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PRELIMINARY DRAFT – PLEASE DO NOT FURTHER DISSEMINATE

Abstract: Capital measurement plays a fundamental role for national accounts and to better understand the sources of economic and productivity growth. Nevertheless, measuring capital is challenging because it implies estimating initial capital stocks and then cumulating and depreciating investment flows over time. This paper discusses the sensitivity of capital and multifactor productivity (MFP) to changes in asset depreciation patterns and initial capital stocks. We focus on geometric approximations of cohort depreciation patterns. Applying the same depreciation rates in the US as in Canada, France or the United Kingdom would significantly increase US depreciation, thereby decrease net investment and reduce the private sector net capital stock by up to a third. By contrast, the growth rates of capital stocks, capital services and MFP are less sensitive to changes in depreciation and retirement patterns. Regarding the estimation of initial capital stocks, usual methods involve stationarity assumptions on either investment growth rates or capital-stock-to-output ratios. The US example shows that assuming stationary investment growth rates may be particularly misleading for capital and MFP measurement, mainly because it fails to account for fluctuations and long-term trends in real-estate investment. Relying on cross-country averages of capital-stock-to-output ratios to estimate initial capital stocks works well for the US economy but given the wide dispersion in capital-stock-to-output ratios across countries, this result may not be universally true. Overall, this sensitivity analysis calls for a more frequent review of the methods used by statistical agencies to estimate the depreciation and retirement of assets, and for using all available sources of information to extend investment time series to the maximum extent before estimating capital stocks.

Keywords: Capital stocks, Capital services, Multifactor Productivity (MFP)

JEL classification: E22, E23

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1. Introduction

1. Capital measurement plays a fundamental role in national accounts, both to assess the economic wealth and the state of infrastructure in a given country, and to better understand the sources of economic and productivity growth. Nevertheless, measuring capital is a challenging exercise, since capital stocks are typically non-observed and need to be estimated by making assumptions on initial capital stocks and cumulating past investment flows while accounting for the depreciation and the retirement of assets, a statistical process known as the Perpetual Inventory Method (PIM).
2. Statistical agencies in different countries tend to use very different assumptions regarding the depreciation and retirement of assets. While such differences may be justified by country-specific factors (OECD, 2009), they may also simply reflect differences in assumptions as depreciation and retirement patterns tend to be based on thin empirical evidence or old research (Bennett *et al.*, 2020).
3. Unexplained differences in depreciation and retirement patterns across countries may harm the cross-country comparability of capital stocks and macroeconomic indicators that rely on consumption of fixed capital (CFC). This is obviously the case of economic aggregates that are measured net of depreciation, such as net investment (the difference between gross investment and CFC) and net domestic product (the difference between GDP and CFC). Since the CFC also enters the calculation of output and value added of non-market activities, uncertainty around CFC estimates also potentially affect prominent gross indicators such as GDP.
4. Another practical issue that statistical agencies face when estimating capital stocks and CFC is the estimation of initial capital stocks at a given date in the past in order to initialise the PIM. This issue is particularly relevant when only short time series of investment are available.
5. This paper analyses the impact of different depreciation and retirement patterns and assumptions to estimate initial capital stocks on capital and multifactor productivity (MFP) measurement. It can be seen as an extension of a previous sensitivity analysis by Inklaar (2010), who focused on the sensitivity of capital services measures to the type of assets taken into account and to the measurement of capital user costs. While he did not analyse the effect of changing depreciation/retirement patterns or initial capital stocks, he acknowledged that they could play a significant role. Our paper extends Inklaar's (2010) paper along these two dimensions and discusses the sensitivity not only of capital services, but also of net capital stocks, net investment, CFC, and MFP.
6. As Inklaar (2010), we use the national accounts produced by the US Bureau of Economic Analysis (BEA) as a laboratory to analyse the sensitivity of capital and MFP measurement to a range of technical assumptions, along with information on how Canada, France, Italy and the United Kingdom implement the PIM. Indeed, the BEA produces among the longest and most detailed investment time series in OECD countries, hence allowing to apply the assumptions adopted by other countries and test their impact on US capital and MFP measurement.
7. The rest of this paper is organised as follows. Section 2 discusses the replication of the PIM implemented by the BEA in order to produce benchmark estimates for our sensitivity analysis. Section 3 describes a synthetic way to compare combined asset depreciation and retirement patterns across countries, and the sensitivity of capital and MFP measurement to such patterns. Section 4 discusses two leading methods to estimate initial capital stocks, relying on stationarity assumptions on either investment growth or capital-stock-to-output ratios, and assesses their impact on capital and MFP measurement. Section 5 concludes.

2. Replication of the Perpetual Inventory Method used by the US BEA

8. In order to build our benchmark estimates of net capital stocks for the sensitivity analysis, we first replicate the PIM implemented by the US BEA.[1] We rely on annual BEA investment (GFCF) series for the US private sector[2] broken down into 86 residential and non-residential assets and 63 economic activities over the period 1901-2019.[3] These series are among the longest and most detailed publicly available GFCF series across OECD countries, which allows us to test different scenarios for the estimation of capital and MFP.

9. For each asset and industry, we compute benchmark net capital stocks, CFC and net investment, using the cohort geometric depreciation rates[4] and the US BEA Permanent Inventory Method applied by the BEA.[5] The BEA estimates the net capital stock of a given asset i at the end of period t as follows:[6]

$$K_{at} = K_{at-1} * (1 - \delta_a) + I_{at} * (1 - \delta_a/2)$$

where:

K_{at} is the net capital stock of asset type a at the end of period t;

δ_a is the geometric cohort depreciation rate of asset type a, which is constant over time and combines both individual asset depreciation and retirement (see Section 3.1);[7]

I_{at} is the volume of GFCF in asset type a during period t.[8]

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[1] See BEA Fixed Asset Accounts: https://apps.bea.gov/national/FA2004/Details/Index.htm, extracted in October 2020.

[2] The US private sector is defined as industries 11 to 81 in the NAICS 2017 classification, and thus excludes federal, state and local government activities.

[3] We exclude autos, computer and peripheral equipment, and nuclear fuel because the BEA applies a non-geometric combined retirement/depreciation profile for these assets (BEA, 2003). In 2019, these assets accounted for 2.1% of total GFCF and 0.56% of the net capital stock of the US private sector. We also focus on the US private sector because the available investment series for the government sector are too aggregated and do not match the detail of depreciation rates used by the BEA, thus preventing us, for the time being, to replicate the BEA Perpetual Inventory Method for the government sector.

[4] See https://apps.bea.gov/national/pdf/BEA_depreciation_rates.pdf.

[5] In the United States, two different statistical agencies produce estimates of capital stocks. The BEA estimates net *wealth* capital stocks, and hence the national balance sheets included in the US national accounts, using geometric cohort depreciation rates. The Bureau of Labor Statistics (BLS) estimates *productive* capital stocks for the business sector assuming a hyperbolic age-efficiency profile. These productive capital stocks are then used in the estimation of capital services and multifactor productivity. The differences between productive and wealth capital are explained in detail in OECD (2009).

[6] Although the industry index is omitted, the formula applies to each asset and each industry. Depreciation rates for a given asset may vary across industries.

[7] For very few assets, the BEA depreciation rates changed at some point (see https://apps.bea.gov/national/pdf/BEA_depreciation_rates.pdf). Nevertheless, we use the most recent value of BEA depreciation rates for the entire period of analysis.

[8] According to Giandrea *et al.* (2021), the BEA also considers in this formula other changes in the volume of the assets. However, in the absence of specific information on other changes in volume,

10. All variables above are volumes and expressed in constant prices of a base period. The last term on the right-hand side implies that investment happens at mid-year, or that it is evenly spread out over the year. We then derive a volume measure of consumption of fixed capital (CFC) associated to asset a in period t as:

$$CFC_{at} = K_{at-1} - K_{at} + I_{at} = K_{at-1}\delta_a + I_{at}\delta_a/2$$

We finally construct measures of net capital stock and CFC in current prices by multiplying the volume measures with the asset price index between the base period and the current period.

11. Our benchmark estimates of capital stocks are well aligned with the official estimates produced by the BEA. Table 2-1 shows that the net capital stock to GDP ratios based on official BEA figures are highly consistent with our benchmark estimates. In the subsequent sections, we will use these benchmark estimates as a basis to analyse the impact of changes in cohort depreciation rates at a detailed asset-industry level, and the use of different approaches to estimate initial capital stocks.

Table 2-1. Replication of the US BEA Perpetual Inventory Method: Net capital-stock-to-output ratios of the US private sector

Current prices, percentage of GDP, average over 1981-2019

Asset / Sector	BEA official estimates	OECD benchmark estimates
Dwellings	1.03	1.02
Other buildings and structures	0.71	0.69
Transport equipment	0.06	0.06
Other machinery and equipment	0.24	0.24
IT equipment and IPP assets excluding R&D	0.09	0.10
R&D	0.07	0.07
TOTAL	**2.21**	**2.18**

Note: BEA benchmark estimates exclude 10 non-residential assets that we exclude from OECD benchmark estimates, namely, autos, computer and peripheral equipment and nuclear fuel.
Source: Authors' calculations based on the BEA Fixed Assets Accounts.

we do not consider them for the estimation of benchmark net capital stocks, which does not impair the accuracy of the replication of official US capital stocks (Table 2-1).

3. Impact of changes in depreciation and retirement patterns on the measurement of capital stocks, capital services and MFP

3.1. Comparison of combined asset depreciation and retirement patterns across countries

12. Net capital stocks result from successive vintages of investment (i.e. Gross Fixed Capital Formation, or GFCF) in productive assets and the combined effect of their depreciation and retirement over time.[9] The depreciation pattern describes how the value of a single asset declines over time as the asset ages. The retirement pattern takes into account that not all assets purchased at the same time (*i.e.* belonging to the same cohort) are removed from the capital stock at the same age. Part of the randomness of the retirement process is captured by the average service life of assets, but non-degenerated probability distributions around average service lives are usually assumed by statistical agencies.

13. Hulten and Wykoff (1981a) showed how the combination of depreciation and retirement gives rise to convex age-price profiles for cohorts of assets, which can usually be approximated by geometric patterns. The main advantage of geometric patterns is that they are characterised by a single and constant parameter (the geometric cohort depreciation rate). This simplicity led several statistical agencies such as the BEA and Statistics Canada to rely on geometric patterns to estimate CFC for their national accounts (Fraumeni 1997, Baldwin *et al.* 2015).

14. However, not all countries rely on geometric patterns combining depreciation and retirement to estimate net capital stocks. For example, France relies on linear depreciation profiles for single assets and combines them with log-normal retirement patterns. Alternatively, the Netherlands and the United Kingdom (UK) derive the combined depreciation and retirement pattern from a hyperbolic age-efficiency profile combined with a Weibull (for the Netherlands) and a normal (for the UK) retirement distribution (Office for National Statistics, 2019; Statistics Netherlands, 2019).[10]

15. In this analysis, we do not rely on Declining Balance Rates (DBRs) to plug the depreciation and retirement patterns of other countries into the PIM used by the BEA. DBRs were first introduced by Hulten and Wykoff (1981b) to provide a simple inverse proportional relationship between geometric cohort depreciation rates (δ) and average asset services lives (T):

$$\delta \equiv \frac{DBR}{T}$$

[9] To avoid any ambiguity, we reserve the term depreciation (without any further qualification) to describe how the value (i.e. the market price) of a single productive asset declines over time due to the shortening of its remaining service life as time goes by. Depreciation is reflected in the age-price profile of a single asset. Nevertheless, the depreciation process does not take into account that assets belonging to the same cohort (i.e. purchased at the same time) may be retired from the productive capital stock at a different age. *Cohort* depreciation corresponds to the combined effect of (single-asset) depreciation and retirement and determines how the value of a stock of assets declines over time if depreciation and retirements are not compensated by investment (GFCF) or other positive changes in volume.

[10] The United Kingdom's Office for National Statistics applies these assumptions to all assets except research and development, for which they combine a Weibull retirement distribution with a geometric age-efficiency function.

Nevertheless, DBRs do not have an obvious economic meaning. Moreover, 5.Annex A shows that they are not universal constants as they depend on the shape of the underlying depreciation and retirement functions used by national statistical agencies. Therefore, DBRs are country specific, and estimating geometric depreciation rates for a country based on its asset service lives and the DBRs of another country would be misleading.

16. In order to introduce the depreciation and retirement patterns of other countries into the PIM used by the BEA, we rather follow Cabannes *et al.* (2013) who suggest estimating geometric approximations of the combined depreciation and retirement patterns and provide such approximations for France. This method consists in combining depreciation and retirement patterns analytically and estimating the geometric function that provides the best fit to the combined pattern in a least square sense. 5.Annex B discusses how these geometric approximations are obtained for France, Italy and the UK.

17. Table 3-1 provides average ratios of Canadian, French, Italian and UK cohort depreciation rates to the corresponding US parameters for aggregate asset categories. In most cases, Canadian, French and UK cohort depreciation rates are (much) higher than the US ones. This is especially true for residential and non-residential buildings, for which average cohort depreciation rates in Canada, France and the UK are between two and three times higher than in the US. The same is also true for Other (civil engineering) structures in Canada.[11] The Italian depreciation rates are closer to the US ones.

Table 3-1. Ratios of Canadian, French, Italian and UK cohort depreciation rates to US cohort depreciation rates

Asset label	Canada	France	Italy	United Kingdom
Dwellings	2.0	5.0	1.6	2.5
Buildings other than dwellings	3.0	2.8	1.4	3.1
Other structures	2.7	1.1	1.6	1.7
Transport equipment	1.5	1.5	1.1	1.3
Computer hardware	1.3	1.2	1.4	1.2
Telecom. equipment	2.1	1.4	2.8	1.2
Other mach. & equipment	1.8	1.1	1.4	1.1
R&D	1.8	1.0	1.3	1.8
Software & databases	1.0	0.7	0.9	0.7
Originals	6.3	2.6	1.4	1.5

Note: For Canada and the US, we rely on the cohort geometric depreciation rates by detailed asset type provided by Statistics Canada and Giandrea *et al.* (2021). For France, we rely on the geometric approximations of combined depreciation and retirement patterns provided by Cabannes *et al.* (2013). For Italy and the United Kingdom, we compute the geometric approximations of combined depreciation and retirement patterns as described in 5.Annex B. Ratios higher than 1.5 are highlighted in orange, and ratios higher than 2.0 are highlighted in red.
Source: Authors' calculations, based on Cabannes *et al.* (2013), Giandrea *et al.* (2021), and replies by Statistics Canada, ISTAT (Italy) and the ONS (United Kingdom) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

[11] Our results for Canada and the US are in line with Giandrea *et al.* (2021). In the present paper, we extend the comparison to France, Italy and the UK.

3.2. Sensitivity of consumption of fixed capital, net investment and net capital stocks to changes in cohort depreciation rates

18. We now analyse the sensitivity of the US CFC, net investment and net capital stocks to changes in cohort depreciation rates. In order to explore the range of possible depreciation patterns, we successively introduce the Canadian, French, Italian and UK geometric cohort depreciation rates[12] into the PIM used by the BEA and recalculate net capital stocks and CFC for all assets based on the original US investment (GFCF) time series.

19. Consistently with the evidence provided in Table 3-1, Figure 3.1 shows that the US CFC to GVA ratio would be significantly higher if the BEA relied on the same cohort depreciation rates as Canada, France and the UK (15.9%, 15.5% and 15.2% against 14.2%, respectively). It would only be slightly higher if the BEA relied on the same cohort depreciation rates as Italy (14.6% against 14.2%). The main differences with the official US accounts relate to the CFC of residential and non-residential buildings.

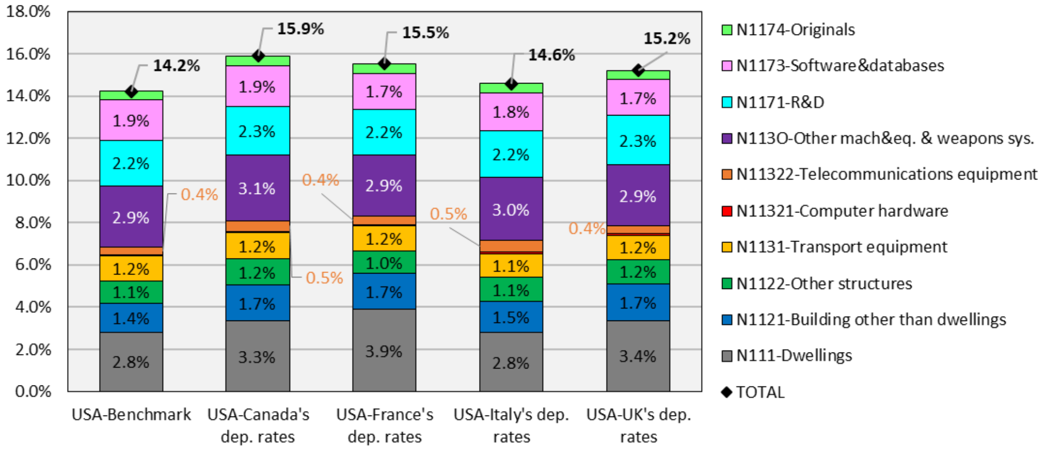
20. Accordingly, Figure 3.2 and Figure 3.3 show that the US net investment and net capital stocks would be significantly lower if the BEA relied on the same cohort depreciation rates as Canada, France and the UK, and only slightly lower if the BEA relied on the Italian cohort depreciation rates. Overall, the US private sector net capital stock would be reduced by up to a third if the BEA relied on the same cohort depreciation rates as Canada, France or the UK. Here again, differences are mainly related to residential and non-residential buildings.

21. Nevertheless, the impact of switching to other countries' cohort depreciation rates is more limited on the growth rate of the US net capital stock (at constant prices) than on its level (at current prices). Figure 3.4 shows that this impact may be more significant for some subperiods, but on average between 1998 and 2019, the annual growth rate of the US net capital stock only changes from 1.9% to 1.8% when using Canadian and French cohort depreciation rates, and it is unaffected when using Italian and UK cohort depreciation rates. The most affected subperiod is the one corresponding to the Great Recession and the immediately following years.

[12] For France, we rely on the geometric approximations provided by Cabannes *et al.* (2013). For Italy and the UK, we compute the geometric approximations of the combined age-price/retirement profiles used by these countries. The asset classifications used in the five countries are mapped together using information from Cabannes *et al.* (2013), Giandrea *et al.* (2021) and the replies by Statistic Canada, ISTAT and the ONS to the 2019 Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks (5.Annex C).

Figure 3.1. Sensitivity of the US private sector consumption of fixed capital to changes in cohort depreciation rates

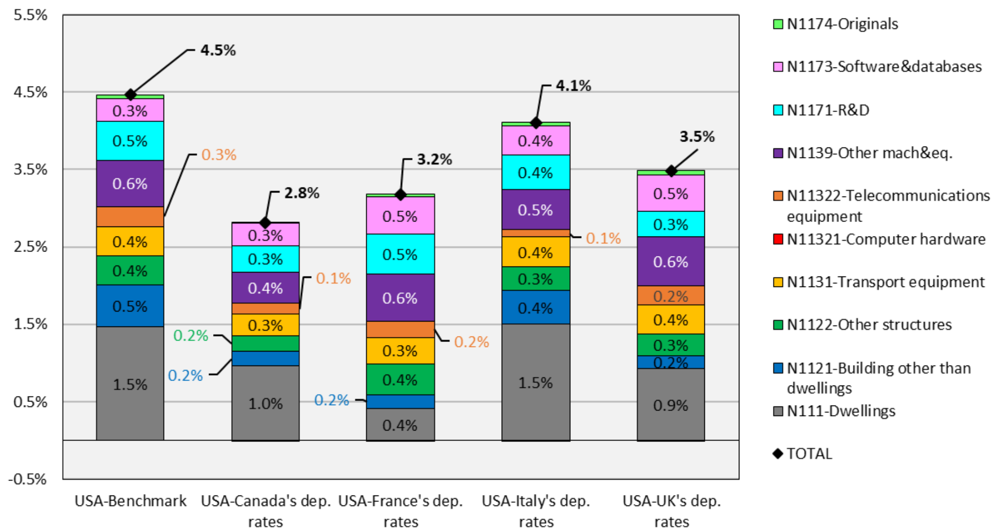
US private sector consumption of fixed capital as a share of gross value added, 2019



Source: Authors' calculations, based on BEA depreciation rates, Cabannes *et al.* (2013), Giandrea *et al.* (2021), and replies by Statistics Canada, ISTAT (Italy) and the ONS (United Kingdom) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

Figure 3.2. Sensitivity of the US private sector net investment to changes in cohort depreciation rates

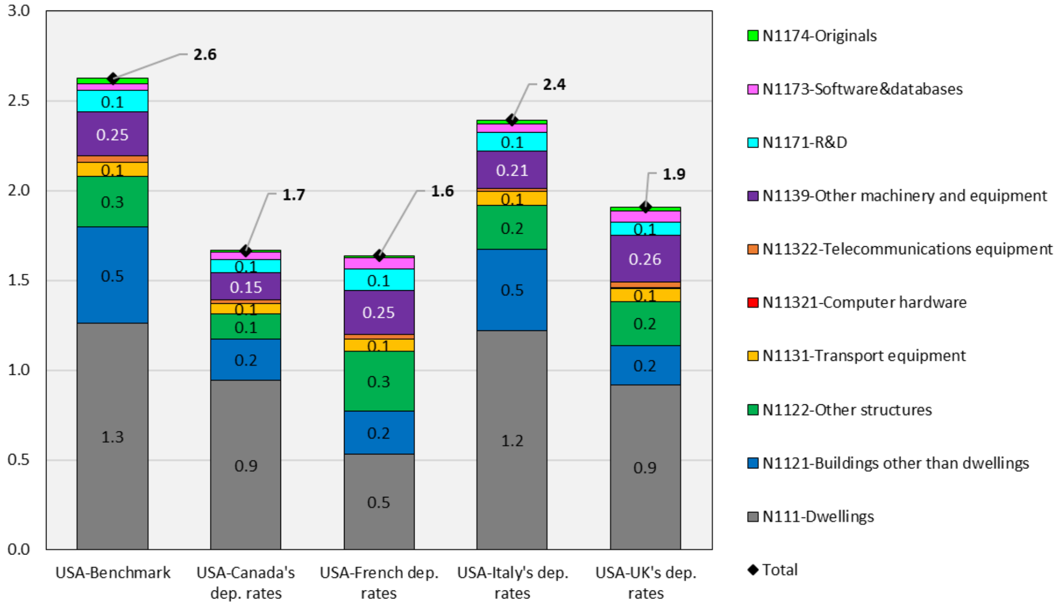
US private sector net investment as a share of gross value added, 2019



Source: Authors' calculations, based on BEA depreciation rates, Cabannes *et al.* (2013), Giandrea *et al.* (2021), and replies by Statistics Canada, ISTAT (Italy) and the ONS (United Kingdom) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

Figure 3.3. Sensitivity of the US private sector net capital stock to changes in cohort depreciation rates

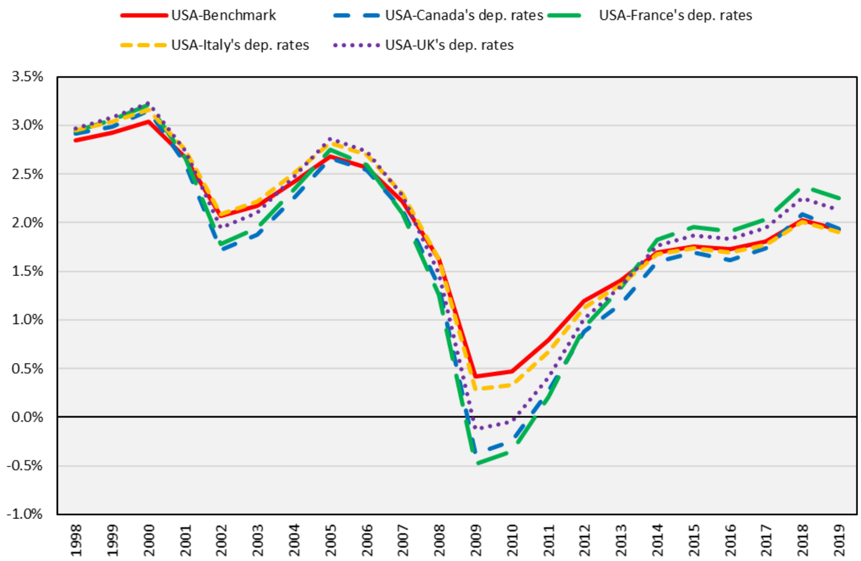
US private sector net capital stock as a share of gross value added, 2019



Source: Authors' calculations, based on BEA depreciation rates, Cabannes *et al.* (2013), Giandrea *et al.* (2021), and replies by Statistics Canada, ISTAT (Italy) and the ONS (UK) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

Figure 3.4. Sensitivity of the growth rate of the US private sector net capital stock to changes in cohort depreciation rates

Constant prices, percentage changes, 1998-2019



Source: Authors' calculations, based on BEA depreciation rates, Cabannes *et al.* (2013), Giandrea *et al.* (2021), and replies by Statistics Canada, ISTAT (Italy) and the ONS (UK) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

3.3. Selecting a rate of return for the measurement of capital services

22. There are two main approaches to calculate the rate of return (rr_{jt}) in the user cost formula for the measurement of capital services:

$$u_{ajt} = p_{ajt-1}\left(d_{ajt} - \Delta p_{ajt} + d_{ajt}\Delta p_{ajt} + rr_{jt}\right)$$

where, following Schreyer *et al.* (2003):

u_{ait} is the user cost of capital of asset type a in the aggregate industry i in period t;

d_{ajt} is the depreciation rate of asset type a in the detailed industry j in period t;

p_{ajt} is the price of of asset type a in the detailed industry j in period t; and

Δp_{ajt} is the 5-year centred moving average of changes in the price of asset type a in the detailed industry j in period t.

23. The first approach to calculate the rate of return consists in estimating an endogenous rate of return ensuring that the value of capital services exactly exhausts the gross operating surplus (GOS) and the capital component of gross mixed income (Jorgenson, 1963). The second approach consists in estimating an exogenous rate of return from financial market information.

24. The estimation of an endogenous rate of return has a number of advantages (in particular, it relies on available national accounts data only and leaves no unexplained residual income) but there are also disadvantages. The endogenous approach is only consistent with a fully competitive economy and production processes under constant returns to scale (OECD, 2009). Moreover, this approach assumes that all assets contributing to the production process are taken into account, which may not be very plausible in light of the increasing importance of certain unmeasured intangibles and natural assets that enter the production process.

25. In spite of some of the caveats that come with endogenous rates of return, we test this approach to update Inklaar's (2010) findings regarding the sensitivity of capital services to the choice of the rate of return.

    In addition, we estimate two exogenous rates of return:

    - a weighted average cost of capital (WACC) taking into account the cost of financing by debt and equity. We estimate this rate using the same method and data sources as Inklaar (2010) and extend his time series from 2005 to 2019.[13]
    - an exogenous nominal rate of return (ENRR) obtained by combining a constant real long-term interest rate and a smoothed inflation rate. In practice, we estimate the real long-term interest rate r^* as the long-term average of the AAA and BAA corporate bonds yields for the US produced by Moody's adjusted for CPI inflation. This leads to a value of 4.2% for r^*. Denoting the 5-year centred moving average of the CPI inflation rate as ρ_t, the ENRR is finally estimated as:

[13] Following Inklaar (2010), we calculate the weighted average cost of capital as follows: $WACC_t = s_t^E C_t^E + (1 - s_t^E)(1 - \tau_t)C_t^D$. s_t^E is the share of equity in total funding, constructed as the ratio of the stock of equity and investment fund shares in the total liabilities of US non-financial corporations, sourced from the OECD National Accounts database (Table 720). C_t^E, the cost of equity, is computed as the sum of the earning and dividend yields of the S&P500. C_t^D is the cost of debt, estimated as Moody's BAA corporate bond yield for the US. τ_t is the marginal corporate tax rate, proxied by the Statutory Corporate Tax Rate sourced from the Tax Foundation.

$$ENRR_t = (1 + r^*)(1 + \rho_t) - 1$$

A similar method is advocated by Diewert (2001), Schreyer *et al.* (2003) and Schreyer (2010).

26. As mentioned above, the endogenous approach assumes that the value of capital services exhausts the sum of GOS and the capital component of mixed income, which happens in a fully competitive economy under constant returns to scale. We estimate an endogenous rate of return for each aggregate industry by equating the value of capital services to a measure of the industry's capital income, measured residually as all income produced in the industry that is not accruing to labour. In practice, we derive this residual income ($KInc$) as the sum of GOS, the capital component of mixed-income, and taxes less subsidies on production[14] (see 5.Annex D for details). Equating the industry's residual income with the total value of capital services leads to:

$$KInc_{it} = \sum_{a=1}^{A} u_{ait} K_{ait} = \sum_{j=1}^{J_i} \sum_{a=1}^{A} u_{ajt} K_{ajt}$$

where

$KInc_{it}$ is the residual income in industry i at date t;

u_{ait} is the user cost of capital of asset type a in industry i at date t;

K_{ait} is the net capital stock of asset a in industry i at date t;[15]

A is the number of assets;

J_i is the number of sub-industries within industry i.

27. In the user cost formula, we take into account that asset depreciation rates and the revaluation of asset prices can vary across sub-industries (*j*), but we estimate endogenous rates of return for only 13 aggregate industries (*i*) belonging to the US private sector. Indeed, data quality is probably lower at the level of sub-industries, and estimating endogenous rates of return at a higher level limits the number of extreme values likely reflecting measurement errors (5.Annex D). Introducing the user cost formula in the previous expression leads to:

$$KInc_{it} = \sum_{j=1}^{J_i} \sum_{a=1}^{A} p_{ajt-1} \left(d_{ajt} - \Delta p_{ajt} + d_{ajt} \Delta p_{ajt} + irr_{it} \right) K_{ajt}$$

The endogenous, or internal, rate of return (irr_{it}) can then be calculated as follows:

$$irr_{it} = \frac{KInc_{it} - \sum_{j=1}^{J_i} \sum_{a=1}^{A} p_{ajt-1} \left(d_{ajt} - \Delta p_{ajt} + d_{ajt} \Delta p_{ajt} + irr_{jt} \right) K_{ajt}}{\sum_{j=1}^{J_i} \sum_{a=1}^{A} p_{ajt-1} K_{ajt}}$$

[14] These are taxes net of subsidies that enterprises incur as a result of engaging in production, independently of the quantity or value of the goods and services produced or sold. They may be payable on the land, fixed assets or labour employed, or certain activities or transactions (e.g. property taxes).

[15] The volume of capital services of a given asset in a given industry is assumed to be proportional to the volume of its net capital stock. Time-variation in the factor of proportionality relating the two measures (e.g. due to changes in the capacity utilisation rate of capital) is neglected here.

28. Figure 3.5 compares the WACC, the ENRR and the average internal rate of return across industries over the period 1998-2019. While the WACC and the ENRR are close to each other, the average internal rate of return is higher and shows larger fluctuations. Increases in the internal rate of return may partly capture increases in the overall mark-ups (Calligaris *et al.*, 2018; Basu, 2019; Schreyer and Zinni, 2020).

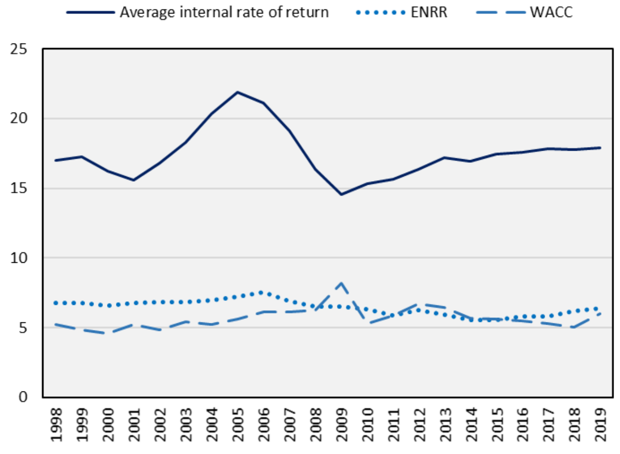
29. Table 3-2 shows the sensitivity of capital services growth in the US private sector over 1998-2019, based on the three different rates of return.[16] The endogenous (or internal) rate of return results in significantly lower growth rates of capital services over 1998-2019 and all sub-periods. However, using one exogenous rate of return or the other leads to very similar growth rates of capital services. The fact that using an endogenous rate of return leads to significantly lower capital services growth in the US private sector after the mid-1990s was also noticed by Inklaar (2010), but his estimates stopped in 2005. Here, we show that the same applies over the next 15 years.

30. Similarly, Table 3-3 shows the sensitivity of MFP growth in the US private sector over 1998-2019, based on the three different rates of return. Here again, using an endogenous rate of return leads to lower MFP growth, and the two exogenous rates of return lead to similar results. Perhaps surprisingly, lower capital services growth with an endogenous rate of return does not translate into higher, but lower, MFP growth. Indeed, a higher endogenous rate of return increases the weight received by capital services in the growth accounts, thus overcompensating their lower growth and reducing growth in MFP.

31. Given all the caveats around endogenous rates of return, we will focus on the ENRR in the rest of the paper, when assessing the sensitivity of capital services and MFP to changes in cohort depreciation patterns and initial capital stocks.

Figure 3.5. Endogenous and exogenous rates of return

US private sector, 1998-2019, percentage points



Note: The average internal rate of return corresponds to the weighted average of the internal rates of return estimated for 13 aggregate industries in the US private sector, where industry shares in gross value added are used as weights.
Source: Authors' estimates.

[16] The calculation of capital services follows the same methodology as in the OECD Productivity Database. See *OECD Productivity Statistics - Methodological Notes* https://www.oecd.org/sdd/productivity-stats/OECD-Productivity-Statistics-Methodological-note.pdf.

Table 3-2. Sensitivity of capital services growth to the use of different rates of return

US private sector, 1998-2019, average annual percentage changes

Period	Rates of return		
	ENRR	WACC	Internal rate of return
1998-2019	**2.8**	**2.9**	**2.4**
1998-2006	3.6	3.9	3.2
2006-2012	1.8	1.9	1.5
2012-2019	2.7	2.8	2.1

Source: Authors' estimates.

Table 3-3. Sensitivity of MFP growth to the use of different rates of return

US private sector, 1998-2019, average annual percentage changes

Period	Rates of return		
	ENRR	WACC	Internal rate of return
1998-2019	**0.6**	**0.6**	**0.5**
1998-2006	0.7	0.8	0.4
2006-2012	1.5	1.5	1.4
2012-2019	-0.3	-0.3	-0.2

Source: Authors' estimates.

3.4. Sensitivity of capital services and MFP to changes in cohort depreciation rates

32. Similarly to what is observed for the evolution of net capital stocks, the average evolution of capital services between 1997 and 2019 is not significantly affected by changes in cohort depreciation rates. As shown in Table 3-4, the average growth rate of capital services is 2.9% per year with the US depreciation rates (benchmark), and 2.7%, 2.8%, 3.0% and 2.9% when using Canadian, French, Italian and UK cohort depreciation rates, respectively.

33. The impact of changes in cohort depreciation rates is more significant during the Great Recession and the immediately following years. Over 2006-2012, the average growth rate of capital services is 1.8% per year when using the US and Italian depreciation rates, 1.5% with Canadian and UK depreciation rates, and it is further reduced to 1.2% with French depreciation rates (Figure 3.6). Residential and non-residential buildings are the main contributors to these differences. With French depreciation rates, which are significantly higher than the US and even Canadian and UK depreciation rates for dwellings, the net capital stock of dwellings declines over the sub-period and receives a higher weight (i.e. a higher user costs share) in the calculation of total capital services growth.

34. As shown by Table 3-5, and consistently with the results obtained for capital services, MFP growth rates are only significantly affected by changes in depreciation patterns over the period 2006-2012. In this case, MFP growth rates are slightly higher with French, UK and Canadian depreciation rates than with US and Italian depreciation rates.

Table 3-4. Sensitivity of the growth rate of capital services to changes in cohort depreciation rates

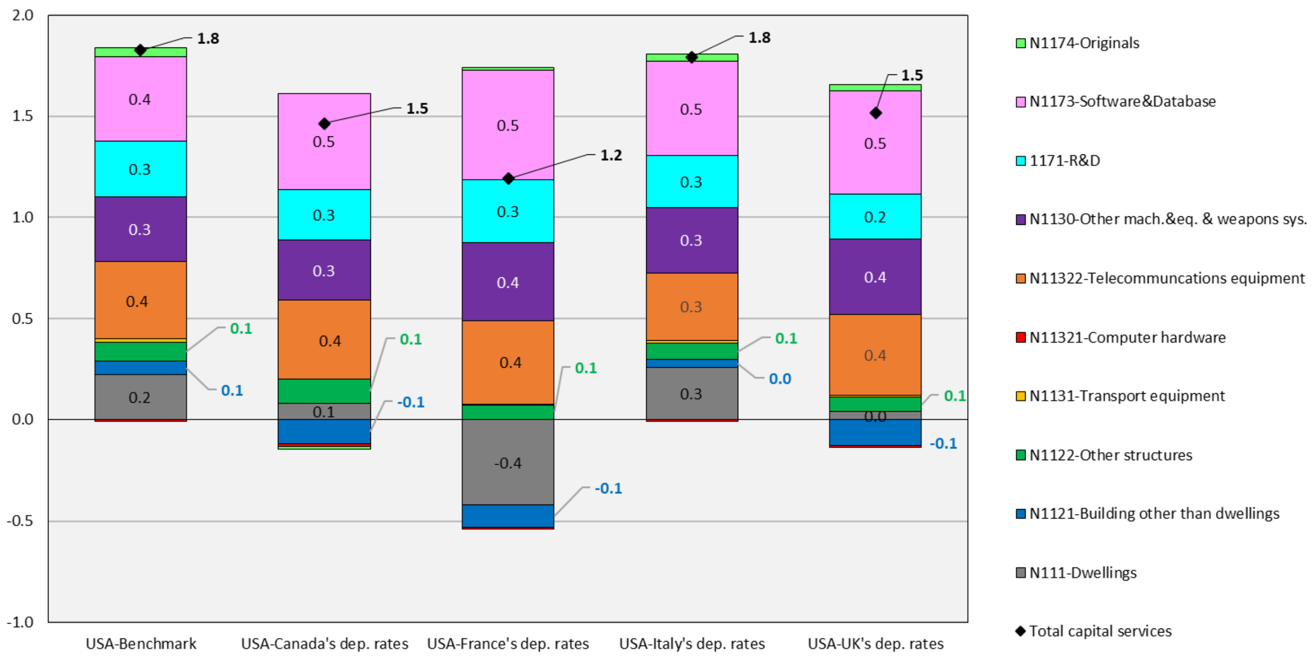
US private sector, average annual percentage change

	USA-Benchmark	USA – Canadian depreciation rates	USA – French depreciation rates	USA – Italian depreciation rates	USA – UK depreciation rates
1997-2019	**2.9**	**2.7**	**2.8**	**3.0**	**2.9**
1997-2006	3.7	3.6	4.0	3.8	3.8
2006-2012	1.8	1.5	1.2	1.8	1.5
2012-2019	2.7	2.8	2.7	2.8	2.8

Source: Authors' estimates.

Figure 3.6. Sensitivity of the growth rates of capital services to changes in cohort depreciation rates, 2006-2012

US private sector, average annual percentage change



Source: Authors' estimates.

Table 3-5. Sensitivity of the MFP growth rate to changes in cohort depreciation rates

US private sector, average annual percentage change

	USA - Benchmark	USA – Canadian depreciation rates	USA – French depreciation rates	USA – Italian depreciation rates	USA – UK depreciation rates
1998-2019	**0.6%**	**0.7%**	**0.7%**	**0.6%**	**0.6%**
1998-2006	0.7%	0.8%	0.6%	0.7%	0.7%
2006-2012	1.5%	1.7%	1.8%	1.6%	1.7%
2012-2019	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%

Source: Authors' estimates.

4. Impact of initial capital stock estimates on the measurement of capital stocks, capital services and MFP

4.1. Options for estimating initial capital stocks in the absence of long investment time series

35. In addition to specific assumptions on the depreciation and the retirement of assets, the estimation of capital stocks using the PIM requires investment time series and initial capital stocks to initiate the estimation process. Initial capital stocks matter all the more if the available investment time series are relatively short and the corresponding assets have rather long service lives.

36. Unlike the US, a number of European countries, mostly in Central and Eastern Europe, only dispose of investment series going back to the mid-1990s. In such cases, there are two main avenues for the estimation of initial capital stocks. The first possibility is to estimate initial capital stocks from national sources such as population censuses (giving information on the number of dwellings owned by households) and company accounts (giving information on the fixed assets owned by firms). Note that company accounts usually value assets at their book value (i.e. at their historical purchase price) and need to be supplemented with specific assumptions on the depreciation and information on the date of purchase of all assets in order to be able to value them at the price of a given year using national accounts' deflators. The second possibility is to rely on stationarity assumptions to backcast investment time series, or estimate initial capital stocks directly. In the absence of long investment time series, both avenues to estimate initial capital stocks require making strong assumptions. Since the use of national sources to estimate initial capital stocks is country specific and the lessons one may draw for the US would be difficult to generalise to other countries, we will focus on the second possibility.

37. When the available investment time series are shorter than the desired length of the capital stock series plus the maximum service life of the asset, researchers and statistical agencies usually rely on stationarity assumptions to estimate initial capital stocks. These assumptions may concern investment, in which case they are used to backcast investment time series, or capital stock-to-output ratios, in which case initial capital stocks can be derived from the value of output at the initial date.

4.1.1. Stationarity assumption on investment growth rates

38. A standard procedure to estimate initial capital stocks is to assume that investment in each asset grows at a constant rate, usually taken equal to the average growth rate observed over the period where data are available (OECD, 2009). In this case, if the average growth rate of investment in asset *i* is equal to θ_i and its geometric depreciation rate is equal to δ_i, and if *N* is taken at least as large as its service life, the initial capital stock of asset *i* at the end of period *t* can be calculated as follows:

$$K_{i,t} = \sum_{j=0}^{N}(1-\delta_i)^j I_{i,t-j} = \sum_{j=0}^{N}\left(\frac{1-\delta_i}{1+\theta_i}\right)^j I_{i,t}$$

Provided that $\left|\frac{1-\delta_i}{1+\theta_i}\right| < 1$ and letting *N* tend to infinity, the previous formula simplifies to:

$$K_{i,t} = \frac{1+\theta_i}{\theta_i+\delta_i} I_{i,t}$$

4.1.2. Stationarity assumption on capital stock-to-output ratios

39. Alternatively, it is possible to assume that the capital stock-to-output ratio is constant over time. This assumption relies on the Solow (1957) growth model where, on a balanced growth path, capital and output grow at the same rate. Initial capital stocks in the Penn World Tables are estimated in this way (Inklaar and Timmer 2013, Feenstra *et al.* 2015).

4.2. Accuracy of initial capital stock estimates and impact on net capital stocks at later dates

40. In order to assess the accuracy of initial capital stock estimates and their impact on net capital stocks at later dates, we assume that the US investment time series start in 1950, 1980 or 1995, instead of 1901 in the BEA national accounts.[17] We then apply the above-described stationarity assumptions on investment growth rates and capital stock-to-output ratios for specific assets.

41. In the first case, we estimate average investment growth rates for each aggregate asset and industry[18] over the first 20 years for which investment series are available.[19] We then use these average growth rates to backcast investment series for each underlying asset and industry.

42. In the second case, we use the asset-specific capital stock-to-output ratios calculated by Inklaar and Timmer (2013) as our starting point. They are reported in Table 4-1. These are average capital stock-to-output ratios that they estimated on a sample of 142 countries with

[17] These cut-off dates are representative of the typical length of publicly available investment time series across OECD countries. While according to the 2019 Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks, many OECD countries rely on unpublished historical investment series to implement their PIM, this is apparently not the case for Central and Eastern European countries, for which investment time series do not seem to available before 1995.

[18] More precisely, we estimate average investment growth rates for Dwellings, Buildings other than dwellings, Other structures, Transport equipment, Computer hardware, Telecommunication equipment, Other machinery and equipment, R&D, Software and Originals, in each aggregate industry shown in Table D.1 of 5.Annex D.

[19] For example, for the scenario where investment series are assumed to start in 1950, we estimate average investment growth rates over the period 1950-1969 for each aggregate asset/industry.

investment series going back at least to 1970.[20] Output corresponds to GDP and both capital and GDP are measured at current national prices.

Table 4-1. Stationarity assumptions on capital stock-to-output ratios to estimate initial net capital stocks

Asset category	Capital stock-to-output ratio (total economy)
Structures (residential and non-residential)	2.2
Transport equipment	0.1
Other machinery and equipment	0.3
All other assets (i.e. IT equipment, Software, and Originals)	0

Note: Inklaar and Timmer (2013) did not cover R&D which, at the time, was considered intermediate consumption (not investment) in the System of National Accounts (SNA).
Source: Inklaar and Timmer (2013, Table 4).

43. For the purpose of this sensitivity analysis focusing on the US private sector, we simply rescale the three capital stock-to-output ratios given by Inklaar and Timmer (2013) by a factor 0.8, corresponding to the ratio between the capital stocks in the US private sector and the US economy as a whole.[21] We then further break down initial capital stocks into assets and industries based on their respective investment shares over the first 20 years where investment series are available. Finally, we use these initial capital stocks as starting points to apply the PIM and estimate net capital stocks at the same level of detail as the BEA (see Section 2).

44. Table 4-2 shows the accuracy of both methods to estimate initial capital stocks by comparing their results with the official capital stocks published by the BEA.[22] As expected, initial capital stocks have a long-lasting influence on future capital stocks for Structures and, to a lesser extent, for Transport equipment and Other machinery and equipment. For example, of the initial capital stocks of structures estimated in 1950, 1980 and 1995, 25%, 52% and 76%, respectively, remain in use in 2005.[23] It is especially for long-lived assets that the accuracy of the methods to estimate initial capital stocks should be assessed.

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[20] The reader should note that we do not implement one further adjustment advocated by Inklaar *et al.* (2019) to account for slight increase in cross-country average capital stock-to-output ratios over time. Since the US capital stock-to-output ratios in the BEA accounts do not show any time trend (see Figure 4.3 to Figure 4.5), this adjustment would not improve the accuracy of the initial capital stocks estimates we compute for the US.

[21] We take this ratio from the actual BEA accounts. Nevertheless, this rescaling does not bias our results in favour of this method because the actual capital-stock-to-output ratio for the US economy as a whole (2.75) is close to the cross-country average (2.6) calculated by Inklaar and Timmer (2013). This rescaling simply allows focusing on the US private sector rather than the US economy as a whole.

[22] The BEA capital stock series start in 1947, or even 1925 for some assets, but these estimates are based on unpublished historical investment time series. Based on publicly available investment series starting in 1901, we cannot recalculate capital stocks for the longest-lived assets (residential buildings) before 1981. Therefore, we rely on the BEA official capital stock series in Table 4-2.

[23] These numbers are implied by the BEA geometric cohort depreciation rates. See the note underlying Table 4-2.

Table 4-2. Accuracy of stationarity assumptions to estimate initial net capital stocks

			Stationarity assumptions on investment growth rates		Stationarity assumptions on capital stock-to-output ratios	
Starting date of investment series (D)	Asset	Share of initial capital stock remaining in 2005 (%)	Ratio between estimated and official (BEA) capital stocks at initial date (D)	Ratio between estimated and official (BEA) capital stocks in 2005	Ratio between estimated and official (BEA) capital stocks at initial date (D)	Ratio between estimated and official (BEA) capital stocks in 2005
1950	All structures	24.9	2.0	1.0	1.0	1.0
	Of which: Dwellings	20.5	1.5	1.0	1.0	1.0
	Of which: Other buildings and structures	25.0	2.7	1.0	1.0	1.0
	Transport equipment	0.6	1.0	1.0	1.6	1.0
	Other machinery and equipment	0.8	1.1	1.0	1.1	1.0
	IT equipment, Software and Originals	0.1	0.9	1.0	0.0	1.0
	R&D	0.0	0.9	1.0	not estimated	not estimated
	Total		**1.8**	**1.0**	**1.0**	**1.0**
1980	All structures	51.9	1.3	1.1	1.0	0.9
	Of which: Dwellings	41.3	0.7	0.9	0.9	0.9
	Of which: Other buildings and structures	52.0	2.3	1.3	1.0	1.0
	Transport equipment	5.2	1.8	1.1	1.1	1.0
	Other machinery and equipment	6.5	1.0	1.0	0.8	1.0
	IT equipment, Software and Originals	2.3	1.2	1.0	0.0	1.0
	R&D	1.0	1.0	1.0	not estimated	not estimated
	Total		**1.3**	**1.0**	**0.9**	**0.9**
1995	All structures	76.4	26.1	15.8	1.2	1.0
	Of which: Dwellings	64.7	3.8	2.7	1.1	1.0
	Of which: Other buildings and structures	76.4	59.0	37.1	1.2	1.1
	Transport equipment	24.6	1.2	1.0	1.5	1.0
	Other machinery and equipment	28.2	1.1	1.0	1.0	1.0
	IT equipment, Software and Originals	15.2	1.2	1.1	0.0	0.9
	R&D	11.3	1.1	1.0	not estimated	not estimated
	Total		**20.5**	**13.0**	**1.1**	**1.0**

Note: The asset-specific shares of initial capital stock remaining in 2005 are calculated as $(1-\delta_i)^{2005-D}$, where δ_i is the geometric cohort depreciation of asset *i* and *D* the initial starting date of investment series. These shares only depend on geometric cohort depreciation parameters, not on initial capital stocks themselves. In case assets have industry-specific depreciation parameters, or these parameters are set at a low level of the asset classification, an unweighted average of the corresponding shares is reported in Table 4-2. This unweighted average is only reported for quite homogeneous asset categories (e.g. Structures or Transport equipment), but not for the whole economy.
When relying on stationarity assumptions on capital-stock-to-output ratios, R&D is not estimated but taken from BEA accounts because R&D is not covered by Inklaar and Timmer (2013).

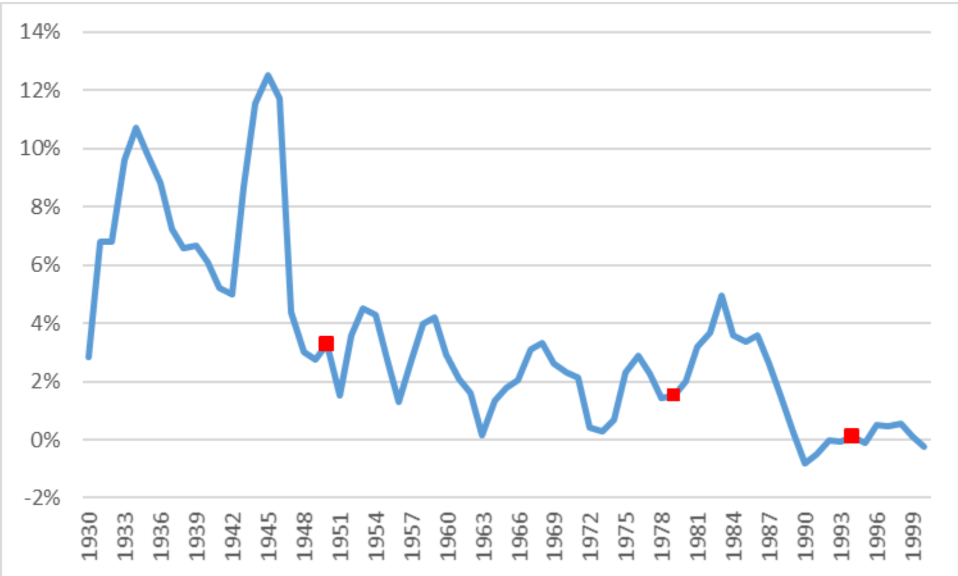
Source: Authors' calculations.

45. The first conclusion that can be drawn from Table 4-2 is that the stationarity assumption on investment growth rates to estimate initial capital stocks can be very misleading, especially in the case of Structures for which estimated capital stocks with investment series starting in 1995 are 16 times higher than in the official BEA accounts in 2005. This reflects the fact that the growth rate used to backcast investment series before 1995 is far below the actual average growth rate over the past, which leads to way too large estimates of past investment, especially for Buildings other than dwellings (Figure 4.2).

46. As shown by Figure 4.1 and Figure 4.2, the US economy exhibits large fluctuations and/or long-term trends in the growth rates of investment in Dwellings and Buildings other than dwellings, even when these growth rates are averaged over 20 years.[24] Therefore, using investment growth rates that are observed on a specific sample to backcast investment series over long periods in the past may lead to very inaccurate results. This issue is of course magnified if available time series are short, like in the 1995 scenario. Nevertheless, given that more than half of the initial capital stock in structures remains in use after 25 years, a similar issue could have easily happened in the 1980 scenario. Therefore, we do not recommend relying on the stationarity assumption of investment growth rates to estimate initial capital stocks of long-lived assets such as structures, except maybe if the PIM is run over several decades (e.g. 50 years) before the resulting capital stocks start to be used for economic analysis.

Figure 4.1. Investment growth rate in Dwellings (20-year forward moving average, 1930-2000)

Average annual percentage changes

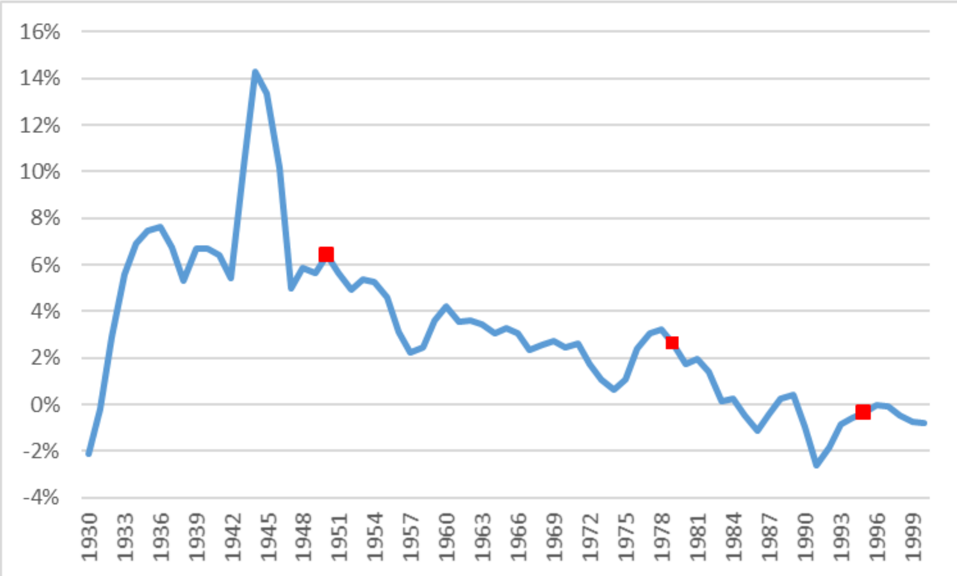


Note: The red dots indicate the moving average investment growth rates that are used to backcast investment time series from 1950, 1980 and 1995 backwards, respectively.
Source: Authors' calculations, BEA Fixed Assets Accounts.

[24] Buildings other than dwellings account for the largest part of Other buildings and structures, the remaining part corresponding to Other (civil engineering) structures.

Figure 4.2. Investment growth rate in Buildings other than dwellings (20-year forward moving average, 1930-2000)

Average annual percentage changes



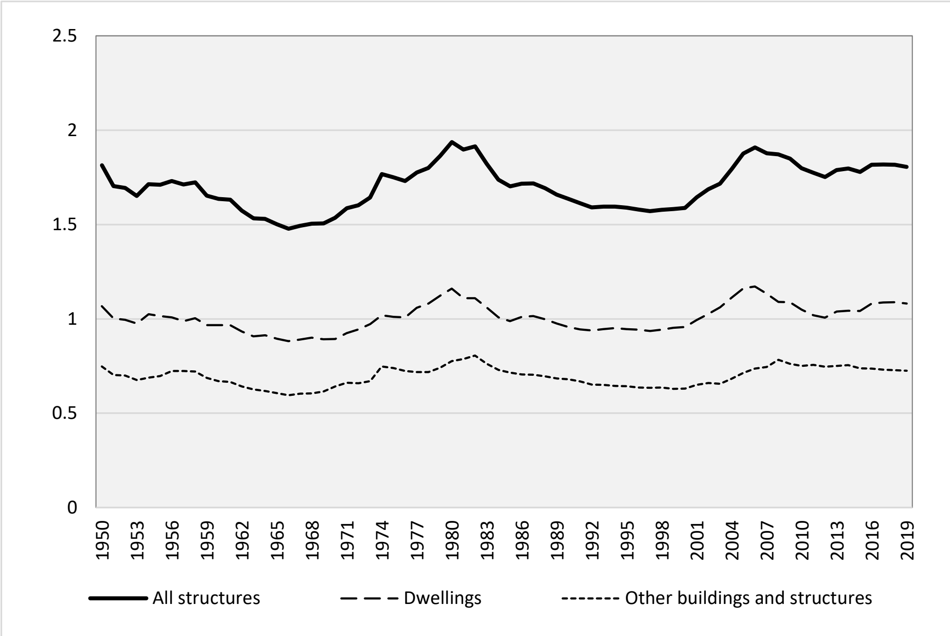
Note: The red dots indicate the moving average investment growth rates that are used to backcast investment time series from 1950, 1980 and 1995 backwards, respectively.
Source: Authors' calculations, based on BEA Fixed Assets Accounts.

47. By comparison, Figure 4.3, Figure 4.4 and Figure 4.5 show that capital-to-output ratios for the US private sector are much more stable over time than investment growth rates. They are also relatively close to the cross-country averages estimated by Inklaar and Timmer (2013), especially once they have been rescaled by a factor 0.8 to take into account that we are focusing on the US private sector. Assuming zero initial net capital stocks for IT equipment, Software, and Originals as Inklaar and Timmer (2013) looks reasonable given the actual values for these ratios and the relatively short service lives of these assets.

48. Overall, estimates of net capital stocks in 2005 are in the +10/-10% range around official values reported by the BEA for all main asset categories and under all scenarios (investment series starting in 1950, 1980 or 1995). Nevertheless, given the dispersion around the mean of capital-stock-to-output ratios across countries reported by Inklaar and Timmer (2013, Figure 1), we cannot exclude that the same assumptions about the capital stock-to-output ratios would give less reliable results for other countries than the US. We leave it for further research to explore this issue.

Figure 4.3. US private sector capital-stock-to-output ratios for structures

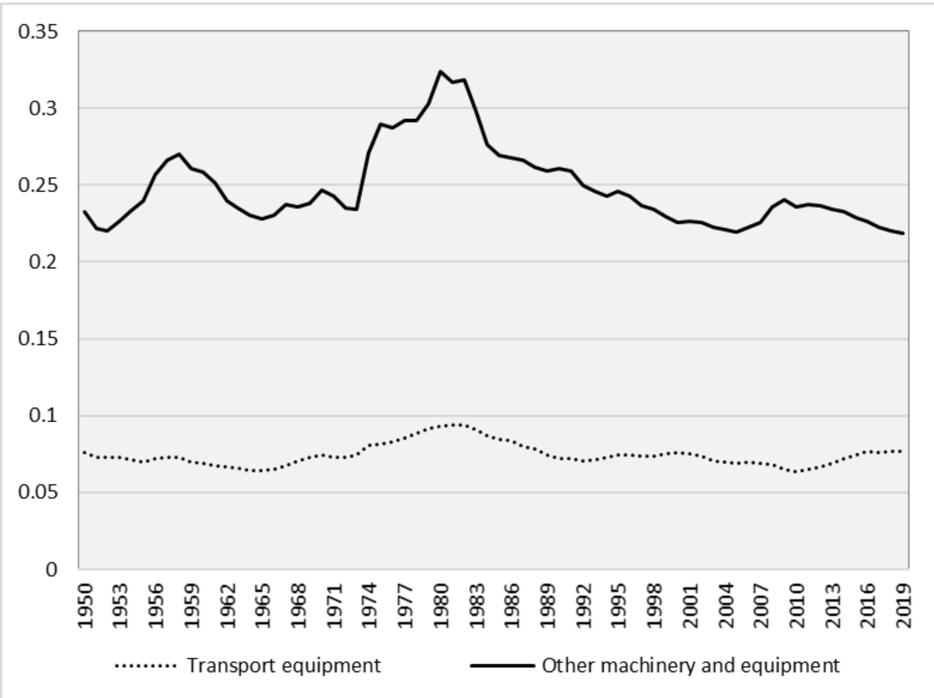
Current prices, 1950-2019



Source: Authors' calculations based on official BEA accounts.

Figure 4.4. US private sector capital-stock-to-output ratios for Transport equipment and Other machinery and equipment

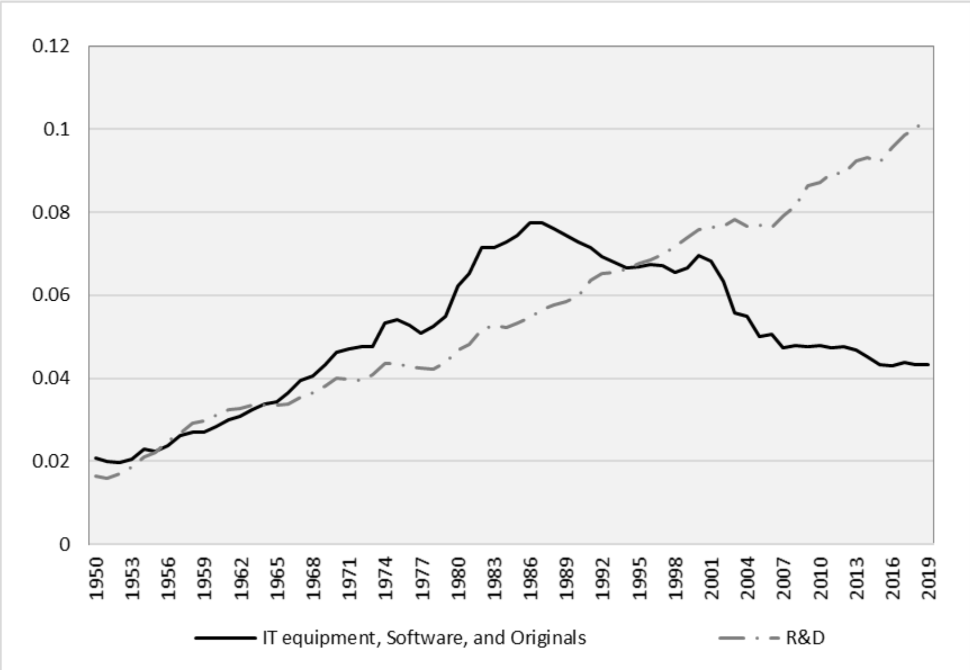
Current prices, 1950-2019



Source: Authors' calculations based on official BEA accounts.

Figure 4.5. US private sector capital-stock-to-output ratios for IT equipment, Software, Originals and R&D

Current prices, 1950-2019



Source: Authors' calculations based on official BEA accounts.

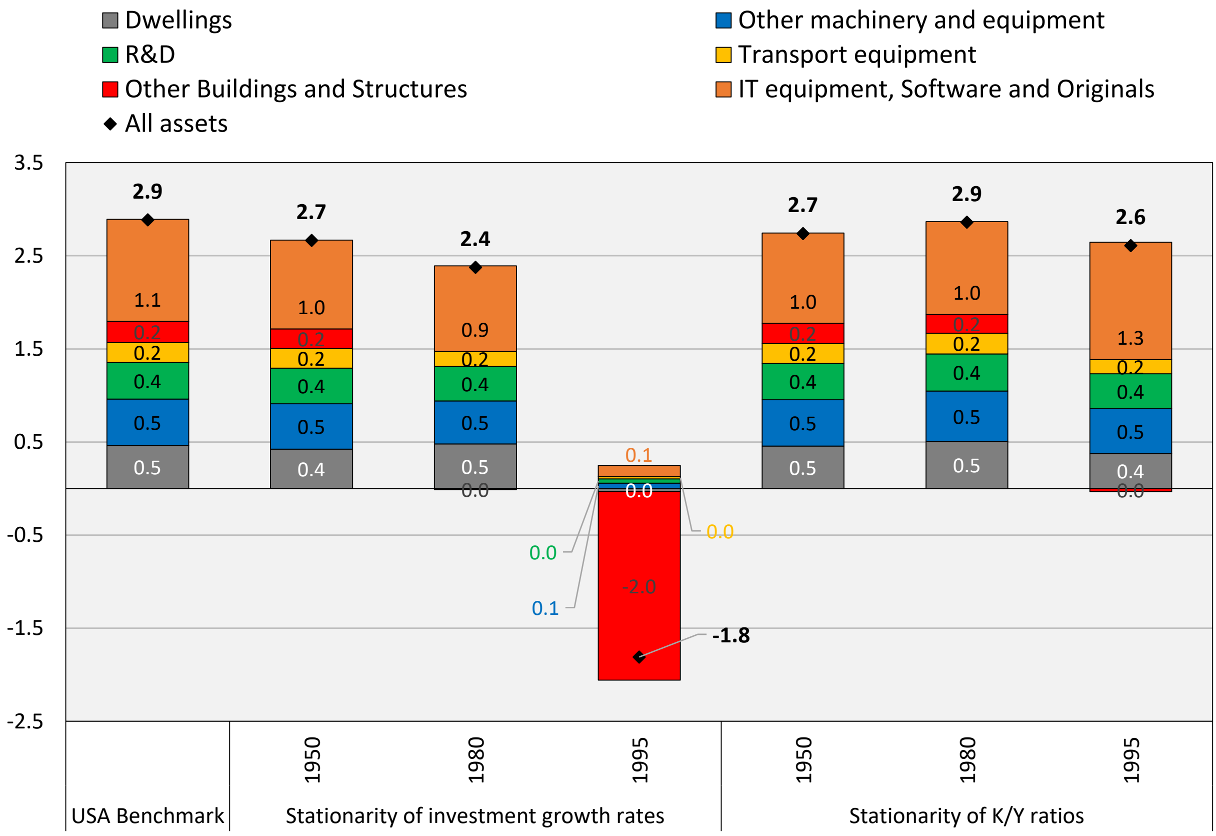
4.3. Sensitivity of capital services and MFP to initial capital stock estimates

49. Figure 4.6 shows that the combination of stationarity assumptions on investment growth rates and short investment time series may lead to very inaccurate estimates of capital services growth. This reflects to a large extent the difficulty to estimate initial capital stocks for structures and hence capital services, in particular of non-residential buildings, when relying on stationarity assumptions on investment growth. While shorter time series (e.g. 20-25 year long) may be enough for other assets, very long time series (e.g. 50 year long) are required for structures in order to accurately estimate capital stocks and hence capital services using initial capital stocks derived from stationarity assumptions on investment growth.

50. Conversely, Figure 4.6 shows that stationarity assumptions on capital-stock-to-output ratios to estimate initial capital stocks give relatively accurate estimates of US capital services growth, even when short investment time series are available. Nevertheless, the same caveat as for the estimation of net capital stocks holds (Section 4.2). Indeed, our findings are only limited to the US private sector, where the average capital-stock-to-output ratios estimated by Inklaar and Timmer (2013) on a large cross-section of countries prove to work reasonably well. In light of the dispersion in capital-stock-to-output ratios across countries, this method may give less reliable results for other countries than the US.

Figure 4.6. Sensitivity of the growth rate of capital services to initial capital stock estimates, US private sector

Average annual percentage changes, 1997-2019



Note: This figure shows the sensitivity of capital services growth in the US private sector over 1997-2019 to initial capital stock estimates. Two different methods (relying on stationarity assumptions on investment growth rates or capital-stock-to-output ratios) and three possible starting dates for investment time series (1950, 1980 and 1995) are considered.
Source: Authors' estimates.

51. As shown by Table 4-3, the sensitivity of MFP growth to initial capital stocks estimates reflects the sensitivity of capital services growth, although in a mitigated way due to the weighting (by roughly one third) of capital services growth in explaining economic growth. Indeed, MFP growth estimates only stand out as inaccurate when initial capital stocks are estimated in 1995 by assuming stationary investment growth rates over the past.

Table 4-3. Sensitivity of the growth rate of MFP to initial capital stocks

US private sector, 1999-2019

	USA - Benchmark	Stationarity of investment growth rates			Stationarity of capital-stock-to-output ratios		
		1950	1980	1995	1950	1980	1995
1999-2019	**0.7**	0.7	0.8	3.1	0.7	0.7	0.8
1999-2006	**1.0**	1.0	1.1	3.4	1.0	1.0	1.0
2006-2012	**1.5**	1.6	1.6	3.4	1.6	1.6	1.6
2012-2019	**-0.3**	-0.3	-0.2	2.5	-0.3	-0.3	-0.2

Note: This table shows the sensitivity of MFP growth in the US private sector over the period 1999-2019 to changes in the estimation of initial capital stocks. Two different methods (relying on stationarity assumptions on investment growth rates or capital-stock-to-output ratios) and three possible starting dates for investment time series (1950, 1980 and 1995) are considered.
Source: Authors' estimates.

5. Conclusion

52. The measurement of capital stocks in an economy typically implies estimating initial capital stocks at a given date in the past and then cumulating and depreciating investment flows over time. In this paper, we discussed the sensitivity of capital and MFP measurement to changes in the depreciation and retirement patterns of assets, and to the way initial capital stocks are estimated. These two aspects were left out in a previous sensitivity analysis of capital services by Inklaar (2010), who focused on the sensitivity of capital services to changes in the asset boundary and the measurement of capital user costs. Therefore, our two papers can be seen as complementing each other. By considering France, Italy and the UK, and assessing the reliability of different methods to estimate initial capital stocks, we also complemented a more recent sensitivity analysis by Giandrea *et al.* (2021), focusing on Canada and the US.

53. In order to capture differences in combined depreciation and retirement patterns across countries, we focused on geometric approximations of cohort depreciation patterns. This method allowed us to compare the asset depreciation and retirement patterns used by national accountants in the US and Canada, like Giandrea *et al.* (2021), but also in France, Italy and the UK, where functional forms for asset depreciation and retirement differ from those used in Canada and the US.

54. Applying Canadian, French and UK geometric cohort depreciation rates in the US would reduce the US private sector net capital stock by up to a third, and significantly increase CFC and decrease net investment. This largely reflects the faster depreciation of residential and non-residential buildings in Canadian, French and UK national accounts. The use of Italian depreciation rates, which are only slightly higher than those used in the US, have a much more limited impact on the US CFC, net investment and capital stocks. The growth rates of capital stocks, capital services and MFP are less sensitive to changes in depreciation and retirement patterns, no matter which country's depreciation rates are used.

55. We also assessed the accuracy of two commonly used options to estimate initial capital stocks and their impact on capital and MFP measurement. These methods involve stationarity assumptions on either investment growth rates or capital-stock-to-output ratios. While the estimation method of initial capital stocks is innocuous for rapidly depreciating assets, it has a more significant impact for long-lived assets.

56. The US example shows that structures may exhibit large fluctuations and/or long-term trends in investment growth. Therefore, we do not recommend relying on the stationarity assumption of investment growth rates to estimate initial capital stocks for such assets, except maybe if the PIM is run over several decades before the resulting capital stocks and capital services start to be used for economic analysis.

57. On the contrary, relying on the capital-stock-to-output ratios estimated by Inklaar and Timmer (2013) on a large cross-section of countries works reasonably well to estimate initial capital stocks for the US economy. Even shortly after the estimation date of initial capital stocks, the resulting capital stocks and capital services are quite accurate in this case. Nevertheless, given the wide dispersion in capital-stock-to-output ratios across countries, this result may not be universally true and relying on the cross-country average of capital-stock-to-output ratios may give less reliable results for other countries than the US. We leave it for further research to explore this issue.

58. Overall, the empirical evidence presented in this paper calls for a more frequent review of the methods used by statistical agencies to estimate the depreciation and retirement patterns of assets in order to ensure that differences across countries reflect country-specific factors rather than measurement errors. It also calls for a careful use of stationarity assumptions to estimate initial capital stocks, especially for long-lived assets. Efforts should be made to extend investment time series as much as possible based on historical vintages of national accounts, and to also use the external information on capital stocks provided by population censuses, company accounts and administrative sources whenever possible.

59. While this paper focuses on the US private sector because the investment series released by the BEA are detailed and long enough to replicate the calculation of CFC and net capital stocks for this part of the US economy, it does not address how changes in cohort depreciation patterns and initial capital stocks would affect the CFC of the government sector and, in turn, GDP. Additional research along these lines is on-going.

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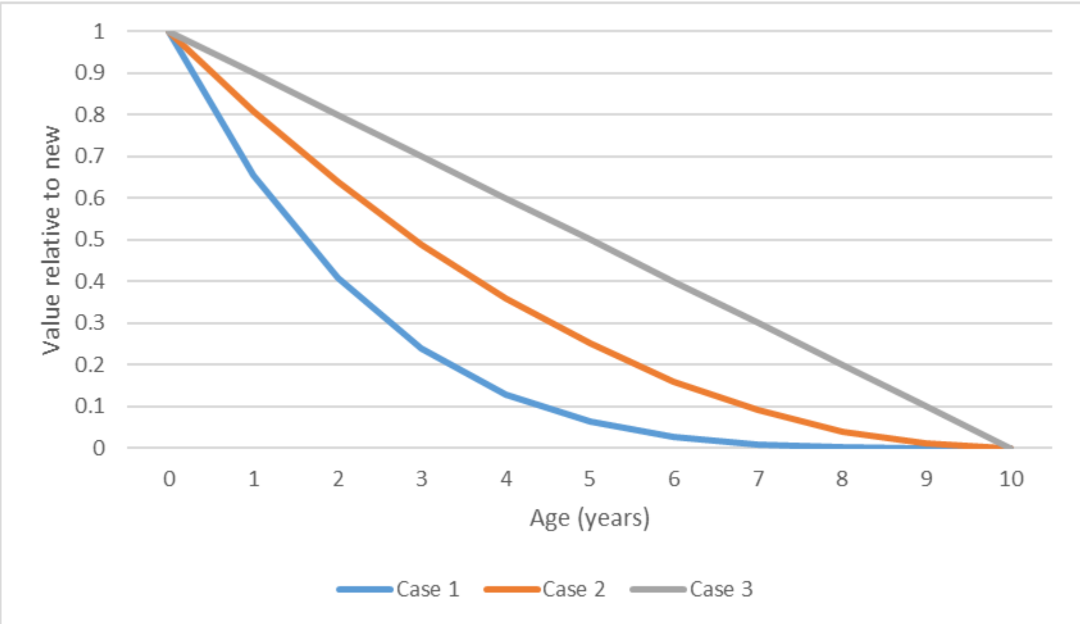
Annex A. Interpretation and limits of Declining Balance Rates (DBRs)

60. Age-price profiles describe how the value (i.e. the market price) of single assets declines over time due to the shortening of their remaining service life. In this Annex, we consider three different age-price profiles that belong to the same family of (power) functions. Like age-price profiles that can be derived from linear and hyperbolic age-efficiency functions (OECD 2009, Chapter 3), those in cases 1 and 2 are convex to the origin. Case 3 considers a linear age-price profile (Figure A.1).

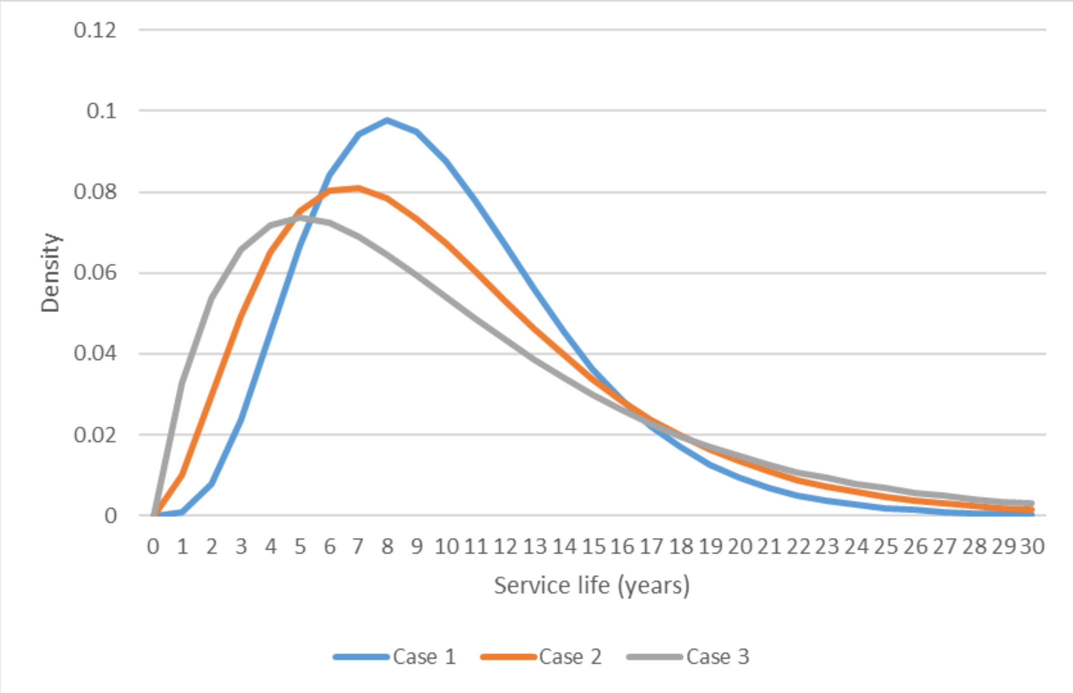
61. Each age-price profile is then combined with a specific retirement profile, belonging to the same family of (gamma) functions. These three retirement profiles are consistent with an asset average service life of 10 years and even though their shapes differ, they are all skewed to the left, in agreement with many asset survival studies (Figure A.2).

Figure A.1. Three individual age-price profiles, each with a service life of 10 years



Note: In this example, all age-price profiles are based on power functions of the type $\left(1-\frac{s}{L}\right)^{\nu-1}$ where s stands for the age of the asset and L for its service life. The parameter ν is set at 5, 3 and 2 in cases 1, 2 and 3, respectively. All assets shown in Figure A1 have a service life of 10 years.

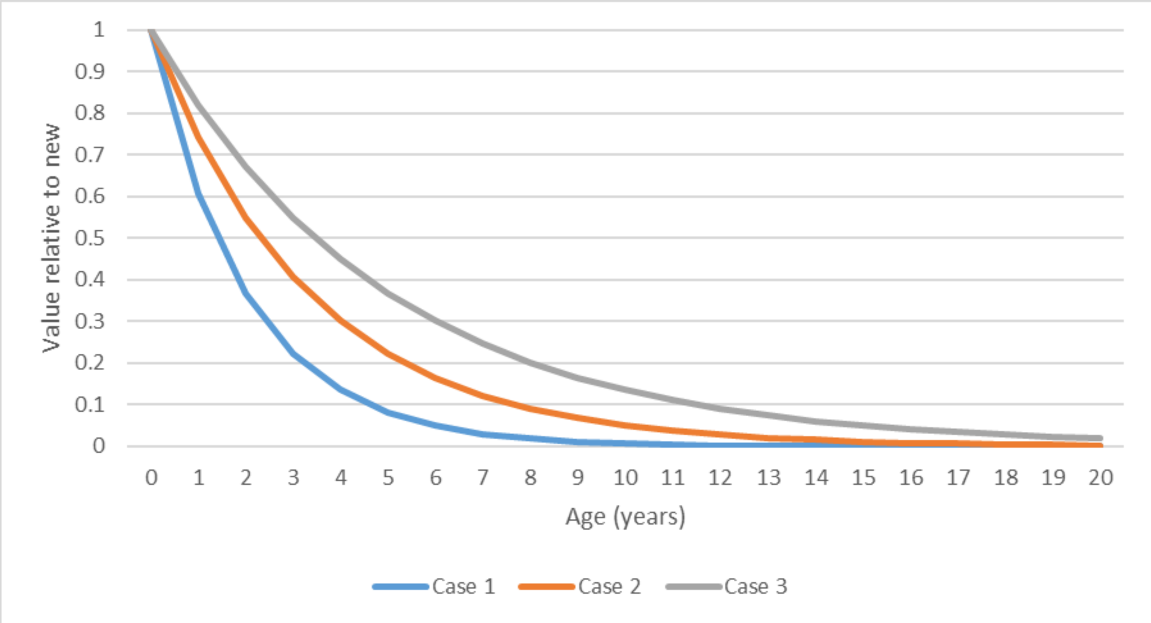
Figure A.2. Three retirement functions, each with an average service life of 10 years



Note: Retirement functions capture the randomness in asset service lives. In this example, Gamma functions with a density $\delta^{\nu} \cdot L^{\nu-1} \cdot \frac{e^{-\delta L}}{\Gamma(\nu)}$ are used. They are parameterised by ν (same parameter as for age-price profiles) and δ. Their mean is given by the ratio $\frac{\nu}{\delta}$ and corresponds to the asset average service life. It is fixed at 10 years, thus implying that the parameter δ is set at 0.5, 0.3 and 0.2 in cases 1, 2 and 3, respectively.

62. Sliker (2018) demonstrates that the combination of such age-price and retirement profiles leads to exactly geometric depreciation patterns for cohorts of assets. The implied geometric parameters depend on the parameters of the underlying depreciation and retirement functions. Figure A.3 shows that the implied geometric cohort depreciation rates are different in all three cases, even though the average service life of assets remains fixed at 10 years.

Figure A.3. Implied geometric cohort depreciation profiles combining age-price and retirement profiles



Note: Sliker (2018) shows that the combination of the depreciation and retirement functions used in Figures A.1 and A.2 leads to exactly geometric functions parameterised by the same parameter δ as in the retirement functions used for Figure A.2.

63. This example shows that DBRs depend on the shape of the underlying depreciation and retirement functions. Therefore, DBRs are country specific, and estimating geometric depreciation rates for a country based on its asset service lives (ASLs) and the DBRs of another country would be misleading. This is further illustrated in Table A.1 showing that assets with similar ASLs in Canada and the US (e.g. medical buildings) may have very different geometric cohort depreciation rates, and conversely that assets with similar geometric cohort depreciation rates (e.g. construction tractors) may have very different ASLs. This shows the wide heterogeneity of DBRs across countries, including for similar assets.

Table A.1. Comparison of geometric cohort depreciation rates (δ), average service lives (ASLs) and declining balance rates (DBRs) for specific assets in Canada and the US

Asset SNA code	Country	Asset label	δ	ASL (years)	DBR
N1121	**US BEA**	Medical building	0.02	36	0.89
	Statistics Canada	Hospitals, health centres, clinics, nursing homes and other health care buildings	0.06	35	2.17
N1139	**US BEA**	Household appliances	0.17	10	1.65
	Statistics Canada	Small electric appliances	0.21	11	2.29
		Major appliances	0.23	10	2.31
N1139	**US BEA**	**Construction tractors**	0.16	8	1.31
	Statistics Canada	**Logging, mining and construction machinery and equipment**	0.17	13	2.23

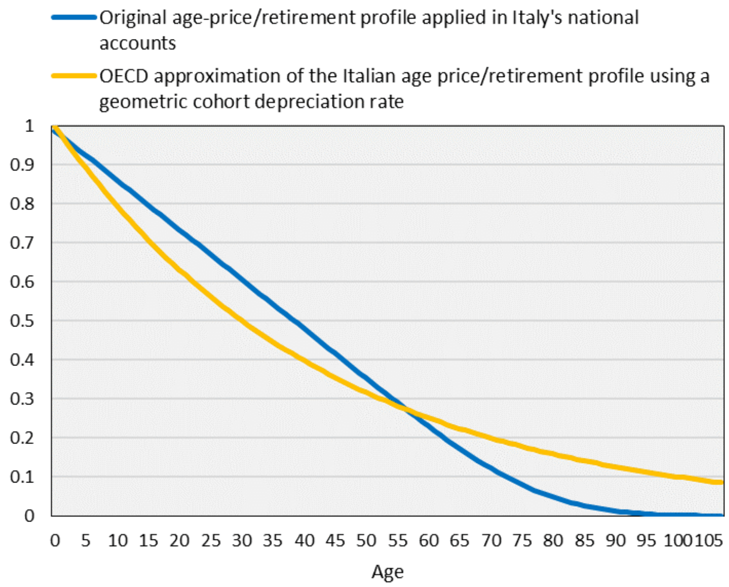
Source: BEA, Statistics Canada, and Giandrea *et al.* (2021).

Annex B. Geometric approximations of combined asset depreciation and retirement patterns

64. In France, depreciation for a cohort of assets is calculated by combining a log-normal retirement distribution with a straight-line depreciation pattern for single assets. In Italy, with the exception of R&D, cohort depreciation is calculated by combining a straight line depreciation with a truncated normal retirement function. In the UK, with the exception of R&D, the age-price profile for single assets is derived from a hyperbolic age-efficiency profile and then combined with a truncated normal retirement function. In all these cases, the combination of age-price and retirement profiles for single assets leads to a cohort depreciation profile that is convex to the origin.

65. Cabannes *et al*. (2013) estimated the geometric function that best fits the combined retirement and depreciation profiles applied in France. We follow their work and compute for each asset and industry the combined age-price/retirement profile $Z_{i,s}$ that is consistent with the PIM assumptions in Italy and the UK. We approximate these profiles with geometric profiles $Z^*_{i,s} = (1-\delta_i)^s$ and estimate the parameters δ_i using non-linear least squares.

Figure B.1. Combined depreciation and retirement pattern and its geometric approximation for dwellings in Italy

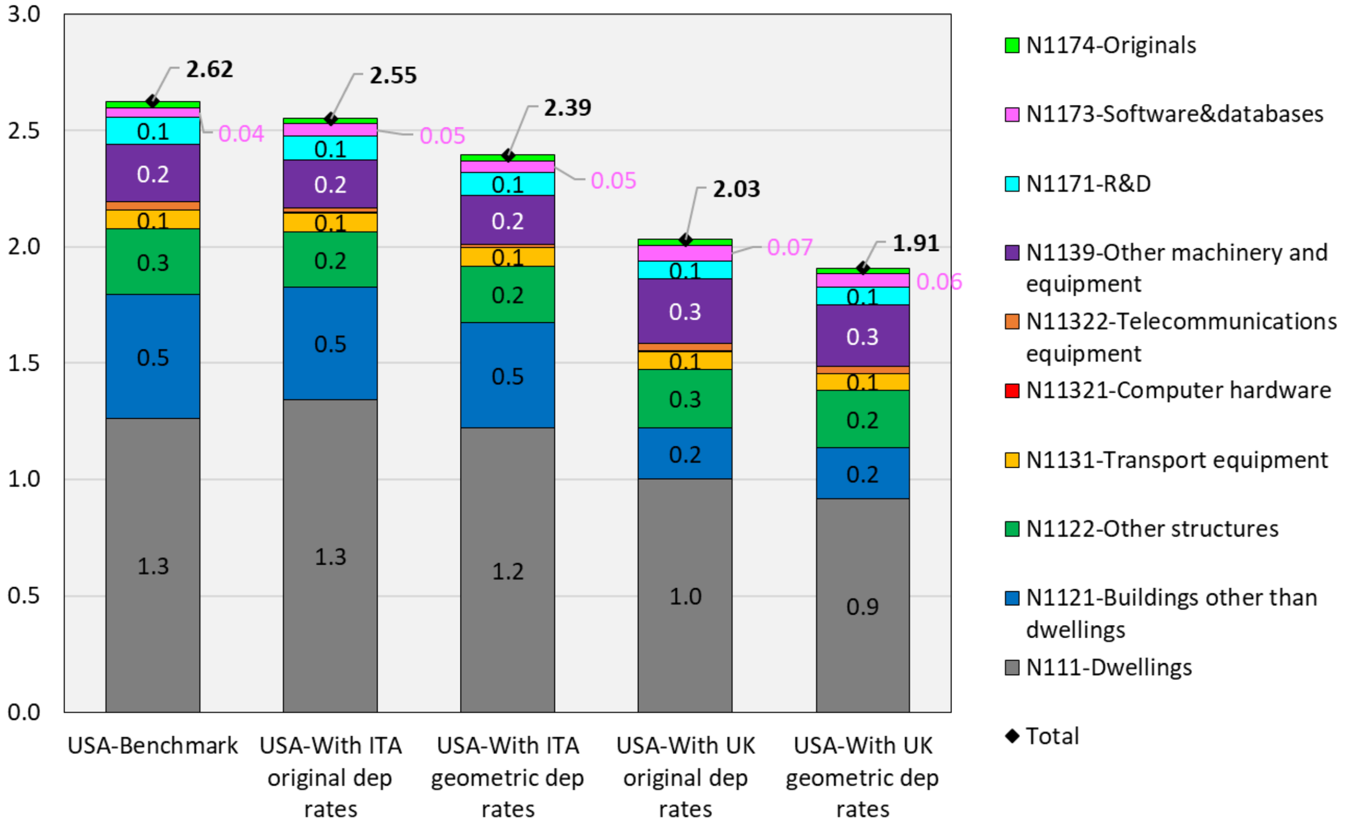


Source: Authors' calculations based on the reply by ISTAT (Italy) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

66. Figure B.2 shows alternative estimates of the US net capital stock when the cohort depreciation profiles of the BEA are replaced with the original profiles of Italy and the UK or their geometric approximations. It shows that the original profiles of Italy and the UK and their geometric approximations lead to consistent results. In both cases, the Italian assumptions lead to capital stocks that are relatively close to the official ones released by the BEA, while the UK assumptions lead to capital stocks that are significantly lower. Since geometric (approximations of) cohort depreciation rates simplify cross-country comparisons, we consistently use them in this paper.

Figure B.2. Alternative estimates of the US net capital stock when the cohort depreciation profiles of the BEA are replaced with the original profiles of Italy and the UK or their geometric approximations

US private sector, net capital stock to GVA ratio, 2019



Source: Authors' calculations based on the replies by ISTAT (Italy) and the ONS (UK) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

Annex C. Cohort depreciation rates asnd asset correspondence across countries

BEA asset label	OECD asset code	OECD asset label	Statistics Canada asset label	Geometric cohort depreciation rate				
				United States	Canada	France	Italy	United Kingdom
RESIDENTIAL ASSETS								
1-to-4-unit structures-new	DWE	Dwellings	new housing	0.0114	0.02	0.071	0.023	0.036
1-to-4-unit structures-additions and alterations	DWE	Dwellings	renovations	0.0227	0.04	0.071	0.023	0.036
1-to-4-unit structures-major replacements	DWE	Dwellings	renovations	0.0364	0.04	0.071	0.023	0.036
5-or-more-unit structures-new	DWE	Dwellings	new housing	0.014	0.02	0.071	0.023	0.036
5-or-more-unit structures-additions and alterations	DWE	Dwellings	renovations	0.0284	0.04	0.071	0.023	0.036
5-or-more-unit structures-major replacements	DWE	Dwellings	renovations	0.0455	0.04	0.071	0.023	0.036
Brokers' commissions and other ownership transfer costs /26/	DWE	Dwellings	ownership transfer costs	0.1375	1	0.071	0.023	0.036
Manufactured homes	DWE	Dwellings	Other commercial buildings	0.0455	0.081	0.071	0.023	0.036
Other structures	DWE	Dwellings	Other commercial buildings	0.0227	0.081	0.071	0.023	0.036
Equipment	DWE	Dwellings	Other commercial buildings	0.15	0.081	0.071	0.023	0.036
MACHINERY AND EQUIPMENT								
Communications	COM	Telecommunications equipment	Weighted average of many asset categories: EP20	0.111	0.228	0.154	0.282	0.178
Nonelectro medical instruments	OMEW	Other machinery and equipment	Medical, dental and personal safety supplies, instruments and equipment	0.135	0.301	0.117	0.138	0.129
Electro medical instruments	OMEW	Other machinery and equipment	Measuring and control devices; electrical, medical, scientific and technical instruments	0.1834	0.236	0.117	0.138	0.129
Nonmedical instruments	OMEW	Other machinery and equipment	Measuring and control devices; electrical, medical, scientific and technical instruments	0.135	0.236	0.117	0.138	0.129
Photocopy and related equipment	HARD	Computer hardware	Weighted average of many asset categories: EP31	0.18	0.242	0.244	0.261	0.241
Office and accounting equipment	HARD	Computer hardware	Weighted average of many asset categories: EP12	0.3119	0.323	0.244	0.261	0.241
Other fabricated metals	OMEW	Other machinery and equipment	Weighted average of many asset categories: EI12	0.0917	0.198	0.117	0.138	0.129
Steam engines	OMEW	Other machinery and equipment	Turbines and turbine generator set units	0.0516	0.086	0.117	0.138	0.129
Internal combustion engines	OMEW	Other machinery and equipment	Weighted average of many asset categories: EI22	0.2063	0.093	0.117	0.138	0.129
Metalworking machinery	OMEW	Other machinery and equipment	Metalworking machinery	0.121	0.197	0.117	0.138	0.129
Special industrial machinery	OMEW	Other machinery and equipment	Weighted average of many asset categories: EI40	0.102	0.195	0.117	0.138	0.129
General industrial equipment	OMEW	Other machinery and equipment	Weighted average of many asset categories: EI50	0.106	0.182	0.117	0.138	0.129
Electric transmission and distribution	OMEW	Other machinery and equipment	Weighted average of many asset categories: EI60	0.05	0.113	0.117	0.138	0.129
Light trucks (including utility vehicles)	TRANS	Transport equipment	Light-duty trucks, vans and SUVs	0.1925	0.235	0.171	0.172	0.162
Other trucks, buses and truck trailers	TRANS	Transport equipment		0.190	0.238	0.171	0.172	0.162
Aircraft	TRANS	Transport equipment	Weighted average of many asset categories: ET30	0.106	0.138	0.171	0.098	0.162
Ships and boats	TRANS	Transport equipment	Weighted average of many asset categories: ET40	0.0611	0.112	0.171	0.098	0.162
Railroad equipment	OMEW	Other machinery and equipment	Railroad rolling stocks	0.0589	0.099	0.117	0.138	0.129
Household furniture	OMEW	Other machinery and equipment	Weighted average of many asset categories: EO11	0.1375	0.25	0.117	0.137	0.129
Other furniture	OMEW	Other machinery and equipment	Weighted average of many asset categories: EO12	0.1179	0.26	0.117	0.137	0.129
Other agricultural machinery	OMEW	Other machinery and equipment	Agricultural, lawn and garden machinery and equipment	0.1179	0.178	0.117	0.138	0.129
Farm tractors	TRANS	Transport equipment	Agricultural, lawn and garden machinery and equipment	0.1452	0.178	0.171	0.098	0.162
Other construction machinery	OMEW	Other machinery and equipment	Logging, mining and construction machinery and equipment	0.155	0.172	0.117	0.138	0.129
Construction tractors	TRANS	Transport equipment	Logging, mining and construction machinery and equipment	0.1633	0.172	0.171	0.098	0.162
Mining and oilfield machinery	OMEW	Other machinery and equipment	Logging, mining and construction machinery and equipment	0.15	0.172	0.117	0.138	0.129
Service industry machinery	OMEW	Other machinery and equipment	Commercial and service industry machinery	0.150	0.265	0.117	0.138	0.129
Household appliances	OMEW	Other machinery and equipment	Weighted average of many asset categories: EO71	0.165	0.222	0.117	0.138	0.129
Other electrical	OMEW	Other machinery and equipment	Weighted average of many asset categories: EO72	0.1834	0.115	0.117	0.138	0.129
Other	OMEW	Other machinery and equipment	Weighted average of many asset categories: EO80	0.1473	0.193	0.117	0.138	0.129

BEA asset label	OECD asset code	OECD asset label	Statistics Canada asset label	Geometric cohort depreciation rate				
				United States	Canada	France	Italy	United Kingdom
NON RESIDENTIAL ASSETS								
Office	BOD	Buildings other than dwellings	Office buildings	0.0247	0.068	0.067	0.039	0.075
Hospitals	BOD	Buildings other than dwellings	Hospitals, health centres, clinics, nursing homes and other health care buildings	0.019	0.062	0.067	0.039	0.075
Special care	BOD	Buildings other than dwellings	Hospitals, health centres, clinics, nursing homes and other health care buildings	0.0188	0.062	0.067	0.039	0.075
Medical buildings	BOD	Buildings other than dwellings	Hospitals, health centres, clinics, nursing homes and other health care buildings	0.025	0.062	0.067	0.039	0.075
Multimerchandise shopping	BOD	Buildings other than dwellings	Shopping centers, plazas, malls and stores	0.0262	0.093	0.067	0.039	0.075
Food and beverage establishments	BOD	Buildings other than dwellings	Other commercial buildings	0.026	0.081	0.067	0.039	0.075
Warehouses	BOD	Buildings other than dwellings	Other commercial buildings	0.0222	0.081	0.067	0.039	0.075
Mobile structures	BOD	Buildings other than dwellings	Other institutional buildings	0.056	0.062	0.067	0.039	0.075
Other commercial	BOD	Buildings other than dwellings	Weighted average of many asset categories: SC02	0.0262	0.087	0.067	0.039	0.075
Manufacturing	BOD	Buildings other than dwellings	Industrial buildings	0.031	0.075	0.067	0.039	0.075
Electric	OST	Other structures	Weighted average of many asset categories: SU30	0.0211	0.055	0.031	0.039	0.050
Wind and solar	OST	Other structures	Weighted average of many asset categories: SU60	0.030	0.065	0.031	0.039	0.050
Gas	OST	Other structures	Weighted average of many asset categories: SU40	0.0237	0.074	0.031	0.039	0.050
Petroleum pipelines	OST	Other structures	Weighted average of many asset categories: SU50	0.024	0.074	0.031	0.039	0.050
Communication	OST	Other structures	Weighted average of many asset categories: SU20	0.0237	0.104	0.031	0.039	0.050
Petroleum and natural gas	OST	Other structures	Weighted average of many asset categories: SM01	0.075	0.117	0.031	0.039	0.050
Mining	OST	Other structures	Mining engineering construction	0.045	0.159	0.031	0.039	0.050
Religious	BOD	Buildings other than dwellings	Churches, and other religious buildings	0.019	0.055	0.067	0.039	0.075
Educational and vocational	BOD	Buildings other than dwellings	Schools, colleges, universities and other educational buildings	0.0188	0.056	0.067	0.039	0.075
Lodging	BOD	Buildings other than dwellings	Other commercial buildings	0.028	0.081	0.067	0.039	0.075
Amusement and recreation	BOD	Buildings other than dwellings	Other commercial buildings	0.03	0.081	0.067	0.039	0.075
Air transportation	OST	Other structures	Other engineering construction	0.024	0.102	0.031	0.039	0.050
Other transportation	OST	Other structures	Marine engineering construction	0.0237	0.08	0.031	0.039	0.050
Other railroad	OST	Other structures	Other transportation construction	0.018	0.063	0.031	0.039	0.050
Track replacement	OST	Other structures	Other transportation construction	0.0249	0.063	0.031	0.039	0.050
Local transit structures	OST	Other structures	Weighted average of many asset categories: SB44	0.024	0.092	0.031	0.039	0.050
Other land transportation	OST	Other structures	Other transportation construction	0.0237	0.063	0.031	0.039	0.050
Farm	BOD	Buildings other than dwellings	Weighted average of many asset categories: SN00	0.024	0.089	0.067	0.039	0.075
Water supply	OST	Other structures	Waterworks engineering construction	0.0225	0.057	0.031	0.039	0.050
Sewage and waste disposal	OST	Other structures	Sewage engineering construction	0.023	0.062	0.031	0.039	0.050
Public safety	OST	Other structures	Other institutional buildings	0.0237	0.062	0.031	0.039	0.050
Highway and conservation and development	OST	Other structures	Highway, roads, streets, bridges and overpasses	0.023	0.101	0.031	0.039	0.050

BEA asset label	OECD asset code	OECD asset label	Statistics Canada asset label	Geometric cohort depreciation rate				
				United States	Canada	France	Italy	United Kingdom
INTELLECTUAL PROPERTY PRODUCTS								
Prepackaged software	SOFT	Computer software and databases	General purpose software	0.550	0.550	0.244	0.325	0.256
Custom software	SOFT	Computer software and databases	Custom software design and development services	0.33	0.33	0.244	0.325	0.256
Own account software	SOFT	Computer software and databases	Own-account software design and development services	0.330	0.330	0.244	0.325	0.245
Pharmaceutical and medicine manufacturing	RD	Research and development	Research and development services	0.1	0.275	0.1	0.200	0.287
Chemical manufacturing, ex. pharma and med	RD	Research and development	Research and development services	0.160	0.275	0.160	0.200	0.287
Semiconductor and other component manufacturing	RD	Research and development	Research and development services	0.25	0.275	0.25	0.200	0.287
Computers and peripheral equipment manufacturing	RD	Research and development	Research and development services	0.400	0.275	0.400	0.200	0.287
Communications equipment manufacturing	RD	Research and development	Research and development services	0.27	0.275	0.27	0.200	0.287
Navigational and other instruments manufacturing	RD	Research and development	Research and development services	0.290	0.275	0.290	0.200	0.287
Other computer and electronic manufacturing, n.e.c.	RD	Research and development	Research and development services	0.4	0.275	0.4	0.200	0.287
Motor vehicles and parts manufacturing	RD	Research and development	Research and development services	0.310	0.275	0.310	0.200	0.287
Aerospace products and parts manufacturing	RD	Research and development	Research and development services	0.22	0.275	0.22	0.200	0.287
Other manufacturing	RD	Research and development	Research and development services	0.160	0.275	0.160	0.200	0.287
Scientific research and development services	RD	Research and development	Research and development services	0.16	0.275	0.16	0.200	0.287
Software publishers	RD	Research and development	Research and development services	0.220	0.275	0.220	0.200	0.287
Financial and real estate services	RD	Research and development	Research and development services	0.16	0.275	0.16	0.200	0.287
Computer systems design and related services	RD	Research and development	Research and development services	0.360	0.275	0.360	0.200	0.287
All other nonmanufacturing, n.e.c.	RD	Research and development	Research and development services	0.16	0.275	0.16	0.200	0.287
Private universities and colleges	RD	Research and development	Research and development services	0.160	0.275	0.160	0.200	0.287
Other nonprofit institutions	RD	Research and development	Research and development services	0.16	0.275	0.16	0.200	0.287
Theatrical movies	ELAO	Entertainment, literary, and artistic originals	Movies, television programs and videos	0.093	1.000	0.331	0.172	0.183
Long-lived television programs	ELAO	Entertainment, literary, and artistic originals	Movies, television programs and videos	0.168	1	0.331	0.172	0.183
Books	ELAO	Entertainment, literary, and artistic originals		0.121	0.121	0.331	0.172	0.183
Music	ELAO	Entertainment, literary, and artistic originals		0.267	0.267	0.331	0.172	0.183
Other entertainment originals	ELAO	Entertainment, literary, and artistic originals		0.109	0.109	0.331	0.172	0.183

Note: The table above provides a mapping between the different assets types considered by national accountants at Statistics Canada, INSEE (France), ISTAT (Italy), the ONS (UK) and the BEA (US), and compares the corresponding geometric cohort depreciation rates.

For Canada, these depreciation rates are averages across industries. They correspond to the “weighted averages of many asset categories” provided by Giandrea *et al*. (2021). Canadian cohort depreciation rates are not available for books, music, and other entertainment originals. Our sensitivity analysis keeps the US depreciation rates unchanged for these assets.

For France, the geometric approximations of the combined depreciation and retirement patterns provided by Cabannes *et al.* (2013) are used. French cohort depreciation rates are not available for R&D. Our sensitivity analysis keeps the US depreciation rates unchanged for these assets.

For Italy and the UK, we compute the geometric approximations of the combined depreciation and retirement patterns for the purposes of this exercise on the basis of the replies provided by ISTAT (Italy) and the ONS (UK) to the 2019 Joint Eurostat-OECD Questionnaire on the Methodology underlying Capital Stocks data.

Annex D. Estimation of endogenous rates of return

67. In this paper, we compute endogenous rates of return for 13 aggregate industries belonging to the US private sector (Table D.1).

Table D.1. Industry level at which the internal rates of return are estimated

NAICS code	NAICS label	OECD code	OECD label
11	Agriculture, forestry, fishing, and hunting	VA0	Agriculture, forestry and fishing
21	Mining	VB	Mining and quarrying
22	Utilities	VD+VE	Electricity, gas, steam and air conditioning supply & Water supply; sewerage, waste management and remediation activities
23	Construction	VF	Construction
31-33	Manufacturing	VC	Manufacturing
42 & 44-45	Wholesale trade and retail trade	VG	Wholesale and retail trade; repair of motor vehicles and motorcycles
48-49	Transportation and warehousing	VH	Transportation and storage
51	Information	VJ	Information and communication
52-53	Finance, insurance, real estate, rental, and leasing	VK+VL	Financial and insurance activities & Real estate activities
54-56	Professional and business services	VM+VN	Professional, scientific and technical activities & Administrative and support service activities
61-62	Educational services, health care, and social assistance	VP+VQ	Education & Human health and social work activities
71-72	Arts, entertainment, recreation, accommodation, and food services	VR+VI	Arts, entertainment and recreation & Accommodation and food service activities
81	Other services, except government	VS	Other service activities

Note: OECD codes are industry codes used in the OECD Annual National Accounts database.

68. Estimating the residual income KInc accruing to capital is not straightforward. This aggregate corresponds to the sum of the gross operating surplus (GOS), the capital income component of mixed income, and taxes less subsidies on production. For each industry, the BEA accounts include a single aggregate summing up GOS and mixed income. We denote this aggregate by GOSMXI. In order to estimate the labour component of mixed income, we assume that the average labour compensation received by a self-employed person in a given industry is equal to the labour compensation received by an employee in the same industry.[25] This is a standard assumption in the literature, which is also used in the OECD Productivity database and the EU KLEMS database.

[25] The BEA accounts include the number of hours worked by employees, but not the number of hours worked by self-employees, thus preventing to impute the labour compensation of self-employed workers based on the same hourly compensation as employees.

69. In order to estimate KInc, we proceed as follows:

Step 1: We calculate the number of self-employed workers by detailed industry as

$$SE_{it} = TPE_{it} - EE_{it}$$

where SE_{it} is the number of self-employed workers, EE_{it} the number of full-time equivalent employees, and TPE_{it} the number of total persons engaged in production in industry i in period t.

Step 2: We impute a labour compensation to self-employed workers as follows:

$$LMX_{it} = \frac{COE_{it}}{EE_{it}} * SE_{it}$$

where COE_{it} is the total compensation of employees in industry i in period t.

Step 3: We subtract the labour component of self-employed income from GOSMXI and add taxes less subsidies on production (D29_D39):

$$KInc_{it} = GOSMXI_{it} - LMX_{it} + D29\_D39_{it}$$

70. We source data on taxes less subsidies on production from the OECD Annual National Accounts database, where they are available by ISIC rev. 4 industry. We then use the correspondence between NAICS and ISIC Rev. 4 shown in Table D.1. This allows estimating endogenous rates of return for the 13 aggregate industries, which are then used for the calculation of capital services.