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ENTERPRISE INFORMATION AND COMMUNICATIONS TECHNOLOGY SOFTWARE PRICING AND DEVELOPER PRODUCTIVITY MEASUREMENT

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The 1999 addition of business sector software and services spending to the National Income and Product Accounts was an important 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. The transformation has raised questions about the extent of the decline of ICT function software prices. As a software producing sector, the business sector ICT function now has a much wider array of production factor choices. In addition, labor and multifactor software development productivity, an important sources of value creation, varies widely from year to year. With the use of a two-sector model and a standard growth accounting framework, a business sector ICT function shadow price is estimated, finding that software price declines have been underestimated by 4.4 percentage points (ppt) over 2015 to 2021. The impact on GDP growth is a 0.1 ppt underestimate. Correcting the underestimate increases software spending from 19.6% to 24.7% of nonresidential fixed investment, and from 47.4% to 59.9% of real intellectual property product spending.

1. INTRODUCTION

Since the introduction of business expenditures for computer software as capital formation into the National Income and Product Accounts (NIPA) 20 years ago, both software development and computing infrastructure have changed dramatically (see Parker & 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 more recently productive artificial intelligence (AI) models 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, cloud computing, as it is known today, was not available, and AI models remained nascent. Over a remarkably brief period, ICT has migrated away from

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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 fast, inexpensive AI models.

The new technology has moved rapidly to include the 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 spending occurs in the context of an organizational unit—the ICT business unit. Many firms have multiple units, each consisting of highly skilled software developers, cloud engineers, data scientists, and others, all producing software solutions for the function they support. The resources are acquired at market prices, including software developers, cloud computing services, open-source software, and third-party software from both domestic and non-domestic sources.

As a result, U.S. software spending, as currently reported in the NIPA, increased from 6.2% of real nonresidential fixed investment in 2007 to 15.0% in 2023 with software spending growing from 1.2% of real GDP in 2007 to 3.6% in 2023.¹ In real terms, software spending has grown at an annual rate of 9.3% between 2007 and 2023.

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.

In addition, the current method of estimating the NIPAs software price index is largely based on software license prices and the wages rates of computer programmers and systems analysts with an adjustment for productivity changes.

As reported, the NIPA software price index declined at an annual rate of 1.8% from 2007 to 2022.² However, recent research finds the current approach underestimates realized price declines. Byrne and Corrado find a 5.5% annual decline in software prices from 1994 to 2004, a 3.5% decline from 2004 to 2008, and a 4.1% decline from 2008 to 2014.³

In addition to an apparent underestimate of software price declines, the current method suffers from two additional shortcomings. First, investment in software is measured by the real value of software sector output. The approach neglects the consumption of the services provided by the stock of software capital along with the services provided by the stock of computing, storage, and communications equipment capital and the intermediate services provided by cloud providers, open-source software, and imported software. Second, software constitutes about

²See: National Income and Product Accounts, Table 5.3.4. Price Indexes for Private Fixed Investment by Type, Index numbers, 2017 = 100. Last Revised on: September 29, 2023.

³See: Byrne and Corrado (2017a), Appendix A2.

¹See: National Income and Product Accounts, Table 1.1.6. Real Gross Domestic Product and Table 5.3.6. Real Private Fixed Investment by Type, billions of chained (2017) dollars, seasonally adjusted at annual rates. Last Revised on: April 25, 2023.

half the resources necessary for the business sector ICT function, as opposed to the sole input implied in the current approach.

To address these shortcomings, the central focus of this paper is to measure the value created by the portfolio of resources engaged in software production. The method includes the resources necessary, their market prices, and the productivity of development teams in the software production sector to meet the needs of the demand sector as measured in the NIPAs. The approach proposed takes explicit account of a wide range of required inputs with a systematic accounting of productivity changes.

A two-sector model is developed in which a software development sector provides capabilities to the software production sector at market prices. Software production is embedded in the much broader business sector which also acquires resources at market prices. While market competition creates pressure to manage resource cost, 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 in capturing the opportunity cost in choosing one alternative over another. The shadow price is the weighted average of the changes in input prices and wage rates adjusted for productivity improvement.

While the real value of software development sector output, as measured by the current NIPA method, is useful in measuring developer productivity, capital services and compensation data are necessary for the improved measurement of the ICT function output and price index. The Bureau of Economic Analysis (BEA) Integrated Industry-Level Production Account (IILPA) provides the necessary data. The IILPA data captures the demand side usage of such resources in contrast to the supply side measure in the current method. The IILPA data are revised and curated based on a variety of public sources.

The result finds that the software price index declines have been underestimated by 4.4 percentage points (ppt) over 2015 to 2021 for an average annual decline of 6.4% compared with a NIPA published decline of 2.0%.⁴ The impact on real GDP growth is to increase growth by a 0.1 ppt over the period. The improved price index increases real software spending in 2021 from 19.4% to 24.7% of real nonresidential fixed investment, and from 47.4% to 59.9% of real intellectual property product spending.⁵ In real terms, software spending growth with the improved price index increases the 2007 to 2021 annual rate from 9.0% to 13.4%.

The outline of this paper is as follows. Section 2 reviews the current NIPA methodology. Section 3 outlines a conceptual framework for the development and

⁴Findings are limited to 2021, the most recent year of the BEA's Integrated Industry Production Account.

⁵Software is also produced in the research and development sector for product development and service delivery, but such software is excluded from this paper.

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production of software. Section 4 outlines the influences on software developer productivity and estimates software development sector productivity. Section 5 develops a two-sector model, estimates the software production multifactor productivity (MFP), and the software price index. Section 6 concludes.

2. CURRENT NIPA METHODOLOGY

The current NIPA methodology for estimating business investment in new or significantly enhanced software comprises the purchase of (1) prepackaged software, (2) customized software from companies primarily engaged in software development, and (3) the resources necessary for own-account software production.^{6,7}(See BEA Chapter 6: Private Fixed Investment, pp. 6–37.)

- 1. Prepackaged software data are obtained from the Quarterly Services Survey (QSS) with revenues of software publishers (NAICS 5132) and data processing, hosting, and related services (NAICS 518).
- 2. Custom software consists of current dollar bespoke purchases from firms engaged in computer system design and related services. Revenue data of firms in North Amercian Indsutry Classification System (NAICS) 5415 are also obtained from the QSS.
- 3. Expenditure for own-account software is the sum of production costs, which include wage and nonwage employee compensation, intermediate input cost, and a BEA-derived measure of capital services including depreciation. Compensation is derived by multiplying employment in select occupations associated with software development by the occupation-specific wage rates prevailing in each industry. At the industry level, data from the Bureau of Labor Statistics (BLS) Occupational Employment Statistics are obtained on the number of employees and wages for computer programmers and systems analysts.^{8,9}

Deflators for these measures include adjustment for prepackaged software, reflecting historic differences between BEA hedonic and various matched-model BLS PPI indexes. For prepackaged software, the BLS PPI for Software Publishing, except games, is used with a downward bias adjustment of 3.192% annually.¹⁰

¹⁰Sherry and Thompson (2021), analyzing data from 57 textbooks and more than 1137 research papers, find that algorithmic progress for the median algorithm family increased substantially over recent

⁶Prepackaged software consists of current dollar software purchases intended for nonspecialized use, sold or licensed in a standard form with software-as-a-service revenue included.

⁷The methodology presented here is based on the practice of the US BEA. Price index methodologies vary among national statistical offices (see Schreyer, 2002).

⁸Employment and wages for computer programers is found in Standard Occupation Code 15-1131and employment and wages of systems analysts is found in Application Software Developers 15–1132, Systems Software Developers 15–1133, and Computer Systems Analysts 15–1211.

⁹To avoid double counting, in NAICS 5415 a portion of computers programers and system analysts' wages representing the production of custom software for sale is removed. An operating expense and payroll increment of approximately 2.02 is applied to estimate total costs, including operating expenses and other nonwage costs. Total spending is reduced by one half, assuming employees spend one half of their time working on new or enhanced software.



Figure 1. Bureau of Labor Statistics (BLS) Software Price Index with Productivity Adjustment

Figure 1 shows the BLS PPI for Software Publishing, except games with the productivity adjustment.

At the heart of the deflator measurement, is the BLS PPI for Software Publishing, except games. This collection of indexes measure prices of enterprise software which is typically sold to businesses, institutions, and value-added resellers, and are not mass marketed to the general public.

Figure 2 shows the structure of the PPI Software Publishers category. Prices are collected for enterprise software licenses and, beginning with the 2022 NAICS revision, for software-as-a-service prices. The figure shows Software Publishing, except games, is comprehensive and includes prices of systems and application software as well as prices for maintenance, technical support, and other services.

- 1. System software consists of operating system software, network software, database management software, and development tools and programming languages software.
- 2. Desktop and portable device application software is installed directly onto a PC, laptop, or other mobile devices, including word processing software, spreadsheet software, personal finance software, and tax accounting software.

decades. About half of all algorithm families experience little or no improvement. At the other extreme, 14% experience transformative improvements, radically changing how and where they can be used. For moderate-sized problems, 30%–43% of algorithmic families had improvements comparable or greater than those that users experienced from Moore's law and other hardware advances. Collectively, the results highlight the importance of algorithms as an important source of computing improvement.

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Figure 2. Bureau of Labor Statistics (BLS) Software Publishers Price Index Industry Structure

- 3. Other application software includes utility software as well as cross-industry and vertical market enterprise software. Utility software includes anti-virus software and screen savers. Cross-industry enterprise application software performs or manages a specific business function or process that is not unique to a particular industry, including human resource software and accounting software. Vertical market enterprise application software performs a wide range of business functions for a specific industry group such as manufacturing, retail, healthcare, or finance.
- 4. Software maintenance, technical support, and other services include first year software maintenance, renewals for software maintenance agreements, technical support, consulting, implementation, and training services.

In collecting data and avoiding new item bias, BLS uses a procedure to verify that there is no new item bias or to direct the BLS researcher to substitute items to avoid bias. The procedure has been used every year since the late 1990s for the PPI Software Publishing industry. This procedure ensures that the software priced in the PPI is representative of the market for software.

In addition, sample augmentation is used by BLS when there are industries with rapid changes in services provided, such as the software industry. Sample augmentation is used to add additional items to current establishments, incorporate new services, and add establishments to the industry. Many times, the newest services are provided by new entrants. New establishments are selected and new services from those establishments are added to the current PPI index, thereby, ensuring the index is up to date.

Finally, software publishers are constantly enhancing their software products with new features and functionality. BLS substitutes by direct comparison when the differences between the current and new products are minimal. When there are large changes in functionality, such as the release of a new version, BLS attempts

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Figure 3. BEA Software Price Indexes

to approximate the value of the quality change by asking respondents to estimate the development costs associated with the enhancements made to the new version as well as the total number of licenses or units sold of the previous version, providing a per-unit estimate of the production costs associated with the software quality change with which to make a price adjustment. With rapid technological change, it is necessary to periodically augment the sample to capture revolutionary products. The augmentation allows for pricing a better overall mix of current software products, licensing models, and related services offered in the marketplace.¹¹

BEA uses the BLS PPI for Software Publishing, except games with the productivity adjustment for custom and own-account software. A weighted composite of the BEA index and the own-account input cost measure adjusted for MFP from 1997 to 2006 is used. From 2007 forward, the MFP measure is a hybrid of MFP and a BEA-derived custom-software productivity measure is used. Figure 3 shows the BEA software price indexes.

Thus, in measuring software spending and related price indexes, the software sector is defined as software publishers (NAICS 5132), data processing, hosting,

¹¹For more BLS methodological detail, see Swick et al. (2006). Despite recent BLS improvements in measuring software prices, there remain limitations. The PPI measures prices of domestically produced software, potentially missing imported offerings from emergent non-U.S. locations, such as eastern Europe and India. Also, despite best efforts, the PPI faces difficulties in accurately capturing quality changes and incorporating new offerings. Bundling or dynamic pricing can be challenging to accurately represent in the index as transaction and list prices can often deviate.

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and related services (NAICS 518), and firms engaged in computer system design and related services (NAICS 5415).

As defined, the software sector includes the sale and/or rental of software and computing services as well as the provision of skilled labor. In general, the development, deployment, and use of software requires labor services. In business and government organizations, customization and integration of software applications and tools—tasks provided by software developers and management consultants—are essential for successful software deployment (see Messerschmitt & Szyperski, 2005).

The 2017 U.S. Economic Census reports 81% of software publishers revenue is from the sale of software with the balance from labor services.¹² Data processing, hosting, and related service firms realize 46% of their revenue from labor-related services, 52% from hosting-related services, and 2% from software sales.¹³ Among firms engaged in computer system design and related services, 97% of their revenue is from their labor services practices. The small remaining portion of their revenue is from the sale of software.

The current NIPA methodology for estimating business investment in new or significantly enhanced software, in fact, is limited to measuring the output of the software sector, consisting of software publishers; data processing, hosting, and related services; and firms engaged in computer system design and related services. While the current methodology captures software sector output on the one hand, on the other hand, the method neglects the additional inputs and complexities that have emerged in the production of enterprise ICT software. Section 3 shows the nature of the transformation in the enterprise software production function with additional inputs and complexities beyond those included in the current methodology.

3. A Conceptual Framework for the Development and Production of Software

In the 25 years since the introduction of business expenditures for computer software in the NIPA, much has changed in the production and consumption of ICT. Software continues to deliver functionality to users in business and government, but with a much more complex production function, a much wider array of devices, and nearly ubiquitous broadband service.

Virtually every business organization develops and uses software in some fashion (see Zolas et al., 2020). Nearly all business organizations have ICT functions. Most organizations implement a formal structure but among smaller organizations responsibilities are distributed among business leaders. Such ICT functions acquire a variety of resources to deliver software to business functional areas. Finance, human resources, and operation functions are obvious and well-known illustrations of software applications, but increasingly functions such as customer relationship

¹²See U.S. Census Bureau 2017 Economic Census. https://www.census.gov/programs-surveys /economic-census/year/2017/economic-census-2017/data.html.

¹³As a means of gaining market share, firms providing data processing, hosting, and related services often provide software for which little revenue is recorded. See Greve and Song (2017).

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Computer, Communications. and	Software Services License On- 	Labor Services Software 	Imports of Services Software
 Storage Services On-Premise Capital Services Cloud Services 	Premise Capital Services • Software-as-a- Service • Open Source	 Developers Other Support Roles All Located Domestically 	Cloud Other Services

п.

Figure 4. Technology Resources Required for Business Sector information and communication technology (ICT) Software Production

management (CRM), 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 4.

- 1. System resources can be acquired either because of an asset purchase with the installation of the asset providing a capital service or as a cloud service which is an intermediate purchase.¹⁴ Each has an associated price. The capital service provided by the asset has a rental rate while the cloud service has a transaction price.
- 2. Software resources are similarly acquired with one notable and important exception. Licensed software is an asset purchase providing a capital service with a rental rate while software-as-a-service is an intermediate purchase at a transaction price. 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 the right to use, change, and distribute the source code at a zero acquisition price.
- 3. Labor services, located domestically, principally consist of software developers but also include computer and information analysts, support specialists, network administrators, and systems architects.
- 4. Imports of services, providing resources to the business sector ICT function, consist of software, consulting and implementation services, and maintenance and repair services. Imported services principally reflect the labor services provided by software developers and others in non-domestic locations.

To fix ideas, consider CRM software which helps business leaders nurture and grow client relationships. See Figure 5. CRM software improves salesforce productivity and with confidential client information builds intangible assets. CRM platforms connect data from sales leads through transaction outcomes; records and analyzes meta data from conference calls, emails, and meetings; and most recently,

¹⁴Spending for cloud computing services increased at an annual rate of 38.7% in nominal terms between 2005 and 2021 and 38.0% in real terms over the same period. See: BEA Digital Economy Satellite Account. See Coyle and Nguyen (2018).

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Figure 5. Customer Relationship Management Software. *Source:* https://www.perfectviewerm.com/what-is-crm/.

provides increased analytic insight. With the ability to track and segment client data, AI tools assess the probability opportunities will be won or lost, forecast period revenue, and assess the probability of seller retention or attrition.

Most firms have a CRM capability. Among larger enterprises, CRM usage is virtually universal. Most often the business sector ICT function provides additional tailoring to a third-party tool to address unique organizational needs, key performance metrics, and reporting requirements. Among small business, sellers often 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. Table 1 shows software spending on a worldwide basis. With a zero price, open-source use is not included. Over six-years, software-as-a-service spending

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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%	-25.4 ppt
SaaS or Subscription	123.5	344.9	+18.7	48.0%	73.4%	+25.4 ppt
Total	257.4	470.2	+10.6	100.0%	100.0%	-

TABLE 1	
Worldwide Software Revenue by Type Billions of Dollars 2016–202	22

Abbreviation: ppt, percentage points. *Source*: IDC.



Figure 6. Software Delivered by the Business Sector information and communication technology (ICT) Function Relies on Input from the Software Development Sector

grew at an annual rate of almost 19%, accounting for 73% of total software spending.

As suggested by the CRM illustration, a substantial portion of software delivered by the business sector ICT function relies on input from the software development sector. Consequently, software delivered to the business sector requires a two-sector model.¹⁵ A **software development sector**, which is an upstream sector, providing software to the business sector ICT function, which is the **software producing sector**, a downstream sector. The 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 6).

In modeling productivity and prices across two sectors, the software producing sector, produces output in a competitive market and similarly acquires resources in competitive markets.¹⁶ In producing software, the ICT function transacts for

¹⁵See Corrado et al. (2021) for treatment of a two-sector model.

¹⁶Consideration 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.

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resources in competitive markers but provides output to internal users, not in competitive markets. Thus, to describe resource allocation decisions in the ICT functions of business organizations, a two-sector model, consisting of an upstream sector and a downstream sector, is required.

For modeling purposes, the upstream sector consists of firms whose business is to produce new commercial knowledge in the form of computing, storage, and communications equipment; software; and related services. Such firms are in the business of software development, tangible computing asset manufacturing and production, cloud computing service provision, and consulting and integration service delivery. All develop software, as well as provide other services or equipment for the software producing units of the downstream sector.

The downstream sector acquires ICT assets as commercial knowledge inputs. The sector can acquire asset ownership from the upstream sector (license software and purchase tangible capital assets) whose services are available at a known user cost of capital. In addition, the downstream sector can also choose to purchase the functionality of such assets from the upstream sector as-a-service on an as-needed basis (cloud computing and software-as-a-service). The upstream providers can be either domestic or non-domestic firms.¹⁷

4. Software Developer Labor Productivity

Software production is embedded in business and government organizations that acquire resources at market prices while 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 the output of the ICT organizational function (see Starrett, 2000).

The change in the shadow price is the weighted average of the changes in input prices and wage rates, accounting for productivity improvements. However, measuring the productivity of such an internal function is challenging. While in theory one can calculate project level productivity estimates, productivity among software developers and software development teams is highly heterogenous (see Shrikanth et al., 2021). If software development productivity in the upstream software development sector includes knowledge that is diffused to the downstream software producing sector, measurement of software development sector productivity can be representative of productivity in the software producing sector as well. Such an assumption is developed in more detail in the sections that follow.

4.1. Software Developer Productivity

Software developer productivity in the business sector is subject to wide variation at the project level. Shrikanth et al. find substantial heterogeneity among developers and development teams. In a review of the recent computer scientist literature, they write: "… researchers acknowledge the widely held belief that some good

¹⁷As in Jorgenson (1966), each sector has a production possibility frontier, a flow equation, and due to competition covers cost.

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developers are much better (almost $10\times$) than many poor developers." Further, observing that individual developer performance varies considerably, developers who are productive in one task may not be as productive in another task.

Shrikanth et al. point to the relationship among quality, on-time delivery, and productivity. With data from thousands of developers doing the same set of tasks, using a wide variety of programming methods and tools, they find that a focus on quality, early in the project life cycle minimizes rework and increases on-time delivery. They find "quality entails productivity" and "… on-time delivery is achieved with a quality-driven focus." In achieving quality, on-time delivery, and productivity, there are a number of recent trends that have impacted software development.

Software-as-a-Service

Like many professions and occupations, software developers are finding their ways of working changing as new tasks, tools, and requirements emerge. Table 1 shows with the emergence of software-as-a-service a large proportion of development is occurring in the software development sector. Thus, developers' productivity in the ICT software producing sector is dependent on productivity in the software development sector.

Bout et al. (2021) find that software-as-a-service has proven capable of meeting as much as 90% of the needs of a given business function. Loukis et al. (2019) in a survey of 102 Dutch firms find that software-as-a-service can enable cost reduction and quality improvement of existing operations and provide rapid and low-cost innovation.

In addition, across both sectors, new development methods have been adopted widely, a deeper set of tools are more broadly available, application performance has become more important than lines of code produced, and developers continue to move across sectors sharing ideas and best practices. While productivity measurement is a challenge, ultimately, software development sector revenue per developer is the only meaningful market-driven result that is based on trustworthy data.

Agile and Devops Methods

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 Table 2. For both approaches, data are collected, most often with the use of third-party tools, for development time, task completion, and other productivity metrics. The software development methods shown in Table 2 are deployed by internal development teams—own-account—and external development teams—custom development—in the business sector as well as the software development sector.

Delaet and Lau (2017) found that sound Devops practices can contribute to a 25% to 30% increase in capacity creation, a 50% to 75% reduction in time to market, and more than a 50% reduction in failure rates. Jadoul et al. (2021) find evidence that business sector ICT units are adopting agile and devops methods learned from software development sector organizations and other "digital" firms that are delivering increased productivity.

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	Customer software requirements	Gap	Developer and tester	Gap	IT operations and infrastructure
Agile methods Devops	Iterative approach focuses on customer collaboration Devops takes software ready for release and deploys in a reli- able and secure manner	Agile methods addresses fast changing and evolv- ing requirements	Small teams with members having similar skills 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 opera- tional scale	Emphasis on development methods with handoff to operations Manage end-to-end engi- neering processes with focuses on constant testing and delivery
Source: Ham:	ilton (2023).				

TABLE 2 Software Development Methods

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Software Development Tools

While software development tools have been available and used by developers for decades, recent new entrants are most notable. Atlassian and Amazon Web Services (AWS), for example, have expanded both variety and access of such tools, creating more uniformity across both software sectors. These tools optimize software applications, frameworks, and programs by editing, managing, supporting, and debugging code. JIRA, Bugzilla, and Kanboard are popular Agile tools that track projects and effort. Puppet, Chef, TeamCity, and OpenStack are popular Devops tools. In addition, recent surveys suggest that open-source software platforms provide highly favored development tools. These platforms provide developers with tools to manage and improve projects while accessing software resources. Allowing users to host and share code and other content, with open-source software developers can collaborate by sharing projects, or hosting projects for private use.

In addition, the recent emergence of generative AI offers the possibility of broad-based improvement in developer productivity. Cihon and Demirer (2023) report results from experimental research with GPT-3 and GitHub Copilot.

- 1. Peng et al. (2023) showed that the completion time of those with access to Copilot was 55.8% lower than those without access, suggesting the possibility of a significant increase in software development productivity. However, there was no significant effect on task success. In terms of heterogenous effects, less experienced developers, developers facing a heavier workload, and older developers in the age range of 25 to 44 years experienced greater benefits from using Copilot.
- 2. Campero et al. (2022) find that GPT-3 significantly enhances performance with programmers achieving a 27% speed improvement and non-programmers, who could not complete the task without GPT-3, achieving performance as high as that of programmers.
- 3. Mozannar et al. (2022) conducted a user study with 21 programmers solving coding tasks with Copilot, to understand how developers allocate time across these activities. The main finding is that nearly half of the participants' time was spent explicitly interacting with Copilot as developers double-checked and edited Copilot suggestions, suggesting there is a learning curve facing development teams.

Software Performance Engineering

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, with the emergence of AI, 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 et al., 2020).

Leiserson et al. suggest that as hardware has become increasingly specialized and heterogenous, high-performing code has become more difficult to write. Consequently, software sector developers—more highly trained and with application specific skills—have taken on more of the development burden. Since

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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 in gaming applications. However, the use of GPUs has broadened for a variety of nongraphical tasks, such as those that are linear algebra intensive which are at the heart of AI applications. 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 6).

Developer Movement Across Sectors

With the similarity of skills and requirements in both the upstream software development sector and the downstream ICT software producing sector, there is substantial movement by developers from sector to sector. As is well known, it is difficult to protect the movement of intellectual property. The movement of professionals from company to company and sector to sector is one of the means by which intellectual property—best practices, new ideas, and trade secrets—moves.

The clustering of technology companies and the inevitable intellectual property spillovers have long been understood to create important effects (see, e.g., Krugman, 1991; Marshall, 1920; Stigler, 1951). More recently, with an annual turnover rate among highly skilled workers of 20% to 25% in the early 1990s, Saxenian (1994) and Almeida and Kogut (1999) show engineers and technical workers in Silicon Valley changing jobs repeatedly contributing to such spillovers.

4.2. Software Sector Productivity

Software developers are more productive as a result of software-as-a-service, the application of agile and devops methods, a broader set of development tools, a focus on performance engineering, and movement across sectors. MFP measure such benefits.

As with most 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

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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.¹⁸

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 customizing software-as-a-service offerings with the development having been completed by software development sector firms. Additionally, new development methods are shared, tools are broadly available, application performance has become more important, and developers continue to move across sectors sharing ideas and best practices. While productivity measurement is a challenge, ultimately, software development sector revenue per developer is the only meaningful market-driven result that is based on trustworthy data.

4.3. Measuring 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 5132 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 Bureau of Labor Statistics (BLS) produces employment and wage estimates annually for nearly 800 occupations. At the national level, occupational estimates for specific industries are available.¹⁹ For the three NAICS industries of interest, consistent occupation data are available from 2002 to 2020. Two occupations are of interest. Computer and mathematics occupations in the software development sector, as defined, 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. The second occupation of interest is software and web developers, programmers, and testers. Table 3 provides a view of computer and mathematics employment for the software sector. Figure D1. summarized data sources.

Figure 7 shows chained dollar gross output across NAICS 5132, 5182, and 5415 grows faster than developer population after 2015. The preceding 5 years from 2010 to 2015 output growth matched developer population growth.

Software developer productivity, shown in Figure 8, 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

¹⁹See: https://www.bls.gov/oes/oes_emp.htm#scope.

¹⁸Insights into the delivery of quality service have grown out of a voluminous literature, both for services sector firms and increasingly manufacturing firms. The seminal references are Heskett et al. (1997) and Teboul (2006), building on work based at Harvard Business School and Instead, respectively.

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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,	164,920	70, 140	579,150			
Programmers, and Testers						
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 Admin- istrators and Architects	13, 530	22,470	131,980			
Data Scientists and Mathemat- ical Science Occupations	2,490	4, 590	20,210			
Miscellaneous Computer Occupations	9,540	12,350	80,120			

Table 3 Software Development Sector Employment By Four-Digit Industry Computer and Mathematical Occupations 2020

Source: BLS Occupational Employment and Wage Statistics.



Figure 7. Software Development Sector Sum of NAISC 5112, 5182 and 5415 Output and Employment (Index 2012 = 100).

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





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

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.²⁰

Figure 9 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 Table 4.²¹

5. A Two-Sector Model, Labor Productivity, and Software Price Index

As developed in Section 2, the Software Price Index model consists of an upstream sector and a downstream sector. Both sectors employ labor with software

²⁰See Gordon and Sayed (2022) for a view of hiring, separations, and productivity over the business cycle.

²¹The estimates provided in Table 4 are consistent with the estimate used in the current BEA methodology. The current approach uses a fixed annual average. The approach developed here provides annual estimates. In addition, these estimates are aligned with industry observations. As noted above, Delaet and Lau (2017) found that sound Devops practices contribute significant productivity improvements. Also, Deniz et al. (2023) show that software developers can complete coding tasks up to twice as fast with generative AI tools.



Figure 9. Software Development Productivity Weighted by 5112, 5182, and 5415 Sector (% Change). Author's Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and BLS Occupational Employment and Wage Statistics.

	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%

Table 4 Software Sector Developer Productivity Index Weighted by Sector (% Change)

developers as the occupation of principle interest. The downstream sector is a price taker, like many innovation models (See Corrado et al., 2021). Both the upstream sector and the downstream sector acquire assets (K_t) at a price (P_t^K) , purchases services (I_t) at a market price (P_t^I) , and labor (L_t) is employed at wage rate (W_t) . MFP (Z_t) is realized. The change in the net stock of ICT assets is $\Delta \text{ICT}_t = N_t - \delta_K \text{ICT}_{t-1}$ where N_t is new investment and δ_K is depreciation. The upstream sector flow of payments is $P_t^K K_t + P_t^I I_t$.

5.1. Two-Sector Model

Since markets for software services are generally not well developed inside business organizations, it is useful to work with a price-like concept that captures

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the marginal value contribution of the services provided.²² Because most business organizations have alternative capital allocation choices, the marginal profit contribution of such choices, whether recognized explicitly or implicitly, is a primary decision factor. Thus, the cost per unit of software is referred to as a shadow price. In the business sector ICT function, software units (Q_t^{ICT}) are produced at a shadow price (P_t^{ICT}) .

The functional form of the production function and other equations will be identical for both the upstream and downstream sectors with notation simplified for ease of exposition.

(1)
$$Q_t = F\left(L_t, K_t, I_t, Z_t\right).$$

The capital services price (P_t^K) associated with the quantity of capital services is often referred to as the rental price or the user cost of capital (see Jorgenson et al., 2005, pp. 154–155 for more detail). In equilibrium, ignoring uncertainty and adjustment costs, investors—for example, corporate parents or venture capital providers-are indifferent between earning a nominal rate of return from an investment 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 criterion implies the following:

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

where i_{t+1} is the nominal interest rate, $P_{ac,t}^{K}$ is the acquisition price of capital, $c_{k,t}$ is the rental fee or user cost of capital, and δ_{k} is the economic depreciation rate. If $c_{k,t} = P_{t}^{K}$, $\pi_{ac,t} = \frac{P_{ac,t}^{K}}{P_{ac,t-1}^{K}} - 1$, the inflation rate, and $(i_{t} - \pi_{t})$ is the real return

for each asset, then

(2)
$$P_t^K = \left(i_t - \pi_t\right) P_{ac,t-1}^K + \delta_k P_{ac,t-1}^K$$

In the results that follow, capital service prices—Equation (2)—play an important role. For capital assets, existing published price indices are asset acquisition prices. By contrast, the capital services price index is the weighted average of the asset's acquisition price, accounting for period lags with the real rate of return and the depreciation rate as the weights. Jorgenson et al. define the real rate of return as a weighted average of the interest cost of debt and the industry-specific return on equity which includes the debt/capital ratio and the dividend/payout ratio.

Following Oliner and Sichel (2002) Appendix A, assume perfect competition, constant returns to scale, profit maximization and no adjustment costs, the prices for the associated services are:

(3)
$$P_{t}^{I} = P_{t}^{Q} \left(\frac{\partial F_{t}}{\partial I_{t}}\right) \Rightarrow \frac{P_{t}^{I}}{P_{t}^{Q}} = \left(\frac{\partial F_{t}}{\partial I_{t}}\right),$$

²²While transaction prices are, in some instances, assigned to such internal services, they are not arrived at in a competitive marketplace. Such prices are typically administrative.

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(4)
$$P_t^K = P_t^Q \left(\frac{\partial F_t}{\partial K_t}\right) \Rightarrow \frac{P_t^K}{P_t^Q} = \left(\frac{\partial F_t}{\partial K_t}\right),$$

(5)
$$W_t = P_t^Q \left(\frac{\partial F_t}{\partial L_t}\right) \Rightarrow \frac{W_t}{P_t^Q} = \left(\frac{\partial F_t}{\partial L_t}\right).$$

Totally differentiate (1), divide by ∂t and Q_t and substitute (3), (4), and (5). Define rate of change:

$$\dot{K}_{t} = \frac{\partial K_{t}}{\partial t} \frac{1}{K_{t}}, \ \dot{I}_{t} = \frac{\partial I_{t}}{\partial t} \frac{1}{I_{t}}, \\ \dot{L}_{t} = \frac{\partial L_{t}}{\partial t} \frac{1}{L_{t}}, \\ and \ M\dot{F}P_{t} = \frac{\partial Z_{t}}{\partial t} \frac{1}{Z_{t}}$$

(6)
$$\dot{Q}_t = \beta_t^K \dot{K}_t + \beta_t^I \dot{I}_t + \beta_t^L \dot{L}_t + M \dot{F} P_t,$$

 β_t^x is the cost share. The output change is the weighted average of the change in resources consumed and gains from MFP. Subtracting \dot{L}_t from both sides yields labor productivity (LP)

(7)
$$\mathbf{L}\dot{\mathbf{P}_{t}} = \dot{\mathbf{Q}}_{t} - \dot{\mathbf{L}}_{t} = \beta_{t}^{K}\dot{K}_{t} + \beta_{t}^{I}\dot{I}_{t} + \left(\beta_{t}^{L} - 1\right)\dot{\mathbf{L}}_{t} + \mathbf{M}\dot{\mathbf{F}}\mathbf{P}_{t}$$

Solve for $M\dot{F}P_t$

(8)
$$\mathbf{M}\dot{\mathbf{F}}\mathbf{P}_{t} = \dot{\mathbf{L}}\dot{\mathbf{P}}_{t} - \left[\beta_{t}^{K}\dot{K}_{t} + \beta_{t}^{I}\dot{I}_{t} + \left(\beta_{t}^{L} - 1\right)\dot{L}_{t}\right]$$

For the software development sector, labor productivity is:

(9a)
$$LP_{SS,t}^{\cdot} = \beta_{SS,t}^{K} K_{SS,t}^{\cdot} + \beta_{SS,t}^{I} I_{SS,t}^{\cdot} + \left(\beta_{SS,t}^{L} - 1\right) L_{SS,t}^{\cdot} + MFP_{SS,t}^{\cdot}$$

For the business sector ICT function, labor productivity is:

(9b)
$$LP_{ICT,t} = \beta_{ICT,t}^{K} K_{ICT,t} + \beta_{ICT,t}^{I} I_{ICT,t} + \left(\beta_{ICT,t}^{L} - 1\right) L_{ICT,t} + MF\dot{P}_{ICT,t}$$

For the software development sector, MFP is:

(10a)
$$\mathrm{MF\dot{P}}_{SS,t} = \mathrm{LP}_{ss,t}^{\cdot} - \left[\beta_{SS,t}^{K}K_{SS,t}^{\cdot} + \beta_{SS,t}^{I}I_{SS,t}^{\cdot} + \left(\beta_{SS,t}^{L} - 1\right)L_{SS,t}^{\cdot}\right]$$

For the business sector ICT function, MFP is:

(10b)
$$MF\dot{P}_{ICT,t} = LP_{ICT,t}^{\cdot} - \left[\beta_{ICT,t}^{K}K_{ICT,t}^{\cdot} + \beta_{ICT,t}^{I}L_{ICT,t}^{\cdot} + \left(\beta_{ICT,t}^{L} - 1\right)L_{ICT,t}^{\cdot}\right]$$

With estimates of MFP available from Equations (10a) and (10b), the dual approach is used to estimate software shadow 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. The dual yields Equation (11). Appendix A provides the details.

(11)
$$P_t^{ICT} = p_t^K \beta_{ICT,t}^K + p_t^I \beta_{ICT,t}^I + p_t^L \beta_{ICT,t}^L - \text{MFP}_{\text{ICT},t}.$$

5.2. Implementation

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.²³ Based on the premise that software development sector developer productivity is a reasonable measure of business sector ICT function developer productivity, assume from Equations (9a) and (9b),²⁴

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

From Equation (10b), with labor productivity from the software development sector's software developers, programmers, and testers ICT function MFP is calculated. Equation (11) provides the estimate of the ICT function shadow price index. The implementation of Equations (10b) and (11) requires data for resource usage and prices.²⁵

To implement the estimate of the software price index, the BEA IILPA data are employed.²⁶ These data provide both capital services quantities and rental price deflators for computing, communications, software and other capital that deliver the services acquired by the business sector (see Garner et al., 2021). Data for cloud computing and open-source software services are necessary. Employment and wage data are also required. And, data for imported services are required. In all cases both quantities and prices are necessary.

The IILPA provides sector-level capital services data for communication and computing equipment, software, and other capital. For each capital service, a price is associated with the quantity of capital services. A transaction price is associated with such services. The intermediate services are provided by the software development sector to the business sector ICT function.²⁷

The IILPA decomposes industry gross output growth into contributions from growth in intermediate inputs, capital, labor, and MFP. Data on gross output and intermediate inputs by industry are drawn from BEA GDP by industry account, while data on capital and labor inputs come primarily from the BLS productivity program. For the years 1987–1997, revisions to industry gross output and intermediate inputs reflect the late 2019 comprehensive update of the historical GDP by industry accounts. The revisions from 1993 to 1997 reflect improvements in the techniques used to link the time series of historical GDP by industry accounts to the more detailed set of accounts that begin in 1997. For the years 2014–2017, revisions to industry gross output and intermediate inputs reflect the 2019 annual update primarily the use of newly available and more complete source data.

²³In a series of papers, Byrne, Corrado, and collaborators have reviewed current methods and proposed, where possible, improvements. See: Byrne and Corrado (2017a) and (2017b).

²⁴The equality of $LP_{ICT,t}$ and $LP_{ss,t}$ implies a relationship between $P_{ICT,t}$ and $P_{SS,t}$. See Appendix C for details.

²⁵Figure D.2 shows the data sources used for the MFP and price equation calculations.

²⁶Data are available through 2021. https://www.bea.gov/data/special-topics/integrated-industry -level-production-account-klems.

²⁷For modeling purposes, the software development sector includes firms that provide software, cloud computing, and other resources. These firms include pure software firms and others such as Amazon Web Service, Microsoft Azure, and Google Cloud.

One of the innovations this paper brings is to recognize the role of capital services—computing, communications, and software—in the production of ICT enterprise software. Capital services estimates reflect the price and quantity of the annual service flow into production from a capital asset over its useful life. In the current use of the IILPA data, services from the stock of computing, communications, and software capital flow into the production of ICT enterprise software.²⁸

The investment estimates were updated during the 2018 comprehensive update and the 2019 annual NIPA update. Updated rental prices reflect updated value-added estimates resulting from the historical GDP industry account update. In addition, BLS made improvements to the historical estimates of ICT capital services in the federal government based on assignment of detailed asset source data from the BEA government accounts.

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. As inputs, the function requires both the acquisition of capital—for example, computing, communications, and software—and the purchase of intermediate services—for example, cloud computing, software-as-a-service, open-source software, and labor. The ICT function is a software producing sector and delivers its output as software, as reported in the NIPA accounts. 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, as specified in Equation (1).²⁹ Appendix E provides a detailed view of data for the right side of Equation (11).

5.3. Results: Software Price Index

With the factor shares, price changes, and growth rates along with the assumed labor productivity growth, Equation (10b) is used to calculate the MFP level and rate of change. Figure 10 shows the results of the MFP calculation. The MFP level increased 0.6% per year over the 2007 to 2021 period. However, over the 14 years, there were three distinct periods. As aggregate growth declined in the 2007–2010 period, developer employment was little changed with real software sector growth remaining strong and developer productivity increasing 5.7% annually. As aggregate growth recovered from the Great Financial Crisis, developer employment recovered, and labor productivity growth slowed (see Gordon & Sayed, 2022). Over the most recent 6 years, software output grew rapidly, and productivity increased at a 5.0% annual rate.

Figure 11 shows the business sector software 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. Without more rapid growth in resource use, in the absence of productivity declines, the software price

²⁹The model and empirical estimates include all U.S. economic sectors – farm, business, and government. For ease of exposition, references will be to the business sector.

²⁸Capital services are assumed to be proportional to the productive stock. Estimates of productive capital stocks are constructed by BLS as vintage aggregates of real historical investments using the perpetual inventory method. The price of service flows or "rental price" for each asset is constructed so that the discounted value of all future services is equal to the purchase price of the asset.

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Figure 10. Multifactor Productivity Business Sector ICT Function Index 2012 = 1.00



Figure 11. Business Sector ICT Function Price Index 2012 = 1.00

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AND INTERMEDIATE I ORCHASES ANNOAL I ERCENT CHANGE					
	2007-2010	2010-2015	2015-2021	2007-2021	
MFP % change	3.3%	-2.9%	2.1%	0.6%	
Labor productivity % change	5.7%	0.8%	6.7%	3.7%	
Labor services % change	3.6%*	-4.6%**	3.5%***	4.1%****	
Weighted capital services and inter- mediate purchases% change	6.0%	-0.9%	8.1%	7.2%	
ICT software price % change	-5.5%	0.7%	-6.4%	-4.2%	
MFP% change	3.3%	-2.9%	2.1%	0.6%	
Weighted price changes labor ser- vices, capital services and interme- diate purchases	-2.2%	3.6%	-4.3%	-3.6%	

TABLE 5 ICT Software Price, Labor Productivity, multifactor productivity (MFP), and Capital Services and Intermediate Purchases Annual Percent Change

Source: Author's Calculations. From Equation (10b), MFP % change is Labor Productivity % change minus Labor Service % change minus Capital Services and Intermediate Purchases % change. Labor Services % change is percent change in developer wages times the share of labor services minus one. Because labor share is less than one, Labor Services % change is negative.

*2007–2010 labor share is 17.9% and percent change in compensation is 4.4%.

**2010-2015 labor share is 16.5% and percent change in compensation is -5.5%.

***2015–2021 labor share is 14.9% and percent change in compensation is 4.3%.

****2007–2021 labor share is 1479% and percent change in compensation is 4.9%. From Equation (11), ICT Function % change is the weighted price % change for Labor Services plus Capital Services and Intermediate Purchases which is negative in all cases minus MFP % change. All quantity changes are in real terms.

index was virtually flat. However, in the last half of the decade, MFP productivity gains resumed, and the software price index renewed its decline.

Table 5 shows the components of MFP growth and ICT shadow price percent change. In the top panel, MFP growth reflects the variability of labor productivity growth as business conditions change as well as the more limited variability of production factors changes. On the bottom panel of Table 5, the ICT price index fell over the period. The price declines reflect MFP improvement and price declines across the weighted combination of labor service, capital services, and intermediate purchases. In simple terms, the declining ICT shadow price reflects continuous improvement in ICT MFP and the declining cost of production factors.

With all the elements required for the ICT price calculation, Table 6, Figure 12, and Figure 13 compare the change in the ICT shadow price index with the currently published NIPA price index.

As has been shown, there are a number of elements that determine the ICT shadow price index. For ease of exposition, Table 6 shows the incremental impact on the index as resources are added to the index calculation. The largest contributor to the price index decline is from the bundle of capital services. In the bundle, communications equipment is 20%, computing equipment is 20%, software is 59%, and other capital is 6% (see Figure 12). The introduction of the MFP estimates in Equation (11) and capital services with the use of the IILPA data resulted in a 4.4 ppt addition price index decline over the 2015 to 2021 period and a 2.4 ppt decline over the entire 2007 to 2021 period. The methodological change from the use of traditional use BLS software price indices to the introduction of capital services and their associated rental prices has the largest impact on the price index differential.

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	2007-2010	2010-2015	2015-2021	2007-2021
(1) NIPA Index (as Published)	-1.7%	-1.7%	-2.0%	-1.8%
(2) With Capital Services (IILPA	-5.8%	+1.7%	-6.4%	-4.6%
Data without Open-Source Software and Cloud)				
(3) With Open-Source Software and Without Cloud	-5.7%	+1.5%	-6.3%	-4.5%
(4) With Cloud and Without	-5.6%	+0.8%	-6.0%	-4.1%
Open-Source Software				
(5) With Capital Services (IILPA	-5.5%	+0.7%	-6.4%	-4.2%
Data) and with Open-Source Soft-				
ware and Cloud				
(6) Net Increase in Price Decline	3.8 ppts	-1.0 ppts	4.4 ppts	2.4 ppts
(Row 1–Row 5)				

Table 6 Business Sector ICT Price Index 2015 to 2019% CAGR

Source: Author's Calculations.



Figure 12. Capital Services Distribution 2021. *Source:* Author's Calculations.

Table 6 shows that the price of ICT function delivered to business organizations is heavily influenced by less expensive communications and computing equipment (see Kaushik et al., 2012).

Despite the cost of labor services rising over the period, the ICT shadow price index declines. Over the entire 2007 to 2021 period, real spending for domestic labor service rose at a CAGR of 4.6% with software developer wage rates rising at an annual rate of 2.0% over the period. However, the increasing use of technology assets and services offset rising labor costs and contributed to ICT price declines.

As currently measured, cloud computing prices have little impact on the price index. The move to cloud computing services slowed the price decline by 0.4 ppts. The rental price of on-premise computing capital services declined at an annual rate of 3.4% over the 2007–2021 period while the transaction price of cloud

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Figure 13. Business Sector ICT Function Price Index 2015 to 2021% CAGR. *Source:* Author's Calculations.

computing fell 1.8% on average over the period. However, because the rental price of on-premise computing capital services is typically calculated based on the time period of maximum usage while cloud computing prices are based on resources consumed, migration to cloud computing typically results in cost reduction (see Armbrust et al., 2009).

As Figure 13 shows, the published NIPA index declined at an average annual rate of 2.0% over the 2015 to 2021 period. The ICT price index declined—on the right side of the figure—at an average annual rate of 6.4% over the same period for a net increase in the price decline of 4.4 ppts.

The finding that the ICT shadow price index has been declining more rapidly than the NIPA estimates implies investment spending, productivity growth, and real GDP growth have been underestimated. The model follows closely the work of Byrne et al. (2013) and Greenstein and Nagle (2014) who measure productivity and growth improvement from the broader application and adoption of ICT.³⁰ Table 7 shows comparative investment and growth calculations which assumes a 4.4 ppt average annual underestimate of the ICT function price decline between

³⁰Like the two-sector 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.

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Annual growth rates					
2015-2021					
	NIPA data	As calculated	Difference		
GDP	2.2%	2.3%	0.1%		
Gross private fixed investment	2.8%	3.4%	0.7%		
Fixed investment	3.3%	4.0%	0.7%		
Nonresidential fixed investment	3.0%	3.8%	0.9%		
Intellectual property products	8.0%	10.1%	2.1%		
Software	11.4%	15.8%	4.4%		
Sot	ftware Investment	t %			
	2021				
	NIPA Data	As Calculated	Difference		
% of GDP	3.0%	3.8%	0.8%		
% Private fixed investment	15.0%	18.9%	3.9%		
% Nonresidential fixed investment	19.6%	24.7%	5.1%		
% Intellectual property products	47.4%	59.9%	12.4%		

 $TABLE \ 7$ Revised Business Sector ICT Real Spending Estimates Billions of 2017 Dollars

Source: Author's Calculations. Assumes 5.7% underestimate of constant dollar software spending growth.

2015 and 2021 as shown above in Figure 13. As the table shows, investment spending estimates increase meaningfully with a smaller impact on the overall real GDP growth rate.

6. CONCLUSION

The introduction of enterprise software spending in theNIPA, 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 made a meaningful contribution to productivity improvement over the second half of the 1990s. However, over more recent decades much has changed. The nature and manner in which ICT is produced, deployed, and used has changed markedly. As a result, current estimates of price changes in enterprise software appear to underestimate the declines realized in the current century. The consequence is an underestimate of real private fixed investment spending, real GDP growth, and productivity improvement.

Price changes in business sector ICT software—the shadow price change—is the cost-share weighted average of the changes in resource prices minus the change in MFP. 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 2007–2010, a 6.7% CAGR over the more recent 2015–2021 period, and 3.7% over 2007–2021. MFP improvement has been somewhat less consistent with a 0.6% CAGR over 2007–2021, but a 2.1% CAGR over the more recent 2015–2021 period.

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In improving the price index, the largest contribution results from a methodological shift from traditional price indices which measure software acquisition prices as software is purchased from the software development sector to a bundle of capital services prices. The business sector ICT function employs a range of tangible capital assets, including communications, computing, and storage equipment, software, and other capital, such as facilities and buildings. Collectively, these capital assets contribute to less expensive software produced for business sector use.

Additionally, to 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 cost of the largest resource in the enterprise ICT services mix. Software spending is 59% of total ICT spending in 2021.

The view of the business sector ICT function that emerges 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. While, ultimately, software is the output with which business users interact, software is also a critical factor in the production process. Second, the attractiveness and convenience of cloud computing have, apparently, limited transaction price declines for the first decade of its life and slowed software price declines. Third, the use of imported services, which accelerated broadly in the first decade of the century, has slowed recently. Finally, employment and productivity improvement have been sensitive and responsive to aggregate economic conditions.

Taken together, the model and resulting estimates find, between 2015 and 2021, the ICT shadow price index declined at a 6.4% annual rate, 4.4 percent points more than published NIPA estimates. Between 2007 and 2021, the ICT shadow price index declined at a 4.2% annual rate, 2.4 percent points more than published estimates.

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

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site:

Data S1. Supplementary Information.

Appendix A. Cost Minimization in Dual Production Theory.

Appendix B. The Scientific R&D Services Sector.

Appendix C. Business Sector ICT Shadow Price and Software Developer Productivity.

Appendix D. Data Sources and Assumptions.

Appendix E. Resources and Prices.