Enterprise Information and Communications Technology Software Pricing and Developer Productivity Measurement

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Abstract

The 1999 addition of business sector software and services spending was an important National Income and Product Accounts innovation, achieving a novel focus on the measurement of intangible asset investment. Over the intervening years, enterprise information and communication technology (ICT) has fundamentally changed. As a software producing sector, the business sector ICT function now has a much wider array of choices - software-as-a-service; open-source software; computing, storage, and communications cloud services; and developer services from a range of global resources. Labor and multifactor software development productivity are important sources of value creation, making measurement challenging. As the software development sector has become increasingly important in providing business sector ICT productivity, software sector developer productivity has become a viable proxy for business sector ICT developer productivity. With the use of a two-sector model and a standard growth accounting framework, the business sector ICT function shadow price is estimated, finding software price declines have been underestimated by 6.0 percentage points (ppt) over 2015 to 2020. The impact on GDP growth is a 0.1 ppt underestimate and the impact increases software spending from 19.1% to 24.9% of nonresidential fixed investment.

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I. Introduction

Since the introduction of business expenditures for computer software as capital formation into the National Income and Product Accounts (NIPA's), 20 years ago, both software development and computing infrastructure have changed dramatically (See Parker and Grimm 2000). Nearly ubiquitous internet access, the widespread use of mobile devices, the advent of cloud computing, the availability of software-as-a service, and other innovations have fundamentally altered information and communication technology (ICT).

At the dawn of the 21st century, internet use was limited, the iPhone had yet to be launched, and cloud computing, as it's known today, was not yet available. The transformation of ICT away from a focus on basic accounting, finance, human resource, and office tasks to a capability providing digital automation of consumer activities and business processes, near real time information availability, and high-speed search has occurred over a remarkably brief period.

Software spending, as reported in the NIPAs, has increased from 8.5% of real nonresidential fixed investment in 2002 to 20.3% in 2021 with software spending growing from 0.9% of real GDP in 2002 to 2.9% in 2021. The current NIPA methodology focuses on own-account and custom software. Own-account software is defined as software "production by a business for its own use" (See Bureau of Economic Analysis 2019, Chapter 6, page 2). Custom software is software provided by third party developers. The focus here is on the business sector ICT function which incorporates both own-account and custom software.

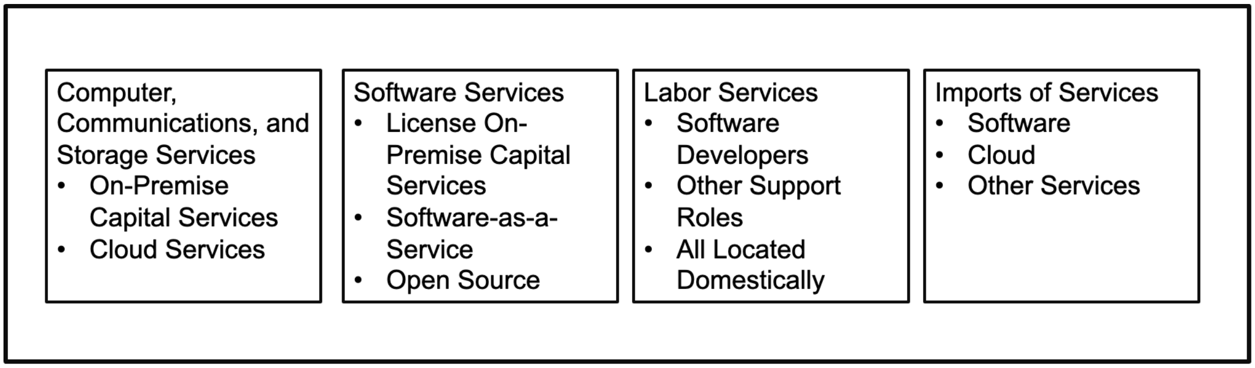
Over the most recent two decades, ICT capability – for consumers, small businesses, and enterprises – has moved rapidly to extensive use of a cloud computing infrastructure that includes computing, storage, massive bandwidth, and low latency user access; the ingestion of vast quantities of structured and unstructured data; the use of machine learning and artificial intelligence to anticipate choice and provide recommended actions; and delivery on mobile, hand-held devices.

With the advent of the new digital technology, business sector software investment spending occurs in the context of an organizational unit delivering software solutions. Many firms have multiple units developing such solutions, each supporting one or more business functions. Resources are acquired at market prices and market competition creates pressure to manage cost and expense. But the resulting output of ICT units is not sold at a market price. Thus, the development of a software price index is the estimate of a shadow price for an organizational function. The shadow price is the marginal profit contribution of the functional activity, considering alternative capital allocation, capturing the opportunity cost in choosing one alternative over another.

The objective of this paper is to outline a methodology for estimating a software own-account and custom price index – the ICT function shadow price – and provide estimates for recent years. In doing so, a methodology and estimates for software developer labor and multifactor productivity (MFP) are required.

Virtually every business organization develops and uses software in some fashion (See Zolas 2020). Except for the smallest business organizations, most have formed ICT functions that acquire a variety of resources and deliver software to business functional areas. Finance, human resources, and operation functions are obvious and well-known illustrations, but

Figure 1
Technology Resources Required for
Business Sector ICT Software Production



increasingly functions such as customer relationship management, enterprise risk management and compliance, and business security are growth applications.

The business sector ICT function is a software producing sector. To produce such software a range of inputs are required. See Figure 1.

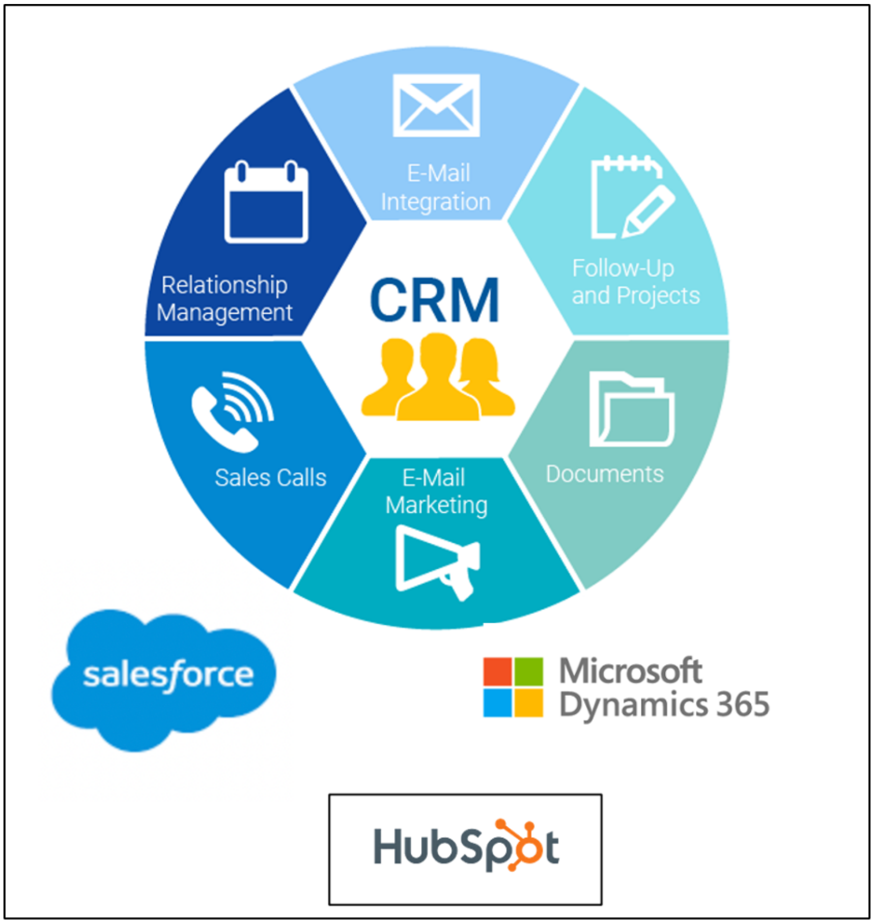
- System resources – computing, communications, and storage – can be acquired either as a result of an asset purchase with the installation of the asset providing a capital service or as a cloud service which is an intermediate purchase, not an asset purchase. Each has an associated price; the capital service provided by the asset has a rental rate while the cloud service has a transaction price.
- Software resources are similarly acquired with one notable and important exception. License software is an asset purchase which provides a capital service with a related rental rate while software-as-a-service is an intermediate purchase at a transaction price – per use or per time period. Over the past two decades, open-source software has become increasingly important. Open-source software is available with a license in which the copyright holder grants users the

right to use, change, and distribute the software with the source code available to anyone for any purpose at a zero price.

- Labor services, located domestically, principally consist of software developers but also include computer and information analysts, research scientists, operators, support specialists, database managers, network administrators, and systems architects.
- Imports of services, providing resources to the business sector ICT function, consist of software, including end-user licenses and customization; cloud computing and data storage services; consulting and implementation services; maintenance and repair services; and facilities management services; and data recovery services. Imported services principally reflect the labor services provided by software developers and others in non-domestic locations.

To help fix ideas, consider customer relationship management (CRM) software which helps business leaders nurture and grow client relationships. See Figure 2. CRM software assists with organization, efficiency, and time management. Such software improves salesforce productivity and with confidential client information builds intangible assets. CRM platforms connect data from sales leads through transaction outcomes – won, lost, or continued open. CRM platforms record and analyze meta data from conference calls, emails, and meetings, helping improve customer service, and address customer needs and requirements. CRM platforms, most recently, have provided increased analytic insight. With the ability to track and segment client data, artificial intelligence tools assess the probability opportunities will be won or lost, forecast period revenue, and assess the probability of seller retention or attrition. Most,

Figure 2
Customer Relationship Management Software



Source: https://www.perfectviewcrm.com/what-is-crm/

Figure 3
Worldwide Software Revenue by Type
Billions of Dollars
2016 - 2022

	2016	2022	2016-2022 CAGR (%)	2016	2022	PPT Change
License or Fee	133.9	125.3	-1.1	52.0%	26.6%	-25.4ppt
SaaS or Subscription	123.5	344.9	+18.7	48.0%	73.4%	+25.4ppt
Total	257.4	470.2	+10.6	100.0%	100.0%	----

Source: IDC

if not all firms, have a CRM capability. Among medium and larger enterprises, CRM usage is virtually universal. Among small business, sellers subscribe to the service on an individual basis.

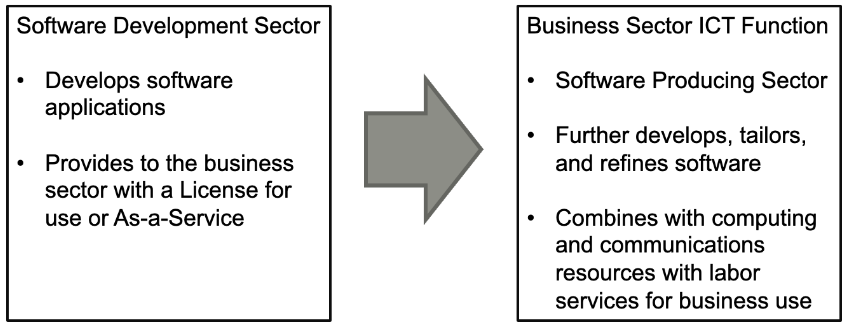
CRM software is representative of a broad class of software that is provided either with a license agreement, as-a-service, or with an open-source agreement. Figure 3 shows worldwide software spending. With a zero price, open-source use is not included. In 2016, 52% of total spending was undertaken with a license while spending for software-as-a-service was 48%. By 2022, however, software-as-a-service spending was 73% of total spending while spending to

license use was 27%. Software-as-a-service spending grew at an annual rate of almost 19% over the six-year period while spending for license software declined at an annual rate of 1%. Consequently, business sector ICT functions are heavily reliant on software development firms for applications development. As a result, the productivity of business sector software developers will, in part, be a function of the productivity of software sector developers.

As suggested by the CRM illustration, a substantial portion of software delivered by the business sector ICT function relies on the input from the software development sector. Software delivered to the business sector requires a two-sector model. A **software development sector** provides software to the business sector ICT function, which is the **software producing sector**, that further develops, tailors, and refines applications for business sector use. Because the software producing sector is an internal business function, the price of such internally produced software does not exist. See Figure 4.

The software development resources employed by the business sector ICT function are acquired at a price – and in the case of labor services at a wage rate. The weighted average of

Figure 4
Software Delivered by the Business Sector ICT Function Relies on Input from the Software Development Sector



the changes in these input prices, accounting for productivity improvements, is the change in the business sector ICT function shadow price. However, measuring the productivity of such an internal function is challenging. While one can imagine project level productivity estimates, productivity among software developers and software development teams is highly heterogeneous (See Shrikanth, Nichols, Fahid, and Menzies, 2021). However, if software development productivity in the software development sector results in knowledge diffusion to the software producing sector, measurement of software development sector productivity can be representative of software development productivity in the software producing sector. Such an assumption is developed in more detail in the section's that follow.

The assumed equality of software developer productivity in both the software developer sector and the software producing sector suggests a relationship between the business sector ICT function shadow price and the software developer sector price. By definition, the change in labor productivity (LP) equals the change output quantity minus the change in labor quantity while the change in output quantity equals the change in output value minus the change in the price.

$$\dot{LP}_{ICT,t} = \dot{Q}_{ICT,t} - \dot{L}_{ICT,t} = \dot{V}_{ICT,t} - \dot{P}_{ICT,t} - \dot{L}_{ICT,t}$$

$$\dot{LP}_{SS,t} = \dot{Q}_{SS,t} - \dot{L}_{SS,t} = \dot{V}_{SS,t} - \dot{P}_{SS,t} - \dot{L}_{SS,t}$$

where

$\dot{LP}_{ICT,t}$ and $\dot{LP}_{SS,t}$	Change in labor productivity (LP) in the business sector ICT function and the change in labor productivity in the software developer sector, respectively
$\dot{Q}_{ICT,t}$ and $\dot{Q}_{SS,t}$	Change in the quantity of output in the business sector ICT function and the change in the quantity of output in the software developer sector, respectively
$\dot{V}_{ICT,t}$ and $\dot{V}_{SS,t}$	Change in the nominal value of output in the business sector ICT function and the change in the nominal value of output in the software developer sector, respectively
$\dot{P}_{ICT,t}$ and $\dot{P}_{SS,t}$	Change in the shadow price of the business sector ICT function output and the change in the output price in the software developer sector, respectively
$\dot{L}_{ICT,t}$ and $\dot{L}_{SS,t}$	Change in labor services in the business sector ICT function and the change in labor services in the software developer sector, respectively

If $\dot{LP}_{ICT,t} = \dot{LP}_{SS,t}$, then

$$\dot{P}_{ICT,t} = \dot{P}_{ss,t} + (\dot{V}_{ICT,t} - \dot{V}_{SS,t}) + (\dot{L}_{SS,t} - \dot{L}_{ICT,t}) \qquad (1)$$

In equation (1), it’s obvious that if the change in the nominal value of output in both sectors is equal and if the change in labor services in both sector is also equal, the change in the shadow price of the business sector ICT function output equals the change in the output price in the software developer sector. Further, if data for the right-side variables are available, estimating the business sector ICT function shadow price would be the change in the software development sector output price. However, because of the unique requirements that the business sector ICT function faces, there is no external market for the software delivered by the ICT function and $\dot{V}_{ICT,t}$ is unknown. To be sure there are consulting and implementation services as well as a range of other external service offering, but except for a limited set of circumstances, the software delivered by the ICT function cannot generally be purchased and readied for deployment as a result of an open competitive market transaction. Thus, value of $\dot{V_{ICT,t}}$ cannot be determined.

Consequently, to estimate the shadow price, there are a number of data requirements. First, the BEA Integrated Industry-Level Production Account (KLEMS) data are employed as they provide both capital services quantities and rental price deflators for computing, communications, software and other capital that deliver the services provided by those assets acquired by the business sector (See Garner, Harper, Russell, and Samuels 2021). Second, data for cloud and open-source software services are necessary. Third, labor services employment and wage data are required. And fourth, data for imported services are required. In all cases both quantities and prices are necessary.

The Integrated Industry-Level Production Account provides sector level data for capital services provide by communication and computing equipment, software, and other capital. For each capital service, a price is associated with the quantity of capital services. The price is often referred to as the rental price or the user cost of capital (See Jorgenson, Ho, and Stiroh 2005, pp. 154-155 for more detail). As is well known, in recent decades intermediate services, such as cloud computing and software-as-a-service are also available to the business sector ICT function. A transaction price is associated with such services. These intermediate services are provided by technology organizations outside the business sector ICT function. The principle focus of this paper is the consumption of ICT-related services and their associated prices.

The business sector ICT function is a business service most often internal to business and government organizations that employ a wide range of ICT resources. While the capital investment such a function represents is labeled as software in the NIPA accounts delivering such software requires a wide range of ICT resources. The end user in a business or government organization benefits from new or improved software tools and capabilities with a portfolio of technology resources required for the production of the resulting software.

The model and empirical estimates provided in this paper include all U.S. economic sectors - farm, business, and government. For ease of exposition, references in this paper will be to the business sector. The methodology developed distinguishes between the software development sector – those organizations engaged in the development of software for use by business and government organizations – and the business sector ICT function that produces and delivers software after further refinement for business and government end users. In alignment with the BEA definition, the software development sector includes NAICS 5112 Software Publishers, NAICS 5182 Data Processing, Hosting and Related Services, and NAICS 5415 Computer Systems Design and Related Services. Each of these industry groups, in whole or in part, produce software for future integration and deployment by a business sector ICT function. For example, organizations in NAICS 5182 Data Processing, Hosting and Related Services, such as Amazon Web Services (AWS), Microsoft, and Google, provide an extensive portfolio of software tools to support their cloud computing users.

The plan of the paper is as follows. Section Two reviews the existing software investment price index methodology and provides a framework and model for an alternative price index. Section Three considers the issue of software developer productivity, outlines the measurement difficulty, and proposes an alternative measure that is implementable. Section

Four develops a novel software investment price index, along with the required data. Section Five concludes.

II. Software Production, Productivity and Pricing

Consideration of an alternative software investment price index builds on the existing NIPA methodology (See BEA 2019, Chapter 6). In the current approach, business sector software investment consists of prepackaged software purchases, custom software applications provided by third-party developers, and own-account production provided by internal development teams. Each provides new or significantly enhanced applications with maintenance of existing applications excluded. See Figure 5.

II.1. Current Software Investment Price Index

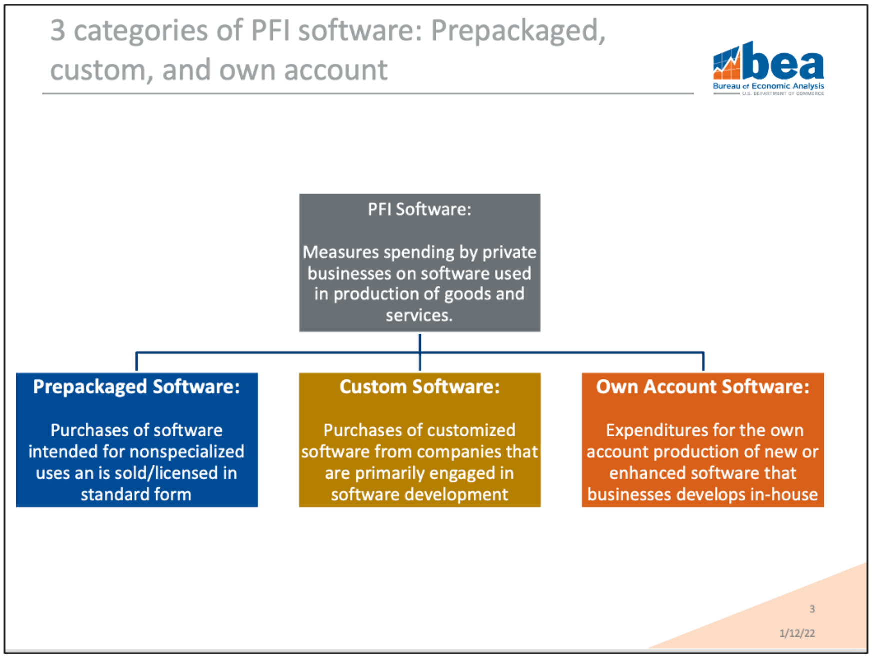
The current-dollar estimates for prepackaged software purchases and custom software are based on software industry receipts data from the Census Bureau's Economic Census and are derived using the commodity-flow method (See BEA 2019, Chapter 4).

The estimates of real prepackaged software expenditures are prepared by deflating the current-dollar estimates. The deflator is a Bureau of Economic Analysis (BEA) price index that is based on the Bureau of Labor Statistics (BLS) *Producer Price Index for Software Publishing, Except Games*.[1] The BLS index is adjusted for quality change by BEA based on studies comparing hedonic-type price indexes with matched-model price indexes. The current adjustment is a downward bias adjustment of 3.192% annually for the years 2006 and after.

Expenditures for own-account software are measured as the sum of production costs, which include wage and non-wage employee compensation; the costs of intermediate inputs;

[1] See: Bureau of Labor Statistics, Producer Price Index by Industry: Software Publishers: Software Publishing, Except Games [PCU5112105112105], https://fred.stlouisfed.org/series/PCU5112105112105.

Figure 5
Current Software Investment Price Index



Source: Bureau of Economic Analysis

and a BEA-derived measure of capital services including depreciation. Own-account software does not include the development of software from which copies are made for sale or incorporated into other products, such as motor vehicles or appliances. Such software is included in research and development (R&D).

The estimates of wages for all years are derived by multiplying the number of own-account programmers and systems analysts in selected industries times the wage rate in those industries. Wages are reduced by half under the assumption that these own-account programmers and analysts spend only about half their time working on the development of new or enhanced software.

The estimates of nonwage compensation are based on relationships between wage and nonwage compensation derived from NIPA data by industry. The estimates of input costs are based on relationships between intermediate inputs and compensation that are derived primarily from the Census Bureau's Economic Census. The estimates of real expenditures for own-account software are derived by deflation, using the BEA price index for custom software.

II.2. Framework for Software Price Index Alternative

While the ultimate implementation of an improved or replaced software price index requires the use of detailed data series with backward compatibility, it is useful to begin with a view of a framework of current and future software production. The framework permits an assessment of existing data sources and gaps to be filled.

Figure 6 provides a view of the labor and capital services in the software production function and the end-use markets. The structure suggests a two-sector model with an upstream software development sector and a downstream software producing sector (See Corrado, Haskel and Jona-Lasinio 2021 and Oliner and Sichel 2002 for treatment of two-sector models). The rows in the table describe the range of software delivered. Most business sector ICT organizations are focused on producing applications shown in the top half of the figure. Software development organizations or software vendors, more limited in number, are focused on delivering the software applications, tools, and data management capabilities shown in the bottom of the figure. Each software vendor has a taxonomy of offerings that will appear similar to the bottom portion of Figure 6. The ICT organizations investing in applications – in the top half - require the output delivered by software vendors – shown in the bottom half - as an input to their production function.

In contrast to currently published price and spending data, whether an application is delivered to the desktop, or a mobile device, is of lesser importance. Most applications are delivered with three interfaces – desktop (on-the-glass), mobile, or application programming interfaces (APIs).

The columns of Figure 6 describe the ICT production function inputs. The breath of inputs has expanded over the most recent two decades. Current estimation methods largely focus on columns 1, 4, 6, and 8 in Figure 6. In the past, most software was produced with operating systems and tools, the rights to which were acquired with an annual license or a one-time fee. Computing and storage resources have generally been on the user's premise, and labor services – whether internal to the user organization or on a contract basis – were domestic U.S. resources.

Over the past two decades advances in ICT have provided a broader range of options permitting new approaches to application development. Software inputs can continue to be acquired with an annual license or a one-time fee and can also be acquired on a transaction basis with per-use payments. In addition, open-source software is available at no cost to users.[2]

As with the expanding range of software inputs, computing and storage resources have also expanded in recent years. Cloud services permit a greater range of flexibility in managing expense and the provisioning of available resource as scale and complexity requires. The expense is typically – though not always – an operating expense, permitting improved marginal cost management.

Very nearly all software production requires labor input. The effort typically requires

[2] Despite the availability of open-source software to user organizations at no cost, from a broader social perspective such software should not be regarded as free. Much like internet search or mobile phone banking apps, significant resources are committed to open-source software development and maintenance. Largely, the development and maintenance are provided on a volunteer basis, either with developer's leisure time or donated time by the software development sector. There is also legal review necessary to ensure that such software does not contain copyright materials.

Figure 6
Framework for Software Price Alternative

		Software			Computing and Communications		Labor Services	Imports of Services	Other Capital Services
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Software Products	License	SaaS	Open Source	On Premise	Cloud	—	—	—
Business Sector									
	Cross-Industry								
	Vertical Industry								
	Other								
Software Sector									
	Operating Systems								
	Database Management								
	Development Tools								
	Other								

developers and consultants, who understand business processes and/or consumer applications, along with - in recent years - data scientists. Such talent and skill can be acquired internally – own-account – or externally – through custom engagements. Both ICT internal teams and external teams are located domestically in the U.S.

Over the last 15 years, imported services have been a meaningful source of expense reduction for software production. These services consist of software, including end-user licenses and customization; cloud computing and data storage services; consulting and implementation services; and facilities management services; and data recovery services.

II.3. Software Spending and Price Index Model

In modeling productivity and prices across two sectors, the business sector and the software development sector, each produce output in a competitive market. However, the software development sector is an upstream sector with its output sold to the downstream sector - the ICT function of business organizations. The ICT function competes for resources in competitive markers but provides output to internal users. Both sectors produce output – software solutions – with inputs consisting of software - license, as-a-service, and open source; systems hardware –computing, storage, and communications – delivered either on premise or as a cloud service; labor services – software developers, data scientists, and others; and other capital services - office space and other support. The functional form of the production function and productivity equations will be identical for both sectors with notation simplified for ease of exposition.

$$Q_t = F(S_t, SS_t, CP_t, CL_t, CM_t, L_t, OC_t, IS_t, z_t) \quad (2)$$

$Q_t =$ Software units produced at time t

$S_t =$ Software capital service consumed at time t

$SS_t =$ Software-as-a-Service consumed at time t

$CP_t =$ Computing and storage capital services consumed at time t

$CL_t =$ Cloud computing services consumed at time t

$CM_t =$ Communications capital services consumed at time t

$L_t =$ Labor hours at time t

OC_t= Other Capital services at time t

IS_t= Imported services at time t

$z_t =$ MFP at time t

Each factor input in equation (2) has an associated price. However, there are a variety of factor prices. The quantity of capital services – computing, communications, software, and other capital – has a corresponding capital services price. Factor inputs that are purchased as intermediate services – cloud computing and software-as-a-service – have a transaction price. Open-source software has a zero price. Labor services have wages and employee benefit rates. And, imported services have an import price.

The capital services price associated with the quantity of capital services is often referred to as the rental price or the user cost of capital (See Jorgenson, Ho, and Stiroh 2005, pp. 154-155 for more detail). In equilibrium, ignoring uncertainty and adjustment costs, investors – e.g. corporate parents or venture capital providers – are indifferent between earning a nominal rate of return from an investment alternative or buying a unit of capital – in this case computing equipment or software – collecting a rental price, and then selling the depreciated asset in the next period. Such a decision criteria implies the following:

$$(1 + i_{t+1})P_{ac,t} = c_{k,t+1} + (1 - \delta_k)P_{ac,t+1}$$

where i_{t+1} is the nominal interest rate, $P_{ac,t}$ is the acquisition price of capital, $c_{k,t}$ is the rental fee, and δ_k is the economic depreciation rate.

If $c_{k,t}$ = $P_{ac,t}$ and $\pi_{ac,t} = \frac{P_{ac,t}}{P_{ac,t-1}} - 1$, the inflation rate, then

$$P_{ac,t} = \left(i_{ac,t} - \pi_{ac,t}\right)P_{ac,t-1} + \delta_k P_{ac,t} \qquad (3)$$

$P_{ac,t}$ is used for the capital asset prices – software (S), computing (CP), and communications equipment (CM), and other capital (OC). Transaction prices are used for software-as-a- service

(SS) and cloud computing (CL). Assume perfect competition, constant returns to scale, profit maximization and no adjustment costs, the prices for the associated services are:

$$p_t^s = P_t\left(\frac{\partial F_t}{\partial S_t}\right) \qquad (4)$$

$$p_t^{ss} = P_t\left(\frac{\partial F_t}{\partial SS_t}\right) \qquad (5)$$

$$p_t^{cp} = P_t\left(\frac{\partial F_t}{\partial CP_t}\right) \qquad (6)$$

$$p_t^{cl} = P_t\left(\frac{\partial F_t}{\partial CL_t}\right) \qquad (7)$$

$$p_t^{cm} = P_t\left(\frac{\partial F_t}{\partial CM_t}\right) \qquad (8)$$

$$w_t^{oa} = P_t\left(\frac{\partial F_t}{\partial L_t^{oa}}\right) \qquad (9)$$

$$p_t^{OC} = P_t\left(\frac{\partial F_t}{\partial OC_t}\right) \qquad (10)$$

$$p_t^{IS} = P_t\left(\frac{\partial F_t}{\partial IS_t}\right) \qquad (11)$$

Following Oliner and Sichel (2002) Appendix A, totally differentiate (2), divide by ∂t and Q_t and substitute (4) to (11) with

$\dot{Z}_t = \frac{\partial Z_t}{\partial t}\frac{1}{Z_t}$ and β^i is cost share

where $\dot{Z}_t$is $\dot{S}_t,\ S\dot{S}_t, C\dot{P}_t, C\dot{L},\ C\dot{M}_t, \dot{L_t}, O\dot{C}_t, I\dot{S}_t$, and $M\dot{F}P_t$.

$$\dot{Q}_t = \beta^s\dot{S}_t + \beta^{SS}S\dot{S} + \beta^{CP}C\dot{P}_t + \beta^{CL}C\dot{L}_t + \beta^{CM}C\dot{M}_t + \beta^L\dot{L_t} + \beta^{OC}O\dot{C}_t + \beta^{IS}I\dot{S}_t + M\dot{F}P_t \qquad (12)$$

The output change is the weighted average of the change in resources consumed and gains from multifactor productivity (MFP). Subtracting $\dot{L_t}$ from both sides yields labor productivity (LP)

$$\dot{LP_t} = \dot{Q}_t - \dot{L_t} = \beta^s \dot{S}_t + \beta^{SS} \dot{SS}_t + \beta^{CP} \dot{CP}_t + \beta^{CL} \dot{CL}_t + \beta^{CM} \dot{CM}_t + (\beta^L - 1)\dot{L_t} + \beta^{OC} \dot{OC}_t + \beta^{IS} \dot{IS}_t + \dot{MFP}_t \qquad (13)$$

Solve for $\dot{MFP}_t$

$$\dot{MFP}_t = \dot{LP}_t - [\beta^s \dot{S}_t + \beta^{SS} \dot{SS}_t + \beta^{CP} \dot{CP}_t + \beta^{CL} \dot{CL}_t + \beta^{CM} \dot{CM}_t + (\beta^L - 1)\dot{L_t} + \beta^{OC} \dot{OC}_t + \beta^{IS} \dot{IS}_t] \quad (14)$$

For the software development sector, labor productivity is

$$\dot{LP}_{ss,t} = \beta^S_{ss,t} \dot{S}_{ss,t} + \beta^{SS}_{ss,t} \dot{SS}_{ss,t} + \beta^{CP}_{ss,t} \dot{CP}_{ss,t} + \beta^{CL}_{ss,t} \dot{CL}_{ss,t} + \beta^{CM}_{ss,t} \dot{CM}_{ss,t} + (\beta^L_{ss,t} - 1) \dot{L}_{ss,t} + \beta^{OC}_{ss,t} \dot{OC}_{ss,t} + \beta^{IS}_{ss,t} \dot{IS}_{ss,t} + \dot{MFP}_{ss,t} \qquad (15a)$$

For the business sector ICT function, labor productivity is

$$\dot{LP}_{ICT,t} = \beta^S_{ICT,t} \dot{S}_{ICT,t} + \beta^{SS}_{ICT,t} \dot{SS}_{ICT,t} + \beta^{CP}_{ICT,t} \dot{CP}_{ICT,t} + \beta^{CL}_{ICT,t} \dot{CL}_{ICT,t} + \beta^{CM}_{ICT,t} \dot{CM}_{ICT,t} + (\beta^L_{ICT,t} - 1) \dot{L}_{ICT,t} + \beta^{OC}_{ICT,t} \dot{OC}_{ICT,t} + \beta^{IS}_{ICT,t} \dot{IS}_{ICT,t} + \dot{MFP}_{ICT,t} \qquad (15b)$$

For the software development sector, multifactor productivity is

$$\dot{MFP}_{ss,t} = \dot{LP}_{ss,t} - [\beta^S_{ss,t} \dot{S}_{ss,t} + \beta^{SS}_{ss,t} \dot{SS}_{ss,t} + \beta^{CP}_{ss,t} \dot{CP}_{ss,t} + \beta^{CL}_{ss,t} \dot{CL}_{ss,t} + \beta^{CM}_{ss,t} \dot{CM}_{ss,t} + (\beta^L_{ss,t} - 1) \dot{L}_{ss,t} + \beta^{OC}_{ss,t} \dot{OC}_{ss,t} + \beta^{IS}_{ss,t} \dot{IS}_{SS,t}] \quad (16a)$$

For the business sector ICT function, multifactor productivity is

$$\dot{MFP}_{ICT,t} = \dot{LP}_{ICT,t} -$$

$$[\beta^{S}_{ICT,t}\dot{S_{ICT,t}} + \beta^{SS}_{ICT,t}\dot{SS_{ICT,t}} + \beta^{CP}_{ICT,t}\dot{CP_{ICT,t}} + \beta^{CL}_{ICT,t}\dot{CL_{ICT,t}} + \beta^{CM}_{ICT,t}\dot{CM_{ICT,t}} +$$

$$\beta^{OC}_{ICT,t}OC_{ICT,t} + \dot{\beta}^{IS}_{ICT,t}\dot{IS_{ICT,t}} + \left(\beta^{L}_{ICT,t} - 1\right)\dot{L_{ICT,t}}] \quad (16b)$$

With estimates of MFP available, the dual approach can be used to estimate software price changes. The dual of profit maximization is cost minimization. The dual approach provides a shadow price and imputes value to the utilization of scarce resources with no accounting loss. Thus,

$$Lo_{ICT,t} = C_{ICT,t}\left(S_{ICT,t}, SS_{ICT,t}, CP_{ICT,t}, CL_{ICT,t}, CM_{ICT,t}, L_{ICT,t}OC_{ICT,t}, IP_{ICT,t}, z_{ICT,t}\right) -$$

$$P_{ICT,t} = 0 \quad (17)$$

$Lo_{ICT,t}$ = Accounting Loss to be Minimized

$C_{ICT,t}$ = Cost function of the software function

$P_{ICT,t}$ = Price of software function

Totally differentiate (17), divide by ∂t and P_t .

Recall

$$\dot{Z}_t = \frac{\partial Z_t}{\partial t}\frac{1}{Z_t} \text{ and } \beta^i \text{ is cost share}$$

And substitute (18) to (26) into the total differential

$$\frac{\partial C_{ICT,t}}{\partial S_{ICT,t}} = \dot{p^{S}_t} \quad (18)$$

$$\frac{\partial C_{ICT,t}}{\partial SS_{ICT,t}} = \dot{p^{SS}_t} \quad (19)$$

$$\frac{\partial C_{ICT,t}}{\partial CP_{ICT,t}} = \dot{p^{CP}_t} \quad (20)$$

$$\frac{\partial C_{ICT,t}}{\partial CL_{ICT,t}} = \dot{p^{CL}_t} \quad (21)$$

$$\frac{\partial C_{ICT,t}}{\partial CM_{ICT,t}} = \dot{p_t^{CM}} \quad (22)$$

$$\frac{\partial C_{ICT,t}}{\partial L_{ICT,t}} = \dot{p_t^{L}} \quad (23)$$

$$\frac{\partial C_{ICT,t}}{\partial OC_{ICT,t}} = \dot{p_t^{OC}} \quad (24)$$

$$\frac{\partial C_{ICT,t}}{\partial IS_{ICT,t}} = \dot{p_t^{IS}} \quad (25)$$

$$\frac{\partial C_{ICT,t}}{\partial z_{ICT,t}} = -1 \quad (26)$$

Yields ICT price equation

$$\dot{P_{ICT,t}} = \dot{p_t^{S}}\beta_{ICT,t}^{S} + \dot{p_t^{SS}}\beta_{ICT,t}^{SS} + \dot{p_t^{CP}}\beta_{ICT,t}^{CP} + \dot{p_t^{CL}}\beta_{ICT,t}^{CL} + \dot{p_t^{CM}}\beta_{ICT,t}^{CM} +$$

$$\dot{p_t^{L}}\beta_{ICT,t}^{L} + \dot{p_t^{OC}}\beta_{ICT,t}^{OC} - MF\dot{P}_{ICT,t} \quad (27)$$

III. Software Developer Labor Productivity

To estimate the software price index, equation (27), not only are resource prices, factor shares, and cost shares required but an estimate of MFP is also necessary. From equations (14) and (27), an estimate of either LP or MFP is necessary. The approach is to estimate LP and subsequently estimate MFP (equation 14) and then the price index (equation 27).

III.1. Measuring Software Developer Productivity

As with all measures of labor productivity, the volume of output per unit of labor is calculated. For four decades one widely used measure of software developer output has been the function point, originally defined by Albrecht (1979). Function point methodology is asserted to be

> ….. the most accurate approach available for determining software size. Traditionally, function point counting is done by trained, certified function point counters. Function points are a unit of measure used to define the value that the end user derives, or the functional business requirements the software is designed to accomplish. Each application has a specific number of function points, which are used to benchmark cost and productivity or development and maintenance activity.[3]

In recent years, automated function point counting has emerged using static analysis to reverse engineer the application architecture and data model.

Function point data are collected by the International Software Benchmarking Standards Group (ISBSG) including data on 10,600 software development projects. The projects have been

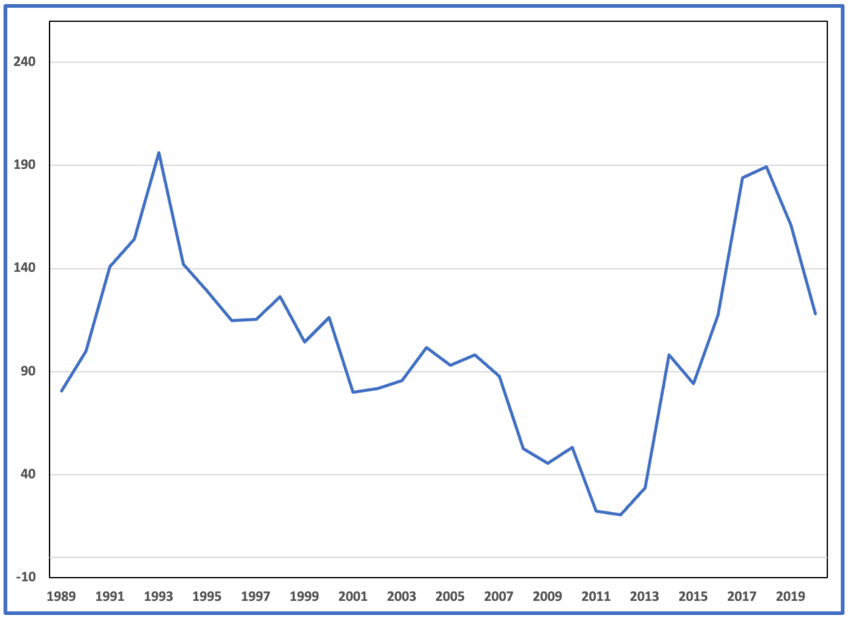
[3] https://www.castsoftware.com/glossary/function-point-counting

submitted by corporate organizations as well as industry associations from more than 26 nations. Most submissions are from developed economies with submissions also from Mexico, India, and China. As expected, most projects are in the communications; banking, financial services, and insurance; and government sectors. With projects also in manufacturing; medical and health care; and electronics and computer sectors. Projects are largely enhancement projects with new developments consisting of slightly more than a quarter of the total and with maintenance projects excluded. Nearly all projects are developed for internal use with slightly less than a third developed in-house – own-account – the remainder outsourced – custom projects. Most projects report using a waterfall method in which a sequential development process requires that each phase is completed before the next phase begins. Other methodologies include agile, joint application development, rapid application development, multifunctional teams, and timeboxing (See ISBSG 2021a).

The project data covers the period 1989 to 2020. Data elements include function point count, development team full-cycle work effort, and productivity delivery rate. The productivity delivery rate, measured in hours per functional size unit, is calculated from work effort for the development team divided by functional size (ISBSG 2021b). The productivity delivery rate is the inverse of labor productivity.

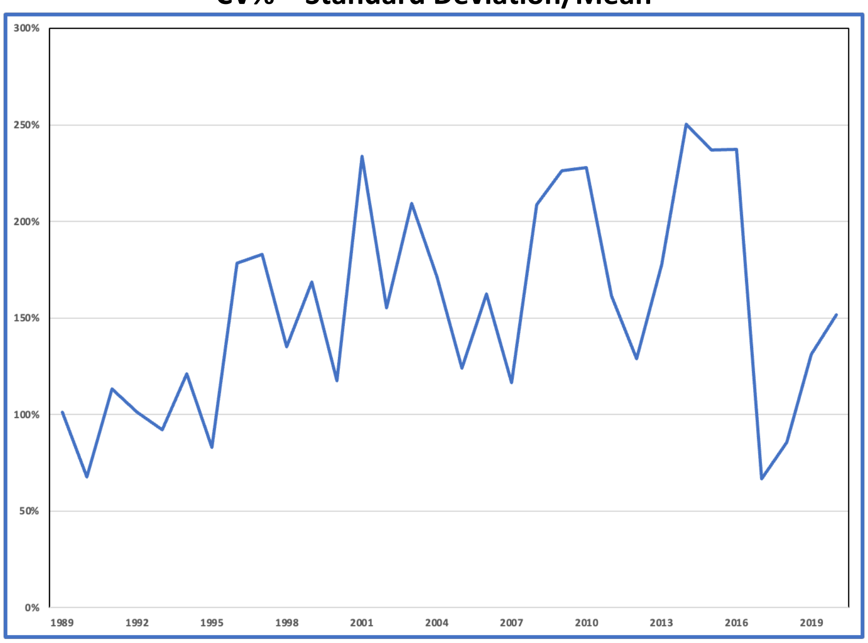
Figure 7 shows the resulting software developer productivity data. Clearly, the productivity level declines over the period from 1993 to 2012 with productivity rising thereafter. A ten-year falling productivity level seems questionable as a functional and industry trend. Figure 8 shows the coefficient of variation (CV) for each year. Generally, a CV less the 10% is considered very good, 10% - 20% is good, 20% - 30% is acceptable, and CV>30% is not

Figure 7
Software Developer Productivity Index
1990 = 100



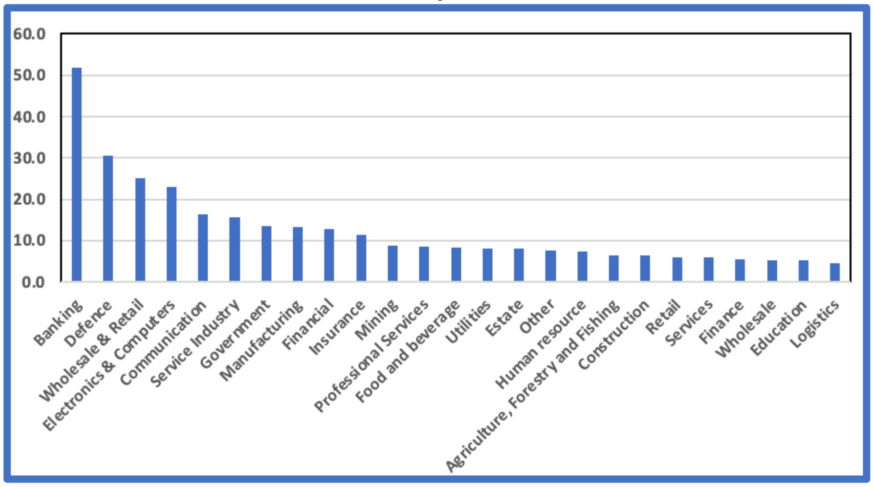
Source: International Software Benchmarking Standards Group (ISBSG)

Figure 8
Annual Coefficient of Variation
CV% = Standard Deviation/Mean



Source: International Software Benchmarking Standards Group (ISBSG)

Figure 9
Productivity Delivery Rate
Industry Mean



The productivity delivery rate, measured in hours per functional size unit, is calculated from work effort for the development team divided by functional size. The functional size is the cumulative function points, a unit of measure used to define the value that the end user derives, per project. Source: International Software Benchmarking Standards Group (ISBSG)

acceptable. The figure shows CVs for many years well more than 100%. Finally, Figure 9 shows industry averages which also shows wide variation across industries. Such variation is also a questionable result, as successful development methods can and do easily diffuse across industries. Notwithstanding unique industry circumstances and challenges, smaller differences across industries are expected.

The notion that an important and substantial segment of the U.S. and global economy would experience a declining level of productivity over an extended period seems unlikely. Market forces – both competitive conditions and the need to deliver profitability – make such an outcome unlikely. Such a result, as shown in Figure 7, calls in to question the measurement of productivity, the focus at the project level, the function point method, and the development team measurement.

In fact, wide productivity variation at the project level is not surprising. Shrikanth, Nichols, Fahid, and Menzies (2021) find substantial heterogeneity among developers and development teams. In a review of the recent computer scientist literature, Shrikanth, et. al. write: "…..researchers acknowledge the widely held belief that some good developers are much better (almost 10X) than many poor developers" (page 5 of 32). Further, observing that individual developer performance varies considerably, developers who are productive in one task may not be as productive in another task. Importantly, Shrikanth, et. al. find "quality entails productivity." They write "…on-time delivery is achieved with a quality-driven focus" (page 28 of 32).

With the introduction of agile and devops methods, quality has been the focus in the application of labor services, significantly transforming software development in recent years. Most enterprises use either or both approaches. See Figure 10. For both approaches, data are collected, most often with the use of third-party tools, for developer time, task completion, and other productivity metrics. The software development methods shown in Figure 10 are deployed by internal development teams – own-account – external development teams - custom development, and in the business sector as well as the software development sector.

Agile methods are an iterative approach that places primary focus on collaboration, customer feedback, and small, rapid software releases. Built around one- or two-week sprints, small teams manage projects in scrums that encourage learning through experience. Agile

Figure 10
Software Development Methods

	Customer Software Requirements	Gap	Developer and Tester	Gap	IT Operations and Infrastructure
Agile Methods	Iterative approach focuses on customer collaboration	Agile methods addresses fast changing and evolving requirements	Small teams with members having similar skills	-----	Emphasis on development methods with handoff to operations
DevOps	DevOps takes software ready for release and deploys in a reliable and secure manner	-----	Larger teams across stack holders with skill set between the development and operations	Deliver code to production daily or every few hours to achieve constant operational scale	Manage end-to-end engineering processes with focuses on constant testing and delivery

Source: https://www.guru99.com/agile-vs-devops.html

methods help to manage complex projects where customer needs are evolving and feedback is important. Teams are small and team members have similar and equal skills. Emphasis is on fast turnaround and timely delivery. JIRA, Bugzilla, and Kanboard are popular Agile tools that track projects and effort. Atlassian and Amazon Web Services (AWS) are prominent tool providers.

DevOps is a software development method, bringing development and IT operations teams together with a focus on communication and collaboration enabling rapid deployment. The central concept is managing end-to-end engineering processes with constant testing and frequent delivery. The goal, in a software-as-a-service environment, is to deliver code to production daily or every few hours. Automation is the primary objective. DevOps teams are often large with skills spread between development and operations, across all IT stack elements. Feedback comes from the internal team. Developing, testing and implementation are all equally important. Puppet, Chef, TeamCity OpenStack, AWS are popular DevOps tools and a potential data source.

To the extent software developers are more productive as a result of the application of agile and devops methods, economists would measure such benefit as multifactor productivity (MFP). The value creation is realized with the application of little or no incremental resource. Recognizing that some limited support resource is likely required as the agile and devops methods are deployed and developers are trained, only very limited additional systems or software resource are required, delivering MFP gains.

III.2. Software Sector Productivity

As with most goods and service providers, software development sector firms have well-established standards for consistent quality. In part, quality standards are achieved in the management of critical functions and the interface between such functions. In the software development sector, research, product development, and production are among the most critical. Setting and achieving quality standards from the development process' beginning and throughout the product life cycle can improve developer productivity. In addition, as software development sector firms compete, market feedback and customer purchases made, or not made, provide important market disciple. As freestanding entities, software development sector firms - some long established and others in early stages of life - have senior corporate leaders providing leadership and guidance. Software development sector firms with delivery and go-to-market teams are well structured to provide consistent quality solutions and service, developing continuously improving developer productivity.

However, internal functions, such as business sector ICT functions, are generally not as well structured to smooth productivity noise and random events. By definition, such organizations are removed from market disciple, often supporting units who in turn engage in customer contract. However, very often business sector ICT functions serve units who, provide a clear set of requirements based on internal needs, but lack customer contact – e.g. human resources and finance. In such circumstances, market disciple is difficult to achieve. While agile methods and devop processes can be helpful, ICT units are frequently buffeted by changing requirements and misunderstood needs. Consequently, achieving consistent productivity improvement requires other means.

With the challenges faced by ICT functions, software development sector productivity is increasingly representative of developer productivity in business sector ICT functions generally. The business sector ICT functions are (1) customizing software-as-a-service offerings with the development having been completed by software development sector firms; (2) focused on the time it takes to run an application, as opposed to the time it takes to develop an application; and (3) building relationships with software development sector firms just as some R&D teams engage with scientific R&D firms.

Software development in the post-Moore's law era has generally focused on minimizing the time it takes to **develop an application**, rather than the time it takes to **run the application** once it is deployed. Increasingly, however, software developers in the ICT function are engaged in performance engineering, collaborating with hardware architects so that new processors present simple and compelling abstractions that make it as easy as possible to exploit hardware (See Leiserson, Thompson, Emer, Kuszmaul, Lampson, Sanchez, and Schardl 2020).

Leiserson et. al. suggest that as hardware has become increasingly specialized and heterogeneous, high-performing code has become even more difficult to write. Consequently, software sector developers - more highly trained and with application specific skills – have taken on more of the development burden. Because faster software has become increasingly important, Leiserson et. al. also suggest various segments of the technology industry have been motivated to develop performance-engineering technologies. Algorithmic advances have already made contributions to performance growth and will continue to do so. A major goal is to solve a given problem with less computational work.

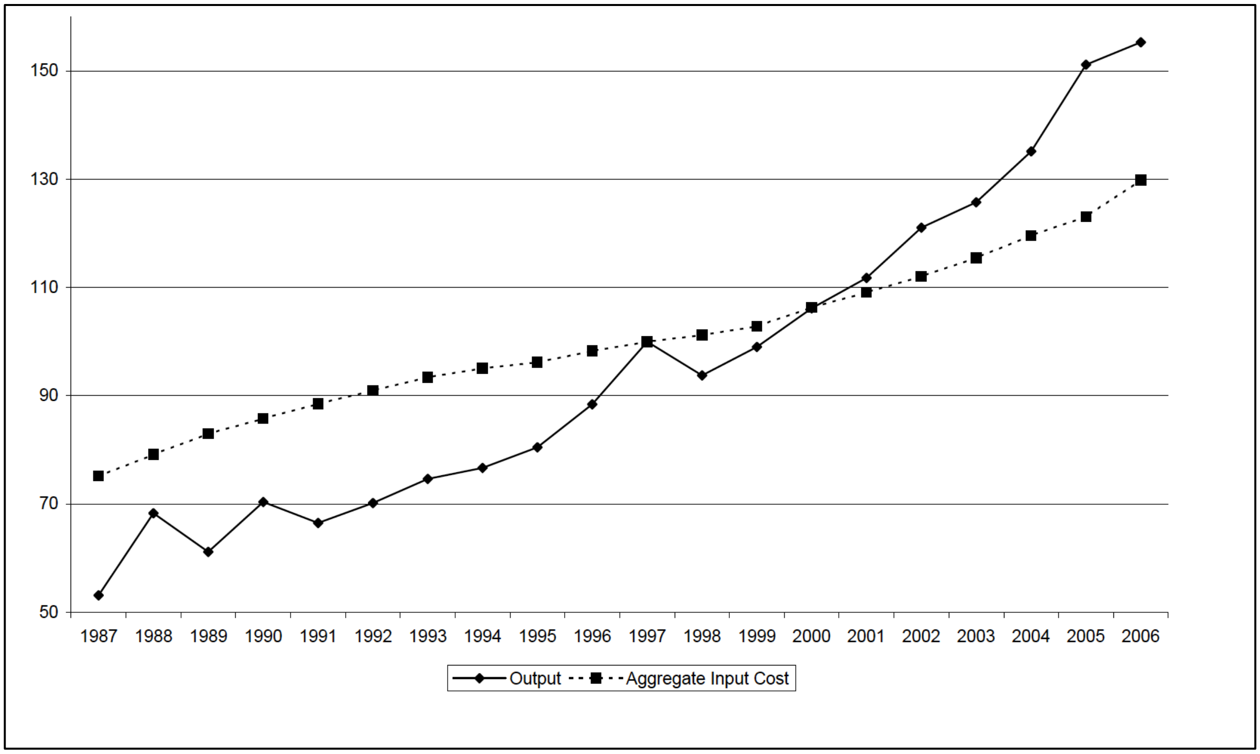
With domain specialized hardware, applications are enabled to run tens to hundreds of times faster. For example, Graphics-Processing Units (GPUs) were originally developed for rendering graphics. However, the use of GPUs has broadened for a variety of nongraphical tasks, such as those that are linear algebra intensive. Because they are capable of training large neural networks that general-purpose processors could not train fast enough, GPUs are crucial for linear algebra intensive "deep-learning" models. In addition, Google has developed Tensor-Processing Units (TPUs) specifically for deep learning. Software sector developers, who play a large and growing role in application development, hand off completed solutions to ICT developers in the business sector. See Figure 4.

Analogous to the insight provided by the software sector in gaining a view of software developer productivity, Copeland and Fixler (2009) develop a framework for a view that the scientific R&D services sector provides for internally provided R&D activity. It is the use of a market facing sector to develop an understanding of how an internal organizational function is likely influenced by an external sector. Not only is the scientific R&D sector market facing, but knowledge is defused and then absorbed, and skilled workers move from sector to sector. Much like the software development sector, the scientific R&D services sector provides innovation to the broader business sector, providing a means to discover both R&D services productivity and prices. Copeland and Fixler suggest that unlike industries such as pharmaceutical or semiconductor manufacturing, where R&D is undertaken largely internally, scientific R&D services “provide a clean look at the production of innovation” (Page 1). Over the period 1987 to 2006, Copeland and Fixler estimate labor productivity in the scientific R&D services sector increased at an average annual rate of 1.5%.

Based on a model of innovation, Copeland and Fixler develop a framework for constructing an R&D output price index. They show that the price of innovation is equal to the expected discounted profit stream attributable to the adoption of the innovation. The estimates show R&D output prices increased at an annual average rate of 5.8% from 1987 to 2006. Using the R&D service firm’s output price index, nominal scientific R&D services revenues are deflated and find that real revenues grew at an average rate of 2.6%. By contrast, the traditional input-price approach - largely R&D worker wage rate growth - shows a price increase of 2.9%. See Figure 11. Price increases based on R&D worker wage rate growth fails to capture productivity gains and incremental R&D services firm’s value creation.

By comparison, deflating total R&D nominal expenditures with two price indexes; the output-based price index for the portion of total R&D expenditures from scientific R&D services (25%) and an aggregate input-cost price index for the remainder of R&D expenditures (75%), Copeland and Fixler find that real total R&D expenditures grew at an average annual rate of 1.4% compared with 2.6% in published data. Using an aggregate input-cost price index

Figure 11
Research and Development Price Indexes
1997 = 100



Source: Copeland and Fixler (2009)

understates R&D price growth for scientific R&D services and, thus, over states real growth. If the scientific R&D sector performance is representative of the functioning of the broader business R&D function, the 1.2 percentage point growth rate differential leads to substantial mismeasurement of R&D growth which would be weaker in real terms that reported. Such a finding is the reverse of the hypothesized issue in the software development space.

III.3. Software Sector Labor Productivity

From the Census Bureau's Quarterly Service Survey, dollar value of output is available. Three sectors are included in the definition of the software development sector – NAICS 5112 Software Publishers; NAICS 5182 Data Processing, Hosting, and Related Services; and NAICS

5415 Computer Systems Design and Related Services. Each is deflated with a price index based on BLS PPI series. The result is chained dollar gross output - a measure of software sector real revenue.

In addition, the Occupational Employment and Wage Statistics (OEWS) program of the BLS produces employment and wage estimates annually for nearly 800 occupations. At the national level, occupational estimates for specific industries are available.[4] For the industries of interest, consistent occupation data are available from 2002 to 2020. Two occupations are of interest. Computer and mathematics occupations in the defined software development sector is the most comprehensive measure of employment, consisting of software developers, programmers, testers, information analysts, research scientists, support specialists, administrators, architects, data scientists and mathematicians. Figure 12 provides a view of employment for the software sector. In addition, the important sub-category - software developers, programmers, and testers - are also of interest. Figure 13 shows chained dollar gross output across NAICS 5112, 5182, and 5415 grows faster than developer population after 2015. The preceding five years from 2010 to 2015 output growth matched developer population growth. See Figure 14 for a summary of the productivity data sources.

Software developer productivity, shown in Figure 15, generally improved across recent decades. Improvement stagnated after 2008 – 2010 Great Recession - when the developer population declined at a 2.2% annual rate while real software sector output rose at a 4.5% annual rate. Following the recession from 2011 to 2016 developer population increased at a 6.3% annual rate while real software sector output rose at a 6.0% annual rate.

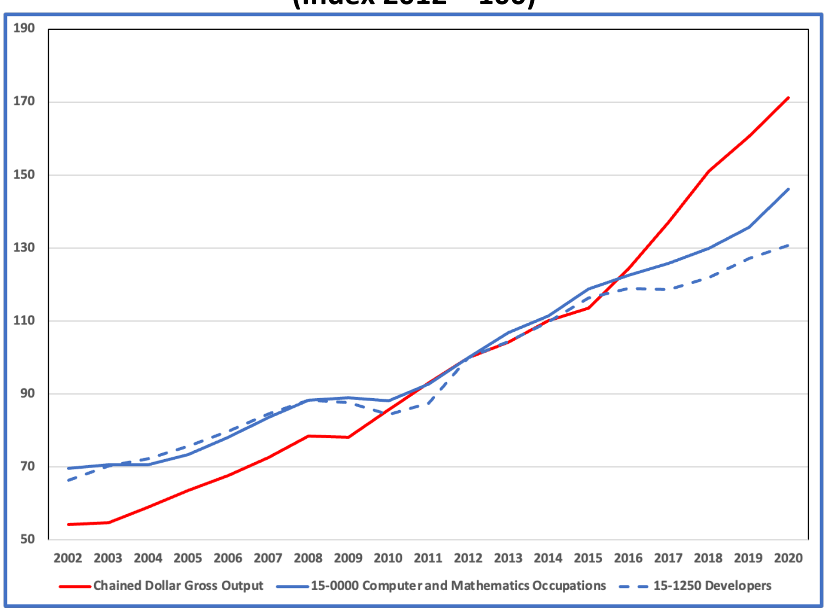
[4] See: https://www.bls.gov/oes/oes_emp.htm#scope

Figure 12
Software Development Sector Employment
By Four-Digit Industry
Computer and Mathematical Occupations
2020

Industry Code	5112 Software Publishers	5182 Data Processing, Hosting, and Related Services	5415 Computer Systems Design and Related Services
Total	240,110	150,940	1,202,310
Software and Web Developers, Programmers, and Testers	164,920	70,140	579,150
Information Analysts	14,280	15,960	193,890
Research Scientists	2,760	460	5,120
Support Specialists	32,600	24,980	191,840
Database and Network Administrators and Architects	13,530	22,470	131,980
Data Scientists and Mathematical Science Occupations	2,490	4,590	20,210
Miscellaneous Computer Occupations	9,540	12,350	80,120

Source: BLS Occupational Employment and Wage Statistics.

Figure 13
Software Development Sector
Sum of NAISC 5112, 5182 and 5415Output and Employment
(Index 2012 = 100)

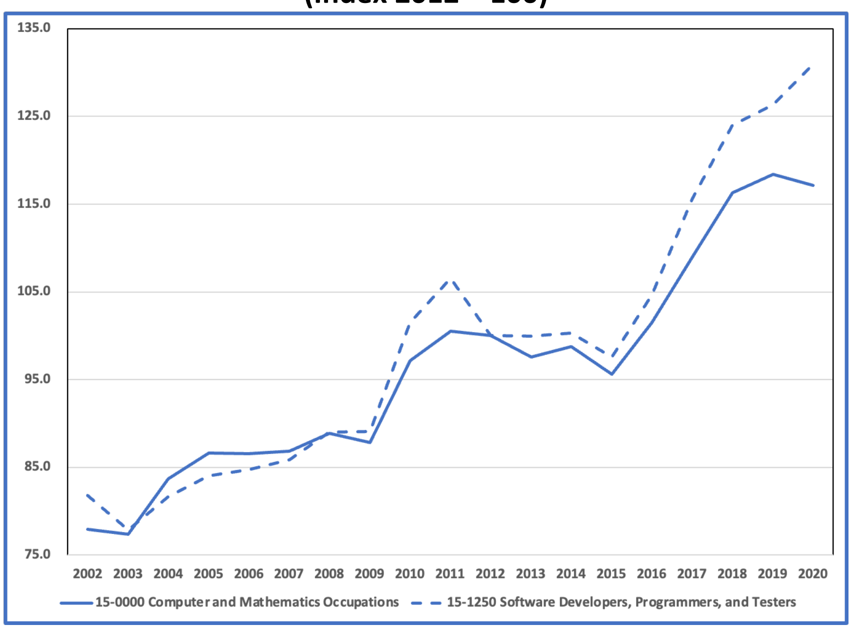


Source: Author's Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and 5415; and BLS Occupational Employment and Wage Statistics.

Figure 14
Developer Productivity Data Sources

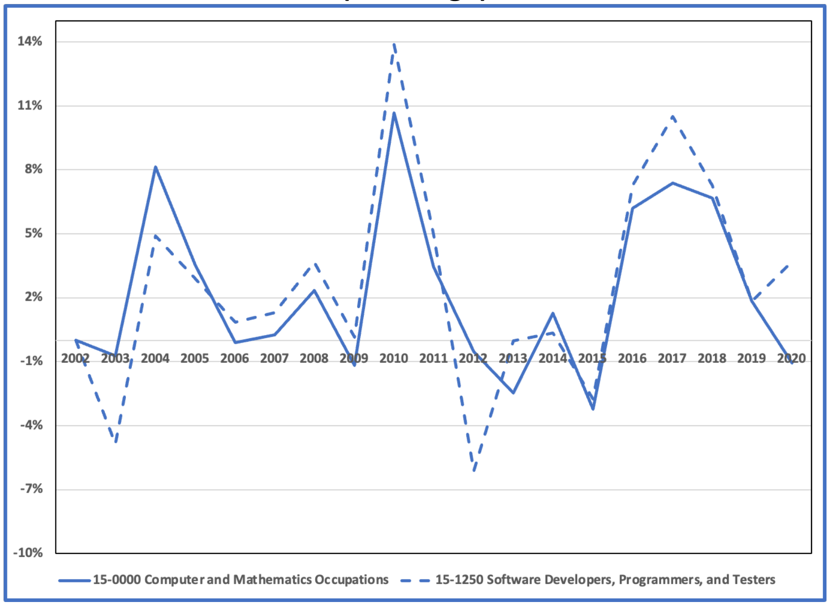
Concept	Data Element	Components	Source
Output	Chained Dollar Gross Output (Millions of 2012 Dollars)	5112 Software Publishers 5182 Data Processing, Hosting, and Related Services 5415 Computer Systems Design and Related Services	BEA
Employment	Number of Employees	15-0000 Computer and Mathematics Occupations 15-1250 Software Developers, Programmers, and Testers 15-1256 Software Systems and Application Developers	BLS OEWS

Figure 15
Software Developer Labor Productivity
Weighted by NAISC 5112, 5182 and 5415 Sector
(Index 2012 = 100)



Source: Author’s Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and 5415; and BLS Occupational Employment and Wage Statistics.

Figure 16
Software Developer Productivity
Weighted by 5112, 5182 and 5415 Sector
(% Change)



Source: Author's Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and 5415; and BLS Occupational Employment and Wage Statistics.

Figure 17
Software Sector
Developer Productivity Index
Weighted by Sector
Index 2012 = 100

	Productivity Index Weighted by Sector Index 2012 = 100	
	15-0000 Computer and Mathematics Occupations	15-1250 Software Developers, Programmers, and Testers
2002 - 2007	2.2%	1.0%
2007 - 2010	3.8%	5.7%
2010 - 2015	-0.3%	-0.8%
2015 - 2020	4.2%	6.1%

Source: Author's Calculations

Figure 16 shows developer productivity growth rates for both computer and mathematics occupations and software developers, programmers, and testers. Across the broadest developer population, computer and mathematics occupations realized an annual average productivity growth of 2.5% from 2002 to 2020. Across the narrower developer population – 51% of total - software developers, programmers, and testers realized an annual average of 3.1% productivity growth from 2002 to 2020. See Figure 17.

IV. Software Own-Account and Custom Multifactor Productivity and Price Index

The very significant transformation of ICT over the past two decades has increased the focus of both scholars and practitioners on improved measurement and work methods.[5] Based on the premise that software development sector developer productivity is a reasonable measure of business sector ICT function developer productivity, assume from equations 15a and 15b,

$$L\dot{P}_{ICT,t} = L\dot{P}_{ss,t}$$

From equation 16b, with labor productivity from the software development sector's software developers, programmers, and testers occupation yields ICT function multifactor productivity (MFP). Equation 27 provides the estimate of the ICT function shadow price index. The implementation of equations 16b and 27 requires data for factor shares, resource prices and resource compensation. Figure 18 shows the data sources used for the MFP and price equation calculations.

IV.1. Computing and Communications Usage and Prices

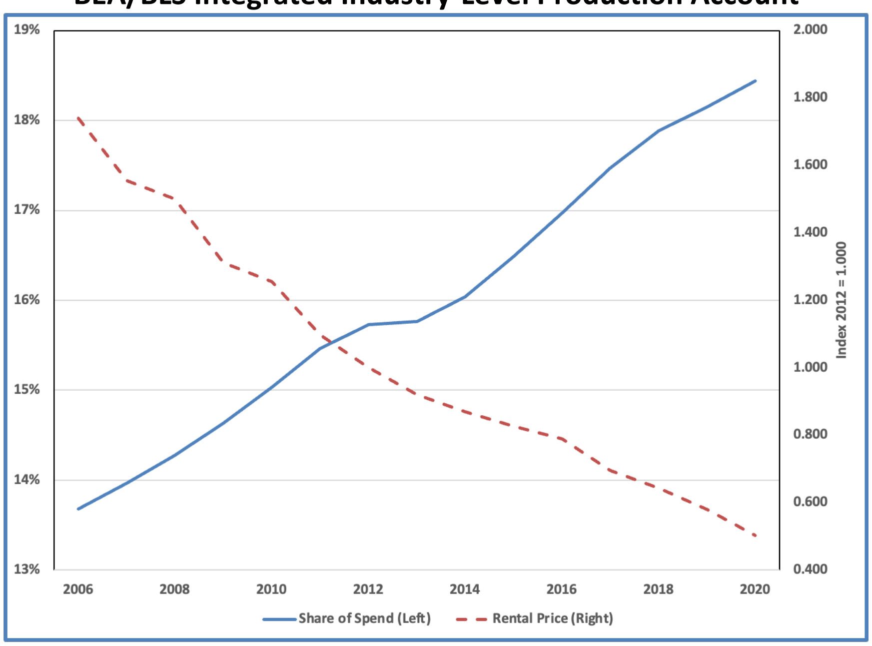
Capital services and the associated rental prices are available from the BEA's Integrated Industry-Level Production Account (KLEMS).[6] Nominal and real compensation by type of capital are reported and rental price deflators, which are the user cost of capital, are calculated. Capital rental rates are the prices that users incur to acquire services from the capital stock.

[5] In a series of papers, Byrne, Corrado and collaborators have reviewed current methods and proposed, where possible, improvements. See: Byrne and Corrado (2017a) and (2017b).
[6] https://www.bea.gov/data/special-topics/integrated-industry-level-production-account-klems

Figure 18
Multifactor Productivity and Price Equation Data Sources

Concept	Data Items	Source	Years
Communications Equipment Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Computer Equipment Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Cloud Computing Services	Real Cloud Services Gross Output	BEA Digital Economy Satellite Account	2005-2021
Cloud Computing Services	Cloud Services Price Index	Sichel (2019)	2003-2021
Software Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Open-Source Software Services	Open-Source Software % of Total	Murciano-Goroff, Zhuo and Greenstein (2021)	2000-2020
Other Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Labor Services	Software Developer and Computer Operations Employment and Wages	BLS Occupation Employment and Wage Survey	2002-2021
Imports of Services	U.S. Trade in Services, by Type of Service Telecommunications, Computer, and Information (Millions of Dollars)	BEA Digital Economy Satellite Account	1999-2021
Imports of Services	PPI Telecommunications (PCU517) PPI Computer Services (PCU5112) PPI Data Procession (PCU5182)	BLS Producer Price Index	2007-2021

Figure 19
Communications Equipment Capital Services
Rental Price Deflator and Share of Spend
BEA/BLS Integrated Industry-Level Production Account



Source: Author's Calculations and BEA Integrated Industry-Level Production Account

Figure 19 shows the rental price deflator and the share of total ICT spending for communications equipment capital services. The rental price fell 8.3% CAGR from 2007 to 2020 while the share of communication equipment services in total ICT spending rose by 4.4 percent points (ppts) from 14.0% to 18.4%.

Business sector ICT organizations have the option of acquiring computing and storage services from on-premise equipment or, as a substitute, from a cloud service provided by a third-party vendor. For on-premise computing and storage, the on-premise capital equipment provides a service and a rental rate provides a price. By contrast, cloud computing is a service sold at a market price. A third party – for example Amazon, Google, Microsoft - has acquired, deployed, and maintains the computing and storage equipment capital stock and incurs a rental rate as the cost of doing so. The user – in this case the ICT function – consumes the service and pays a market price. The contrasting computing and storage models provides similar services at competing prices.

The center of computing activity is the hyperscale cloud data center. Housing the most mission critical network equipment and systems, cloud data centers specialize in collecting, processing, storing, and sharing data.[7]

Cloud data centers rely on technologies to manage an organization's data and include servers; storage and network connectivity infrastructure; security measures and appliances; cooling, air flow, and fire protection systems; and policies to maintain efficiency, security, and performance.

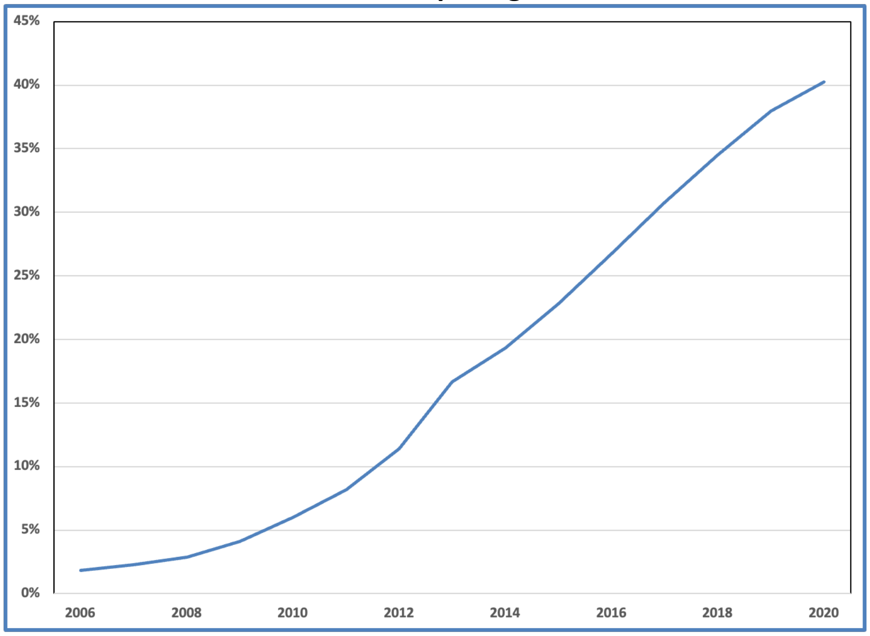
[7] Cloud computing capability is also supplemented with edge computing. New technologies, such as autonomous vehicles, generate massive data volumes, require low latency, and must provide near-real time response. Edge servers can be considered within the boundaries of the cloud data center segment.

Cloud data centers typically encompass a full building, part of a building, or for large organizations, multiple buildings where systems and data reside alongside other necessary equipment. Different tiers and standards exist, from a basic server room to a truly robust environment with fully redundant systems that can operate uninterrupted for indefinite time despite power outages.

Figure 20 shows, with data from the BEA's Digital Economy Satellite Account, cloud usage increased from one percent of total computing and storage services in 2005 to 40% in 2020. The increased usage of cloud services has not only altered the business sector computing and storage model, but it has also impacted the trend in the prices. As is well known, improvements in semiconductor technology over six decades have resulted in a continued decline in computing costs. The challenge has been, and will likely remain, quality improvements and the needed price adjustments capturing improvements.[8] However, Figure 21 suggests that the introduction of cloud services in 2006 has resulted in a new equilibrium with the rental price of on-premise computing declining at an annual rate of 7.5% between 2006 and 2012 with little change in cloud computing transaction prices. Over the period, 2016 to 2020, the rental price of on-premise computing declining at an annual rate of 10.7% while the transaction price of cloud computing and storage services declined at an annual rate of 5.4%.

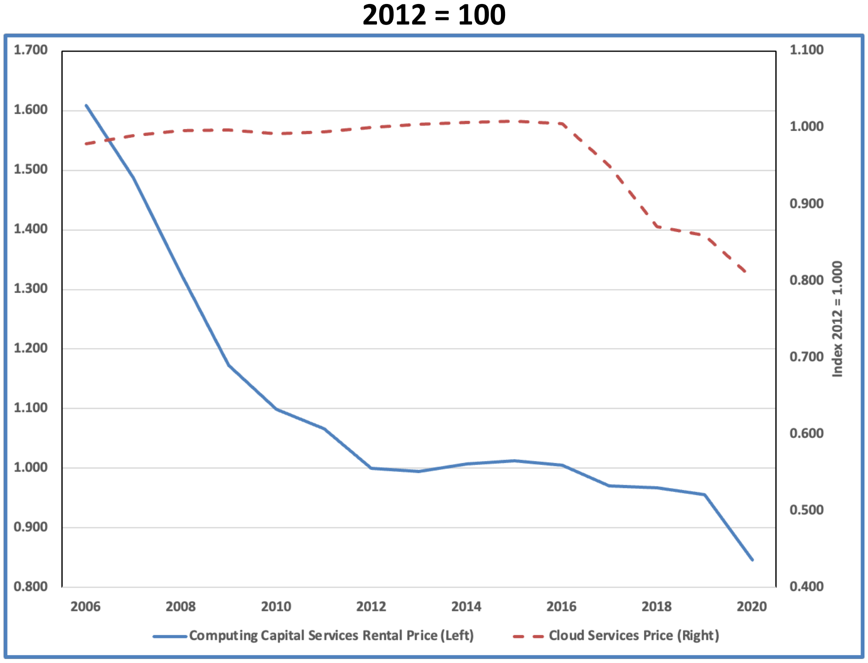
[8] See: Cole, R., Y. C. Chen, J. A. Barquin-Stolleman, E. Dulberger, N. Helvacian, and J. H. Hodge (1986). "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment", *Survey of Current Business*, 66, pp. 41-50.

Figure 20
Cloud Computing and Storage
Percent of Computing Services



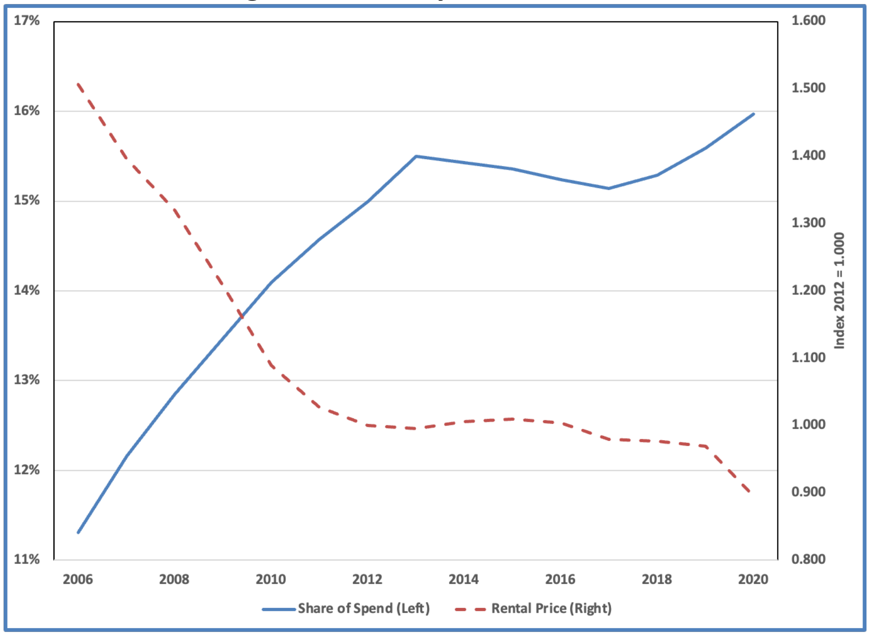
Source: Author's Calculations and BEA Digital Economy Satellite Account

Figure 21
Computing and Storage Services
Price Index
2012 = 100



Source: Author's Calculations and BEA Digital Economy Satellite Account

Figure 22
Computer and Storage Equipment Capital and Cloud Services
Price Index and Share of Spend
BEA/BLS Integrated Industry-Level Production Account



Source: Author's Calculations and BEA Integrated Industry-Level Production Account.

Figure 22 shows that share of ICT spending for computing and storage rose from 11.3% in 2006 to 15.7% in 2012 but increased to only 16.0% in 2020. The increased use of cloud services over the period, apparently, slowed computing and storage spending relative to spending for other ICT resources. The figure also shows the computing price index, including the prices of both computing equipment capital services and cloud computing, fell at an annual rate of 6.6% between 2006 and 2012 but slowed to a decline of 1.4% over the sequent eight years. The adoption of cloud services for a wider set of applications between 2012 and 2020 resulted in much slower price declines.[9]

[9] An issue for future research is whether the slower decline in prices reflect the limits of semiconductor technology or strong demand for cloud computing services.

Figure 23 shows the rental price deflator and the share of total ICT spending for other capital services. In contrast to other resource services, the rental price index rose 2.2% CAGR from 2006 to 2019 and fell by 6.8% in 2020. Not surprisingly, the share of other capital services fell by 4.4 ppts from 8.1% to 3.7% over the 2006 to 2020 period. From the BEA Integrated Industry-Level Production Account, 1% of other capital services are assumed to support, the ICT function.

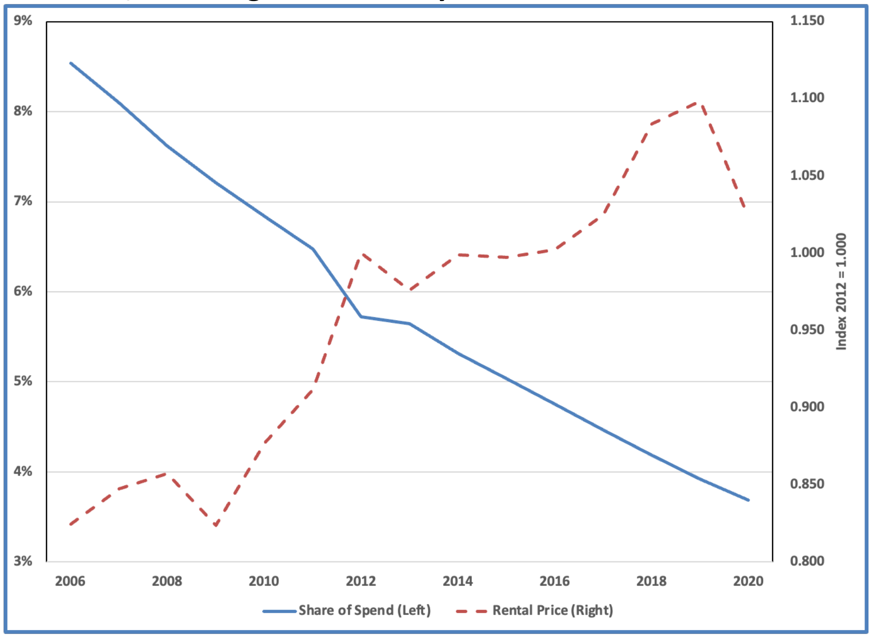
IV.2. Software Usage and Prices

Like the transformation of the computing and storage model, the means by which software is acquired, deployed, and used has also experienced two decades of transformation. Not only has software-as-a-service taken on increased importance, but open-source software has taken on an expanded role as well. The critical nuance in the economics of open-source software is that while there is no price attached to an open-source license, its increased usage reduces the usage of software licensed for a fee and software-as-a-service. The result is a reduction in the weighted average software price. A larger proportion of the required functionality is available at a zero price. Further, despite its zero price, developer services are still required in the software deployment process.

Figure 24 shows the change in the quality adjusted capital stock of web server software, a representative category of open-source software. Murciano-Goroff, Zhuo, and Greenstein (MZG 2021) have built an extensive database of U.S. web server use between 2001 and 2018.

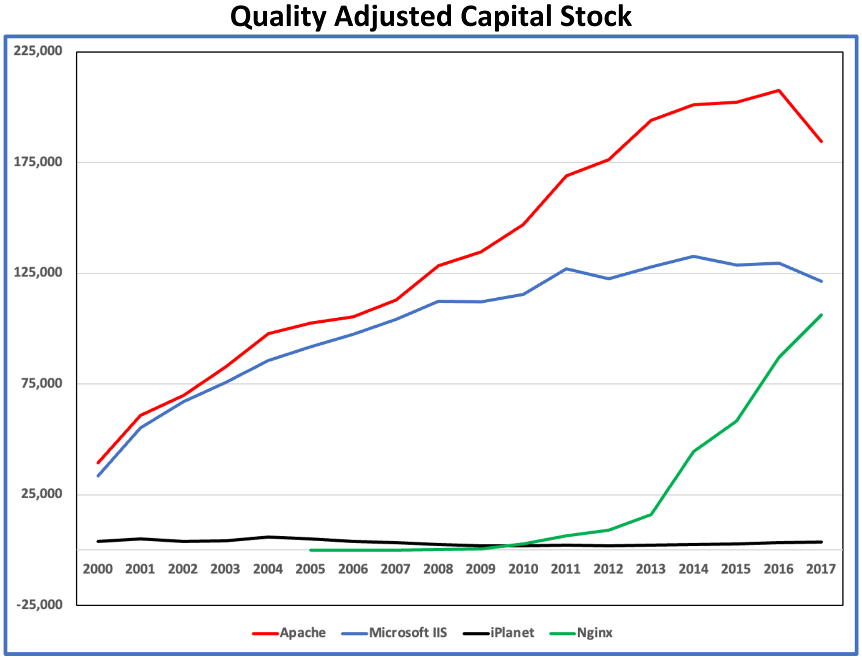
MZG find that the omission of economic value created by open-source web server software is over $4.5B of mismeasured server software across organizations in the U.S. MZG

Figure 23
Other Capital Services
Rental Price Deflator and Share of Spend
BEA/BLS Integrated Industry-Level Production Account



Source: Author's Calculations and BEA Integrated Industry-Level Production Account

Figure 24
Web Server Software
Quality Adjusted Capital Stock



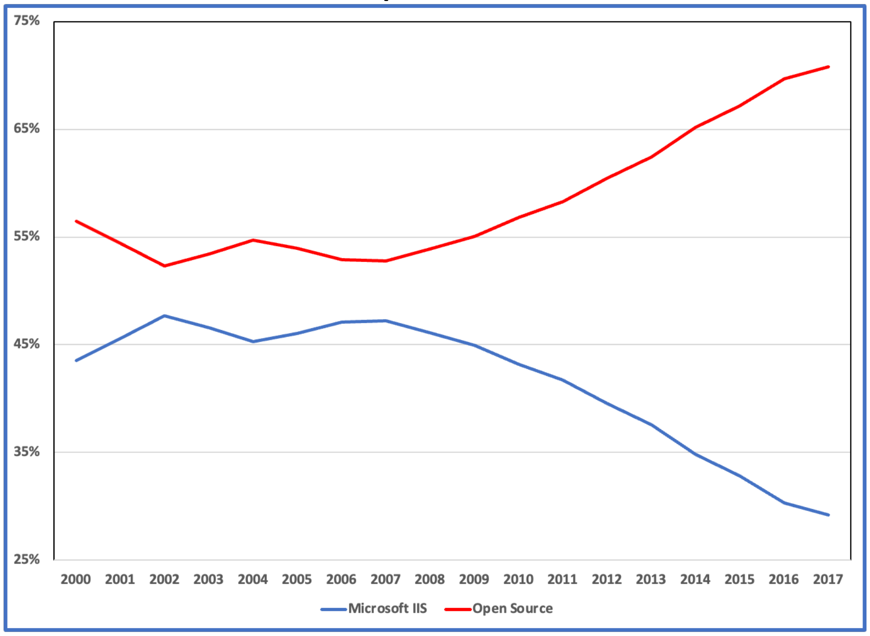
Source: Author's Calculations and Murciano-Goroff, Ran and Greenstein (2021).

calculate the quality adjusted capital stock of web server software. For value calculation, capital services are assumed proportional to the stock and Microsoft price reflects market value. Figure 25 shows open-source software grows to nearly 75% of usage among applications with open-source options. Also, for value calculation, 50% of software applications are assumed to be possible candidates for open-source substitution. Bringing together software license for a fee, software-as-a-service, and open-source software Figure 26 shows software spending increased from 48.7% of total sending in 2006 to 49.2% in 2019 – a 0.5 ppt increase – with the imputed value of the open-source applications offsetting the proportionate decline in license and as-a-service software. Software remains the largest factor input in the business sector ICT production function. Over the 2006 to 2020 period, the weighted average software price fell by 5.5% CAGR.

IV.3. Imports of Services

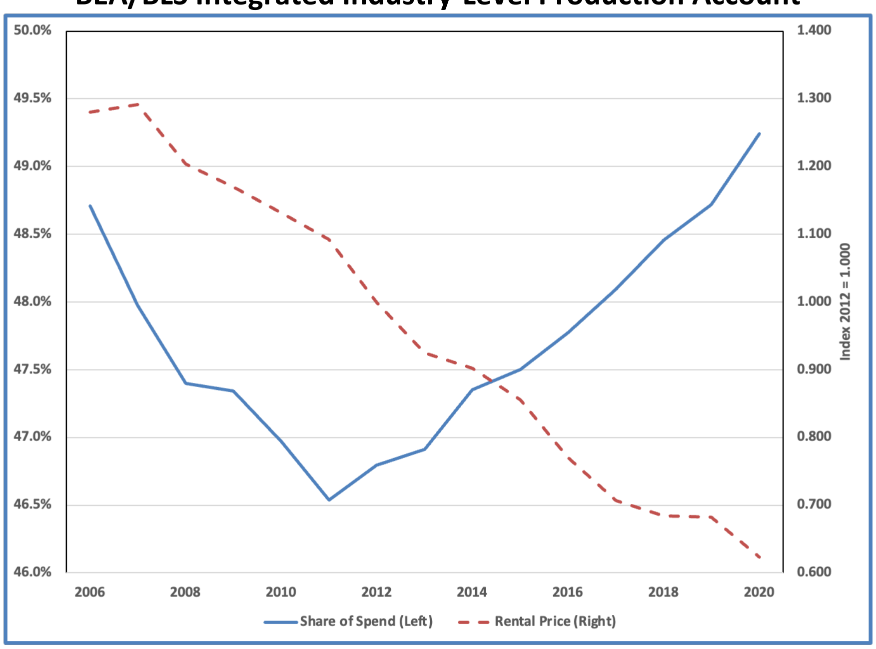
The third transformation experienced by the ICT function is the increased of non-U.S. labor, often located in easter Europe, India, and other Asian nations. With data from BEA's international services estimates, trade in ICT services, rose marginally between 2006 and 2011. See Figure 27. However, the share of imported services fell after 2011. In real terms, imported telecommunications, computer, and data processing services grew at a CAGR of 9.8% between 2006 and 2011. However, after 2011 growth slowed to a CAGR of 4.3% to 2020. As shown in Figure 28, computer services - end-user licenses and customization of software; cloud computing and data storage services; consulting and implementation services; and facilities management services; and data recovery services – constitute the bulk of imported services

Figure 25
Web Server Software
License and Open Source % of Total



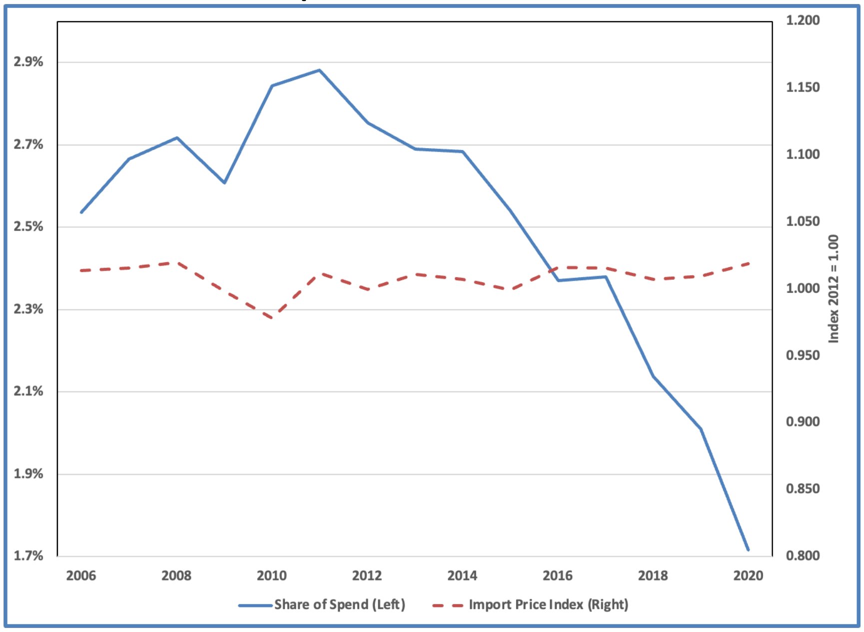
Source: Author's Calculations and Murciano-Goroff, Ran and Greenstein (2021).

Figure 26
Software Capital and Open-Source Services
Rental Price Deflator
BEA/BLS Integrated Industry-Level Production Account



Source: Author's Calculations and BEA Integrated Industry-Level Production Account

Figure 27
Imported ICT Services % of Total Spend
And Imported Services Price Index



Source: Author's Calculations and BLS Occupational Employment and Wage Survey.

Figure 28
Real Telecommunications, Computer, and Data Processing Services

	Compound Annual Growth Rate		% of Total	
	2006 to 2011	2011 to 2020	2006	2020
Telecommunications, Computer and Data Processing Services	+9.8%	+4.3%	100%	100%
Telecommunications Services	+1.6%	-3.4%	29%	13%
Computer Services	12.9%	3.4%	68%	80%
Data Processing Services	25.1%	5.2%	3%	7%

Source: Author's Calculations and BES Imports of Services and BLS PPI.

with growth slowing substantially over the past decade. As shown in Figure 27, there has been little change in import prices over the 2006 to 2020 period.

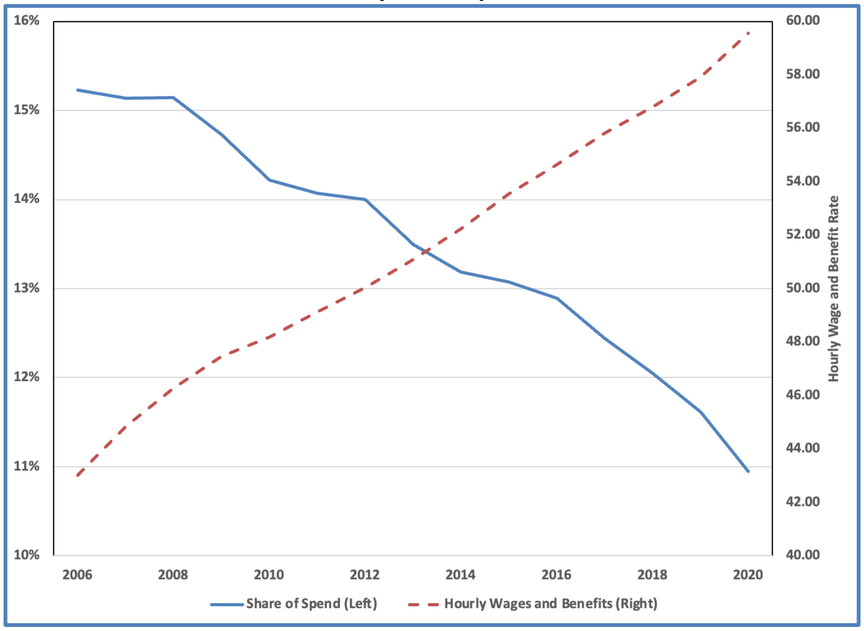
IV.4. Labor Services and Wages

Figure 29 shows domestic labor services with hourly wages and benefits rising from $43 in 2006 to nearly $60 in 2020 while the share of spending for domestic labor services fell from 15.2% in 2006 to 10.9% in 2020. Over the entire 2006 to 2020 period, real spending for domestic labor service rose at a CAGR of 5.1% while real spending in imported services rose at a CAGR of 4.7%.

IV.5. ICT Function Software Price Index

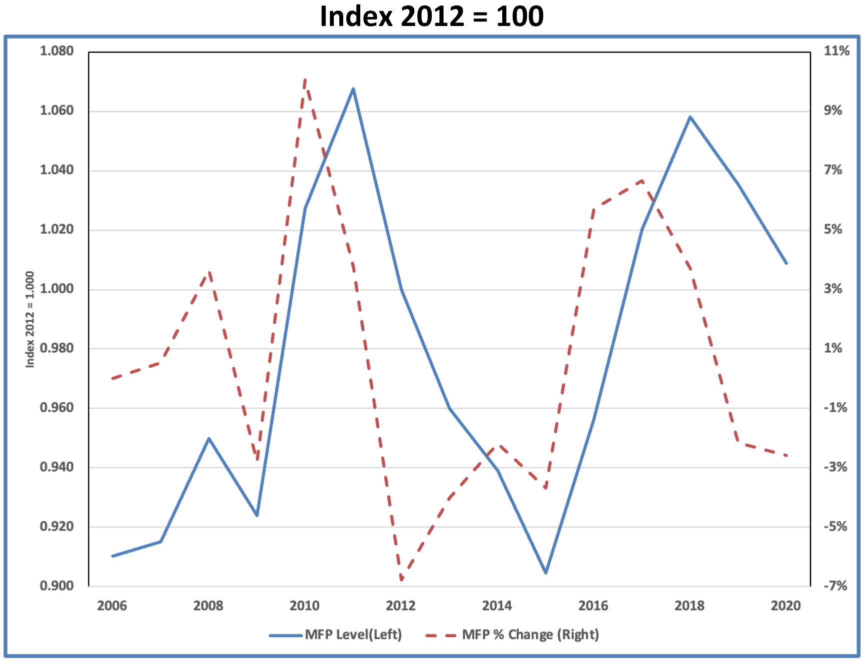
With the factor shares, price changes, and growth rates along with the assumed labor productivity growth, equation 16b is used to calculate the multifactor productivity level and rate of change. Figure 30 shows the results of the calculation. The MFP level increased 0.7% per year over the 2007 to 2020 period. However, over the 14 years, there were three distinct periods. As aggregate growth declined in the 2007 to 2010 period, developer employment was little changed with real software sector growth remaining strong and developer productivity increasing 5.7% annually. As aggregate growth recovered, developer employment recovered, and labor productivity growth slowed. Over the most recent five years, software grew rapidly, and productivity increased. MFP growth followed a similar trend.

Figure 29
Labor Share of ICT Function Spend and Software Developer Hourly Wage Rates (Dollars)



Source: Author's Calculations and BEA International Data, International Services, Table 3.1. U.S. Trade in ICT and Potentially ICT-Enabled Services, by Type of Service.

Figure 30
Multifactor Productivity Business Sector ICT Function Index 2012 = 100



Source: Author's Calculations.

Figure 31, based on equation 16b and equation 27, shows the components of MFP growth and ICT function price % change. In the top panel of the table, MFP growth reflects the variability of labor productivity growth as business conditions change as well as the more limited variability of compensation changes. As hiring resumed in the 2010 to 2015 period, compensation increases accelerated over the prior and following period. The growth of capital services and intermediate purchases accelerated throughout the period, as technology resources were applied at increasing rates.

On the bottom panel of Figure 31, the ICT function price fell continuously over the period. The price declines reflect MFP improvement and the accelerating price declines across the weighted combination of prices of labor service, capital services, and intermediate purchases.

Figure 32 shows the business sector ICT function price index and its rate of change. The index trended down throughout the period, interrupted from 2010 to 2015 when MFP growth turned negative as development teams scaled up anticipating stronger growth later in the decade. Without more rapid growth in resource use, in the absence of productivity declines, the ICT function price was virtually flat. However, in the last half of the decade, developer productivity gains resumed, and the ICT function price renewed its decline.

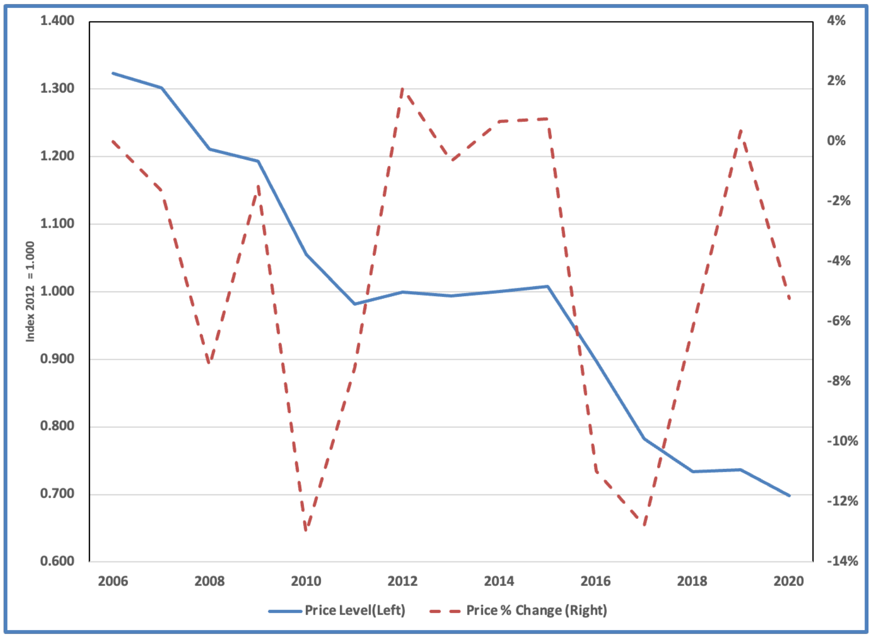
Figures 33 and 34 compare the change in the ICT function price with the currently published price index. As Figure 33 shows, the published index declined at an average annual rate of 1.1% over the 2015 to 2020 period. The business sector ICT function index declined – on

Figure 31
ICT Function Shadow Price, Labor Productivity, MFP, and Capital Services and Intermediate Purchases
Percent Change

	2007 to 2010	2010 to 2015	2015 to 2020
MFP % Change	3.9%	-2.5%	2.2%
Labor Productivity % Change	5.7%	-0.8%	6.1%
Labor Services % Change	3.7% *	5.1% **	4.0% ***
Weighted Capital Services and Intermediate Purchases% Change	5.5%	6.8%	7.8%
ICT Function Price % Change	-6.7%	-0.9%	-7.1%
MFP % Change	3.9%	-2.5%	2.2%
Weighted Price Changes Labor Services, Capital Services and Intermediate Purchases	-2.8%	-3.4%	-4.9%

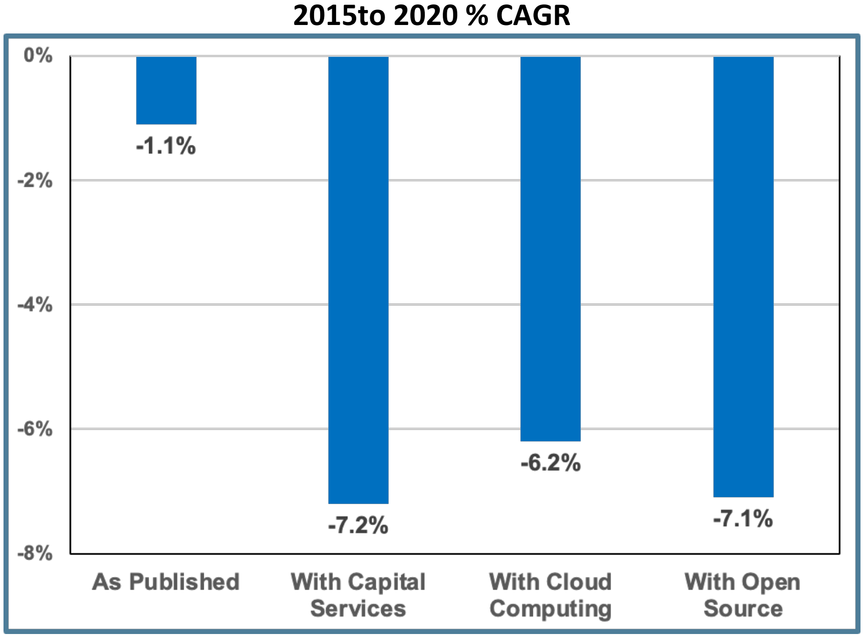
Source: Author's Calculations. From equation 16b, MFP % change is Labor Productivity % change plus Labor Service % change plus Capital Services and Intermediate Purchases % change.
Labor Services % change is percent change in developer wage and benefit payments time the share of labor services in total resources minus one. Because labor share is less than one, Labor Services % change is negative.
* 2007 to 2010 labor share is 14.8% and percent change in compensation is 4.4%.
** 2010 to 2015 labor share is 13.6% and percent change in compensation is 5.9%.
**** 2015 to 2020 labor share is 12.0% and percent change in compensation is 4.4%.
From equation 27, ICT Function Price % change is weighted prices % change for Labor Services plus Capital Services and Intermediate Purchases which is negative in all cases minus MFP % change.
Excluding ICT Function Price, all % changes are in real terms.

Figure 32
Business Sector ICT Function
Price Index
Index 2012 = 100



Source: Author's Calculations.

Figure 33
Business Sector ICT Function
Price Index
2015to 2020 % CAGR



Source: Author's Calculations.

Figure 34
Business Sector ICT Price Index
2015 to 2019 % CAGR

	2007 to 2010	2010 to 2015	2015 to 2020
As Published	-1.7%	-1.3%	-1.1%
With Capital Services, Labor Services and Imports of Services	-5.9%	+0.4%	-7.2%
Cloud Computing	-5.7%	+1.1%	-6.2%
Open Source Software	-6.7%	-0.9%	-7.1%
Net Increase in Price Decline	5.0 ppts	-0.4 ppts	6.0 ppts

Source: Author's Calculations.

the right side of the figure - at an average annual rate of 7.1% over the same period for a net increase in the price decline of 6.0 ppts. The steeper decline occurred in three steps.

- First, the introduction of the MFP estimates in equation 27 and capital services with the use of the BEA Integrated Industry Production Account data resulted in a 5.1 ppt addition price index decline.
- Second, somewhat surprisingly, the move to cloud computing services provides little price benefit and slowed the price decline. The rental price of on-premise computing capital services declined at an annual rate of 1.6% over the period while the transaction price of cloud computing rose 0.3% on average over the period. Similarly, the rental price of communications capital services declined at an annual rate of 8.0% over the same five-year period.
- Third, the increased penetration and usage of open-source software resulted in a further 0.9 ppt decline in the price index, almost offsetting the effect of cloud computing prices.

Finally, large price index declines were experienced in the second half of the last decade. See Figure 34. The substantial MFP improvement in the period and the increased use of open-source software resulted in more rapid price declines.

Of course, the finding that the price of business sector ICT function shadow price has been declining more rapidly than previously estimated suggests investment spending, productivity growth, and real GDP growth have been underestimated. The model developed in Section II, follows closely the work of Byrne, Oliner and Sichel (2013) and Greenstein and Nagle (2014) who measure productivity and grow improvement from the broader application and adoption of ICT.[10] Figure 35 shows comparative productivity, investment and growth calculations which assumes a 6.0 ppt average annual underestimate of the ICT function price decline between 2015 and 2020 as shown above in Figure 34 As the figure shows investment spending estimates increase meaningfully with a small impact on the overall real GDP growth rate.

[10] Like the Section II model, Byrne, Oliner and Sichel consider the use and deployment of a broad portfolio of ICT resources. Greenstein and Nagle focus on the introduction of Apache open-source software.

Figure 35
Revised Business Sector ICT
Real Spending Estimates
Billions of 2012 Dollars

Annual Growth Rates			
2015 to 2020			
	As Published	**Proposed**	**Difference**
GDP	1.3%	1.4%	0.1 ppt
Gross Private Fixed Investment	1.2%	1.7%	0.5 ppt
Fixed Investment	2.2%	2.8%	0.5 ppt
NonResidential Fixed Investment	2.0%	2.6%	0.7 ppt
Software	9.7%	15.7%	6.0 ppt
Software Investment % of Total			
2020			
	As Published	**Proposed**	**Difference**
% of GDP	2.7%	3.6%	0.8 ppt
% Private Fixed Investment	15.3%	20.0%	4.7 ppt
% Nonresidential Fixed Investment	19.1%	24.9%	5.8 ppt

Source: Author's Calculations. Assumes 6.0% underestimate of constant dollar software spending growth.

V. Conclusion

The introduction of enterprise software and services spending in the National Income and Product Accounts, more than 20 years ago, represented one of the first successful measures of intangible asset investment. The innovation was a recognition that the global technology sector had made a meaningful contribution to productivity improvement, at least for a brief period over the second half of the 1990s. However, over more recent decades much has changed. The nature and manner in which information and communication technology is produced, deployed, and used has change markedly. Consequently, current estimates of the shadow price paid by enterprise ICT functions appears to underestimate the declines realized in the current century. The consequence is an underestimate of private fixed investment spending, GDP growth, and productivity improvement.

While some, but not all, prices paid for enterprise ICT resources and services have declined, the productivity of software developers has advanced substantially over the period. Estimates indicate a 5.7% developer productivity CAGR over 2007 to 2010 and a 6.1% CAGR over the more recent 2015 to 2020 period. Multifactor productivity improvement has been somewhat less consistent with a 0.9% CAGR over 2007 to 2020 but a 2.2% CAGR over the more recent 2015 to 2020 period.

Beyond substantial labor productivity advances the advent of open-source software represents an important source of downward price pressure. While software available at a zero price continues to require labor services, the increased use of open-source software lowers the weighted average cost of the largest resource in the enterprise ICT services mix. Software spending is 49.2% of total ICT spending in 2020.

The view of the business sector ICT function that emerges of this work is one in which the growth in technology resources has accelerated over the most recent decade-and-a-half. The development, deployment, and use of software, including open-source software, is at the heart of the functions' activity and its shadow price. Second, the attractiveness and convenience of cloud computing, apparently, limited transaction price declines for the first decade of its life and slowed ICT function shadow price declines. Third, the use of imported services, which accelerated broadly in the first decade of the century, has slowed recently with further offshoring opportunities limited. Finally, employment and productivity improvement have been sensitive and responsive to aggregate economic conditions.

The business sector ICT function can substantially influence aggregate investment, productivity, trade, and growth. The effectiveness, quality, and the implicit price of service delivery to the business organizations in which they live is an important contributor to business success and, ultimately, living standards.

References

Albrecht, A.J. (1979). "Measuring Application Development Productivity". *Proceedings of IBM Applications Development Symposium*, Monterey, October, p. 83 link.

Byrne, D., C. A. Carrado, and D. Sichel (2018). "The Rise of Cloud Computing: Minding Your P's, Q's, and K's" NBER Working Paper 25188.

Greenstein, Shane, and Frank Nagle (2014); "Digital Dark Matter and the Economic Contribution of Apache"; *Research Policy* (Vol. 43, pp. 623-631).

Greenstein, S (2020). "The Basic Economics of Internet Infrastructure", *Journal of Economic Perspectives*, V. 34, No. 2, pp 192 – 214.

Byrne, David M., Stephen D. Oliner, and Daniel E. Sichel (2013); "Is the Information Technology Revolution Over?" *International Productivity Monitor*, Center for the Study of Living Standards (Spring, pp. 20-36).

Byrne, D. M. and C. A. Corrado (2017a). "ICT Services and their Prices: What Do They Tell Us About Productivity and Technology?" *International Productivity Monitor*, Centre for the Study of Living Standards, vol. 33, pages 150-181, Fall.

Byrne, D. M. and C. A. Corrado (2017b). *ICT Asset Prices: Marshalling Evidence into New Measures,* Finance and Economics Discussion Series, 2017-016, Board of Governors of the Federal Reserve System, October.

Bureau of Economic Analysis (2019). *NIPA Handbook: Concepts and Methods of the U.S. National Income and Product Accounts,* link.

Cole, R., Y. C. Chen, J. A. Barquin-Stolleman, E. Dulberger, N. Helvacian, and J. H. Hodge (1986). "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment", *Survey of Current Business*, 66, pp. 41-50.

Copeland, A. and D. Fixler (2009). *Measuring the Price of Research and Development Output*, Bureau of Economic Analysis, U.S. Department of Commerce, WP2009-02, link.

Coyle, D. and D. Nguyen (2018). "Cloud Computing and National Accounting." Economic Statistics Centre of Excellence, Discussion Paper 2018-2019.

Corrado, C., J. Haskel, and C. Jona-Lasinio (2021). "Artificial Intelligence and Productivity: An Intangible Asset Approach", *Oxford Review of Economic Policy*, 37, pp. 435-458.

Greenstein, S (2020). "The Basic Economics of Internet Infrastructure", *Journal of Economic Perspectives*, V. 34, No. 2, pp 192 – 214.

ISBSG (2021a). *Demographics – Development and Enhancement Repository*, Corporate Release R1 2021.

ISBSG (2021b). *Field Descriptions – Development and Enhancement Repository*, Corporate Release R1 2021.

Jorgenson, Dale W., Mun S. Ho, Kevin J. Stiroh (2005); Productivity Volume 3: Information Technology and the American growth Regurgence; (MIT Press, Cambridge, MA).

Leiserson, C. E., N. C. Thompson, J. S. Emer, B. C. Kuszmaul, B. W. Lampson, D. Sanchez, and T. B. Schardl (2020). "There's Plenty of Room at The Top: What Will Drive Computer Performance After Moore's Law?", *Science* 368, 1079.

Murciano-Goroff, Raviv, Ran Zhuo, and Shane Greenstein (2021), Hidden Software and Veiled Value Creation: Illustrations From Server Software Usage, NBER WP# 28738.

Oliner, Stephen D. and Daniel E. Sichel (2002), "Information Technology and Productivity: Where Are We Now and Where Are We Going?", *Federal Reserve Bank of Atlanta, Economic Review*, Third Quarter, pp. 15- 44.

Parker, R. and B. T. Grimm (2000). *Recognition of Business and Government Expenditures for Software as Investment: Methodology and Quantitative Impact, 1959–98*, Technical report, U.S. Bureau of Economic Analysis, link.

Sichel, D. (2019). *Using 451 Research Cloud Price Index for U.S. National Economic Accounts*, (Mimeo, Wellesley College).

Shrikanth, N.C., Nichols W., Fahid, F. M., and Menzies T. (2021). "Assessing Practitioner Beliefs About Software Engineering", Empirical Software Engineering 26:73

Varian, H. (2018). "Artificial Intelligence, Economics, And Industrial Organization", NBER Working Paper 24839.

Zolas, Nikolas, Zachary Kroff, Erik Brynjolfsson, Kristina McElheran, David N. Beede, Cathy Buffington, Nathan Goldschlag, Lucia Foster, and Emin Dinlersoz (2020), *Advanced Technologies Adoption and Use by U.S. Firms: Evidence from the Annual Business Survey*, NBER Working Paper 28290, December.