Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Investment, depreciation and obsolescence of R&D

Peter Chinloy\textsuperscript{a}, Cheng Jiang\textsuperscript{a, b, *}, Kose John\textsuperscript{b}

\textsuperscript{a} Department of Finance, Temple University, 1801 Liacouras Walk, Philadelphia, PA 19122, United States
\textsuperscript{b} Department of Finance, New York University, 44 West 4th Street, New York, NY 10012, United States

**A R T I C L E   I N F O**

Article history:
Received 6 June 2019
Received in revised form 15 June 2020
Accepted 24 June 2020
Available online 25 June 2020

JEL classification:
E22
O3
O4

Keywords:
R&D
Time-varying depreciation
Pharmaceuticals
Semiconductors
Software

**A B S T R A C T**

Time-varying depreciation rates are estimated for research and development of the United States aggregate economy and innovation-intensive industries. Mean annual R&D depreciation rates are 31.5% for software, 41% for pharmaceuticals, 42% for semiconductors, and 30.4% for aggregate economy during 1978–2014. R&D depreciation rates vary across industries.

R&D investment demand has separate elasticities in time-varying depreciation, interest rate and price growth, allowing for different rates of technology shifts across industries. Software R&D investment has the same magnitude of elasticities to depreciation, interest rate and price, supporting a user cost to apply. For pharmaceuticals and semiconductors, depreciation leads to more R&D investment that implies the effect of scale. For aggregate economy, depreciation reduces R&D investment more than interest rate, indicating obsolescence.

Forecasting of R&D investment is improved at both industry and aggregate level. Forecastable time-varying depreciation, interest rate and price growth predict R&D investment based on the estimated demand function. The in-sample forecast comparison for 2015–2019 confirms the superiority to the alternative methods. Out-of-sample forecasts of R&D investment are carried out through 2025, and R&D capital stocks are constructed across industries and aggregate U.S. economy.

© 2020 Elsevier B.V. All rights reserved.

1. Introduction

Time-varying depreciation in intellectual property products, or research and development (R&D) has been applied by Hall (2005) and Li and Hall (2020). A natural extension is to construct a user cost of R&D investment with variable depreciation, and to study the effect of time-varying depreciation on investment demand. With estimated R&D investment, back-checking the accuracy of in-sample forecast against actual observations and predicting future investment become possible.

In the theoretical model, the demand of R&D investment is affected by a time-varying depreciation rate along with the interest rate and price growth. R&D investment demand has separate elasticities in time-varying depreciation, interest rate and price appreciation, allowing for different rates of technology shifts across industries. When elasticities of depreciation, interest and price are equal in absolute value, R&D investment depends on a single factor as the user cost. When the elasticities are not equal, time-varying depreciation indicates technology shifts from obsolescence or scale.

Obsolescence increases the cost of depreciation, which reduces R&D investment. Scale decreases the cost of depreciation, resulting in more R&D investment. Such effect of scale especially applies to R&D investment in pharmaceuticals. The trials and tests for drug and vaccine research and development have positive externalities. A drug or vaccine failing to address one disease has potential use for another disease with comparable genetic makeup. Coronavirus families including SARS, MERS, and Covid-19 are cases where pharmaceutical firms with previous R&D investment have low barriers and cost to enter the subsequent efforts to cure new disease, leading to more R&D investment. These findings are particularly timely and relevant, given the financial instability and unquiet times that encompass the world currently.

Stationary time-varying depreciation rate, interest rate, and price growth are forecastable. Their forecasts, along with their estimated relationship with R&D investment, enable the prediction of R&D investment. By reserving a portion of the sample, observed actual investment compared with in-sample forecast allow for the verification of model accuracy.

\textsuperscript{*} We are grateful to Elyas Elyasiani, Iftekhar Hasan [Editor], Victoria Ivashina, Yi Liang, Oleg Rychkov, Pavel Savor, Charles Swenson, Joe Williams and two anonymous reviewers for very helpful comments.

\textsuperscript{a} Corresponding author.

E-mail addresses: peter.chinloy@temple.edu (P. Chinloy), cheng.jiang@temple.edu (C. Jiang), kjohn@stern.nyu.edu (K. John).

https://doi.org/10.1016/j.jfs.2020.100757
1572-3089/© 2020 Elsevier B.V. All rights reserved.
The application is to the aggregate economy of United States, and R&D-intensive industries, such as software, pharmaceuticals, and semiconductors over a time window between 1978 and 2025. The sample period used for estimation is 1978–2014. The period 2015–2019 is reserved for in-sample forecast accuracy confirmation. The out-of-sample predicting ranges from 2020 to 2025.

This paper finds that time-varying depreciation rates vary across aggregate economy and industries. The mean time-varying depreciation rate of overall U.S. R&D is 30.4% yearly, and the annual depreciation rate of software R&D is 31.5%. Li and Hall (2020) find the depreciation rate in software ranges between 31% and 34% annually, and it is 37% in Warusawitharana (2015). We also demonstrate that the mean time-varying depreciation rate of pharmaceutical R&D is 41% annually, and that of semiconductors is 42%. Warusawitharana (2015) finds 41% depreciation rate in pharmaceuticals and 34% semiconductors.

Unit root tests show stationarity in time-varying R&D depreciation, real interest rate, and real R&D price growth. The real R&D investment is nonstationary, but the growth rate of real R&D investment is stationary. These series enter the investment demand function, allowing for forecasting of R&D investment. The model of intertemporal investment projects that investment is decreasing in interest rate and increasing in price appreciation. This condition applies to R&D investment in all estimations, including aggregate economy, software, semiconductors, and pharmaceuticals.

In software, the depreciation elasticity of investment is not different from those for interest rate and price growth in absolute value, which supports a single factor as the user cost. The elasticity of software R&D investment in the user cost is −0.2. For the aggregate economy, the elasticity of investment to depreciation is −1.4, exceeding those for interest rates and appreciation. Reduced investment from depreciation in excess of that from interest rate implies obsolescence.

For pharmaceuticals, the depreciation elasticity of R&D investment is 1.5, and it is 0.8 for semiconductors. An increase in depreciation in these industries raises R&D investment, implying scale. Scale decreases the cost of depreciation, resulting in more investment. The estimates provide possible explanations for otherwise puzzling results in R&D estimation found by previous studies. Hall (2005) finds negative depreciation rates for pharmaceuticals, computers, and electrical machinery. On the other end, Knott et al. (2003) report depreciation rates of up to 100% annually for pharmaceuticals. These phenomena are consistent with scale, reducing the cost of subsequent R&D investment.

Across the aggregate economy and industries, the driver of change in R&D investment is time-varying depreciation. The interest rate and price appreciation elasticities of R&D investment are usually bounded in absolute value by the 0.2 for the user cost. Given the relative size of the elasticities, R&D investment responds to time-varying depreciation as opposed to interest rate and price. The results reinforce incorporating a time-varying depreciation rate in R&D investment modeling.

Our estimation improves forecasting of R&D investment at both aggregate and industry level. Forecasting R&D investment using its historical data is challenging, because it is nonstationary and subject to unpredictable events. The past data of R&D investment does not provide credible information in forecasting. This paper suggests forecasting R&D investment using the time-varying depreciation rate and their estimated relationship in demand function. The in-sample forecast of 2015–2019 is compared with actual observed R&D investment for verification. The mean forecast error of software R&D investment of our method is 2.0%, as opposed to 7.3% with the best alternative. The mean forecast error of aggregate R&D investment is 1.4%, as opposed to 3.5% of best alternative. This suggests that the model incorporates time-varying depreciation and estimated demand function of investment has superiority in forecasting. Out-of-sample predictions of R&D investment for 2020–2025 are carried out using time-varying depreciation, given the verified better performance. The R&D capital stock is derived using time-varying depreciation rates and fitted R&D investment, so is its forecast.

Section 2 describes the treatment of time-varying R&D depreciation and summarizes industry-specific estimates found by previous studies. Section 3 outlines the theoretical model for depreciation and investment. The data are described in Section 4. Section 5 reports the estimated relationship among R&D investment, time-varying depreciation, interest rate and price, as well as the forecast of R&D investment and R&D capital. A conclusion is in Section 6.

2. Background

Table 1 shows depreciation rates applied in the United States at the aggregate level to tangible and non-tangible assets. An annual depreciation rate of 15%–16.5% is for R&D, doubled for declining balances (Mead, 2007; Okubo et al., 2006; Slikker, 2007; Fixler, 2009). R&D predicts returns at the firm and industry (Lev and Sougiannis, 1996; Lev et al., 2008), facilitating technology transfer (Griffith et al., 2004). Tax laws and accounting procedures incentivize the expensing of R&D, despite benefits lasting for longer than a year. In the United States, research and development is fully 100% expensed in the current year. Outside the United States, research is expensed by development including prototypes is capitalized and subject to a depreciation schedule. Firms using accelerated depreciation rates carry out greater investments than those using lower straight-line forms (Jackson, Liu and Cecchini 2009).

Table 2 summarizes R&D depreciation rates in various industries found by recent studies. Hall (2005) uses production function and market valuation approaches, and the estimated R&D depreciation rate in computers range from −5% to 25% annually. Bernstein and Mamuneas (2005, 2006) find that the R&D depreciation rate is 29% in electronics and 26% in machinery. Huang and Dievert (2011) use a production function with an allowance for monopolistic competition, and their estimated annual R&D depreciation rates range from 1% in chemicals to 27% in transportation. Warusawitharana (2015) finds a 28% annual depreciation for computer R&D using a market valuation procedure. Li and Hall (2020), based on Li (2012) use a depreciation rate that solves a net present value condition. Computer R&D depreciates at between 28% and 36% annually. Computer design has a depreciation rate between 25% and 49% per year. Estimation is conducted via generalized method of moments and nonlinear least squares.

A measure of R&D output is by patent quantity count and quality in citations. Using counts, depreciation rates in manufacturing are 11%–19% annually (Pakes and Griliches, 1984; Pakes, 1986).

---

1 The capital stock determines R&D’s contribution to output and its growth (Griliches, 1979, 1994, 1998; Griliches et al., 1987). A firm’s domestic sales as a proportion of gross domestic product measures contributions to output (Dorn, 1961; Hulten, 1978). The derived capital stocks exclude household consumer durables which embed R&D (Sichel and von Hippel, 2019). Governments in developed countries construct capital stocks of R&D (Organization for Economic Cooperation and Development, 2000, 2009). For the United States, the Bureau of Economic Analysis in the National Income and Product Accounts, has recognized R&D with a capital stock since 2013. During 2012–2017, equipment was 46%, structures 23% and R&D 31% of annual U.S. fixed investment.

2 The United States rule is Accounting Standard Codification (ASC) 730, Research and Development under generally accepted accounting procedures (GAAP). The tax code recognizes the 100% expensing in https://www.irs.gov/businesses/corporations/facts-irc-41-gres-and-asc-730-facts-directive#Accounting%20Standards%20Codification%20(ASC)%20730. Outside the United States, International Financial Reporting Standards (IFRS) 39, requires firms to separate research and development expenses.
or 25% in Pakes and Schankerman (1984). R&D has low costs of reproduction and difficulty of excluding others from use if patents are not enforceable. Adjusted for citations, the R&D depreciation rate is 2%–6% annually (Langouw and Schankerman, 2004). Quality-adjusted patents outperform in explaining firm market values (Hall et al., 2005). The depreciation rate for patents held by U.S. firms is between 13% and 27% annually using forward and backward citations (Bessen, 2008; Bessen and Maskin, 2009). Knott (2017) finds that the top 10% of patents earn 80% of royalties. Using to-date and future values, the depreciation rate is 3.4% annually for Australian patents (de Rassenfosse and Jaffe, 2018). Annual depreciation estimates in manufacturing range between 2% and 17% by Hirschey and Weygandt (1985), between 5% and 20% by Goel (1990) and 12% by Nadiri and Prucha (1996). Across industries within manufacturing, the annual R&D depreciation rate is between 11% and 20% (Lev and Sougiannis, 1996) and 2%–46% (Ballester et al., 2003). Internationally, the annual R&D manufacturing depreciation rate is 24% in Canada and 25% in the United States (Bernstein and Mamuneeas, 2005, 2006).

Hall (2005) notes a shift of R&D from pharmaceutical firms to biotechnology in health care. A similar movement of R&D from hardware to software occurs in information technology. The shift to software occurs as this industry has become decentralized and global (Branstetter et al., 2019). Future earnings and R&D intensity increase with firm size (Ciftci and Cready, 2011), affected by the proximity to investor clusters (Bell et al., 2020). Industrial concentration of R&D leads to the emergence and focus of star firms. Some firms invest intensively, leading to accelerated sales growth and concentration (Autor et al., 2017, 2020). Concentration increases when R&D investment is sensitive to tax policy and credits (Thompson, 2017).

### 3. Depreciation and investment model

The investment with time-varying depreciation structure is applicable to any long-term capital expenditure, including property, plant, and equipment, as well as intangible intellectual property products. The model involving a time-varying depreciation rate adjusted for obsolescence and scale is particularly relevant to R&D investment.

The price of investing in a unit of R&D is \( P = I(P) \). The demand of investment is downward sloping in price with \( \theta_r < 0 \). The price has capital gain \( p = \frac{\theta_r}{r} \). Innovation that reduces the cost of R&D leads to price deflation with \( p < 0 \).

The investment’s intertemporal maximization has discount rate \( \theta r + \lambda d \). The interest rate is \( r \) with a multiplier \( \theta \) for equity costs, leverage, and taxes, so the cost of financing is \( \theta r \). When \( \theta = 1 \) the interest rate is sufficient for the cost of capital. R&D depreciation is at rate \( d \), which varies over time and across industries. The technology shift by \( \lambda \), so the cost of depreciation is \( \lambda d \). When the coefficients on interest rate and depreciation are equal, they have the same impact on R&D investment. In this case, demand depends on the user cost \( r + d \). A common elasticity applies to the user cost. Depreciation has the same investment elasticity in absolute value as interest rate and price change. When depreciation is constant, depreciation has no impact on incremental investment, regardless of its rate. Without time variation, depreciation is part of the intercept, and the user cost is \( r - p \).

---

3 The concentration of R&D and the rise of superstar firms is not universal. Star firms locate in specific industries (Crouzet and Eberly, 2018, 2019). In consumer products R&D leads to productivity but in health care to increased margins, given patent protection. Superstar firms are not becoming larger or more productive (Gutiérrez and Philippon, 2019). While firms with over 500 employees carry out two-thirds of R&D, they are no more productive than the overall economy.
Having a separate coefficient on time-varying depreciation allows for obsolescence or scale in technology shifts. A well-behaved elasticity of investment demand in interest rate is negative. When the elasticity of investment in depreciation is larger and more negative than that for interest rate, there is obsolescence. There is scale when the elasticity of investment in depreciation is smaller than that for interest rates. A smaller elasticity for scale includes where investment is increasing in depreciation. In the limit, scale reduces the cost of depreciation, leading to a rise in investment.

Scale implies that 100% annual depreciation as found in Knott et al. (2003) for pharmaceuticals does not choke off subsequent investments. The stock of knowledge disappearing every year acts as an incentive to invest in R&D. With genome sequencing, an unsuccessful R&D project of a drug or vaccine for one disease generates positive externality, with a low cost and barrier for entering the efforts of curing a related illness. This externality is strengthened by the requirement of sequential tests on animals and humans before drug and vaccine approval. Investing currently in pharmaceutical R&D lowers the cost and barrier of R&D going forward. Hall (2005, 2010) finds negative depreciation in pharmaceuticals, computers, and electrical machinery. These are the industries that have R&D scale phenomena, which provide possible explanations for otherwise puzzling results in R&D estimation.

The investment generates a flow of services renting for C. At the discount rate \( \theta r + \lambda d \) and price \( P \), the rental price satisfies

\[
C = -\frac{\partial}{\partial t} [Pe^{-(\theta r + \lambda d)t}] = \left[ (\theta r + \lambda d) P - P e^{-(\theta r + \lambda d)t} \right]
\]

The undiscounted rental is \( C e^{(\theta r + \lambda d)t} = (\theta r + \lambda d - p)P \). The asset price of the investment per unit of rental or when \( C = 1 \) is

\[
P = \frac{1 + \theta r + \lambda d}{\theta r + \lambda d - p}
\]

Investment \( I(P) = f \left( \frac{1 + \theta r + \lambda d}{\theta r + \lambda d - p} \right) \) depends on rates of depreciation \( d \), interest \( r \) and price appreciation \( p \), the finance margin \( \theta \) and technology \( \lambda \).

In discrete time, the discount rate as yield of \( \theta r + \lambda d \) is earned one period ahead. The current numerator in the price formula becomes unity, resulting in the price of investment as \( P = \frac{1}{\theta r + \lambda d - p} \). Inverting, investment depends on \( \theta r + \lambda d - p \). With the sign change from the inversion, investment is decreasing in interest rate and variable depreciation, and increasing in capital gains. For logarithmic investment and to a first-order approximation

\[
\ln I = \alpha - \eta(\lambda d + \theta r - p) = \alpha - \eta \theta d - \eta r + \eta p
\]

The elasticity of investment in time-varying depreciation is \( \eta d \). The interest rate elasticity of investment is \( \eta r \). The elasticity of investment to price appreciation or cost growth is \( \eta p \).

The interest rate elasticity of investment is negative. When the elasticity of investment for time-varying depreciation exceeds that for interest rate in absolute value, there is obsolescence. Depreciation reduces investment more than interest rate, for a basis point increase in each. Scale happens when the depreciation elasticity is less than interest rate elasticity. Sufficient scale allows the depreciation elasticity to change sign. Increased depreciation raises investment, notably in industries with scale and externalities including pharmaceuticals and semiconductors. When depreciation rate is constant, depreciation’s effect is part of the intercept \( \alpha \), and depreciation has no impact on the incremental change in R&D investment.

### 4. Data

The time-varying depreciation application is to the R&D investment in aggregate economy and R&D-intensive industries in the United States, such as software, pharmaceuticals, and semiconductors. The source is the U.S. Bureau of Economic Analysis.

Aggregate and software data are quarterly R&D investments in nominal terms, ranging from 1978 to 2019. Pharmaceutical and semiconductor series are annual nominal R&D investments over the same time window. Real R&D investments are obtained by deflating the nominal series by R&D price appreciation. The real interest rate is the yield to maturity on the 3-month Treasury bill net of inflation. Real price appreciation in R&D is the growth rate of the relevant industry or aggregate R&D price index less inflation.

Expected time-varying depreciation is calculated as the difference between the expected investment-capital ratio and the expected capital stock growth rate. The best-fitting process of each derives the depreciation rate. The procedure is analogous to that in Warusawitharana (2015). Therefore, a rate of obsolescence is a premium. Here, the coefficient of depreciation is a premium for obsolescence or a discount for scale. In each case, the cost of depreciation is the product of a rate and a technology shift. The process allows for sufficient scale and a negative impact of depreciation (Hall, 2005) even as the rates are positive. The depreciation rate, along with the remaining variables, are subject to time-series testing for stationarity and forecasting. Apart from consistency and extension of procedures, back-check is allowed from the in-sample forecasting performance.

Summary statistics of time-varying depreciation rate are listed in Table 3. For the aggregate economy, the sample mean is 12.4% on a quarterly basis. Dividing 12.4% by the declining-balance factor 1.65 of Table 1, the quarterly mean depreciation rate is 7.51%, annualized to be 30.4%. Using a comparable procedure for software, the annual mean depreciation rate is 31.5%. The mean depreciation rate is 41% for pharmaceuticals R&D and 42% for semiconductors R&D, both of which are on an annual basis. Fig. 1 depicts time-varying R&D depreciation rates for the aggregate economy and software industry based on quarterly data, and for pharmaceuticals and semiconductors with annual data.

The time-series properties of the real interest rate, depreciation, real price appreciation, and real R&D investment determine their specification of the demand function. Table 4 reports stationarity results from Augmented Dick-Fuller Unit Root tests (Dickey and Fuller, 1981) for aggregate U.S., software, pharmaceutical, and semiconductor sectors. The real interest rate, time-varying depreci-

### Table 3

| Frequency | Aggregate | Software | Pharmaceutical | Semiconductor |
|-----------|-----------|----------|----------------|--------------|
| Mean      | 0.124     | 0.130    | 0.424          | 0.411        |
| Median    | 0.123     | 0.130    | 0.421          | 0.424        |
| Standard Deviation | 0.002     | 0.007    | 0.031          | 0.051        |
| Maximum   | 0.129     | 0.147    | 0.503          | 0.472        |
| Minimum   | 0.121     | 0.112    | 0.372          | 0.261        |

Table 3 reports the summary statistics of time-varying depreciation rates for the aggregate R&D investment in the U.S., and the sectoral R&D investment in software, pharmaceutical and semiconductor industries. Due to the frequency of available data, depreciation rate is calculated quarterly for aggregate and software R&D, and yearly for pharmaceutical and semiconductor R&D.
Aggregate R&D Investment

Software R&D Investment

Pharmaceutical R&D Investment

Semiconductor R&D Investment

Fig. 1. Time-Varying Depreciation Rates of R&D Investment.

Fig. 1 shows the quarterly time-varying depreciation rate for aggregate R&D investment and software R&D investment, and annual time-varying depreciation rate for pharmaceutical R&D investment and semiconductor R&D investment between 1978 and 2014.

Table 4

|                | Aggregate          | First Difference | Software          | First Difference | Pharmaceutical | First Difference | Semiconductor | First Difference |
|----------------|--------------------|------------------|-------------------|------------------|----------------|------------------|---------------|------------------|
| Real R&D Investment | 0.009***           | (2.605)          | 0.001             | (0.187)          | -0.022         | (-0.804)         | -0.005        | (-0.150)         |
| Real Interest    | -0.276***          | (-4.345)         | -0.276***         | (-4.545)         | -0.537***      | (-3.793)         | -0.537***     | (-3.793)         |
| Rate of R&D      | -0.128***          | (-4.304)         | -0.108***         | (-2.946)         | -0.746***      | (-4.237)         | -1.001***     | (-4.019)         |
| Real Cost Growth | -0.338***          | (-6.101)         | -0.338***         | (-6.101)         | -1.641***      | (-5.612)         | -1.641***     | (-5.612)         |

Table 4 displays the augmented Dickey-Fuller unit root tests for stationarity. The estimating equation for each variable is $\Delta x_t = \alpha + \gamma x_{t-1} + \sum_{i=1}^m \beta_i \Delta x_{t-i} + \epsilon$. The null hypothesis is that $\gamma \geq 0$ and the variable $x_t$ is nonstationary. The alternative hypothesis is that $\gamma < 0$ and the variable $x_t$ is stationary. The lag order of the augmented part is selected based on Akaike information criterion. The t-statistic of $\gamma$ are in the parenthesis, *** indicates significance at 1% level, ** indicates significance at 5% level, and * indicates significance at 10% level. Variables for aggregate and software R&D investment are in the quarterly frequency. Variables for pharmaceutical and semiconductor R&D investment are in the yearly frequency. Conclusion: the time-varying depreciation rates, real interest rate and R&D price growth are stationary in levels. R&D investments are stationary in first differences.
Table 5
Regression Results of Software R&D Investment.

| Software R&D Investment | 1       | 2       | 3       | 4       | 5       | 6       |
|-------------------------|---------|---------|---------|---------|---------|---------|
| Intercept               | 0.016   | 0.035   | 0.080*  | 0.007   | 0.019***| −0.006**|
| (0.450)                 | (1.012) | (2.554) | (1.737) | (2.696) | (2.283) |
| Real Interest Rate r_t  | −0.220***| −0.101***| −0.002***|         |         |         |
| (−3.373)                | (−3.221) |         |         |         |         |         |
| R&D Depreciation Rate d_t| −0.189  | −0.400  | −0.709**|         |         |         |
| (−0.654)                | (−1.478) | (2.808) |         |         |         |         |
| Real R&D Price Growth p_t| 0.194*  | 0.172   | 0.218** |         |         |         |
| (1.977)                 | (1.706) | (2.394) |         |         |         |         |
| User Cost r_t + d_t − p_t|         |         |         | −0.211***|         |         |
|                       |         |         |         | (5.508) |         |         |
| User Cost r_t − p_t     |         |         |         |         | −0.236***|         |
|                       |         |         |         |         | (5.461) |         |
| Adjusted R²             | 0.155   | 0.138   | 0.095   | 0.159   | 0.166   | 0.164   |

F-Tests Results of the Equality of Regression Parameters

| Null Hypothesis of F-Tests | F-Statistics | P-value |
|---------------------------|-------------|---------|
| H₀: η₁ = η₂               | 0.01        | 0.921   |
| H₀: η₁ = η₃               | 0.06        | 0.808   |
| H₀: η₂ = η₃               | 0.00        | 0.989   |

Table 5 reports the regression results of R&D investment in software quarterly over 1978–2014. Dependent variables are combinations of the real interest rate, time-varying aggregate R&D depreciation rate and real R&D price growth. The signs are reversed to be consistent with the theoretical model. T-statistics are listed in the parenthesis. *** indicates the significance at 1%, ** indicates the significance at 5%, and * indicates the significance at 1%. In columns 1–4, software R&D investment declines when interest rates and depreciation rate rise. The elasticities of R&D investment have similar magnitude in depreciation, interest, and price, suggesting user cost. Columns 5–6 impose the user cost, where identical elasticities apply for interest rate, and software depreciation and real cost appreciation. The elasticity of software R&D investment in its user cost is about −0.2.

The lower table shows the F-test results of the equality of parameters of regression 1. The p-values are all greater than 10%, indicating the absolute values of all the regression parameters are equal, suggesting the application of user cost.

5. Empirical results

Table 5 reports the regression results of software R&D investment quarterly over 1978–2014. Specifications include combinations of real interest rate, time-varying R&D depreciation, and real R&D price growth for software. In columns 1–4, software R&D investment declines when interest rate and depreciation rate rise. Software R&D investment rises with its price appreciation. Software R&D investment demand is relatively inelastic, with absolute values all below one.

In column 1, R&D investment in software has similar elasticity magnitudes to the interest rate, depreciation, and price growth. F-test results show that the absolute values of regression parameters for interest rate, depreciation, and price growth are statistically equal, supporting the user cost. Given these results, regressions in columns 5 and 6 are appropriate, as they report the user cost elasticities on software R&D investment. Imposed are identical elasticities in absolute value for the interest rate, depreciation, and price appreciation. The user cost is the real interest rate plus depreciation rate less real price growth. The elasticity of software R&D investment in its user cost ranges between −0.211 and −0.236. A 100-basis point increase in the user cost reduces R&D investment in software by between 21.1 and 23.6 basis points. There is no additional obsolescence above depreciation. Software is an industry where code modifications and fixes allow for ongoing updating. This updating allows software to remain competitive for years and even generations. Examples include Microsoft Windows and Apple iOS, where software fixes and upgrades are automatically incorporated.

In column 4, where the depreciation rate is constant, its effect is embedded in the intercept of the regression. R&D investment depends only on the interest rate and price growth adjusted for inflation. The interest rate elasticity of R&D investment declines from −0.22 to near-zero at −0.002. With a constant depreciation rate, R&D investment responds minimally to the remaining signal of interest rate. The results confirm the necessity of having a time-varying depreciation.

Table 6 reports estimates of R&D investment for the aggregate U.S. economy quarterly over 1978–2014. Dependent variable is the real aggregate R&D investment growth. Independent variables are combinations of the real interest rate, depreciation rate and real R&D price growth. Column 1 has the flexible form, with separate investment elasticities in interest rate, depreciation, and price appreciation. The elasticity of R&D investment for time-varying depreciation rate is −1.375. The real interest rate elasticity is −0.166, whose absolute value is significantly lower than unity. Price appreciation has an elasticity of 0.176, significantly less than one. The aggregate R&D investment is elastic in depreciation, but relatively inelastic in interest rates and price appreciation. At the aggregate level, depreciation reduces R&D investment more than interest rate, suggesting obsolescence. The F-tests show that the depreciation elasticity is different from the elasticities for other two variables, supporting obsolescence given the sign.

Column 4 shows the case when the depreciation rate is constant and its effect on R&D investment is in the intercept. Aggregate R&D investment depends only on the real interest rate and real price growth. Compared to results in column 1, the R&D interest elasticity falls to −0.001 and that of price growth is reduced to 0.152.
Table 6: Regression Results of Aggregate R&D Investment.

| Aggregate R&D Investment | 1     | 2     | 3     | 4     | 5     | 6     |
|--------------------------|-------|-------|-------|-------|-------|-------|
| Intercept                | 0.165** | 0.116 | 0.017 | −0.008** | 0.010* | −0.007*** |
| Real Interest Rate $r_t$ | (−2.043) | (1.435) | (0.226) | (2.396) | (1.835) | (−3.875) |
| R&D Depreciation Rate $d_t$ | (−3.937) | (4.038) | −0.189 | (−3.289) |
| Real R&D Price Growth $p_t$ | 0.176** | 0.192*** | 0.152** |
|                         | (2.838) | (2.949) | (2.459) | −0.139*** | (−4.605) | −0.132*** | (−4.496) |

F-Tests Results of the Equality of Regression Parameters

| Null Hypothesis of F-Tests | F-Statistics | P-value |
|----------------------------|-------------|---------|
| $H_0: \beta_1 = \beta_2$  | 3.71**      | 0.056   |
| $H_0: \beta_1 = \beta_3$  | 0.02        | 0.892   |
| $H_0: \beta_1 = \beta_4$  | 3.53**      | 0.062   |

Table 6 reports the regression results of aggregate R&D investment in the U.S. quarterly over 1978–2014. Dependent is the real R&D investment growth. Independent variables are combinations of the real interest rate, the time-varying aggregate R&D depreciation rate and the real R&D price growth. The signs are reversed to be consistent with the theoretical model. T-statistics are listed in the parenthesis. **” indicates the significance at 1%, “” indicates the significance at 5%, and “” indicates the significance at 10%. In columns 1–4, the elasticity of R&D investment to interest rate ranges nearly zero and −0.17. In R&D price appreciation, the elasticity of investment is between 0.15 and 0.19. The depreciation elasticity is ranges from −0.10 to −1.4. R&D investment is elastic in depreciation, but relatively inelastic in interest rates and price appreciation. Depreciation reduces R&D investment more than interest rate, indicating obsolescence. Columns 5–6 impose the user cost. The elasticity of aggregate R&D investment to the user cost is −0.14. Imposing a user cost leads to an inelastic demand that suppresses the depreciation response. The lower table shows the F-test results of the equality of parameters of regression 1. The results indicate the absolute value of regression parameter of depreciation is different from the other two variables, supporting obsolescence given its sign. With constant depreciation, R&D investment responds minimally to interest rates and prices, and obsolescence is eliminated. The driver of aggregate R&D investment is time-varying depreciation.

In Table 7, panel A reports the estimates of R&D investment for pharmaceuticals with annual data. In columns 1–3, pharmaceutical R&D investment is not sensitive to real interest rates or price appreciation, but the elasticity of R&D investment to time-varying depreciation is significant, ranging between 1.46 and 1.51. A higher depreciation rate leads to more R&D investment, implying scale.

Scale creates positive externality of R&D investment on drug and vaccine, reduces costs of depreciation and subsequent pharmaceutical trials, and increases future R&D investment. Regulatory bodies require preclinical tests and a sequence of multiple clinical phases. After feasibility on non-human subjects, there are three steps in clinical trials. Phase 1 tests the treatment on healthy volunteers to gauge human reaction. Phase 2 tests on patients with the specific condition experimentally with the developer. Phase 3 increases the patient sample size, involving the developer and medical providers. Even if the success ratio for pharmaceutical R&D projects is relatively low, an unsuccessful R&D investment in a drug or vaccine for one disease has potential for other related ones. Related viruses have common genetic codes. The result is scale, with apparent depreciation in one area lowering ongoing costs in other areas. Coronavirus families including SARS, MERS, and Covid-19 are cases where pharmaceutical firms with previous R&D investment have low barriers and cost to enter the subsequent efforts to cure new disease, resulting in an increase in R&D investment. These findings are particularly timely and relevant, given the financial instability and unique times that encompass the world at the current moment. The effect of scale in pharmaceutical R&D reduces the cost of depreciation and lowers the hurdle rate, leading to more R&D investment. The results potentially explain Hall (2005, 2010) with a negative depreciation rate in pharmaceutical development ranging from −11% to 15% annually.

Panel B of Table 7 shows results for R&D investment for semiconductors with annual data. In columns 5–7, semiconductor R&D investment increases significantly with the depreciation rate, with an elasticity between 0.82 and 0.86. Semiconductor R&D investment is not sensitive to interest rate or real price growth. In column 4 without a time-varying depreciation rate, the only significant component is the intercept. The results reinforce the necessity of having a time-varying depreciation rate.

Semiconductors have similar scale effects. Moore (1965) in Moore’s Law, posited that integrated circuits on a quarter square inch of a chip double every two years.5 In an update, Moore (2006) finds that the pattern continues. Ongoing technological change in semiconductors has proceeded, despite rising costs of building fabrication plants as Moore’s second law. R&D investment leads to scale in chip design and the efficiency in producing added units in fabrication plants. The impact of depreciation is to reduce the adjusted discount rate, incentivizing semiconductor firms to take on R&D investments. Scale potentially explains findings of negative depreciation rates in industries related to semiconductors. Hall (2005) finds rates of R&D depreciation ranging between −5% to 25% in computers, −3% to 36% in electronics and −2% to 32% in machinery. The negative depreciation rates are not necessarily perverse.

Our estimation improves forecasting of R&D investment. R&D investment is nonstationary and subject to unpredictable events. The past data of R&D investment does not provide credible information in forecasting. The time-varying depreciation rate, interest rate, and price growth are stationary and forecastable based on their best-fitted time-series models. The forecasts of these variables and their estimated relationship with R&D investment allow for

---

5 Moore (1965) plotted the logarithm of the number of components per integrated function against time, showing a linear pattern as Moore’s Law. In 1965, 500 components were crammed per linear inch in 1965, or a quarter million per square inch, and 65,000 per quarter square inch doubling every year.
Table 7 reports the regression results of R&D investment for pharmaceutical industry and semiconductor industry annually over 1978–2018. Dependent is the real R&D investment growth in pharmaceutical industry and semiconductor industry, respectively. Independent variables are combinations of the real interest rate, the time-varying aggregate R&D depreciation rate and the real R&D price growth. The signs are reversed to be consistent with the theoretical model. T-statistics are listed in the parenthesis. ** indicates the significance at 1%, *** indicates the significance at 5%, and * indicates the significance at 10%.

In columns 1–4, pharmaceutical R&D investment is increasing in depreciation rate, with an elasticity of between 1.46 and 1.51. It is not sensitive to interest rates or price appreciation. Time-varying depreciation leads to more R&D investment in pharmaceutical industry, suggesting scale.

In columns 5–8, semiconductor R&D investment is increasing in depreciation rate, with an elasticity of between 0.82 and 0.86. It is not sensitive to interest rates or price appreciation. Time-varying depreciation leads to more R&D investment in semiconductor industry, suggesting scale.

Table 8 shows the maximum likelihood estimation results for all the parameters of ARIMA models. The t-statistics are listed in the parentheses. *** indicates significance at 1% level, ** indicates significance at 5% level, and * indicates significance at 10% level.

within-sample verification and out-of-sample prediction for R&D investment.

Table 8 shows the autoregressive integrated moving average (ARIMA) properties of quarterly time-varying depreciation for software and the aggregate U.S., along with interest rates and real R&D cost appreciation. The autocorrelation function (ACF) and partial autocorrelation function (PACF) are estimated. The ACF show gradual decaying in both variables. The PACF cuts at lag 1 for software depreciation rate and at lag 6 for aggregate depreciation rate. The software depreciation is best fitted in an ARIMA(1,0,0) model and the aggregate depreciation is best fitted in an ARIMA(6,0,0) model. The Box-Ljung Chi-squared tests show that residual terms for depreciation rate ARIMA models have no autocorrelation and are white noise, confirming that the estimated ARIMA models are appropriate and adequate. The same procedure is also applied to interest rate and price growth.

Fig. 2 displays the point forecast and interval forecast of R&D depreciation in software and aggregate economy from 2015 to 2025. The blue line is the point forecast. The purple area shows the 95% forecast interval. The gray area shows the 80% forecast interval. Predictions of time-varying depreciation rates, interest rate, and price growth allow for forecasting of R&D investment based on its estimated relationship with these variables. The in-sample forecasts of 2015–2019 is compared with actual observations for validation.

Table 9 depicts the summary statistics of forecast errors generated by our method using time-varying depreciation rate and two best alternatives that forecast R&D investment using its historical data. One is an exponential smoothing state space (ETS) model described by Hyndman et al. (2002) and Hyndman et al. (2008). The other is a trigonometric Box-Cox transformation, ARMA residuals, trend and seasonality (TBATS) model as illustrated by
Software R&D Depreciation Rate

Aggregate R&D Depreciation Rate

Fig. 2. Point Forecast and Interval Forecast of Time-Varying R&D Depreciation Rates. Fig. 2 displays the graphs of forecasted time-varying depreciation rates for software R&D investment and aggregate R&D investment. The blue line is the point forecast based on ARIMA models. The purple area shows the 95% forecast interval and the gray area shows the 80% forecast interval.

Table 9
In-sample Forecast Error Comparison for R&D Investment.

|                  | Our Forecast | ETS Forecast | TBATS Forecast |
|------------------|--------------|--------------|----------------|
| Panel A: Software R&D Investment |             |              |                |
| Mean             | 2.019%       | 9.040%       | 7.316%         |
| Standard Deviation | 1.079%     | 5.093%       | 4.056%         |
| Maximum          | 3.658%       | 16.965%      | 13.833%        |
| Minimum          | 0.026%       | 0.402%       | 0.650%         |
|                  |              |              |                |
| Panel B: Aggregate R&D Investment |         |              |                |
| Mean             | 1.359%       | 3.709%       | 3.501%         |
| Standard Deviation | 0.821%     | 2.678%       | 2.114%         |
| Maximum          | 2.846%       | 8.066%       | 7.154%         |
| Minimum          | 0.260%       | 0.332%       | 0.672%         |

Table 9 shows the in-sample forecast error comparison for software R&D investment (Panel A) and aggregate R&D investment (Panel B) quarterly from 2015 to 2019. Our forecast is based on the forecasts of time-varying depreciation rate, interest rate, price growth and their estimated relationship with R&D investment. The ETS model forecasts the future values of R&D investment based on its historical data via an exponential smoothing state space model (see Hyndman et al., 2002, and Hyndman et al., 2008). The TBATS model forecasts the future values of R&D investment based on its historical data via a trigonometric Box-Cox transformation, ARMA residuals, trend and seasonality method (De Livera et al., 2011).

De Livera et al. (2011). The mean forecast error of software R&D investment of our method is 2.02%, which is much less than 9.04% of ETS method and 7.32% of TBATS method. The standard deviation of forecast error of our method is 1.079%, compared to 5.093% for ETS method and 4.056% for TBATS method. Similar results are found in the in-sample forecast error comparison of aggregate R&D investment. The mean forecast error of aggregate R&D investment of our method is 1.36%, as opposed to 3.71% of ETS method and 3.50% of TBATS method. The standard deviation of forecast error of our method is 0.82%, compared to 2.68% for ETS method and 2.11% for TBATS method.

The numerical comparison of in-sample forecasts confirms improvement over alternatives. Based on in-sample forecasting performance, the time-varying depreciation is applied to out-of-sample predictions for R&D investment for 2020–2025. In-sample and out-of-sample forecasts for software and aggregate R&D investment are displayed in Fig. 3. The black solid line indicates the actual R&D investment from 2015 to 2019. The red dashed line indicates the in-sample and out-of-sample forecast of R&D investment with time-varying depreciation rate and estimated demand function proposed by this study from 2015 to 2025. The blue dotted line indicates in-sample and out-of-sample forecasts of R&D investment using an ETS model from 2015 to 2025. The orange dotted line indicates in-sample and out-of-sample forecasts of R&D investment using a TBATS model from 2015 to 2025.
30.4% for U.S. aggregate economy and 31.5% in software industry during 1978–2014. Pharmaceuticals and semiconductors have mean annual depreciation of 41% and 42%.

Without time variation, constant depreciation has no impact on the incremental investment. The estimated time-varying depreciation rates are used together with interest rate and price growth to estimate the demand for R&D investment for 1978–2014.

The R&D investment demand has separate elasticities in time-varying depreciation, interest rate, and price growth. For software and R&D, investment has the same magnitude of sensitivity to depreciation as to interest rate and price, allowing a user cost to apply. For semiconductors and pharmaceuticals, depreciation leads to more R&D investment, suggesting scale. For the aggregate economy, depreciation reduces R&D investment more than interest rate, indicating obsolescence.

Forecastable time-varying depreciation, interest rate and price appreciation predict subsequent R&D investment. The in-sample period 2015–2019 has been reserved for back-checking the accuracy of R&D investment forecasting. The in-sample forecast comparison confirms that forecasting using time-varying depreciation and estimated investment demand function is superior to the alternative methods. Based on these outcomes, out-of-sample forecasts of R&D investment have been carried out through 2025, and capital stocks are constructed at both aggregate and industry level.

The investment structure is applicable to any type of depreciable asset. High technology has been confirmed as being a rapidly depreciating asset. Motor vehicles and equipment are candidates for testing time-varying depreciation too. The application is also appropriate to more slowly depreciating assets including commercial and residential structures.

Fig. 4. R&D Capital Stocks.

Results in Fig. 3 visually confirm the superiority of time-varying depreciation method over the traditional alternatives.

The capital stock of R&D is a weighted sum over depreciation and R&D investment. Fig. 4 displays the R&D capital stock of software and aggregate economy under three different methods. The black curve represents the R&D capital stock using a constant depreciation rate and actual investment. The red curve represents the R&D capital stock from Method 1 with constant depreciation rate and actual R&D investment. The blue curve represents R&D capital stock from Method 2 with time-varying depreciation rate and actual R&D investment. The blue curve represents R&D capital stock from Method 3 with time-varying depreciation rate and estimated R&D investment based on the demand function, which also enables the forecasting of R&D capital stock.

6. Conclusion

Time-varying depreciation rates are estimated for research and development of the United States aggregate economy and innovation-intensive industries, such as software, semiconductors, and pharmaceuticals. Mean annual R&D depreciation rates are

References

Autor, D., Dorn, D., Katz, L., Patterson, C., Van Reenen, J., 2017. Concentrating on the fall of the labor share. Am. Econ. Rev. Pap. Proc. 107, 180–185.

Ballester, M., Garcia-Ayuso, M., Livnat, J., 2003. The economic value of the intangible asset. Eur. Account. Rev. 12, 605–633.

Bell, A., Chetty, R., Jaravel, X., Petkova, N., Van Reenen, J., 2020. Do tax cuts produce more Einsteins? The impacts of financial incentives vs. Exposure to innovation on the supply of inventors. J. Eur. Econ. Assoc., forthcoming.

Bernstein, J., Mamuneas, T., 2005. Depreciation estimation, R&D capital stock, and North American manufacturing productivity growth. Ann. Econ. Stat. 79–80, 383–404.

Bessen, J., Mamuneas, T., 2006. R&D depreciation, stocks, user costs and productivity growth for US knowledge intensive industries. Struct. Chang. Econ. Dyn. 42, 70–98.

Bessen, J., 2008. The value of U.S. patents by owner and patent characteristics. Res. Policy 37, 932–945.

Bessen, J., Maskin, E., 2009. Sequential innovation, patents, and limitation. Rand J. Econ. 40, 611–635.

Braunstetter, L., Glennon, B., Jensen, B., 2019. The IT revolution and the globalization of R&D: In: Lerner, J., Stern, S. (Eds.), Innovation Policy and the Economy, vol. 19. University of Chicago Press, Chicago, pp. 1–37.

Campbell, J., Shiller, R., 1988. The dividend-price ratio and expectations of future dividends and discount factors. Rev. Financ. Stud. 1, 195–228.

Cifci, M., Cready, W., 2011. Scale effects of reflected in earnings and returns. J. Account. Econ. 52, 62–80.

Crouzet, N., Eberly, J., 2018. Intangibles, investment, and efficiency. Am. Econ. Rev. Papers Proc. 108, 426–431.

Crouzet, N., Eberly, J., 2019. Understanding weak capital investment: the role of market concentration and intangibles, National Bureau of Economic Research working paper 25869.

De Livera, A., Hyndman, R., Snyder, R., 2011. Forecasting time series with complex seasonal patterns using exponential smoothing. J. Am. Stat. Assoc. 106, 1513–1527.

De Rassenfosse, G., Jaffe, A., 2018. Ecometric evidence on the depreciation of innovations. Eur. Econ. Rev. 101, 625–642.

Dickey, D., Fuller, W., 1981. Likelihood ratio statistics for autoregressive time series with a unit root. Econometrica 49, 1057–1072.

Domar, E., 1961. On the measurement of technological change. Econ. J. 71, 709–729.
Financial Accounting Standards Board, 2020. Accounting Standards Codification ASC 730, Accounting for Research and Development Costs. www.fasb.org/en-us/standards/fasb/asc730.

Fixler, D., 2009. Accounting for R&D in the National Accounts. Bureau of Economic Analysis, Washington, DC.

Goel, R., 1990. The substitutability of labor, capital and R&D in US manufacturing. Bull. Econ. Res. 42, 211–227.

Gordon, M., 1959. Dividends, earnings and stock prices. Rev. Econ. Stat. 41, 99–105.

Griffith, R., Redding, S., Van Reenen, J., 2004. Mapping the two faces of R&D: productivity growth in a panel of OECD industries. Rev. Econ. Stat. 86, 883–895.

Griliches, Z., 1979. Issues in assessing the contribution of research and development to productivity growth. Bell J. Econ. Manag. Sci. 10, 92–116.

Griliches, Z., 1994. Productivity, R&D, and the data constraint. Am. Econ. Rev. 84, 1–23.

Griliches, Z., 1998. R&D And Productivity: the Econometric Evidence. National Bureau of Economic Research, Cambridge, MA.

Hall, B., 2005. Measuring the Returns to R&D: The Depreciation Problem. Annales d'Economie et de Statistique 79–80, Special Issue in Memory of Zvi Griliches, July/December, 2005. Also available as National Bureau of Economic Research Working Paper 13473, October 2007.

Hall, B., Jaffe, A., Trajtenberg, M., 2005. Market value and patent citations. Rand J. Econ. 36, 16–38.

Hickman, M., Weygandt, J., 1985. Amortization policy for advertising and research and development expenditures. J. Account. Res. 23, 326–335.

Huang, N.H., Diewert, E., 2011. Estimation of R&D depreciation rates: a suggested methodology and preliminary application. Can. J. Econ. 44, 387–412.

Hulten, C., 1978. Growth accounting with intermediate inputs. Rev. Econ. Stud. 45, 511–518.

Hulten, C., Wykoff, F., 1981a. The measurement of economic depreciation using vintage asset prices. J. Econom. 15, 367–396.

Hulten, C., Wykoff, F., 1981b. The measurement of economic depreciation. In: Hulten, C. (Ed.), Depreciation, Inflation and the Taxation of Income from Capital. Urban Institute, Washington, DC, pp. 81–125.

Hyndman, R., Koehler, A., Snyder, R., Grose, S., 2002. A state space framework for automatic forecasting using exponential smoothing methods. Int. J. Forecast. 18, 439–454.

Hyndman, R., Akram, M., Archibald, B., 2008. The admissible parameter space for exponential smoothing models. Ann. Stat. Math. 60, 407–426.

International Financial Reporting Standards, 2020. International Accounting Standards 38. Intangible Assets (IAS 38) www.ifrs.org.

Knott, A., 2017. How Innovation Really Works. McGraw-Hill, New York.

Knott, A., Bryce, D., Posen, H., 2003. On strategic accumulation of intangible assets. Organ. Sci. 14, 192–207.

Lanjouw, J., Schankerman, M., 2004. Patent quality and research productivity: Measuring innovation with multiple indicators. Econ. J. 114, 441–465.

Lev, B., Sougiannis, T., 1996. The capitalization, amortization and value-relevance of R&D. J. Account. Econ. 21, 107–138.

Lev, B., Nissim, D., Thomas, J., Chapter 5 2008. On the informational usefulness of R&D capitalization. In: Zambon, S., Marzo, G. (Eds.), Valuing Intangibles: Measuring and Reporting in the Knowledge Economy. Ashgate Publishing, Burlington, VT, pp. 97–128.

Li, W., 2012. Depreciation of Business R&D Capital. Bureau of Economic Analysis, Washington DC.

Li, W., Hall, B., 2020. Depreciation of business R&D capital. Rev. Income Wealth 66, 161–180.

Meade, C., 2007. R&D Depreciation Rates in the 2007 R&D Satellite Account. Bureau of Economic Analysis/National Science Foundation: 2007 R&D Satellite Account Background Paper.

Moore, G., 1965. Cramming more components onto integrated circuits. Electronics 38 (8), 1–4.

Moore, G., 2006. Moore’s law at forty. In: Brock, David, Moore, Gordon (Eds.), Understanding Moore’s Law: Four Decades of Innovation. Chemical Heritage Foundation, Philadelphia, pp. 67–84, Chapter 7.

Nadiri, I., Prucha, I., 1996. Estimation of the depreciation rate of physical and R&D capital in the US. Total manufacturing sector. Econ. Inq. 34, 43–56.

Okubo, S., Robbins, C., Moylan, C., Slicher, B., Schultz, L., Mataloni, L., 2006. BEA’s research and development satellite account. Surv. Curr. Bus. 86, 14–46.

Organization for Economic Cooperation and Development, 2000. Measuring Capital: OECD Manual, first edition. OECD, Paris.

Organization for Economic Cooperation and Development, 2009. Measuring Capital: OECD Manual, second edition. OECD, Paris.

Pakes, A., 1986. Patents as options: some estimates of the value of holding European patent stocks. Econometrica 54, 755–784.

Pakes, A., Griliches, Z., 1984. Estimating distributed lags in short panels with an application to the specification of depreciation patterns and capital stock construction. Rev. Econ. Stud. 51, 243–262.

Pakes, A., Schankerman, M., 1984. In: R & D, Patents, and Productivity, Zvi Griliches (Ed.), The Rate of Obsolescence of Patents, Research Gestion Lags, and the Private Rate of Return to Research Resources. University of Chicago Press, Chicago, pp. 73–88.

Sichel, D., von Hippel, E., 2019. Household Innovation, R&D, and New Measures of Intangible Capital. National Bureau of Economic Research Working Paper 25599.

Slicher, B., 2007. R&D Satellite Account Methodologies: R&D Capital Stocks and Net Rates of Return. Bureau of Economic Analysis/National Science Foundation, Washington DC.

Warasawitharana, M., 2015. Research and development, profits, and firm value: a Structural estimation. Quant. Econ. 6, 531–565.