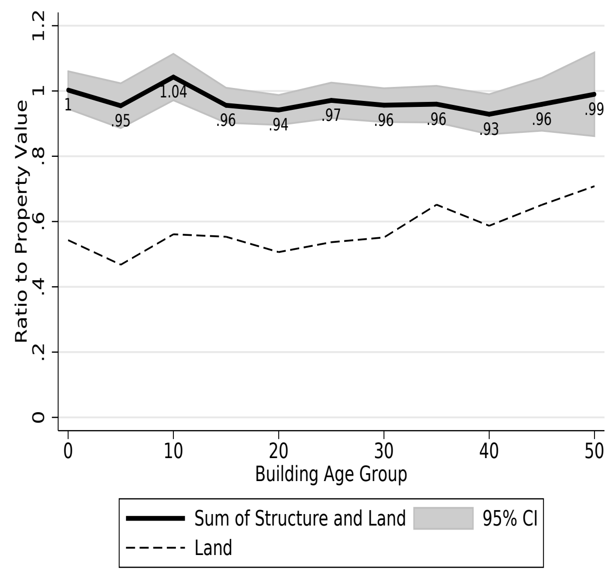
(a) Residential, Tokyo



(b) Residential, Outside Tokyo

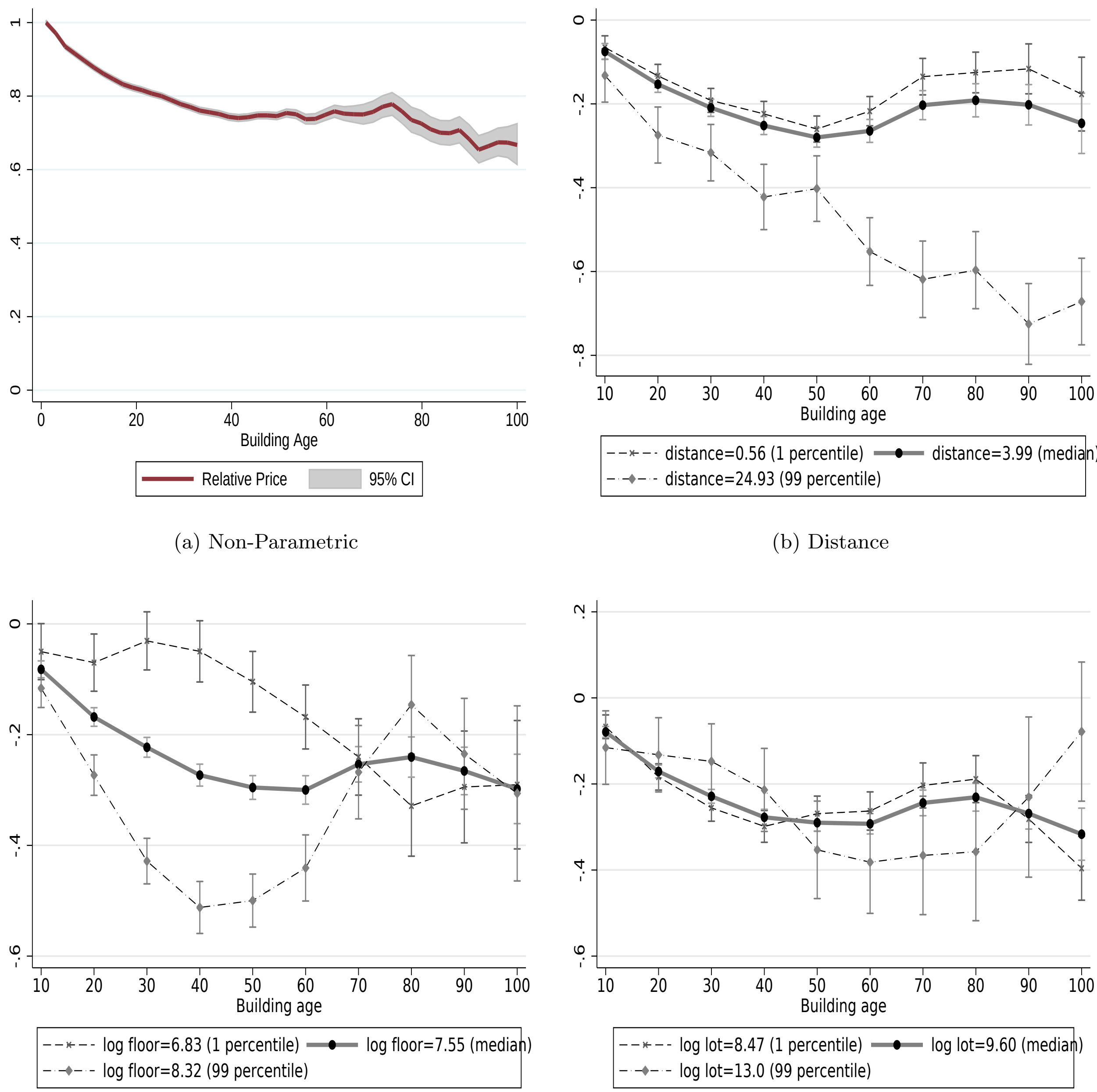


(c) Commercial, Tokyo



(d) Commercial, Outside Tokyo

Figure 2: Structure and Land Value Ratios for Japan (by Age)



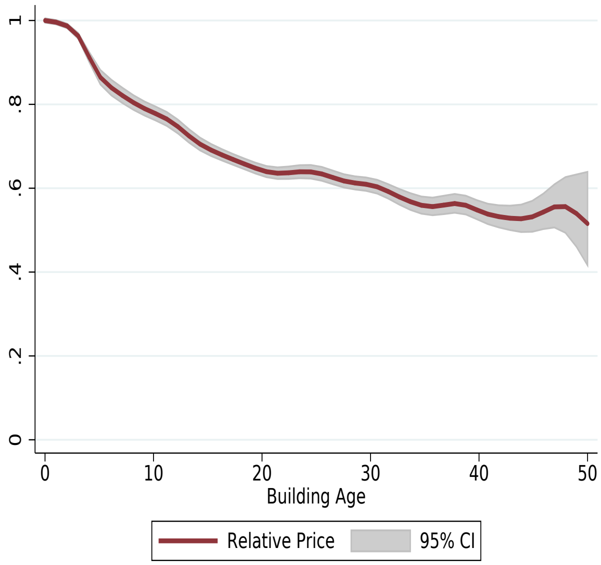
(a) Non-Parametric

(b) Distance

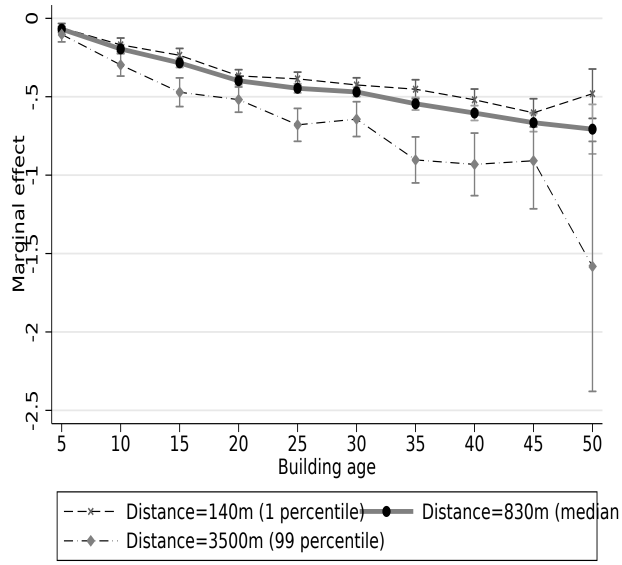
(c) Log Floor Area

(d) Log Lot Area

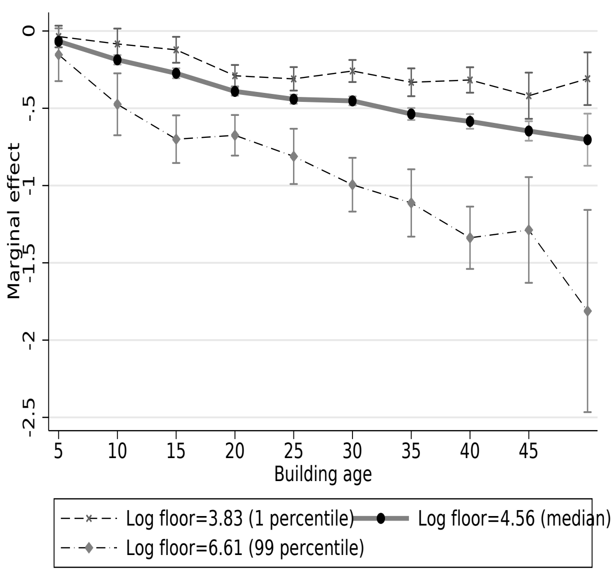
Figure 3: Property Value Depreciation (Residential, Centre County, PA)



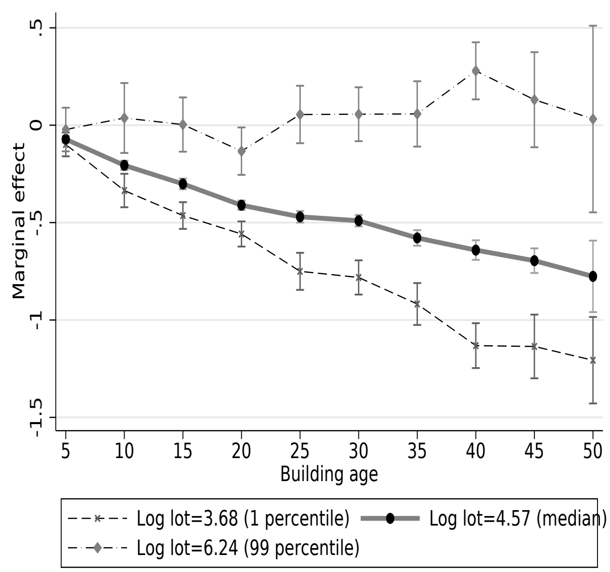
(a) Non-Parametric



(b) Distance

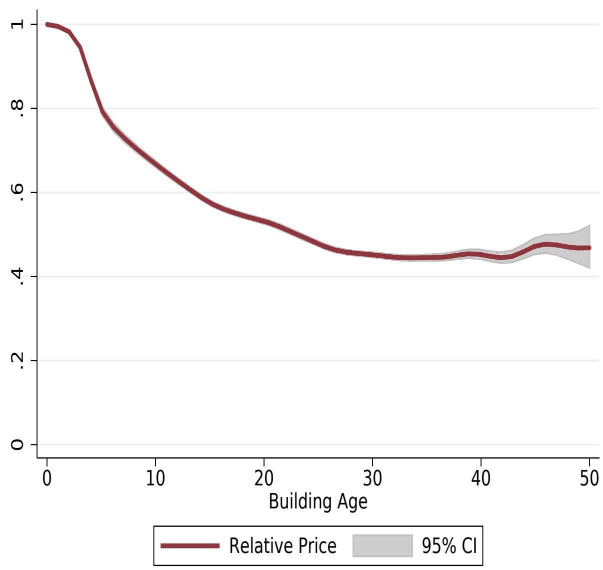


(c) Log Floor Area

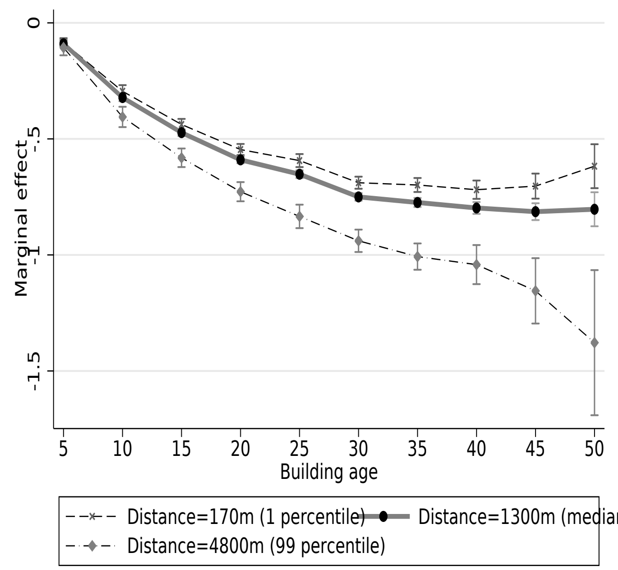


(d) Log Lot Area

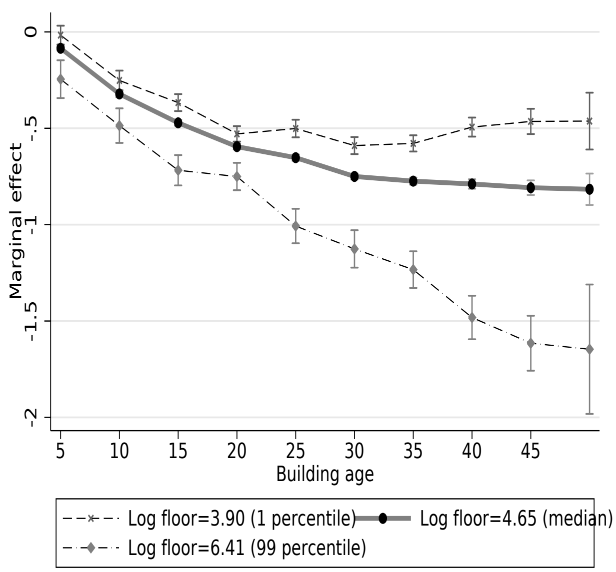
Figure 4: Property Value Depreciation (Residential, Tokyo, Japan)



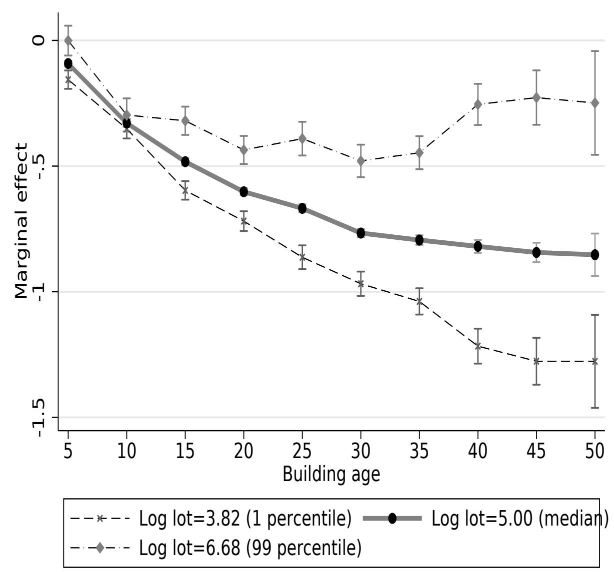
(a) Non-Parametric



(b) Distance

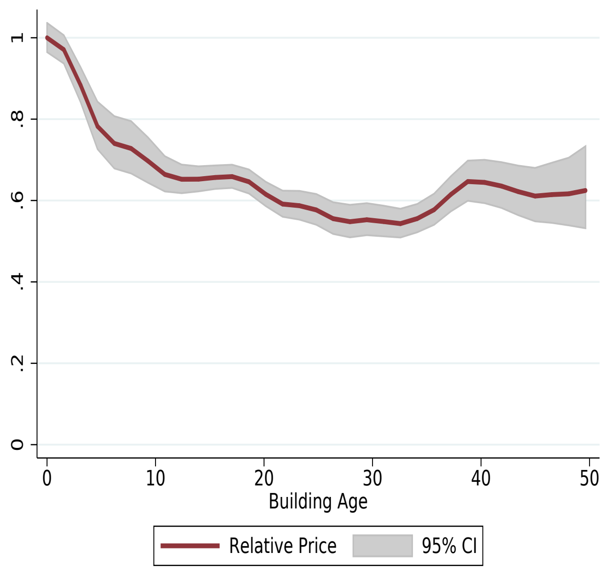


(c) Log Floor Area

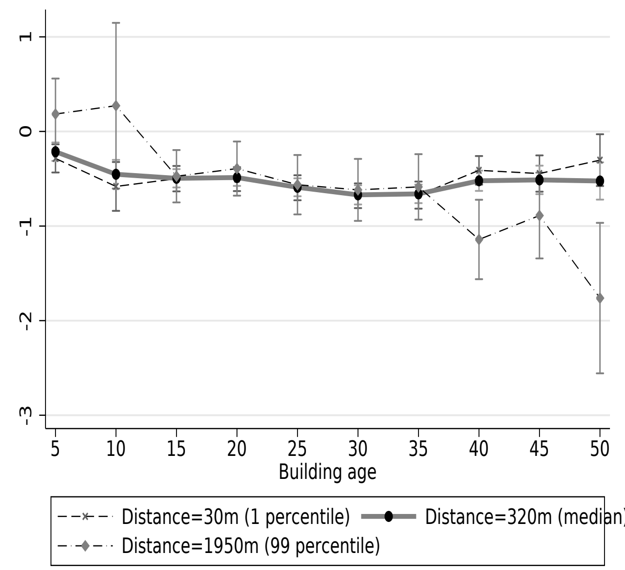


(d) Log Lot Area

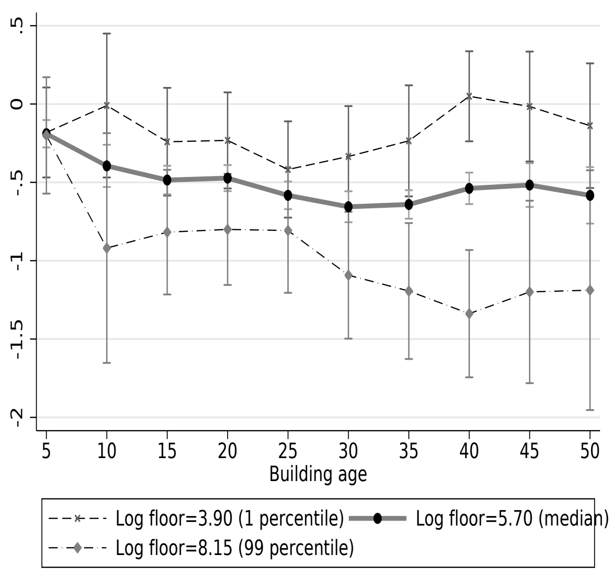
Figure 5: Property Value Depreciation (Residential, Outside Tokyo, Japan)



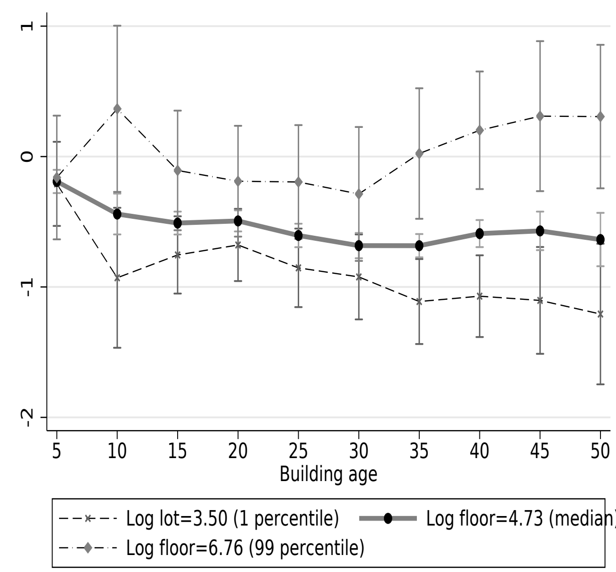
(a) Non-Parametric



(b) Distance

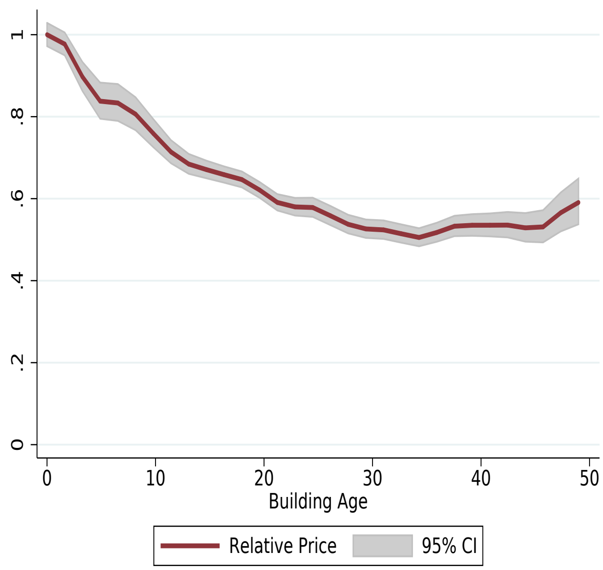


(c) Log Floor Area

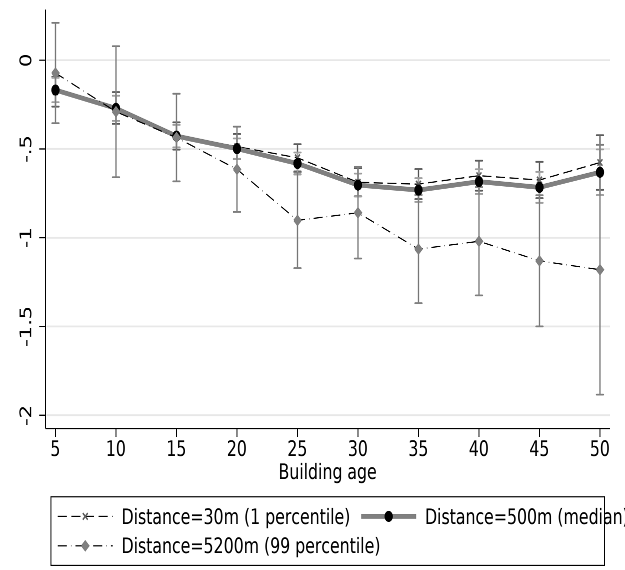


(d) Log Lot Area

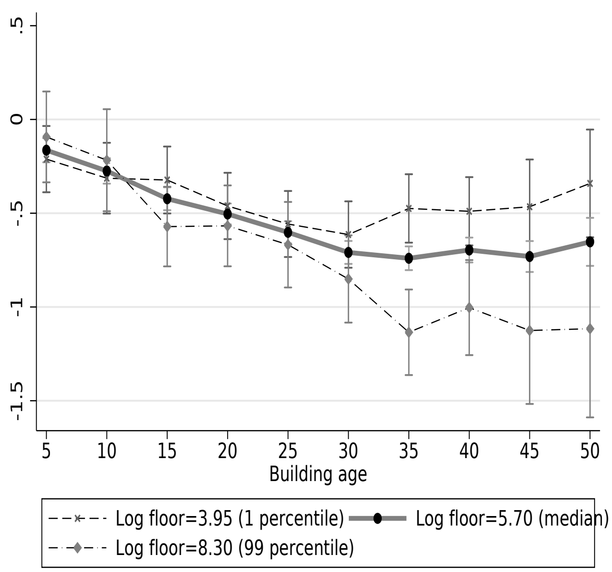
Figure 6: Property Value Depreciation (Commercial, Tokyo, Japan)



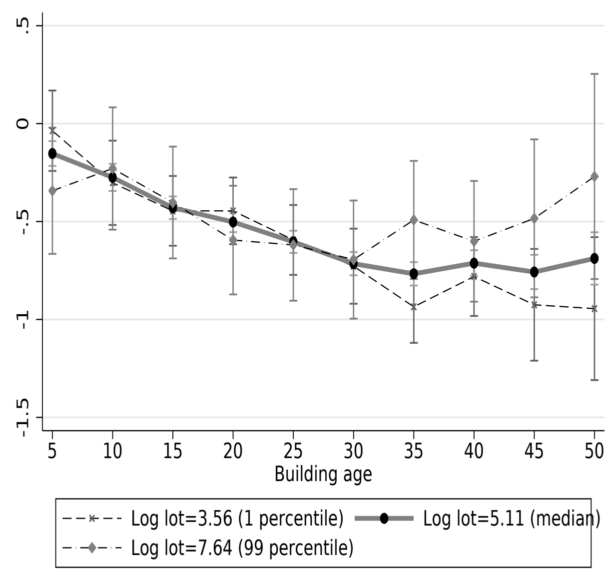
(a) Non-Parametric



(b) Distance

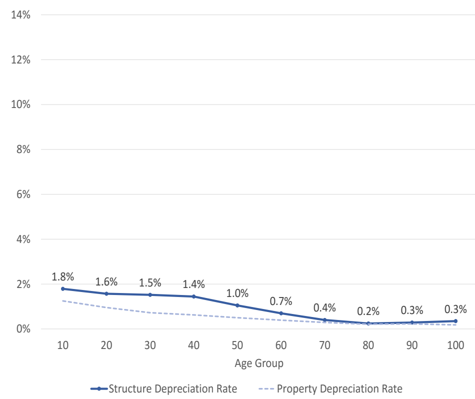


(c) Log Floor Area

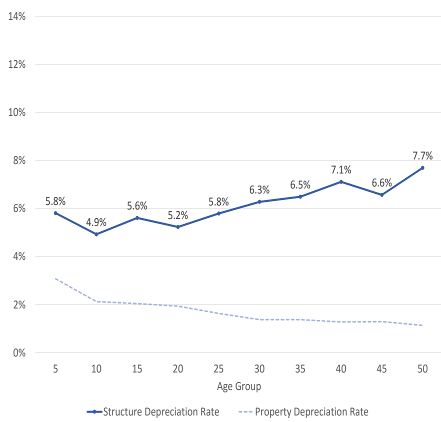


(d) Log Lot Area

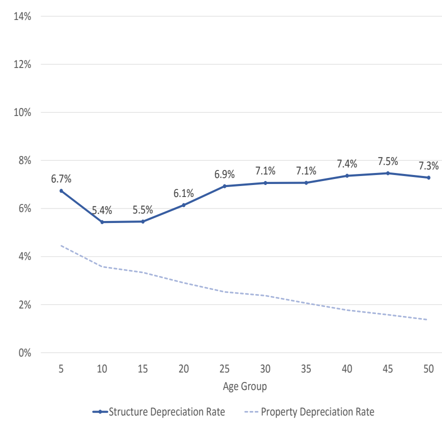
Figure 7: Property Value Depreciation (Commercial, Outside Tokyo, Japan)



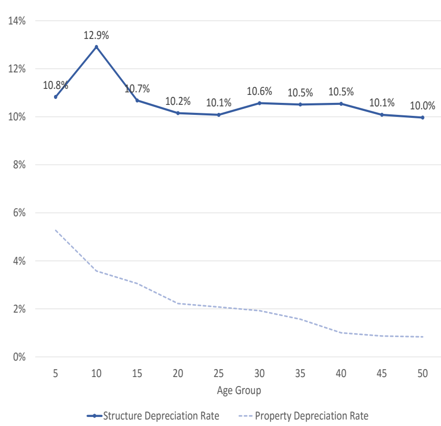
(a) Centre County, Residential



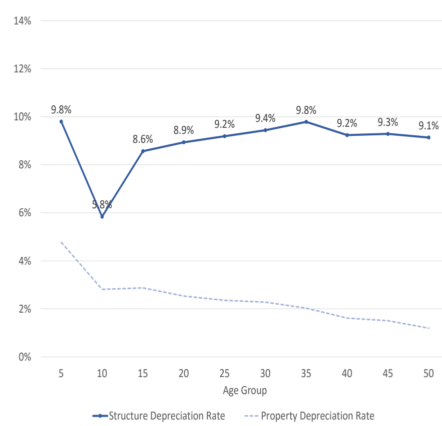
(b) Tokyo, Residential



(c) Outside Tokyo, Residential



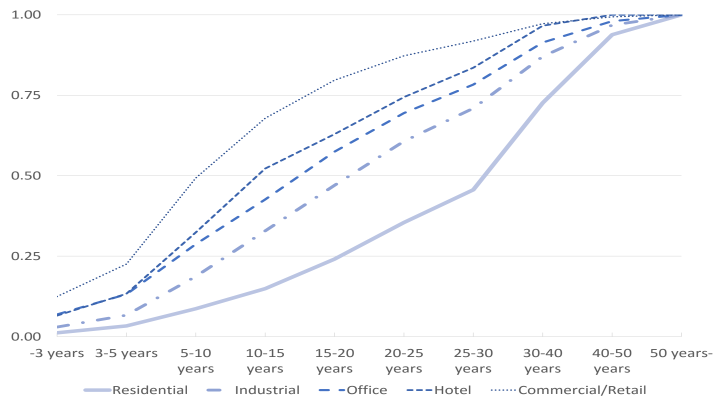
(d) Tokyo, Commercial



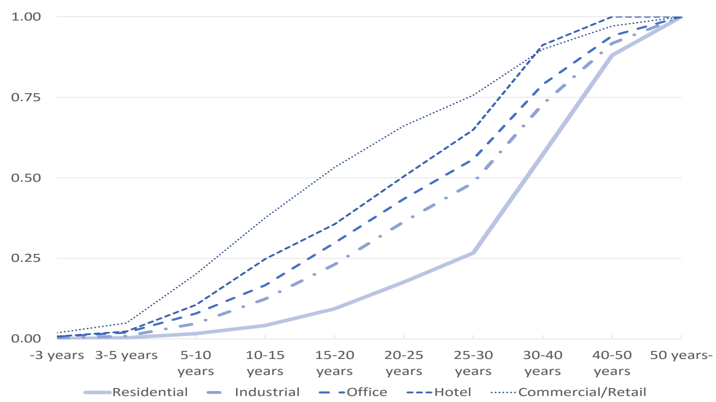
(e) Outside Tokyo, Commerical

Figure 8: Bias-Corrected Rates of Depreciation

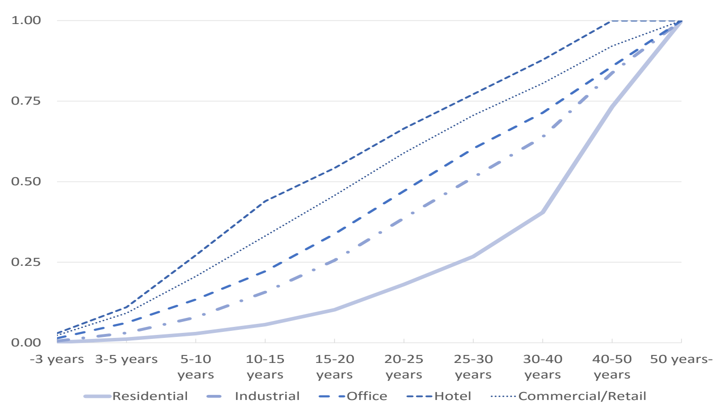
This figure depicts the estimated annual property depreciation rate and the structure depreciation rate corrected for survivorship biases based on Tables VI and VII



(a) Unadjusted

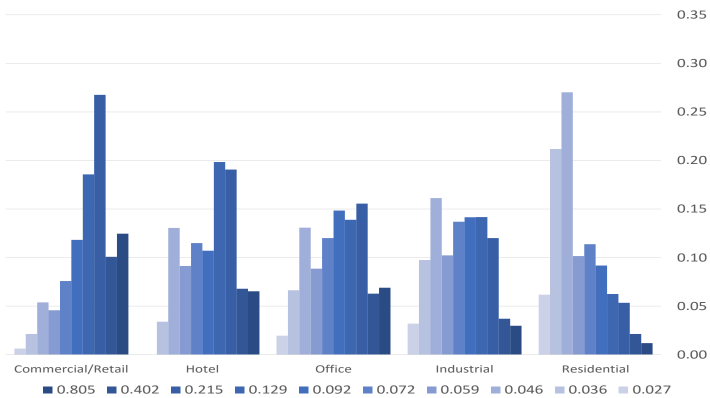


(b) Adjusted for Frequency

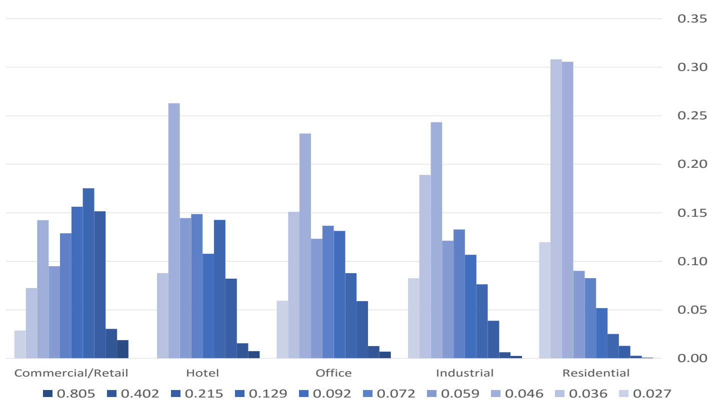


(c) Adjusted for Frequency and Construction Volume

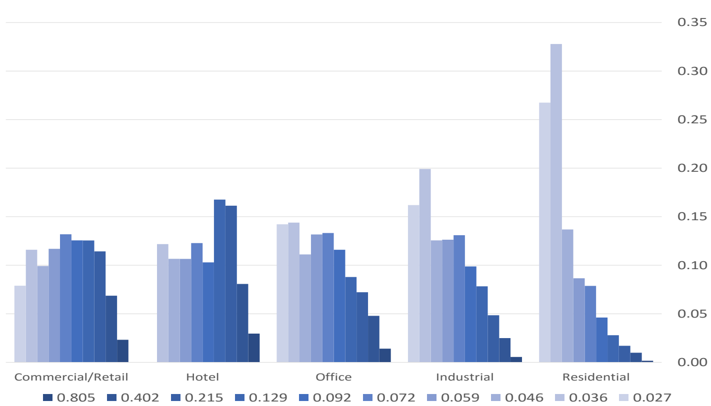
Figure 9: Cumulative Distribution of Building Age at Demolition



(a) Unadjusted



(b) Adjusted for Frequency



(c) Adjusted for Frequency and Construction Volume

Figure 10: Distribution of Depreciation Rates

Appendix A Properties of the production function

The production function (1),

$$H_u = \left[\alpha (E_u S)^{\frac{\theta-1}{\theta}} + (1-\alpha) L^{\frac{\theta-1}{\theta}}\right]^{\frac{\eta\theta}{\theta-1}},$$

has the following properties.

A Elasticity of Substitution

The elasticity of substitution ε is defined as:

$$\varepsilon \equiv \frac{d \ln \frac{E_u S}{L}}{d \ln |TRS|}, \tag{A.1}$$

where TRS is the technical rate of substitution. The TRS for this production function is:

$$\begin{aligned} TRS &\equiv \left. \frac{\partial E_u S}{\partial L} \right|_{dH=0} \\ &= -\frac{\partial H / \partial L}{\partial H / \partial (E_u S)} \\ &= -\frac{1-\alpha}{\alpha} \left(\frac{E_u S}{L} \right)^{\frac{1}{\theta}}. \end{aligned} \tag{A.2}$$

By taking the natural logarithm of equation (A.2), totally differentiating, and rearranging, I obtain:

$$\varepsilon = \theta. \tag{A.3}$$

Thus, the parameter θ represents the constant elasticity of substitution. Two productive factors are complementary when $\theta < 1$ and substitutable when $\theta > 1$. When $\theta = 1$, equation (1) becomes:

$$H_u = (E_u S)^{\alpha\eta} L^{(1-\alpha)\eta}. \tag{A.4}$$

This is a more general function than the Cobb-Douglas function because power parameters may not add up to one: $\alpha\eta + (1-\alpha)\eta = \eta$.

B Returns to Scale

The production function $H(ES, L)$ has the following homogeneity property with respect a positive constant m:

$$H(mES, mL) = \left[\alpha(mES)^{\frac{\theta-1}{\theta}} + (1-\alpha)(mL)^{\frac{\theta-1}{\theta}}\right]^{\frac{\eta\theta}{\theta-1}}$$
$$= m^{\eta} H(ES, L). \tag{A.5}$$

Thus, this production function is homogeneous of degree η. It exhibits increasing returns to scale when $\eta > 1$, constant returns to scale when $\eta = 1$, and decreasing returns to scale when $\eta < 1$.

Appendix B Log-Linear Approximation of Real Estate Value

The logarithm of property value after an infinitesimal period dt is:

$$\ln V_{t+dt} = \ln V_0 + \ln\left[s_0 e^{-\delta(t+dt)} + (1-s_0)\right]. \tag{B.1}$$

By defining a function:

$$f(x) \equiv \ln V_0 + \ln\left[s_0 e^{-\delta(t+x)} + (1-s_0)\right], \tag{B.2}$$

taking the first derivative of $f(x)$, and evaluating at $x = 0$, I obtain:

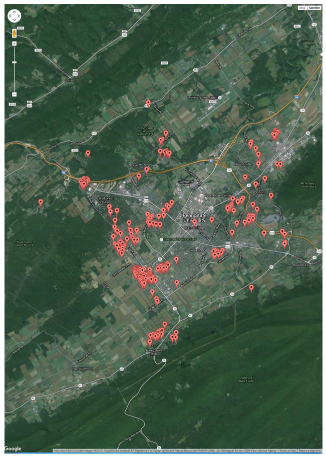
$$f'(x)\,|_{x=0} = \frac{-\delta s_0 e^{-\delta t}}{s_0 e^{-\delta t} + (1-s_0)} = -\delta \frac{P_t^S}{V_t} = -\delta s_t. \tag{B.3}$$

Since $f(x)$ is approximated by $f(x) \approx f(0) + f'(0)x$, the log property price is:

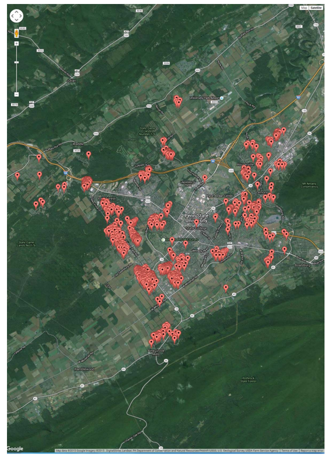
$$\ln V_{t+dt} \approx \ln V_t - \delta s_t dt. \tag{B.4}$$

In other words, the property depreciation rate is δs_t.

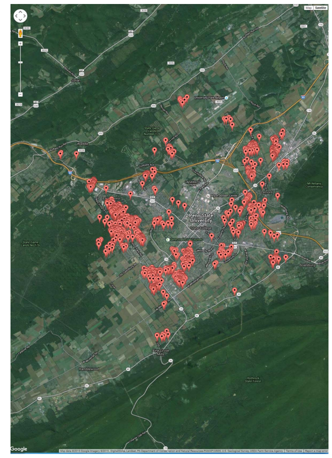
Appendix C Building Age and Location in Centre County, PA



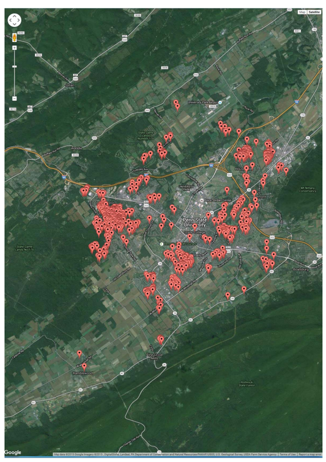
(a) 0-10 years



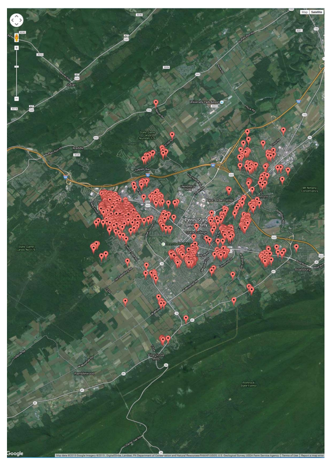
(b) 10-20 years



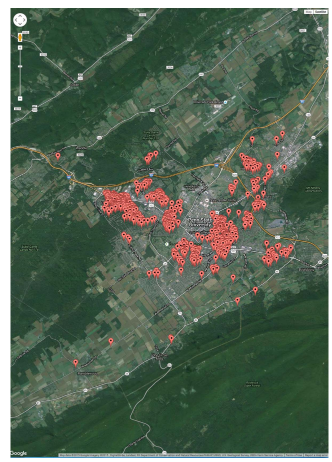
(c) 20-30 years



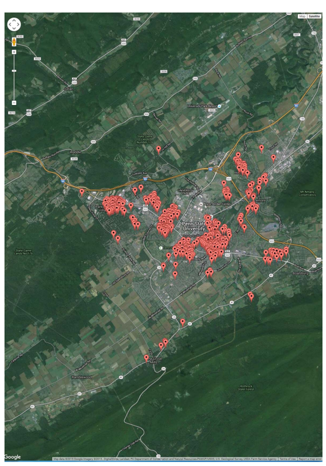
(d) 30-40 years



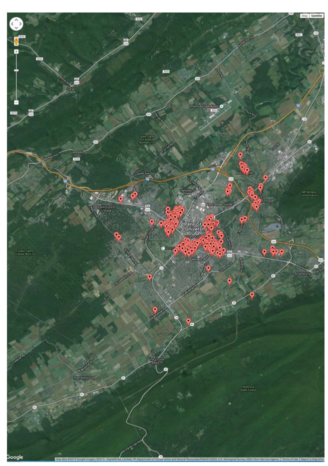
(e) 40-50 years



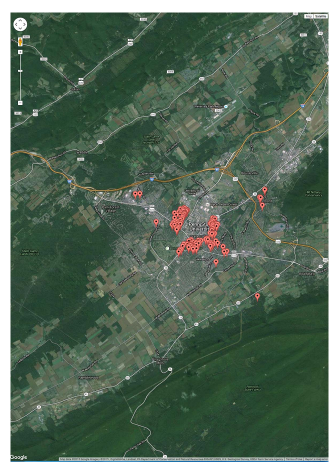
(f) 50-60 years



(g) 60-70 years



(h) 70-80 years



(i) 80-90 years

Figure 11: Building Age and Location