Empirical Analysis of the Impact of Age-Related Property Depreciation on Office Rents

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Kimiaki SHINOZAKI, Head of Price Statistics Division of the Bank of Japan
kimiaki.shinozaki@boj.or.jp

1. Focus of the Study

- In the Services Producer Price Index (SPPI), which the Bank of Japan has been compiling and publishing since January 1991, the item *Office Rent* reflects the age-related depreciation of office building asset values over time as a deterioration in the quality of office rental services.

- The current method of quality adjustment is based on the empirical analysis conducted by Saita and Higo [2010] using data from 2007. However, with 15 years having passed since this analysis, factors such as the long-term rise in real estate prices, technological innovations in the construction sector, and the spread of the COVID-19 pandemic may not have been adequately reflected, potentially leading to a deterioration in the accuracy of the index.

- Until recently, we lacked a widely accessible office rental database, which made it difficult to conduct high-precision empirical analyses using the hedonic method. However, a joint analysis has now been initiated in collaboration with XYMAX Group, Japan’s leading property and asset management company, leveraging the data and expertise held by the group.

2. Literature Review (1): Trends in Real Estate Value & Rent Studies

(1) Studies on improving the accuracy of economic statistics

- Rent is an essential element with significant weight in both the SNA and the CPI (Nishimura, 2018; Lopez and Yoshida, 2022; Yoshida et al., 2024). It is also a key component of capital stock and consumption expenditure (Yoshida and Kawai, 2020; Ambrose, Coulson, and Yoshida, 2015).

(2) Studies on improving the accuracy of investment decisions and collateral valuation

- The importance of real estate as collateral (Goodman and Thibodeau, 1997; Fisher et al., 2005; Nishimura, 2018) and the significance of commercial real estate as an investment target (Yoshida and Kawai, 2020), have been recognized in the literature.

→ Previous research in both contexts aims to achieve the following methodological objectives: (i) the creation of unit price indices and (ii) the estimation of depreciation rates in real estate value and rent over time. This study focuses on the latter, aiming to estimate parameters that enhance the accuracy of the quality adjustment for the SPPI.

2. Literature Review (2): Classification by Estimation Models

- Previous studies have primarily used the hedonic method, which allows for precise control over the attributes of each property.

<table>
<tr><th rowspan="2">method</th><th colspan="2">Rent</th><th colspan="2">Real estate value</th></tr>
<tr><th>Residential</th><th>Commercial</th><th>Residential</th><th>Commercial</th></tr>
<tr><td rowspan="2">Hedonic regression</td><td rowspan="2">Lane et al. 1988
Randolph 1988
Campbell 2006
Lopez and Yoshida 2022</td><td rowspan="2">Brennan, Cannady and Colwell 1984
Dunse and Jones 1998
Takeuchi 2000
Nagai, Kondo and Ohta 2000
Takeshita and Nakamura, 2006
Saita and Higo, 2010
Nakayama and Onishi, 2014, 2015
Yoshida et al. 2024</td><td colspan="2">Francke and van de Minne 2017
Yoshida 2016, 2020</td></tr>
<tr><td>Goodman and Thibodeau 1995, 1997
Coulson and McMillen 2008
Diewert and Shimizu 2015, 2016
Wilhelmsson and Roos 2024</td><td>Hulten and Wykoff 1981a, b
Fisher et al. 2005
Diewert, Fox and Shimizu 2016
Diewert and Shimizu 2017, 2019
Bokhari and Geltner 2018, 2019</td></tr>
<tr><td rowspan="2">Other method</td><td rowspan="2"></td><td rowspan="2">Crosby, Devaney and Law 2012
Crosby, Devaney and Nanda 2016</td><td colspan="2">Hayashi 1991（SNA）</td></tr>
<tr><td>Leigh 1980（SNA）
Harding, Rothendal and Sirmans 2007</td><td>Hulten and Wykoff 1981a（SNA）</td></tr>
</table>

2. Literature Review (3): Classification by Price Data

- In the past, analyses primarily relied on appraisal and listing prices. However, because these do not accurately reflect actual prices and because appraisal prices are subject to a lag, the use of transaction prices has become popular in recent years.

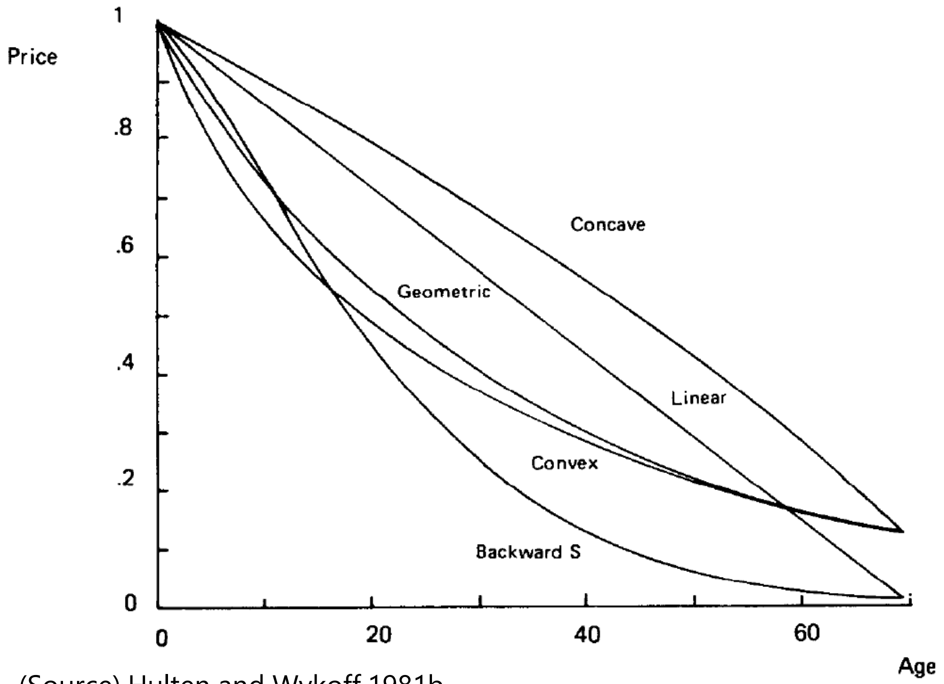
Data	Japan	Other Countries
Survey	Yoshida 2016, 2020	(US) Brennan, Cannady and Colwell 1984* (US) Lane *et al.* 1988, Randolph 1988, Campbell 2006 (US) Hulten and Wykoff 1981b (US) Harding, Rothendal and Sirmanas 2007 (CH) Wilhelmsson and Roos 2024
Appraisal price	Diewert and Shimizu 2017, 2019	(US) Goodman and Thibodeau 1995, 1997 (US) Fisher *et al.* 2005 (UK) Crosby, Devaney and Law 2012* (UK) Crosby, Devaney and Nanda 2016*
Listing price	Nagai, Kondo and Ohta 2000* Takeshita and Nakamura 2006* Saita and Higo 2010* Diewert and Shimizu 2015, 2016	(UK) Dunse and Jones 1998*
Transaction price	Takeuchi 2000* Yoshida 2016, 2020 Diewert and Shimizu 2019 Yoshida *et al.* 2024*	(US) Bokhari and Geltner 2018, 2019 (US) Yoshida 2016 (US) Yoshida 2020 (US) Lopez and Yoshida 2022

(Note) Studies marked with an asterisk (*) focus on the analysis of commercial real estate rents.

2. Literature Review (4): The Relationship between Age & Depreciation

- To the best of our knowledge, there are no studies that specifically focus on the relationship (functional form) between property age and depreciation with regard to office rents in Japan.

Functional Form of Depreciation



(Source) Hulten and Wykoff 1981b

Discussion in Previous Literature

	Residential	Commercial
Rent	(US) Lane *et al.* 1988 ➡Non-linear (US) Lopez and Yoshida 2022 ➡Non-linear	(UK) Crosby, Devaney and Nanda 2016 ➡Geometric or steeper convex-to-origin
Property price	(US) Goodman and Thibodeau 1995 ➡Non-linear	(US) Hulten and Wykoff 1981a, b ➡Closer to geometric (steeper) (US) Bokhari and Geltner 2018 ➡Concave up quadratic function

3. Overview of the Data

- The dataset contains rent data for tenants who signed new leases between 2000-2024 in properties located within the 23 wards of Tokyo and Osaka City, with a total of 80,057 observations.

Variables	Definitions	Min.	Ave.	Med.	Max.	S.D.	Outlier
$rent_t^{(i)}$	The rent of tenant *i* at the time of contract (JPY per *tsubo*)	6003.0	18474.0	17000.0	94025.0	7522.7	6,000 JPY or less, exceeding 100,000 JPY
$age_t^{(i)}$	The age (years) of the property to which tenant *i* belongs at the time of contract	0.0	22.3	22.0	60.0	12.2	More than 60 years
$GFA_t^{(i)}$	The total floor area (*tsubo*) of the property to which tenant *i* belongs	300.3	7242.8	2200.0	139685.4	12895.0	300 *tsubo* or less
$min_t^{(i)}$	The walking time (minutes) from the nearest station to tenant *i*	0.0	3.1	3.0	19.0	2.1	—
$story_t^{(i)}$	The number of floors above ground of the property to which tenant *i* belongs	2.0	13.3	10.0	64.0	8.8	—
$D\_center_t^{(i)}$	1 if the property to which tenant *i* belongs is located in one of the five central wards (*Chiyoda*, *Chuo*, *Minato*, *Shibuya*, and *Shinjuku*)	0.00	0.41	0.00	1.00	—	—
$D\_area_t^{(i)}$	The area where the property to which tenant *i* belongs is located	—	—	—	—	—	—
$D\_RF_t^{(i)}$	1 if the property to which tenant *i* belongs has a raised-floor structure	0.00	0.83	1.00	1.00	—	—
$D\_AC_t^{(i)}$	1 if the property to which tenant *i* belongs has individual air conditioning	0.00	0.82	1.00	1.00	—	—
$D\_machine_t^{(i)}$	1 if the property to which tenant *i* belongs has mechanical security	0.00	0.96	1.00	1.00	—	—
$D\_large_t^{(i)}$	1 if the property to which tenant *i* belongs is large-scale (5,000 *tsubo* or more)	0.00	0.31	0.00	1.00	—	—
$D\_Osaka_t^{(i)}$	1 if the property to which tenant i belongs is located in Osaka City	0.00	0.25	0.00	1.00	—	—
$D\_reno_t^{(i)}$	1 if the property to which tenant *i* belongs has undergone renovations at the time of contract	0.00	0.20	0.00	1.00	—	—
$age\_r_t^{(i)}$	The number of years since renovations were made to the property to which tenant *i* belongs at the time of contract	0.0	8.6	7.0	57.0	7.1	—

(Note) *Tsubo* is a traditional unit of area used in Japan, where 1 *tsubo* equals 3.30578 square meters.

4. Analytical Framework (1): Estimation Model

- By adopting the hedonic method, we control for variables that influence property prices and rent, and interpret the building age term as the cumulative depreciation from the rational price at the time of new construction. $\exp\left(f(\cdot)\right)$ is referred to as the *Cumulative Depreciation Rate (CDR)*, and the first-order difference in CDR is referred to as the *Depreciation Rate (DR)*.

Rent at time *t* | Building age | Continuous variables | Dummy variables

$$\ln rent_t^{(i)} = f\left(age_t^{(i)}\right) + \alpha + \sum_{k=1}^{l} \gamma_k X_{k,t}^{(i)} + \sum_{k=1}^{m} \delta_k D_{k,t}^{(i)} + u_t^{(i)}.$$

The effect of age on the rational price $\left(f(0) = 0\right)$

The log value of the rational price at the time of new construction $\left(= \ln \overline{rent}_t^{(i)}\right)$

$$\widetilde{rent}_t^{(i)} = \exp\left(f\left(age_t^{(i)}\right)\right) * \overline{rent}_t^{(i)}$$

The rational price at the $age_t^{(i)}$

Age-related changes from the rational price at the time of new construction

4. Analytical Framework (2): Explanatory Variables

- In this study, we use building age and various property attributes (such as total floor area, distance from the nearest station, and floor height) as explanatory variables, based on previous research. Additionally, the transaction period and location are treated as categorical variables.

Previous research	Dependent variable	Property attributes				Agglomeration	Categorical variables
		Building age	Total floor area	Distance from the station	Story		
Hulton and Wykoff 1981a, b	●	●					Transaction period
Brennan, Cannaday and Colwell 1984*	△、◎		△				Transaction period, Location
Takeuchi 2000*	◎	△		△	△		
Nagai, Kondo and Ohta 2000*	●	●	●	△		●	Transaction period
Takeshita and Nakamura 2006*	●		◎	◎	◎	◎	Transaction period
Saita and Higo 2010*	●	Dummy	●（REIT）	●	●（rent）		Location
Bokhari and Geltner 2018	◎	△ (Quadratic)	◎				Transaction period, Location
Bokhari and Geltner 2019	◎	Dummy	◎				Transaction period, Location
Yoshida 2020	◎	△	◎（Quadratic）	△ (Cubic)			Transaction period, Location
Yoshida *et al.* 2024*	◎	△, Dummy	◎	△			Transaction period, Location
Our study*	◎	●, Dummy	◎	△	△		Transaction period, Location

(Note 1) Studies marked with an asterisk (*) focus on the analysis of commercial real estate rents.
(Note 2) ● represents the Box-Cox transformation, ◎ represents the logarithm, and △ represents no transformation. The details of the Dummy will be explained later.

4. Analytical Framework (3): Possible Functional Forms for Building Age

- Previous studies have explored various functional forms for building age in relation to depreciation. In this study, to capture the changes in depreciation rates with respect to building age more accurately, we adopt a model using age-dummy variables (Option 1).
- Additionally, we consider a model employing the Box-Cox transformation (Option 2). We also explore a model that combines two linear functions (Option 3), which approximates the estimation results derived from the age-dummy variable model.

Possible Functional Forms for Building Age

Option 1: Age-dummy variables

$$f(x) = \sum_{k=1}^{60} \beta_k \mathbf{1}_{\{x=k\}}$$

$\mathbf{1}_{\{n\}}$: A function that takes the value 1 when condition n is satisfied, and 0 otherwise.

Option 2: Box-Cox transformation

$$f(x) = \begin{cases} \theta \dfrac{(x+1)^{\lambda}-1}{\lambda} & \text{if } \lambda \neq 0 \\ \theta \ln(x+1) & \text{if } \lambda = 0 \end{cases}$$

Option 3: Two linear functions (kinked function)

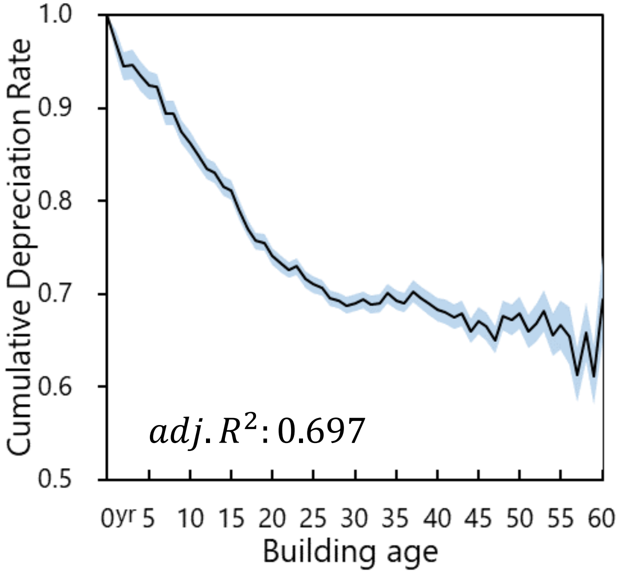
$$f(x) = \left(\mathbf{1}_{\{0 \leq x \leq X\}} \frac{1}{X} x + \mathbf{1}_{\{X < x\}}\right) \theta + \rho x.$$

X : The connection point between two linear functions.

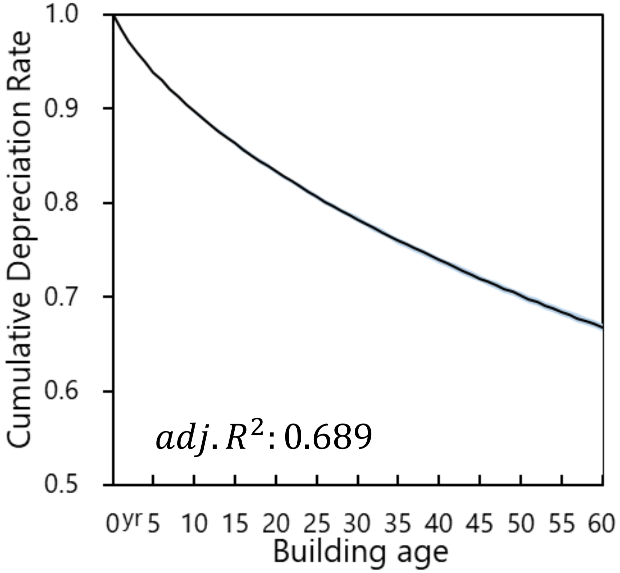
5. Estimation Results (1): Shape of the Building Age Function

- We compare the results from using age-dummy variables and the Box-Cox transformation for the functional form of building age. The CDR function shows a **generally linear decline up to around the age of 25 years, followed by a period of stabilization**. The model with the Box-Cox transformation fails to capture this pattern.

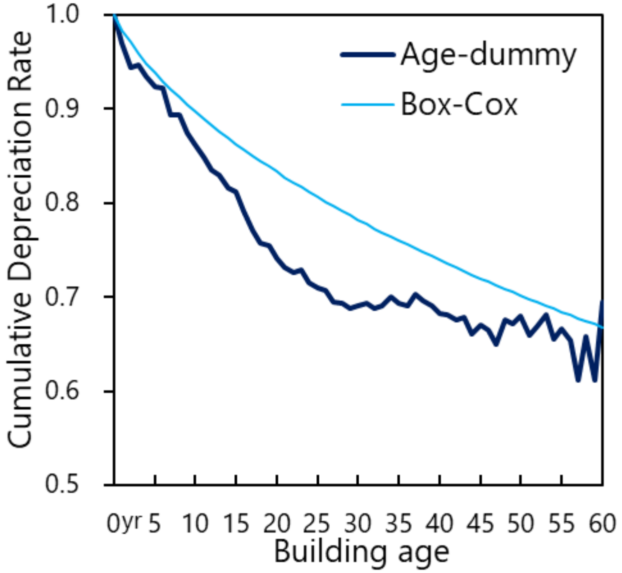
Benchmark Estimation:
Age-Dummy Variables



Benchmark Estimation:
Box-Cox Transformation



Comparison between Age-Dummy
Variables & Box-Cox Transformation

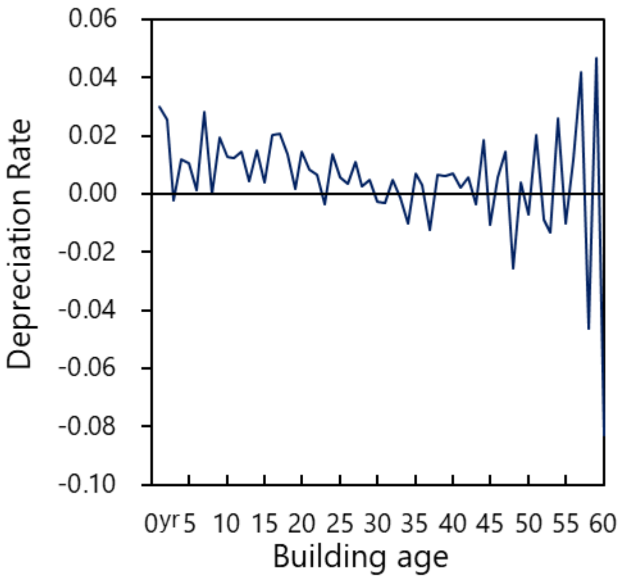


(Note) The shadow indicates ±2 standard deviations. The same applies hereafter.

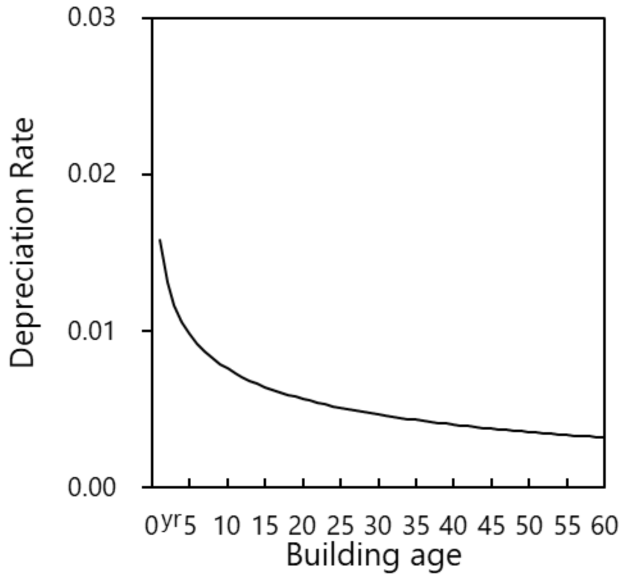
5. Estimation Results (1): Shape of the Building Age Function (cont'd)

- The DR's based on age-dummy variables show significant fluctuations. The average DR up to the age of 60 is approximately **0.51% per year**. The average DR up to around 25 years is approximately **1.16% per year**. The DR's based on the Box-Cox transformation show a smoother transition. The average DR up to the age of 60 is approximately **0.55% per year**, and the average DR up to 25 years is approximately **0.77% per year**.

Benchmark Estimation:
Age-Dummy Variables



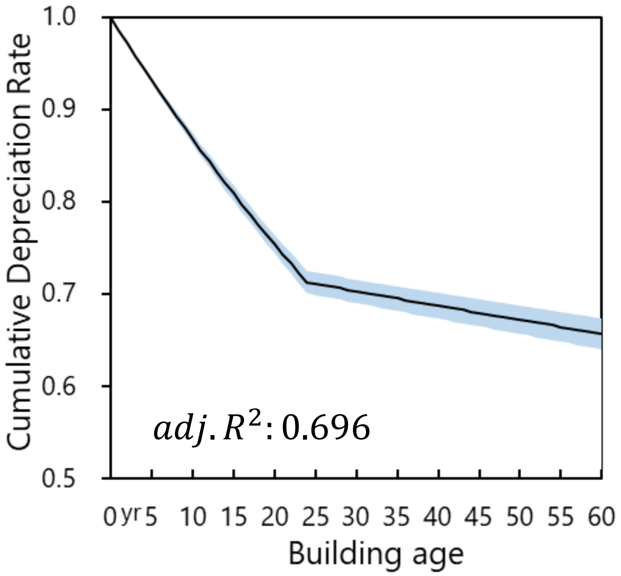
Benchmark Estimation:
Box-Cox Transformation



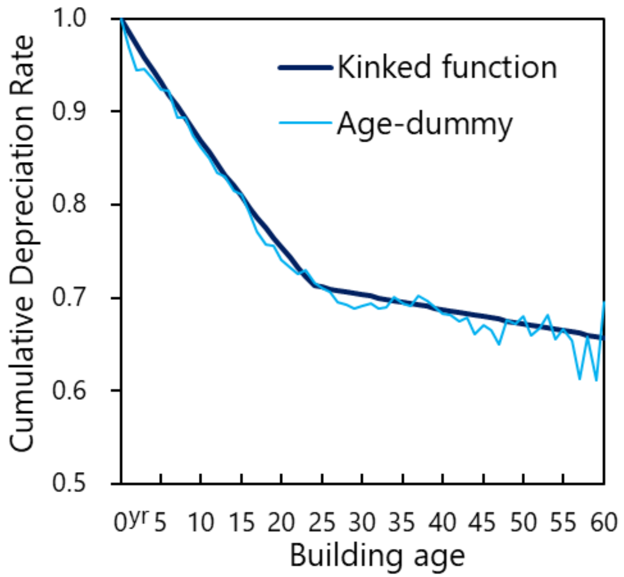
5. Estimation Results (1): Shape of the Building Age Function (cont'd)

- We adopt a kinked function and compare the estimation results with those based on age-dummy variables. The average DR up to the connection point of the two linear functions (around 24 years) is approximately **1.20% per year**. From the connection point to 60 years, the average DR is approximately 0.15% per year, and the average DR over the entire period up to 60 years is approximately **0.57% per year**.

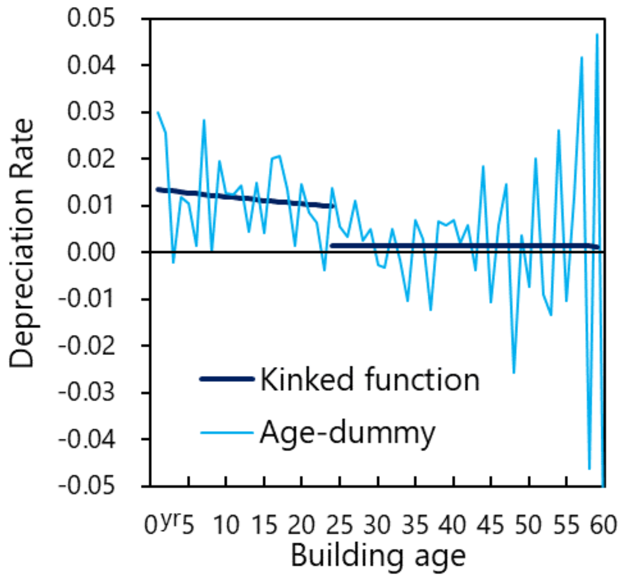
Benchmark Estimation:
Kinked function



Comparison of Kinked Function
& Age-Dummy Variables (CDR)



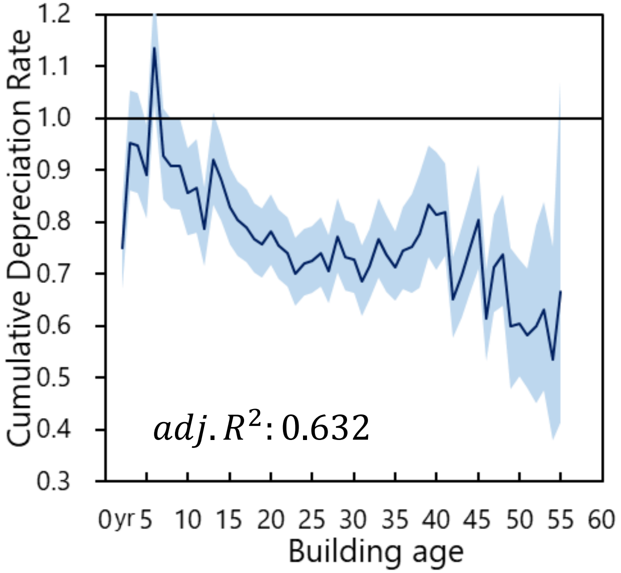
Comparison of Kinked Function
& Age-Dummy Variables (DR)



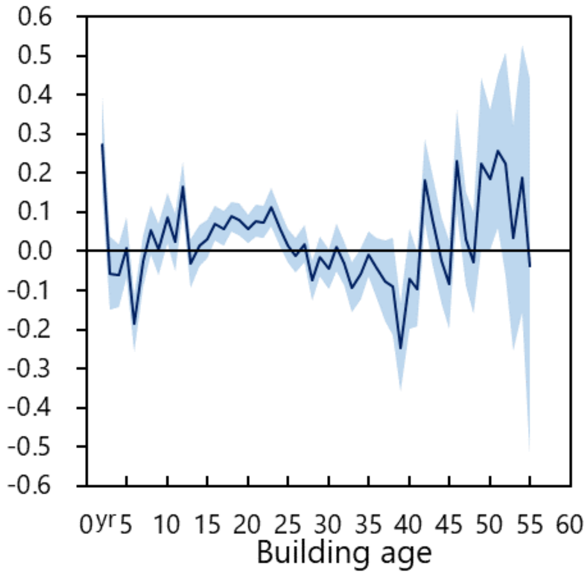
5. Estimation Results (2): Differences between New & Renewal Rents

- In the dataset of this study, for properties managed by XYMAX Group, it is possible to distinguish between new (4,951 cases) and renewal (9,580 cases) rents. To examine the difference between the two, we added the interaction term of building age and the renewal contract dummy. The coefficients are not significant, except for around the 16-24 years, indicating that **the differences between new and renewal rents are not substantial**.

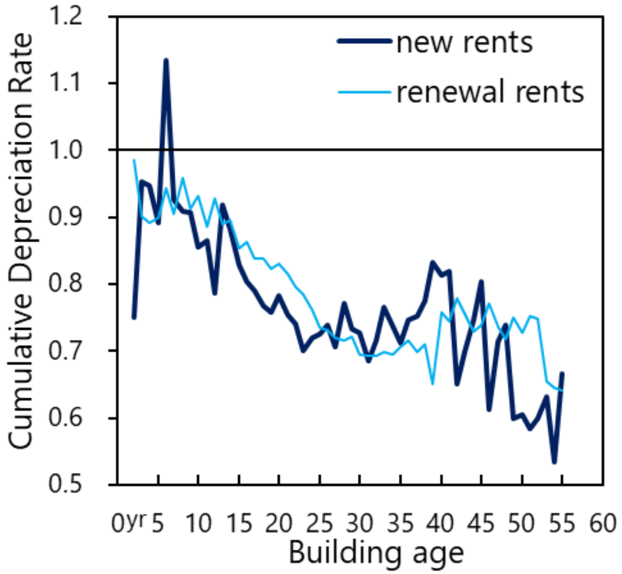
Estimation Results
Based on New Contracts



Coefficient of the
Interaction Term



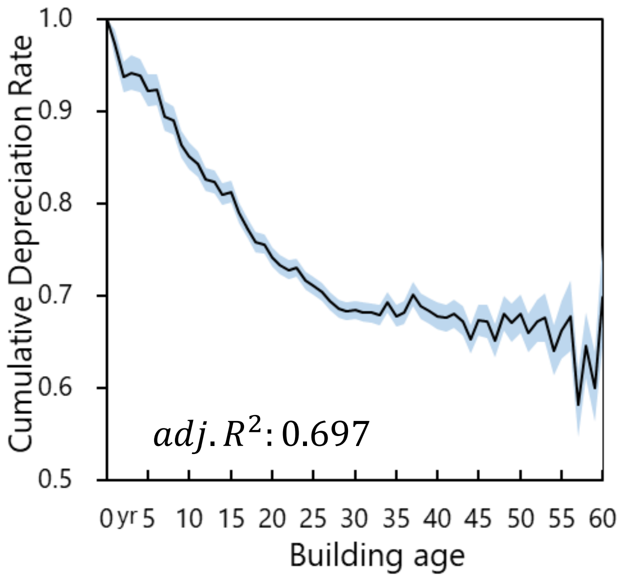
Comparison of New &
Renewal Rents



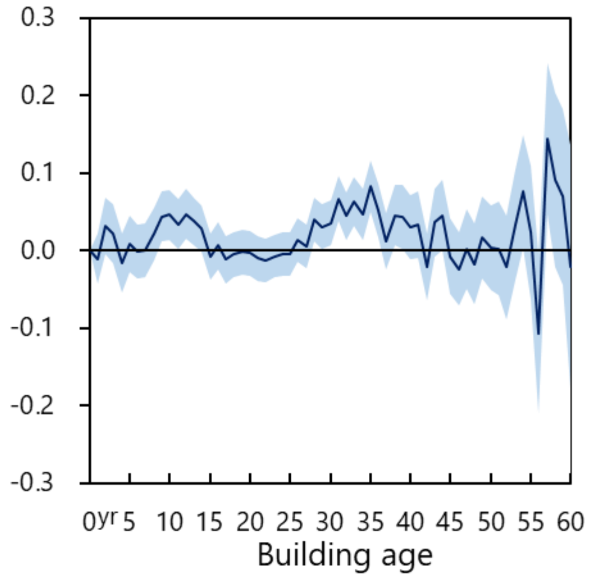
5. Estimation Results (3): Differences in Property Location

- The coefficient of the interaction term between building age and the Osaka City dummy is not significant, except for building ages between 9-14 years and 28-35 years. This suggests that **the region in which the property is located does not have a substantial impact on depreciation.**

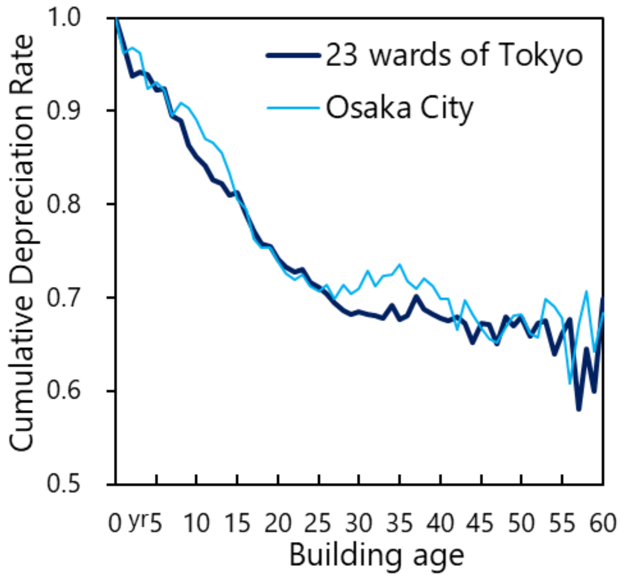
Estimation Results Limited to the 23 Wards of Tokyo



Coefficient of the Interaction Term



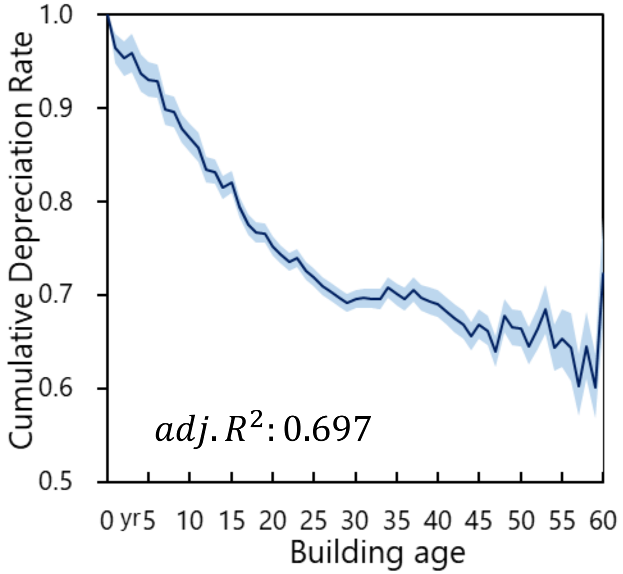
Comparison of the 23 Wards of Tokyo and Osaka City



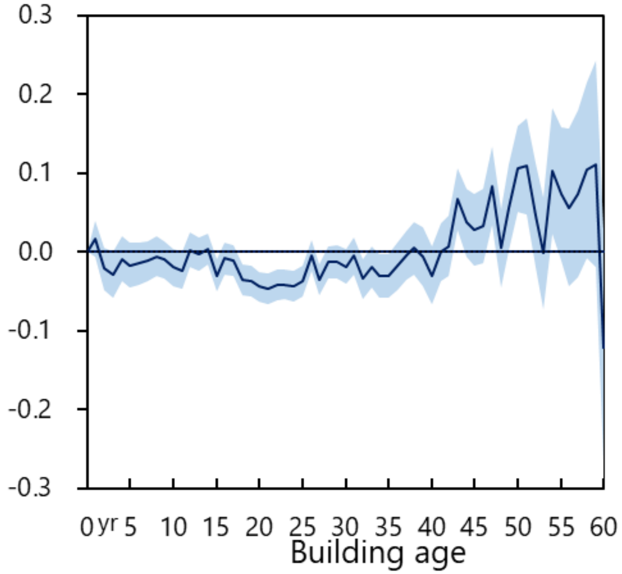
5. Estimation Results (4): Differences in Property Size

- The coefficient of the interaction term between building age and the large-scale property dummy is significantly negative around 18-25 years, but becomes significantly positive after 40 years. **Large-scale properties experience depreciation at a faster rate than smaller properties from the time of new construction up to around 20 years**. After that, **while smaller properties follow a gradual depreciation trend after 25 years, large-scale properties stabilize within a flat range**.

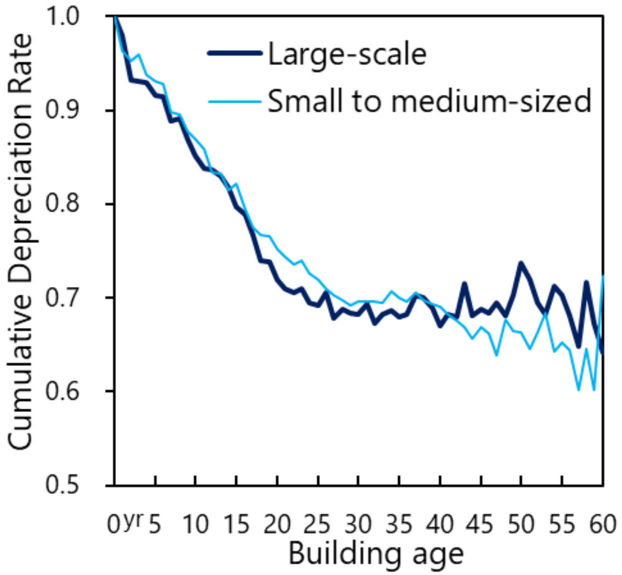
Estimation Results Limited to Small and Medium-Sized Properties



Coefficient of the Interaction Term



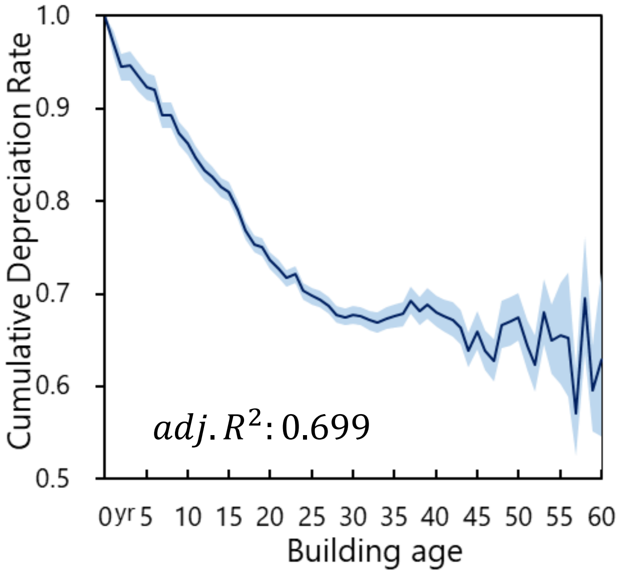
Comparison of Large-Scale & Small to Medium-Sized Properties



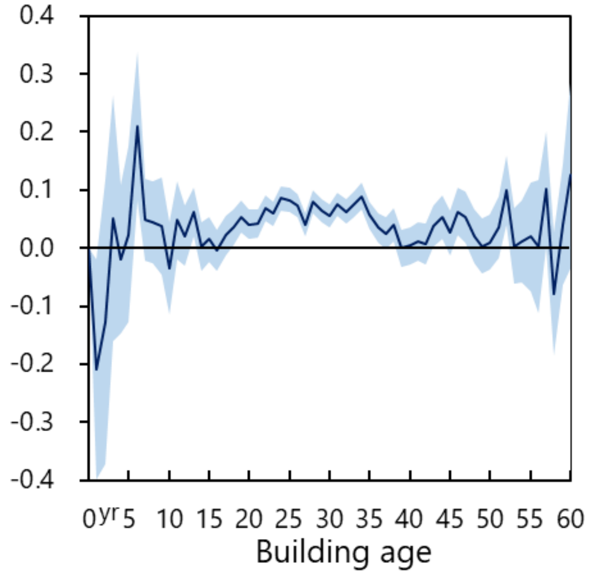
5. Estimation Results (5): Effect of Property Renovations

- Looking at the coefficient of the interaction term between building age and the renovation dummy, we clearly see that implementing renovations shifts the CDR function upward between the ages of 18-38 years. The shift in the CDR function due to renovations is approximately **2.53 percentage points** on average up to 60 years, and approximately **4.24 percentage points** on average between the ages of 18-38 years.

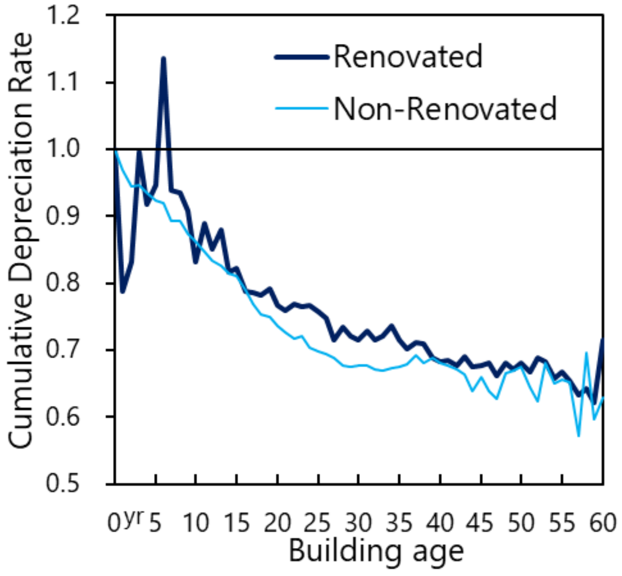
Estimation Results Limited to Non-Renovated Properties



Coefficient of the Interaction Term



Comparison of Renovated and Non-Renovated Properties



5. Estimation Results (5): Effect of Property Renovations (cont'd)

- The CDR function shifts approximately **8.18 percentage points** upward immediately after renovations, and this effect persists for about **16 years**. On average, from the immediate post-renovation period to 16 years later, the rate is about **5.81% per year**. However, in the dataset of this study, only about 20% of tenants have properties with renovation records. There is also variability in the number of years since the renovations.

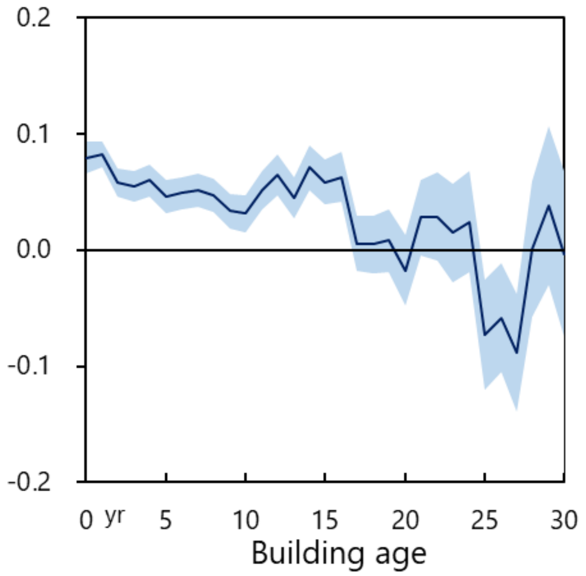
Incorporation of "Years Since Renovation" as dummy variable

$$g\left(age\_r_t^{(i)}\right) = \sum_{k=1}^{60} \varphi_k \mathbf{1}_{\{age\_r_t^{(i)} = k\}}$$

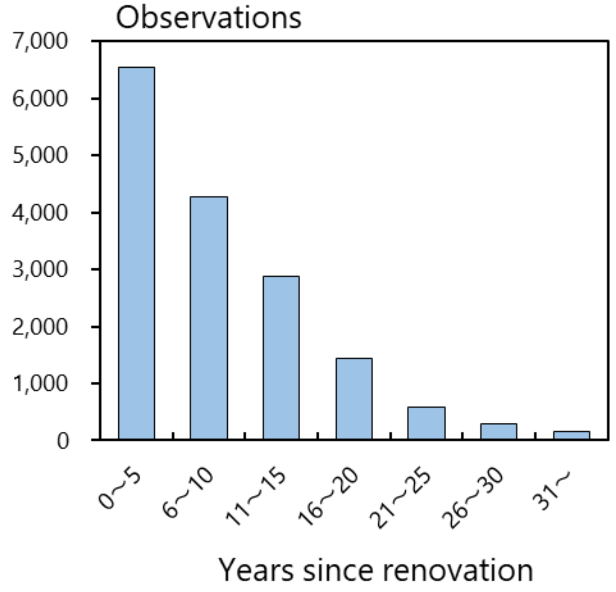
$\mathbf{1}_{\{n\}}$: A function that takes the value 1 when condition n is satisfied, and 0 otherwise.

Add $g(\cdot)$ into the model

Changes in Renovation Effects Over Time



Distribution of "Years Since Renovation"



6. Key Contributions of This Study

(1) A Detailed Analysis of the Impact of Age-Related Depreciation on Office Properties in Japan

- The CDR function decreases linearly from new construction to around 25 years, and then stabilizes. This pattern is similar to the case of commercial real estate prices in the U.S. Previous studies have suggested two reasons for this: (i) the impact of land, which is not subject to depreciation, and (ii) the continued investments made to maintain the property’s value.

(2) Proposal for a Functional Form of Building Age for Statistical Compilation

- We propose a model with a kinked function, which achieves comparable accuracy to the model using age-dummy variables, while also being easily applicable to statistics compilation.

(3) Testing Practitioners’ Intuition About the Office Rental Market in Japan

- Except for certain building ages, factors such as property location and size do not result in significant differences in the shape of the CDR function. Property renovations shift the CDR function upward by an average of approximately 4.24 percentage points between ages 18-38. This effect lasts for about 16 years, with an average upward shift of 5.81 percentage points.