Digitalization and Productivity Growth Slowdown in Production Networks

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Abstract

I examine the recent productivity growth slowdown and the emergence of digital technologies through the lens of production networks. Digital technologies are increasingly embedded in intermediate inputs, and digital-intensive sectors, often key producers of intermediate and capital goods, amplify the positive effects of these technologies across industries. I show that the slowdown in computer-specific technical change has contributed to the decline in aggregate productivity growth, particularly in digital-intensive service industries, with these effects spreading through the economy via intersectoral linkages. My estimates suggest that this accounts for around 45–55% of the productivity growth slowdown in both the UK and the US since the mid-2000s. I attribute this slowdown largely to structural changes within the computers industry, especially the rising value-added intensity of the sector. In general, production in digital technology-producing industries is characterized by perfect complementarity, explaining the waning effects of digital technologies on aggregate productivity since the mid-2000s. In light of these findings, I take a pessimistic view on the future of productivity growth.

JEL Classification: O30, O33, D57, O47, L86, L23
Keywords: digitalization, productivity, production networks, investment-specific technical change

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1 Introduction

Paul Krugman famously remarked that "productivity isn't everything, but in the long run, it is everything." Given the profound impact of productivity on well-being, it is not surprising that the productivity growth slowdown observed in developed countries since the mid-2000s raises concerns about the sustainability of long-term progress and improving living standards. Reversing this slowdown is one of the paramount challenges facing policymakers today.

The causes of the productivity growth slowdown have already sparked an extensive literature, recently reviewed by Goldin et al. (2024). However, the network origins of the productivity growth slowdown have been largely overlooked. In this context, adopting a network perspective is likely the correct approach. In a typical economy, industries are interconnected; the output of one industry often serves as an intermediate or capital good for others. This interdependence implies that productivity improvements in one industry can positively influence productivity growth in the industries that rely on its output. Such linkages play a crucial role in shaping the dynamics of aggregate productivity growth. As Foerster et al. (2022) show, sectoral sources account for approximately 75% of the changes in aggregate productivity in the US during the post-WWII period.

A network perspective is not only crucial for understanding the recent productivity growth slowdown but also for analyzing the productivity effects of emerging technologies, such as digitalization. First, digital technologies are increasingly embedded in intermediate inputs, such as cloud computing and software used in automation and robotics. Second, even when digital technologies take the form of capital goods, these goods often have significantly higher depreciation rates—around 50–60%—compared to typical capital goods, blurring the distinction between intermediate and capital inputs in the context of digitalization. Third, and most importantly, digital-intensive sectors of the economy are generally producers of intermediate and capital goods, occupying highly central positions in production networks. The positive effects of digital technologies on productivity growth are amplified through the industries that use these technologies intensively. Notably, these digital-intensive sectors were instrumental in the productivity growth revival observed between the mid-1990s and mid-2000s (Triplett and Bosworth 2004; Jorgenson et al. 2005; Stiroh 2002).

In this research, I examine the productivity growth slowdown and digitalization through the lens of production networks. This study provides a comparative analysis of the productivity effects of digital technologies in the UK and the US over the past 35 years. I classify digital technologies into three types of capital goods: computers and peripheral equipment, communications equipment, and software (pre-packaged, custom, and own-account). While this classification closely aligns with the conventional ICT capital definition, my model is sufficiently general to accommodate other forms of digital technologies, including cloud computing and robotics. Furthermore, although computers are integral to many other types of capital goods, such as medical equipment and aircraft, my classification does not incorporate this distinction when defining an industry as digital-intensive. However, the model is designed to be flexible enough to account for such cases.

When defining an industry as digital-intensive, I consider the share of digital capital in industrial value added. The median value of this share across industries is approximately 3% for both the US and the UK. Industries with a digital capital share above this threshold are classified as digital-intensive. There is significant overlap between the UK and the US in the identification of digital-intensive industries. These industries are predominantly service sectors that primarily produce intermediate inputs and capital goods, including wholesale trade, finance, professional, scientific, and technical activities, broadcasting and telecommunications, and administrative and support services. In contrast, service industries primarily catering to final consumption—such as food and accommodation, health, and education—are characterized by low digital intensity and similarly low productivity growth. Capital goods producers in the manufacturing sector also exhibit above-average digital intensity, though not as high as that observed in digital-intensive service industries.

The four stylized facts about digital services motivate the main question of this research. First, digital-intensive service industries are highly central within production networks. Second, over time, service industries—and the services sector as a whole—have become increasingly intermediate-intensive, with digital-intensive service industries driving this transformation. Evidence suggests that the growing intermediate intensity in the services sector results from a substitutability between intermediate inputs and value added. Consequently, structural shifts toward services driven by this dynamic counteract the Baumol's cost disease effect on aggregate productivity growth, as first observed by Oulton (2001). Third, aggregate productivity growth patterns in both the UK and the US closely track those of digital-intensive service industries. Fourth, when the definition of capital is restricted to equipment and software, digital-intensive service industries emerge as the most capital-intensive subgroup of the economy. In these industries, capital deepening almost entirely accounts for long-term productivity growth. In fact, in certain digital-intensive service industries—such as finance, business services, and administrative and support services—excluding capital deepening reveals no labor productivity growth at all. In other words, capital-embodied technical change serves as the primary engine of growth in digital-intensive services.

Examining the relative price dynamics of different capital goods between the 1995–2005 period and 2005–2021 reveals a striking pattern: the slowdown in computer-specific technical change. Specifically, the price of computers and peripheral equipment relative to consumption declined by an astonishing 20% per year between 1995 and 2005, but this rate of decline has slowed to just 5% per year since then. Similar trends are not observed for other types of capital goods. This observation forms the central argument of this paper: the slowdown in computer-specific technical change has contributed to a deceleration in productivity growth in digital-intensive service industries, which, in turn, has propagated to the aggregate economy through intersectoral linkages.

To explore this idea in greater detail and quantify the effects of the slowdown in computer-specific technical change, I employ a production networks model that incorporates different types of capital goods. The model is both rich and highly disaggregated, encompassing 60 industries and 30 types of capital. It accounts for sectoral heterogeneity in production and captures the increasing intermediate intensity in the services sector by modeling a non-unitary elasticity of substitution between labor and digital-intensive services. For tractability, I adopt a unitary elasticity specification for other production inputs. The model also includes exogenous technical change for investment and intermediate goods across industries, which accounts for imported intermediates and capital goods while addressing potential measurement issues.

My results indicate that the slowdown in computer-specific technical change alone accounts for approximately 45–55% of the productivity growth slowdown in both the UK and the US. Similarly, this slowdown explains around 50% of the productivity growth deceleration in digital-intensive service industries. While the computers sector is the primary driver of the overall productivity slowdown in both countries, other industries have also made significant contributions. My findings suggest that durable goods, excluding the computer and electronic products industry, have contributed an additional 16% to the productivity growth slowdown. This is largely because durable goods are key suppliers of equipment and intermediate inputs used in capital goods. In the US, wholesale trade emerges as another major contributor to the productivity slowdown, while in the UK, scientific research and development plays a similar role. Overall, approximately 90% of the aggregate productivity growth slowdown in the US since the mid-2000s can be attributed to the computer and electronic products, durable goods, and wholesale trade industries. As all these industries are primary suppliers of capital goods, the recent productivity growth slowdown should be viewed as a broader deceleration in capital-embodied technical change.

I also examine the sources of this slowdown. Evidence from the US highlights three prominent structural changes in computer production. First, the computer system design industry, which is associated with custom and own-account software, has accounted for an increasing share of computer capital production over time—rising from a modest 7% in 1997 to 34% in 2021. Second, service intermediates have grown to represent a larger share of the intermediate inputs used in the computer and electronic products industry. Third, and most strikingly, the production in the computer and electronic products industry has become significantly more value-added intensive, increasing from 40% in 2003 to 85% in 2021. I argue that these structural changes in computer production can be explained by complementarities in production. This perspective also provides an explanation for both the slowdown in computer-specific technical change and the broader productivity growth slowdown. As complementarities in production become more pronounced beyond a certain level, the productivity dynamics of the computer industry increasingly hinge on the weakest links in the production process.

My results also suggest that perfect complementarity in production is not limited to the computers sector but is a general characteristic of all digital-technology-producing industries. Furthermore, production in capital goods producers and their suppliers is typically characterized by strong complementarities. Since capital goods and digital-intensive products are the primary engines of economic growth, it is reasonable to expect that this "cost disease" will impede the productivity growth of the industries that produce them, thereby slowing aggregate productivity growth.

This research provides a complementary perspective on the discussions surrounding the productivity growth slowdown. More specifically, I emphasize the forces within the neoclassical growth model rather than an innovation-centered perspective. The orthodox view on the productivity growth slowdown has largely focused on the long-term detrimental effects of information and communication technologies on innovation, as argued by De Ridder (2024) and Aghion et al. (2023). However, when examining the relative price patterns of R&D before and after 2005, the evidence suggests that the slowdown in R&D-specific technical change is generally too small to fully account for the productivity growth slowdown. Another related point concerns the emphasis on competition policy. In fact, industries most closely associated with Big Tech do not exhibit a slowdown in productivity growth, which challenges this view.

This paper is related to several strands of literature. First, it contributes to the body of research examining the economic growth implications of production networks, including works by Grobovšek (2018), Ngai and Samaniego (2009), Foerster et al. (2022), Gaggl et al. (2023), and Fadinger et al. (2022). It also relates to the literature that incorporates heterogeneous capital goods and capital flows within a production network framework, such as Casal and Caunedo (2024), Ding (2023), and vom Lehn and Winberry (2022). Additionally, this work complements research emphasizing the role of capital-embodied technical change in aggregate productivity, including Aum et al. (2018), Caunedo and Keller (2023), Greenwood et al. (1997), and Takahashi and Takayama (2023). Finally, it connects to studies that extend beyond Cobb-Douglas gross output production functions, highlighting sectoral heterogeneity in production, as explored by Miranda-Pinto (2021), Giannoni and Mertens (2019), and Poirier and Vermandel (2023).

This paper is organized as follows. The next section introduces the classification of digital-intensive service industries and presents several stylized facts about these industries that motivate this study. The third section develops a multi-sectoral model with intersectoral linkages to analyze the relationship between digitalization and the productivity growth slowdown. The fourth section examines counterfactual scenarios related to capital-embodied technical change, quantifying the role of different types of capital goods in aggregate productivity growth. The fifth section discusses structural changes in digital-technology-producing industries. Finally, the last section concludes.

2 Facts on Digitalization

This section focuses on modeling digitalization and classifying digital-intensive industries. Following this classification, I present several stylized facts about production networks, productivity, and the production characteristics of digital-intensive industries.

2.1 Modelling Digitalization and Digital-Intensive Industries

I define digitalization in the context of productivity growth primarily as the production of capital goods. In this framework, digital technologies are represented by the types of capital that produce these technologies, and the productivity effects of digitalization are modeled as greater technical progress in these types of capital goods—manifesting as declines in their prices relative to consumption. Within a production networks setting, this enhanced technical progress in digital capital goods is amplified through the intermediate and capital goods producers that use these technologies intensively.

Among the many capital goods listed in Table 1, digital capital is represented by three categories: computer hardware, communications equipment, and software (including pre-packaged, custom, and own-account types). By restricting the definition of digital capital to these three categories, I exclude certain capital types that also rely on digital technologies. For instance, medical instruments and office equipment embody digital technologies but are not included. Similarly, by focusing on capital goods, this definition does not capture the increasing role of digital technologies in the form of intermediate inputs, such as cloud computing. To address these limitations, I assume that industries intensive in digital capital goods are also, on average, more intensive in other capital goods relying on digital technologies and in intermediate inputs sourced from digital-technology-producing industries. My classification of digital capital aligns closely with the commonly used definition of information and communications technology (ICT) capital in the literature. However, by employing a general model with intersectoral linkages and multiple types of capital, my approach extends beyond the typical ICT capital definition to account for the growing embodiment of digital technologies in intermediate inputs.

I measure the digital intensity of an industry as the share of digital capital in the industry's total value added. Table 2 ranks industries in terms of digital intensity for the UK, while Table 3 provides the same ranking for the US. The data reveal that the median digital intensity is 3.3% for the UK and 2.1% for the US, reflecting greater granularity in the latter case. Despite significant heterogeneity across industries, some common patterns emerge between the UK and the US. The most digital-intensive industries are generally service sectors that primarily produce intermediate inputs and capital goods, including wholesale and retail trade, finance, professional, scientific,

Table 1: Capital Types

Furniture and Fixtures
Fabricated Metal Products
Engines and Turbines
Agricultural Machinery
Construction Machinery
Mining and Oilfield ,Machinery
Metalworking Machinery
Special Industry Machinery, n.e.c.
General Industrial, including Materials Handling, Equipment
Office and Accounting Equipment
Service Industry Machinery
Communication Equipment
Electrical Transmission, Distribution, and Industrial Apparatus
Electrical Equipment, n.e.c.
Light Trucks
Other Trucks, Buses, and Truck Trailers
Autos
Aircraft
Ships and Boats
Railroad Equipment
Photocopy and Related Equipment
Medical Equipment and Instruments
Nonmedical Instruments
Other Equipment
Computers and Peripheral Equipment
Prepackaged Software
Custom Software
Own-Account Software
Research and Development
Structures
Entertainment, Literary, and Artistic Originals

Notes: The data source for capital types is the Bureau of Labor Statistics (BLS).

and technical services, administrative and support services, most transportation industries, and the information sector. Conversely, the least digital-intensive industries are typically service sectors associated with Baumol's cost disease (Baumol, 1967), such as education, health, real estate, food and accommodation, and arts and entertainment. In the goods-producing sector, capital goods manufacturing industries tend to exhibit above-average digital intensity, whereas non-manufacturing goods industries, such as agriculture, mining, and construction, generally have very low digital intensity.

Building on these facts and given the focus of this paper on the services sector—which constitutes approximately 80% of the aggregate economy in both the UK and the US—I adopt a three-sector classification of the economy for the remainder of this analysis. These sectors are: (1) goods (including agriculture, mining, utilities, construction, and manufacturing); (2) digital-intensive services, defined as service industries with above-average digital intensity; and (3) stagnant services, comprising service industries with below-average digital intensity.

This distinction between digital-intensive and stagnant services is not only relevant in the context of digitalization but also in other contexts. For instance, a classification based on high- and low-productivity growth service industries would yield a similar distinction. Digital-intensive services are generally producers of capital and intermediate inputs and are more closely tied to the production side of the economy, whereas stagnant services predominantly cater to final consumption. This classification also highlights differences in capital intensity and the use of specific types of capital across service industries. Digital-intensive services are not only more capital-intensive than stagnant services but also exhibit greater intensity in equipment and software capital, where capital-embodied technical change is significant. In contrast, stagnant services are more intensive in structures capital. Moreover, digital-intensive services are typically tradable, while stagnant services are not. Lastly, the distinction between digital-intensive and stagnant services largely overlaps with the categorization of market and non-market services.[1]

In the remainder of this subsection, I present key facts about digital services that serve as motivation for this paper.

[1]For the remainder of this text, I will refer to digital-intensive services as digital services, acknowledging a slight misuse of terminology. This classification is more appropriate for industries that produce digital service intermediates, rather than those that primarily utilize digital technologies.

Table 2: Ranking of Industries by Digital Intensity - UK

NACE Code	Industry Name	Digital Intensity
J61	Telecommunications	0.295
K	Financial and insurance activities	0.133
J62-J63	Computer programming, consultancy, and information service activities	0.109
S	Other service activities	0.102
G46	Wholesale trade, except of motor vehicles and motorcycles	0.088
M	Professional, scientific and technical activities	0.079
J58-J60	Publishing, motion picture, video, television programme production; sound recording, programming and broadcasting activities	0.063
C28	Manufacture of machinery and equipment n.e.c.	0.062
N	Administrative and support service activities	0.055
H53	Postal and courier activities	0.054
G47	Retail trade, except of motor vehicles and motorcycles	0.053
D	Electricity, gas, steam and air conditioning supply	0.051
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	0.049
C31-C33	Manufacture of furniture; jewellery, musical instruments, toys; repair and installation of machinery and equipment	0.047
H51	Air transport	0.045
C20	Manufacture of chemicals and chemical products	0.041
C19	Manufacture of coke and refined petroleum products	0.036
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles	0.035
C16-C18	Manufacture of wood, paper, printing and reproduction	0.034
C29-C30	Manufacture of motor vehicles, trailers, semi-trailers and of other transport equipment	0.034
	Median	**0.033**
C10-C12	Manufacture of food products; beverages and tobacco products	0.032
H52	Warehousing and support activities for transportation	0.032
R	Arts, entertainment and recreation	0.030
C27	Manufacture of electrical equipment	0.030
E	Water supply; sewerage, waste management and remediation activities	0.029
C22-C23	Manufacture of rubber and plastic products and other non-metallic mineral products	0.026
C26	Manufacture of computer, electronic and optical products	0.025
C24-C25	Manufacture of basic metals and fabricated metal products, except machinery and equipment	0.024
C13-C15	Manufacture of textiles, wearing apparel, leather and related products	0.023
O	Public administration and defence; compulsory social security	0.022
H50	Water transport	0.019
I	Accommodation and food service activities	0.018
P	Education	0.016
Q86	Human health activities	0.015
H49	Land transport and transport via pipelines	0.011
Q87-Q88	Residential care activities and social work activities without accommodation	0.010
B	Mining and quarrying	0.009
F	Construction	0.006
L	Real estate activities	0.003
A	Agriculture, forestry and fishing	0.002

Notes: The digital intensity numbers refer to the average use share of digital capital (computers, communications equipment, and software) in total value added of an industry between 1995 and 2020. The data source is the 2023 release of the EUKLEMS & INTANProd. In the construction of shares I use the rental prices of different assets.

Table 3: Ranking of Industries by Digital Intensity - US

Production Account Code	Industry Name	Digital Intensity
513	Broadcasting and telecommunications	0.321
514	Data processing, internet publishing, and other information services	0.250
524	Insurance carriers and related activities	0.165
532RL	Rental and leasing services and lessors of intangible assets	0.129
521CI	Federal Reserve banks, credit intermediation, and related activities	0.112
511	Publishing industries, except internet (includes software)	0.092
5411	Legal services	0.078
483	Water transportation	0.074
486	Pipeline transportation	0.073
561	Administrative and support services	0.072
42	Wholesale trade	0.065
5412OP	Miscellaneous professional, scientific, and technical services	0.065
481	Air transportation	0.054
334	Computer and electronic products	0.054
485	Transit and ground passenger transportation	0.053
GF	Federal	0.046
22	Utilities	0.044
44RT	Retail trade	0.044
3364OT	Other transportation equipment	0.039
333	Machinery	0.037
55	Management of companies and enterprises	0.031
5415	Computer systems design and related services	0.031
523	Securities, commodity contracts, and investments	0.030
335	Electrical equipment, appliances, and components	0.030
325	Chemical products	0.029
339	Miscellaneous manufacturing	0.027
324	Petroleum and coal products	0.027
562	Waste management and remediation services	0.026
487OS	Other transportation and support activities	0.025
311FT	Food and beverage and tobacco products	0.022
	Median	**0.021**
3361MV	Motor vehicles, bodies and trailers, and parts	0.021
322	Paper products	0.021
323	Printing and related support activities	0.020
525	Funds, trusts, and other financial vehicles	0.019
484	Truck transportation	0.018
327	Nonmetallic mineral products	0.018
326	Plastics and rubber products7 0.018	
721	Accommodation	0.017
332	Fabricated metal products	0.017
713	Amusements, gambling, and recreation industries	0.015
337	Furniture and related products	0.015
61	Educational services	0.015
213	Support activities for mining	0.014
81	Other services, except government	0.014
212	Mining, except oil and gas	0.014
512	Motion picture and sound recording industries	0.013
331	Primary metals	0.012
493	Warehousing and storage	0.012
GSL	State and local	0.012
23	Construction	0.011
313TT	Textile mills and textile product mills	0.011
722	Food services and drinking places	0.010
321	Wood products	0.010
621	Ambulatory health care services	0.009
113FF	Forestry, fishing, and related activities	0.007
211	Oil and gas extraction	0.007
482	Rail transportation	0.007
622HO	Hospitals and nursing and residential care facilities	0.007
315AL	Apparel and leather and allied products	0.006
624	Social assistance	0.004
711AS	Performing arts, spectator sports, museums, and related activities	0.004
531	Real estate	0.004
111CA	Farms	0.000

Notes: The digital intensity numbers refer to the average use share of digital capital (computers, communications equipment, and software) in total value added of an industry between 1987 and 2020. The data source is the May 2022 release of the BEA/BLS Integrated Industry-Level Production Account.

Table 4: Classification of Industries: US and UK

	US	UK
Goods	Farms	Agriculture, forestry and fishing
	Forestry, fishing, and related activities	Mining and quarrying
	Oil and gas extraction	Manufacture of food products; beverages and tobacco products
	Mining, except oil and gas	Manufacture of textiles, wearing apparel, leather and related products
	Support activities for mining	Manufacture of wood, paper, printing and reproduction
	Utilities	Manufacture of coke and refined petroleum products
	Construction	Manufacture of chemicals and chemical products
	Wood products	Manufacture of basic pharmaceutical products and pharmaceutical preparations
	Nonmetallic mineral products	Manufacture of rubber and plastic products and other non-metallic mineral products
	Primary metals	Manufacture of basic metals and fabricated metal products, except machinery and equipment
	Fabricated metal products	Manufacture of computer, electronic and optical products
	Machinery	Manufacture of electrical equipment
	Computer and electronic products	Manufacture of machinery and equipment n.e.c.
	Electrical equipment, appliances, and components	Manufacture of motor vehicles, trailers, semi-trailers and of other transport equipment
	Motor vehicles, bodies and trailers, and parts	Manufacture of furniture; jewellery, musical instruments, toys; repair and installation of machinery and equipment
	Other transportation equipment	Electricity, gas, steam and air conditioning supply
	Furniture and related products	Water supply; sewerage, waste management and remediation activities
	Miscellaneous manufacturing	Construction
	Food and beverage and tobacco products	
	Textile mills and textile product mills	
	Apparel and leather and allied products	
	Paper products	
	Printing and related support activities	
	Petroleum and coal products	
	Chemical products	
	Plastics and rubber products	
Digital Services	Wholesale trade	Wholesale and retail trade and repair of motor vehicles and motorcycles
	Retail trade	Wholesale trade, except of motor vehicles and motorcycles
	Air transportation	Retail trade, except of motor vehicles and motorcycles
	Water transportation	Air transport
	Transit and ground passenger transportation	Postal and courier activities
	Pipeline transportation	Publishing, motion picture, video, television programme production; sound recording, programming and broadcasting activities
	Other transportation and support activities	Telecommunications
	Publishing industries, except internet (includes software)	Computer programming, consultancy, and information service activities
	Broadcasting and telecommunications	Financial and insurance activities
	Data processing, internet publishing, and other information services	Professional, scientific and technical activities
	Federal Reserve banks, credit intermediation, and related activities	Administrative and support service activities
	Securities, commodity contracts, and investments	
	Insurance carriers and related activities	
	Rental and leasing services and lessors of intangible assets	
	Legal services	
	Computer systems design and related services	
	Miscellaneous professional, scientific, and technical services	
	Management of companies and enterprises	
	Administrative and support services	
	Waste management and remediation services	
	Federal	
Stagnant Services	Rail transportation	Land transport and transport via pipelines
	Truck transportation	Water transport
	Warehousing and storage	Warehousing and support activities for transportation
	Motion picture and sound recording industries	Accommodation and food service activities
	Funds, trusts, and other financial vehicles	Real estate activities
	Real estate	Public administration and defence; compulsory social security
	Educational services	Education
	Ambulatory health care services	Human health activities
	Hospitals and nursing and residential care facilities	Residential care activities and social work activities without accommodation
	Social assistance	Arts, entertainment and recreation
	Performing arts, spectator sports, museums, and related activities	Other service activities
	Amusements, gambling, and recreation industries	
	Accommodation	
	Food services and drinking places	
	Other services, except government	
	State and local	

2.2 Centrality in Production Networks and Digital Services

The primary centrality measure used in this paper is outdegree, defined as the sum of row entries for a supplier industry in an input-output matrix. In essence, outdegree measures the importance of a given industry to other industries in the economy as a supplier of intermediate goods. Tables 5 and 6 present a ranking of industries based on their outdegrees for the US and the UK, respectively. As shown in these tables, the most central industries in the production networks of both countries are predominantly digital-intensive service industries, including wholesale and retail trade, finance, professional, scientific, and technical services, administrative and support services, and industries within the information sector. Notably, the least central industries in the production networks are typically stagnant services, such as education, health, and public administration.

The centrality of digital-intensive service industries in the production networks of the UK and the US suggests that any positive or negative shocks to digital-technology producers are likely to propagate throughout the economy via service industries that use these technologies intensively. Given this centrality, it is unsurprising that an overall technological slowdown in digital production could generate economy-wide effects through intersectoral linkages.

2.3 Structural Change in Production Networks and Intermediate Inputs Intensity

Although the centrality of digital-intensive service industries in production networks is well established, their evolving importance over time is less clear. To analyze the evolution of production networks and the role of digital-intensive service industries in driving structural change, I examine changes in the shares of production factors—namely labor, capital, energy, materials, digital-intensive service intermediates, and stagnant service intermediates—in gross output across various levels of aggregation, including the aggregate economy, goods, services, digital-intensive services, and stagnant services.

Figure 1 illustrates the intermediate input intensity of gross output for both the aggregate economy and the services sector in the US, beginning in 1987. While the intermediate input intensity of gross output remains relatively stable for the aggregate economy, as noted in previous studies (e.g., Moro, 2012), it has been steadily increasing for the services sector.[2]

[2]The increasing intermediate input intensity of the services sector does not necessarily contradict studies

Table 5: Ranking of Industries by Outdegree - US

Production Account Code	Industry Name	Outdegree
541AO	All other professional, scientific, and technical services	5.41
42	Wholesale trade	5.38
ORE	Other real estate	5.25
561	Administrative and support services	4.69
55	Management of companies and enterprises	3.83
524	Insurance carriers and related activities	2.95
521CI	Federal Reserve banks, credit intermediation, and related activities	2.86
325AO	Other chemical products	2.32
332	Fabricated metal products	2.15
523	Securities, commodity contracts, and investments	2.02
324	Petroleum and coal products	1.96
331	Primary metals	1.94
513	Broadcasting and telecommunications	1.93
22	Utilities	1.53
532RL	Rental and leasing services and lessors of intangible assets	1.49
487OS	Other transportation and support activities	1.44
81	Other services, except government	1.33
5415	Computer systems design and related services	1.27
311FT	Food and beverage and tobacco products	1.26
23	Construction	1.24
484	Truck transportation	1.22
3344	Semiconductor and other electronic component manufacturing	1.21
493	Warehousing and storage	1.17
326	Plastics and rubber products	1.16
722	Food services and drinking places	1.15
211	Oil and gas extraction	1.12
322	Paper products	1.11
333	Machinery	1.11
5411	Legal services	1.09
3361MV	Motor vehicles, bodies and trailers, and parts	1.03
519	Other information services	0.91
321	Wood products	0.86
GSLE	State and local government enterprises	0.82
111CA	Farms	0.79
313TT	Textile mills and textile product mills	0.79
3364	Aerospace product and parts manufacturing	0.76
3254	Pharmaceutical and medicine manufacturing	0.73
113FF	Forestry, fishing, and related activities	0.73
711AS	Performing arts, spectator sports, museums, and related activities	0.70
335	Electrical equipment, appliances, and components	0.68
518	Data processing, hosting, and related services	0.65
327	Nonmetallic mineral products	0.58
512	Motion picture and sound recording industries	0.54
3342	Communications equipment manufacturing	0.52
3345	Navigational, measuring, electromedical, and control instruments manufacturing	0.51
562	Waste management and remediation services	0.49
323	Printing and related support activities	0.47
212	Mining, except oil and gas	0.47
4A0	Other retail	0.46
481	Air transportation	0.45
GFE	Federal government enterprises	0.36
721	Accommodation	0.34
5112	Software publishers	0.34
482	Rail transportation	0.32
5111	Newspaper, periodical, book, and directory publishers	0.27
485	Transit and ground passenger transportation	0.26
315AL	Apparel and leather and allied products	0.24
3365AO	All other transportation equipment manufacturing	0.24
486	Pipeline transportation	0.22
3391	Medical equipment and supplies manufacturing	0.21
337	Furniture and related products	0.20
3399	Other miscellaneous manufacturing	0.20
334AO	Other computer and electronic product manufacturing	0.19
61	Educational services	0.17
441	Motor vehicle and parts dealers	0.14
213	Support activities for mining	0.14
GSLGAO	All other state and local general government	0.12
621	Ambulatory health care services	0.10
525	Funds, trusts, and other financial vehicles	0.09
5417	Scientific research and development services	0.08
483	Water transportation	0.07
GSLGE	State and local government educational services	0.06
452	General merchandise stores	0.05
623	Nursing and residential care facilities	0.03
713	Amusements, gambling, and recreation industries	0.02
445	Food and beverage stores	0.01
622	Hospitals	0.01
624	Social assistance	0.00
GFGN	Federal general government (nondefense)	0.00
HS	Housing	0.00
GFGD	Federal general government (defense)	0.00

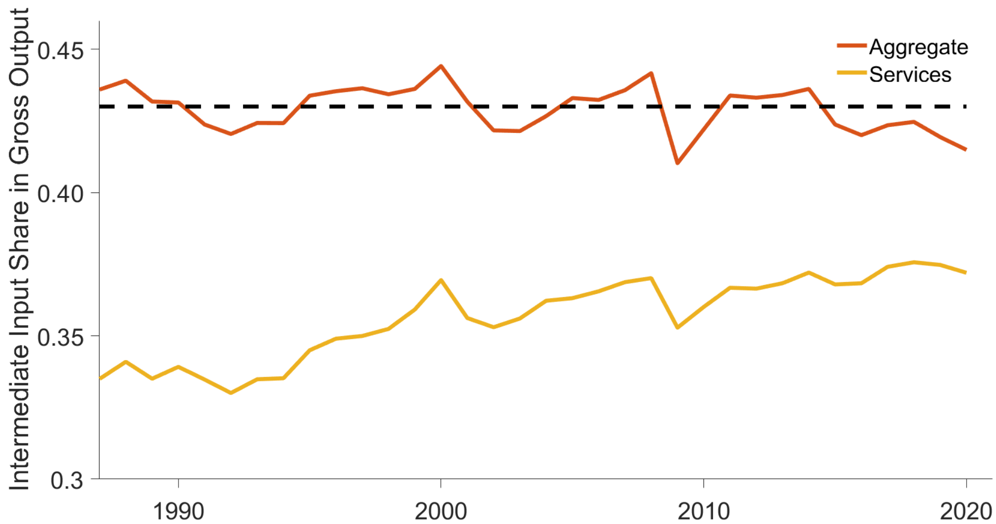
Notes: The outdegrees are calculated as the sum of row entries of the input-output matrix. I use the input-output matrix of the US for 2019 from the BEA.

Table 6: Ranking of Industries by Outdegree - UK

Production Account Code	Industry Name	Outdegree
G46	Wholesale trade, except of motor vehicles and motorcycles	5.44
N	Administrative and support service activities	3.70
K64	Financial service activities, except insurance and pension funding	2.80
D35	Electricity, gas, steam and air conditioning supply	2.39
J62-J63	Computer programming, consultancy and related activities; information service activities	2.33
M69-M70	Legal and accounting activities; activities of head offices; management consultancy activities	2.13
H49	Land transport and transport via pipelines	1.82
F	Construction	1.78
K66	Activities auxiliary to financial services and insurance activities	1.66
G47	Retail trade, except of motor vehicles and motorcycles	1.51
L68	Real estate activities	1.48
H52	Warehousing and support activities for transportation	1.43
C33	Repair and installation of machinery and equipment	1.42
M73	Advertising and market research	1.39
C10-C12	Manufacture of food products, beverages and tobacco products	1.37
C20	Manufacture of chemicals and chemical products	1.18
C25	Manufacture of fabricated metal products, except machinery and equipment	1.10
M74-M75	Other professional, scientific and technical activities; veterinary activities	1.08
M71	Architectural and engineering activities; technical testing and analysis	1.06
H53	Postal and courier activities	1.01
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles	0.98
E37-E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	0.80
K65	Insurance, reinsurance and pension funding, except compulsory social security	0.79
C19	Manufacture of coke and refined petroleum products	0.75
J61	Telecommunications	0.73
P85	Education	0.72
C22	Manufacture of rubber and plastic products	0.67
I	Accommodation and food service activities	0.66
H51	Air transport	0.64
A01	Crop and animal production, hunting and related service activities	0.63
C29	Manufacture of motor vehicles, trailers and semi-trailers	0.59
B	Mining and quarrying	0.58
C28	Manufacture of machinery and equipment n.e.c.	0.57
J59-J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	0.53
C24	Manufacture of basic metals	0.50
M72	Scientific research and development	0.50
C18	Printing and reproduction of recorded media	0.50
E36	Water collection, treatment and supply	0.49
C26	Manufacture of computer, electronic and optical products	0.48
R-S	Other service activities	0.47
C30	Manufacture of other transport equipment	0.47
O84	Public administration and defence; compulsory social security	0.46
C17	Manufacture of paper and paper products	0.41
A02	Forestry and logging	0.41
H50	Water transport	0.29
Q	Human health and social work activities	0.25
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	0.25
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	0.22
C23	Manufacture of other non-metallic mineral products	0.21
C27	Manufacture of electrical equipment	0.17
J58	Publishing activities	0.13
C31-C32	Manufacture of furniture; other manufacturing	0.11
C13-C15	Manufacture of textiles, wearing apparel and leather products	0.09
A03	Fishing and aquaculture	0.02

Notes: The outdegrees are calculated as the sum of row entries of the input-output matrix. I use the input-output matrix of the UK for 2019 from the ONS.

Figure 1: Intermediate Input Shares in Gross Output - US



Notes: The data source is the BEA-BLS Integrated Industry-Level Production Account.

Tables 7 and 8 provide more detailed evidence on the changes in the shares of factor inputs. Table 7 shows that intermediate input intensity remains stable at around 0.45 of gross output for both the US and the UK. While the share of capital in gross output increases in the US, it declines in the UK. The sub-sectors comprising total intermediate inputs exhibit stable shares in the UK. In contrast, in the US, the share of energy and materials (goods) in gross output declines, while the share of intermediate inputs supplied by digital-intensive service industries rises. Overall, the patterns observed for the aggregate economy are consistent with a stable share of intermediate inputs, a non-unitary elasticity of substitution between capital and labor, and a non-unitary elasticity of substitution between energy/materials and digital services.

At a more disaggregated level, a different picture emerges for the US. Table 8 shows that intermediate input intensity increases for the services sector while remaining constant for the goods sector. Although the labor share in gross output declines for services, the corresponding increase in the capital share is insufficient to fully account for the decline. Meanwhile, the

that argue this share is stable for the sector. Many of the studies supporting the stability of intermediate input intensity, such as Moro (2012, 2015), rely on the 35-sector database of Jorgenson (2007). The Jorgenson database is KLEM-based, meaning that services are excluded from the definition of intermediate inputs. In this context, the observed increase in intermediate input intensity in the services sector—driven primarily by service intermediates—is consistent with the stability of intermediate input shares reported in other studies. This evidence aligns with the findings presented in this paper.

Table 7: Shares of Production Factors in Gross Output - Aggregate Economy

	US		**UK**	
	1987	**2014**	**1995**	**2014**
Intermediate Inputs	0.44	0.44	0.46	0.46
Capital	0.18	0.21	0.22	0.19
Labor	0.34	0.30	0.31	0.33
Energy/Materials	0.24	0.20	0.18	0.18
Digital Services	0.14	0.18	0.22	0.21
Stagnant Services	0.05	0.06	0.06	0.07

Notes: The data sources are the BEA-BLS Integrated Industry-Level Production Account and input-output tables of the BEA for the US, and input-output tables from the ONS for the UK.

Table 8: Shares of Production Factors in Gross Output at a Disaggregated Level - US

	Goods		**Services**		**Digital Services**		**Stagnant Services**	
	1987	**2014**	**1987**	**2014**	**1987**	**2014**	**1987**	**2014**
Intermediate Inputs	0.60	0.60	0.33	0.37	0.36	0.41	0.31	0.34
Capital	0.12	0.17	0.22	0.23	0.18	0.20	0.20	0.25
Labor	0.26	0.20	0.40	0.34	0.42	0.35	0.38	0.34
Energy/Materials	0.47	0.49	0.10	0.08	0.07	0.06	0.12	0.10
Digital Services	0.10	0.09	0.17	0.21	0.22	0.27	0.12	0.16
Stagnant Services	0.03	0.02	0.07	0.08	0.06	0.07	0.07	0.08

Notes: The data sources are the BEA-BLS Integrated Industry-Level Production Account and input-output tables of the BEA.

share of digital services in gross output rises. Similarly, examining the changes in the shares of different production factors for digital-intensive services reveals similar patterns.

Surprisingly, despite the constant intermediate input share in the goods sector, the share of energy/materials in gross output increases for this sector, while it declines for both digital and stagnant services. This evidence suggests that the decline in the energy/materials share in the aggregate economy is driven by structural shifts toward services and the lower energy/materials intensity of this sector. Moreover, the increasing intermediate input intensity in the services sector appears to reflect a substitutability between labor and digital-intensive services.

Based on these findings, I model the increasing intermediate input intensity in the services sector as a structural shift toward digital-intensive services, driven by their substitutability with labor. Given the near-stability of other production factors (capital, energy/materials, stagnant services) in both the UK and the US, I adopt a Cobb-Douglas specification for them.

2.4 Labor Productivity Growth in Different Sub-Sectors Over Time

Tables 9 and 10 present labor productivity growth dynamics across different time periods for the UK and the US, respectively, based on the sectoral classification used in this study. The data reveal a 1 percentage point (p.p.) decline in the annual labor productivity growth rate for the UK and a 1.4 p.p. decline for the US since 2005. In the UK, the decline in labor productivity growth is more pronounced in the goods sector compared to digital-intensive service industries, whereas stagnant services exhibit an increase in labor productivity growth after 2005. Notably, the aggregate labor productivity growth rate before and after 2005 closely mirrors the productivity growth rate of digital-intensive services.

A similar pattern emerges for the US, where the decline in labor productivity growth is larger for the goods sector than for digital or stagnant services since 2005. As with the UK, changes in the aggregate labor productivity growth rate in the US closely follow those observed in digital-intensive service industries. Overall, the decline in the labor productivity growth rate for digital-intensive service industries after 2005 is remarkably similar between the UK and the US (-1.40 p.p. vs. -1.48 p.p.).

This evidence suggests that aggregate productivity dynamics are strongly influenced by digital-intensive services and points to the presence of common drivers of productivity growth in this sector across both the UK and the US.

Table 9: Labor Productivity Growth Across Sectors: UK

	1995-2005	2005-2020	Difference
Aggregate	1.58	0.53	-1.04
Goods	3.07	0.31	-2.76
Digital Services	1.74	0.34	-1.40
Stagnant Services	-0.23	0.68	0.91

Notes: The data source is the EUKLEMS & INTANProd.

Table 10: Labor Productivity Growth Across Sectors: US

	1995-2005	2005-2020	Difference
Aggregate	2.40	0.98	-1.42
Goods	3.75	1.61	-2.14
Digital Services	2.74	1.26	-1.48
Stagnant Services	1.16	0.39	-0.78

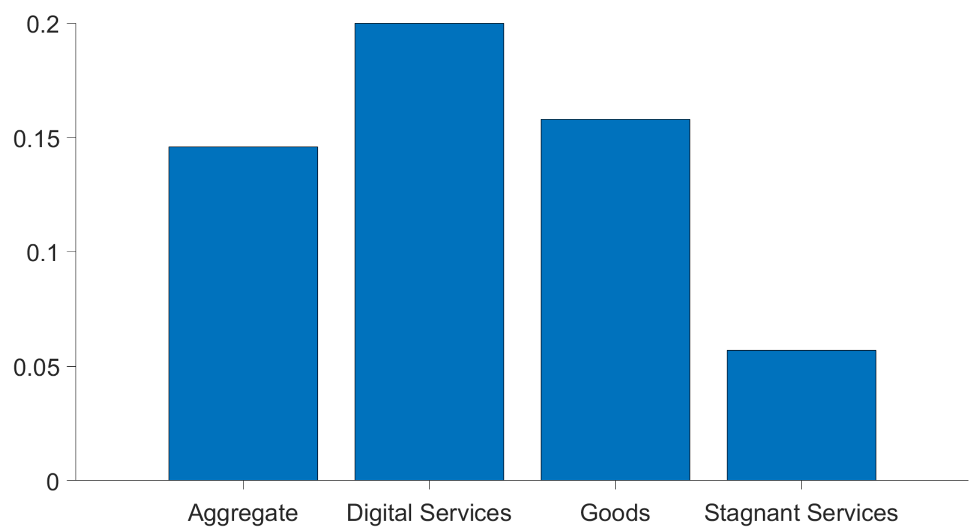
Notes: The data source is the BEA-BLS Integrated Industry-Level Production Account.

2.5 Sources of Productivity Growth in Digital Services

Technical change varies significantly across different types of capital goods, but based on their price dynamics relative to consumption goods, it is strongest in equipment and software capital (Gourio and Rognlie, 2020). Figure 2 illustrates the average equipment and software intensity across various sub-sectors of the US economy. The share of equipment and software in the output of digital-intensive services is approximately 20%, compared to 15% for the aggregate economy and the goods sector, and only about 5% for stagnant services. While digital-intensive services are, by definition, digital capital intensive, their position as the most equipment- and software-intensive sub-sector of the economy also reflects their significant use of equipment excluding digital capital.

More importantly, the equipment used in digital-intensive service industries exhibits greater technical progress than that used in other sub-sectors of the economy—a phenomenon that extends beyond digital capital. In contrast, manufacturing industries are relatively R&D intensive, whereas stagnant services are predominantly structures intensive.

Figure 2: Equipment/Software Shares Across Sub-Sectors - US



Notes: The data source is the BEA-BLS Integrated Industry-Level Production Account. The numbers refer to the use share of equipment and software in total sectoral value added. The values are taken from the last year of the sample, 2020.

Given the high equipment and software intensity of digital-intensive service industries, and the concentration of investment-specific technical progress in the capital types used intensively by this sub-sector, it is relevant to undertake a long-term growth accounting exercise to analyze the extent to which labor productivity growth in digital-intensive services can be attributed to capital deepening alone. Table 11 presents the results of this growth accounting exercise. As shown in the table, capital deepening accounts for the majority of labor productivity growth in digital-intensive service industries in the post-Second World War period in the US. Notably, in certain digital-intensive service industries, such as finance, business services, and administrative and support services, labor productivity growth is entirely driven by capital deepening.

It is important to emphasize that the strong productivity effects of capital deepening in these industries cannot be attributed to the transitional dynamics of capital accumulation, as this growth accounting exercise focuses on the long term, where such dynamics are no longer relevant. Instead, capital deepening in this context reflects technical progress in the capital types used intensively in these industries—specifically, investment-specific technical change embodied in capital.

Table 11: Productivity Growth in Digital Services: US, 1947-2014

	Labor Productivity Growth	**Capital Deepening**	**Percentage**
Wholesale Trade	3.08	1.78	57.72%
Retail Trade	2.08	0.81	38.98%
Information	3.26	2.46	75.24%
Finance	1.56	1.83	117.87%
Professional, Scientific, and Technical Services	1.87	1.91	102.14%
Administrative and Support Services	1.30	1.24	95.18%

Notes: The data source is the WORLD KLEMS. Although most of its industries are digital-intensive, the transportation sector is omitted from this table, since only 20% of its labor productivity growth could be attributed to capital deepening in the period considered. Labor input measure used in calculating labor productivity growth rates accounts for quality improvements.

2.6 Slowdown in Computer-Specific Technical Change

The evidence presented thus far highlights the critical role of digital-intensive services in shaping the dynamics of aggregate productivity growth and underscores capital-embodied technical change as a key driver of productivity growth in these industries. To further explore how changes in technical progress among capital goods producers influence aggregate productivity growth, Table 12 provides evidence on the relative price patterns of different types of capital goods.

Table 12 clearly shows that the decline in the relative price of computers and peripheral

Table 12: Relative Price Dynamics of Different Capital Goods: US

	1995-2005	**2005-2021**
Equipment	-4.51	-2.02
Computers and Peripheral Equipment	-20.56	-5.28
Communication Equipment	-8.09	-9.13
Structures	2.49	1.29
Software	-4.17	-3.09
R&D	-0.16	0.50

Notes: The numbers show the changes in the prices of different capital goods relative to consumption. The data source is the BEA.

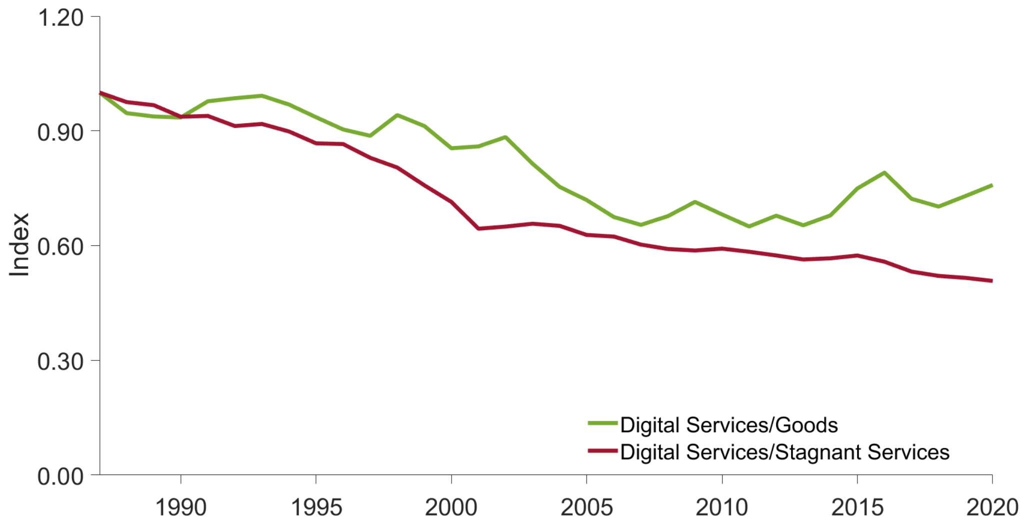
equipment has slowed significantly after 2005, decreasing from 20% per year to 5% per year. While other capital types, such as general equipment, software, and R&D, have also experienced a slowdown in price declines, the magnitude of these changes is far less pronounced compared to computers and peripheral equipment. It is worth noting that digital-intensive service industries, on average, allocate a greater share of their capital to computers compared to the aggregate economy. Figures 3 and 4 provide evidence on how the slowdown in computer-specific technical change[3] has impacted digital services relative to goods and stagnant services.

Figures 3 and 4 show that the rental price of capital has declined significantly in digital-intensive services compared to the goods and stagnant services sectors. However, this decline appears to have largely stalled for both the US and the UK since the mid-2000s. Given the higher intensity of computer capital in digital-intensive services and the more pronounced slowdown in computer-specific technical change after 2005, it can be argued that the slowdown in the decline of the relative rental price of capital in digital services primarily reflects the deceleration in computer-specific technical change.

These stylized facts about digital services form the central premise of this paper. Capital-

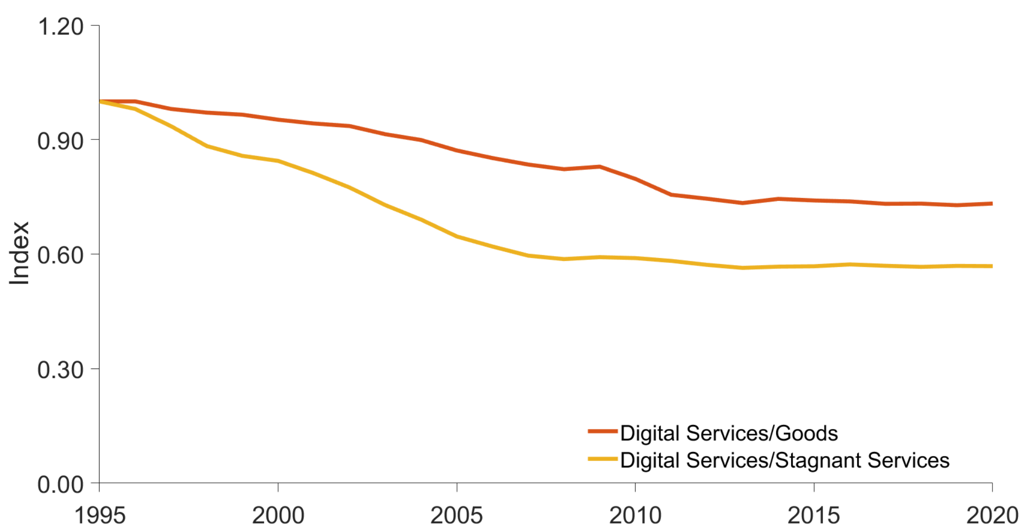
[3]For clarity, computer-specific technical change refers to the decline in the relative price of computers compared to consumption.

Figure 3: Rental Price of Capital Across Sectors: US



Notes: The data source is the BEA-BLS Integrated Industry-Level Production Account. The index is equal to 1 in the beginning year of our analysis, 1987. The index shows the rental rate of capital used in digital services relative to those used in goods and stagnant services.

Figure 4: Rental Price of Capital Across Sectors: UK



Notes: The data source is the EUKLEMS&INTANProd. The index is equal to 1 in the beginning year of our analysis, 1995. The index shows the rental rate of capital used in digital services relative to those used in goods and stagnant services.

embodied technical change serves as the primary engine of productivity growth in digital-intensive service industries. Significant declines in the price of computer capital triggered a revival of productivity growth in these industries through capital deepening, with the effects amplified across the entire economy via intersectoral linkages, given the centrality of digital-intensive services in the production network. However, the slowdown in computer-specific technical change has led to a deceleration in productivity growth within digital services, which, in turn, has negatively impacted productivity growth in the broader economy. To quantify the contribution of this mechanism to aggregate productivity growth dynamics, the next section introduces a production networks model.

3 A Model of Digitalization in Production Networks

In this section, I introduce a model of digitalization with intersectoral linkages. The model includes 63 industries for the US and 54 industries for the UK. Consistent with the sectoral classification outlined in the facts section, these industries are grouped into three sectors: goods, digital services, and stagnant services. The model incorporates 31 types of capital, diverging from standard production network models that typically assume a single homogeneous capital good and explicitly model the investment network of the economy (e.g., vom Lehn and Winberry, 2022). While this model does not explicitly represent the investment network, the capital flow implications suggest that an investment network is implicitly captured within this framework.

3.1 Production Side

The gross output production function for sector j is represented in the following nested form:

$$Q_{jt} = A_{jt} \left[\left[(1-\mu_j)^{\frac{1}{\epsilon_{Qj}}} L_{jt}^{\frac{\epsilon_{Qj}-1}{\epsilon_{Qj}}} + \mu_j^{\frac{1}{\epsilon_{Qj}}} M_{jt}^{D\,\frac{\epsilon_{Qj}-1}{\epsilon_{Qj}}} \right]^{\frac{\epsilon_{Qj}}{\epsilon_{Qj}-1}} \right]^{\alpha_j} \left[\left(\frac{K_{jt}}{\phi_{jk}} \right)^{\phi_{jk}} \left(\frac{M_{jt}^G}{\phi_{jg}} \right)^{\phi_{jg}} \left(\frac{M_{jt}^S}{\phi_{js}} \right)^{\phi_{js}} \right]^{(1-\alpha_j)}$$

In the model, $\epsilon_{Qj} \geq 0$ represents the elasticity of substitution between labor and digital services, which varies across sectors. Aside from this deviation, the model retains a Cobb-Douglas structure for the remaining production factors to ensure tractability. This modeling choice aligns with the stylized facts on structural change in production networks, where the increasing intermediate input intensity in the services sector appears to result from a substitutability between labor and digital services. It is important to note that this assumption is not meant to suggest that the relationship holds universally across all 60 industries considered in this study. However, given the focus on services in this analysis, it serves as a reasonable approximation.

Apart from ϵ_{Qj}, μ_j represents the relative share of digital services (M_{jt}^D) in the composite of the labor and digital services; α_j is the elasticity of the labor/digital services composite with respect to gross output; ϕ_{jk} is the elasticity of capital (K_{jt}) with respect to the composite of capital, energy/materials, and stagnant service intermediates; ϕ_{jg} is the elasticity of energy/materials (intermediate inputs produced by the goods sector) (M_{jt}^G) in the same composite; and ϕ_{js} is the elasticity of intermediate inputs produced by stagnant services (M_{jt}^S) with respect to the same composite. K_{jt}, M_{jt}^G, and M_{jt}^S are scaled to simplify the notation in the derivation of price indexes. Lastly, A_{jt} is the total factor productivity (TFP) term, which is assumed to be exogenous.

The capital used in sector j is defined as follows:

$$K_{jt} = \prod_{k=1}^{N_k} \left(\frac{K_{jt}^k}{\beta_{kj}} \right)^{\beta_{kj}}$$

where β_{kj} represents the elasticity of capital type k with respect to the aggregate capital used in industry j. The capital type k used in industry j accumulates according to the standard capital accumulation equation:

$$K_{jt+1}^k = (1 - \delta_k) K_{jt}^k + X_{jt}^k$$

where δ_k denotes the depreciation rate of capital type k, and X_{jt}^k represents the investment in capital type k for industry j.

The composite of intermediate inputs produced by the goods, digital, and stagnant service sectors and used in sector j is represented by Cobb-Douglas functional forms:

$$M_{jt}^x = A_{jt}^x \prod_{i=1}^{N_x} \left(\frac{M_{ij,t}^x}{\phi_{ij}^x} \right)^{\phi_{ij}^x} \quad for \quad x \in \{D, G, S\}$$

where $M_{ij,t}^x$ represents the intermediate input supplied from industry i to industry j for the intermediate input $x \in D, G, S$. ϕ_{ij}^x denotes the share of industry i in the total intermediates used by industry j for the intermediate input $x \in D, G, S$. A_{jt}^x represents the exogenous technical change in the intermediates x used by industry j.

The investment good for capital type k, used in industry j, is represented by the following Cobb-Douglas form:

$$X_{jt}^{k} = A_{jt}^{k} \prod_{i=1}^{N} \left(\frac{X_{ij,t}^{k}}{\omega_{ij}^{k}} \right)^{\omega_{ij}^{k}}$$

where $X_{ij,t}^{k}$ represents the investment good supplied from industry i to industry j for capital type k. ω_{ij}^{k} denotes the share of industry i in the investment used by industry j for the capital good k. A_{jt}^{k} represents the exogenous technical change in the capital good k used by industry j.

Some explanation is required for the exogenous technical change terms in the intermediate and investment goods. In an ideal scenario, we would expect the price index of intermediate inputs and investment goods used in a particular industry j to represent a weighted average of the prices of the industries contributing to the production of those inputs. In this context, exogenous technical change captures the influence of imported capital goods and imported inputs.

However, this study adopts an output-based approach. Despite the high level of disaggregation in the data, it is not disaggregated enough for the purposes of this analysis. Figure 5 illustrates this issue. The green line in the figure represents the gross output price index of the computer and electronic products industry, a primary producer of computers and communications equipment. When aligning the model to the data, this price index will be used for both the computers and communications equipment capital. However, as seen in the figure, the price index for the computer and electronic products industry does not adequately reflect the changes in the price indexes for these two capital types. Specifically, it significantly understates the decline in the price indexes for computers and communications equipment. This discrepancy is accounted for by the exogenous technical change term in the model.

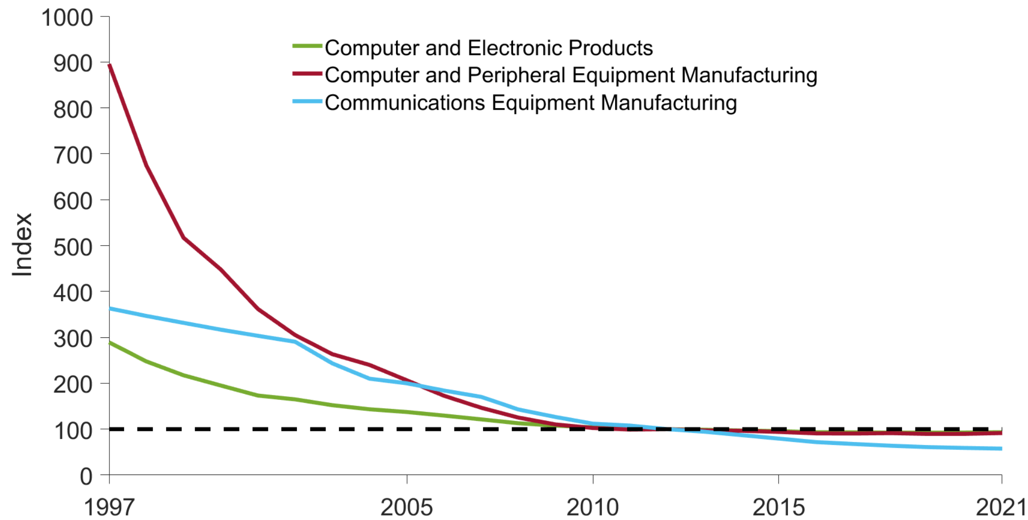
In this sense, A_{jt}^{k} captures measurement limitations in the data. If more disaggregated data were available—specifically, data detailing the sub-industries within the computer and electronic products industry—the role of the exogenous technical change term would diminish accordingly.

3.2 Demand Side

The demand side of the model follows a standard framework. The problem of the representative agent in the economy is defined as follows:

$$\max_{\{C_{jt}\}_{j=1}^{N}} \sum_{t=0}^{\infty} \beta^{t} \log \sum_{j=1}^{N} \left[\theta_{j}{}^{\frac{1}{\epsilon_c}} C_{j,t}{}^{\frac{\epsilon_c - 1}{\epsilon_c}} \right]^{\frac{\epsilon_c}{\epsilon_c - 1}}$$

Figure 5: Price Indexes for the Sub-Industries of the Computer and Electronic Products Industry



Notes: The data source is the BEA. The index is equal to 100 for all industries in 2012.

where ϵ_c represents the elasticity of substitution among different industries in the consumption good.

The resource constraint for the output of industry j is defined as follows:

$$Q_{jt} = C_{jt} + \sum_{i=1}^{N} M_{ji,t}^{D} + \sum_{i=1}^{N} M_{ji,t}^{G} + \sum_{i=1}^{N} M_{ji,t}^{S} + \sum_{k=1}^{N_k} \sum_{i=1}^{N} X_{ji,t}^{k}$$

3.3 Solution of the Model

Since we consider a frictionless environment, the model can be solved as a planner's problem. First, we examine the solution under the assumption of full depreciation ($\delta_k = 1$ for all k). The social planner's problem yields the following system of equations for sectoral prices:

$$P_{jt} = A_{jt}^{-1} \left[(1-\mu_j) + \mu_j \left((A_{jt}^{D})^{-1} \prod_{i=1}^{N_D} (P_{it}^{D})^{\phi_{ij}^{D}} \right)^{(1-\epsilon_{Qj})} \right]^{\frac{\alpha_j}{1-\epsilon_{Qj}}}$$

$$\left[\left((1+r_{t+1}) \prod_{k=1}^{N_k} (A_{jt}^{k})^{-\beta_{kj}} \prod_{k=1}^{N_k} \left(\prod_{i=1}^{N} (P_{it})^{\omega_i^k} \right)^{\beta_{kj}} \right)^{\phi_{jk}} \left((A_{jt}^{G})^{-1} \prod_{i=1}^{N_g} (P_{jt}^{G})^{\phi_{ij}^{G}} \right)^{\phi_{jg}} \left((A_{jt}^{S})^{-1} \prod_{i=1}^{N_s} (P_{jt}^{S})^{\phi_{ij}^{S}} \right)^{\phi_{js}} \right]^{(1-\alpha_j)}$$

After solving for the prices, we derive the following system of equations for quantities:

$$Q_{jt} - \sum_{i=1}^{N} \Gamma_{ji,t} Q_{it} = \theta_j P_{jt}{}^{-\epsilon_c} C_t^{1-\epsilon_c}$$

where

$$\Gamma_{ji,t} = P_{it}[\alpha_i \phi_{ji}^D \mu_i (P_{it}^{M,D})^{(1-\epsilon_{Qi})} \left[(1-\mu_i) + \mu_i (P_{it}^{M,D})^{(1-\epsilon_{Qi})}\right]^{-1} (P_{jt}^D)^{-1}$$

$$+(1-\alpha_i)\phi_{ig}\phi_{ji}^G (P_{jt}^G)^{-1}$$

$$+(1-\alpha_i)\phi_{is}\phi_{ji}^S (P_{jt}^S)^{-1}$$

$$+(1-\alpha_i)\phi_{ik}\beta_{ki}\omega_{jk}(1+r_{t+1})^{-1} P_{jt}{}^{-1}]$$

These two $N \times N$ systems of equations for prices and quantities characterize the solution of the model.

4 Calibration and Quantitative Analysis

To calibrate the model parameters, I primarily use the BEA-BLS Integrated Industry-Level Production Account and the input-output tables from the BEA for the US, covering the period from 1987 to 2020. These two data sources provide nearly all the necessary information on prices and quantities. For the UK, I rely mainly on the OECD STAN database and the input-output tables provided by the ONS for the period from 1995 to 2020. However, the data for the UK is considerably less detailed than that for the US, requiring certain assumptions to proceed with the analysis. For instance, unlike the US, price indexes for different types of intermediate inputs used in any sector are not available for the UK. Consequently, apart from some capital types, I assume constant exogenous technical change terms for intermediate inputs and investment goods in the UK.

To calibrate the elasticity of substitution between labor and digital services, I target the changes in the respective shares of labor and digital services in gross output. For the US, I estimate an elasticity value of 1.66 for the aggregate economy, indicating that labor and digital services are substitutes. This value varies slightly across sub-sectors of the economy: 1.69 for the goods sector, 1.60 for the services sector, and 1.58 and 1.65 for digital and stagnant services, respectively. At the industry level, the largest elasticity values are typically observed in sectors most associated with Baumol's cost disease, such as ambulatory health care services, hospitals, nursing and residential care facilities, state and local government, federal government, food services and drinking places, real estate, social assistance, and accommodation.

These findings suggest that while stagnant service industries may not be intensive users of digital technologies, they indirectly benefit from these technologies through their suppliers, particularly in terms of productivity growth. This result aligns with the counter-force against Baumol's cost disease originally proposed by Oulton (2001).

For the UK, the elasticity of substitution values between labor and digital services suggest a Cobb-Douglas aggregator for labor and digital services in the aggregate economy. This pattern holds for both the goods and services sectors, while for digital services, the elasticity is slightly below unity. The only exception is stagnant services, with an elasticity value of 1.07. Similar to the US, industries most associated with Baumol's cost disease exhibit a substitutability between labor and digital services. These industries include human health and social work activities, education, construction, and public administration.

In solving the model, I assume a common elasticity parameter of 1.66 for the US and 1.00 for the UK. The model closely replicates the aggregate productivity growth dynamics in both countries. For the US, the model predicts an aggregate labor productivity growth rate of 2.25% per year for the period 1995–2005 and 0.50% per year for 2005–2020. While the model slightly underestimates the productivity growth revival during 1995–2005 (data: 2.40% per year), it suggests a more pronounced decline for 2005–2020 compared to the observed data (0.98% per year). Nonetheless, the model effectively captures the magnitude of the productivity growth difference between these two periods.

For the UK, the model predicts an aggregate labor productivity growth rate of 1.55% per year for 1995–2007 and 0.57% per year for the post-2007 period. These values align closely with the observed data, which report 1.58% for 1995–2007 and 0.53% for 2007–2020.

4.1 Counterfactuals

To quantitatively assess the contribution of individual industries to the productivity growth slowdown in the UK and the US, I run several counterfactual analyses. The first counterfactual assumes that the computer and electronic products industry maintained its TFP growth after

2005 and that the decline in the price index of computers and peripheral equipment continued at its pre-2005 pace. Under this scenario, the model predicts a yearly aggregate labor productivity growth of 1.44% for the US, compared to the observed 0.50%, and 1.00% for the UK, compared to the observed 0.57%. These results suggest that the slowdown in computer-specific technical change alone accounts for approximately 54% and 44% of the aggregate productivity growth slowdown in the US and the UK, respectively.

When examining the effects of this counterfactual on the labor productivity growth rate of digital services, the model predicts a yearly growth rate of 1.68% for the US, compared to the observed 0.92%, and 1.12% for the UK, compared to the observed 0.68% after 2005. This indicates that the slowdown in computer-specific technical change accounts for roughly half of the labor productivity growth slowdown in digital services in the US and about one-third of the slowdown in the same sub-sector in the UK.

To identify other key industries contributing to the productivity growth slowdown, I also analyze the durable goods sector, the wholesale trade industry, and the scientific research and development (R&D) industry. Assuming no TFP growth slowdown in the durable goods sector (excluding the computer and electronic products industry) raises the yearly aggregate labor productivity growth rate to 0.78% after 2005, accounting for approximately 16% of the overall slowdown. A similar counterfactual for the wholesale trade industry increases the yearly aggregate labor productivity growth rate to 0.76%, contributing an additional 15% to the productivity growth slowdown. By contrast, the counterfactual for R&D only raises the yearly labor productivity growth rate to 0.56% after 2005, accounting for a relatively small share of the slowdown.

Combining all three counterfactuals—assuming that the computer and electronic products industry, the durable goods sector, and the wholesale trade industry maintained their TFP growth rates after 2005—yields a predicted average labor productivity growth rate of 2.08%. This accounts for more than 90% of the productivity growth slowdown. For digital services, the same counterfactual implies an average labor productivity growth rate of 2.46%, effectively eliminating the productivity growth slowdown in this sub-sector.

For the UK, the counterfactual in which the durable goods sector and the computer and electronic products industry maintained their TFP growth rates after 2005 implies an average yearly labor productivity growth rate of 1.68% for the aggregate economy. This magnitude is so significant that it surpasses the labor productivity growth rate observed during the 1995–2007 period. Unlike the US, the slowdown in TFP growth within the scientific R&D sector contributes more substantially to the aggregate productivity growth slowdown in the UK. The model predicts a yearly labor productivity growth rate of 0.86% under this counterfactual, indicating that declining research productivity accounts for approximately one-third of the aggregate productivity growth slowdown in the UK.

These counterfactuals suggest that the slowdown in computer-specific technical change is the primary contributor to the aggregate productivity growth slowdown in both the US and the UK. In the context of a simple aggregate model with heterogeneous capital, the magnitude of this effect implies that the network structure more than doubles the productivity growth decline in the computer and electronic products industry. Given that all the key industries considered in our counterfactuals are central suppliers of capital goods, it is most appropriate to view the productivity growth slowdown as a deceleration in capital-embodied technical change.

5 Sources of the Slowdown in the Computer-Specific Technical Change

Overall, the waning effects of information technology (IT) on aggregate productivity have often been cited as a primary factor behind the recent productivity growth slowdown (Fernald, 2015). However, the causes of these waning effects are not fully understood. First, it is important to note that the slowdown in IT productivity largely reflects the deceleration in the decline of the price of computers and peripheral equipment capital. In contrast, there has been an acceleration in the price decline of communications equipment, and the slowdown in software prices is relatively small compared to that of computers.

When we examine the changes in computer production after 2005, the evidence points to significant structural changes. First, service intermediates now account for a larger share of total intermediates used in the computer industry. Second, as shown in Table 13, the computer systems design industry, which is linked to custom and own-account software, now represents a larger share of computer capital production. Its share has increased from a modest 7% in 1997 to 34% in 2021. Given that this industry experiences a higher price relative to the computer and electronic products industry, this substantial increase in share can be interpreted as evidence of near-perfect complementarity in production.

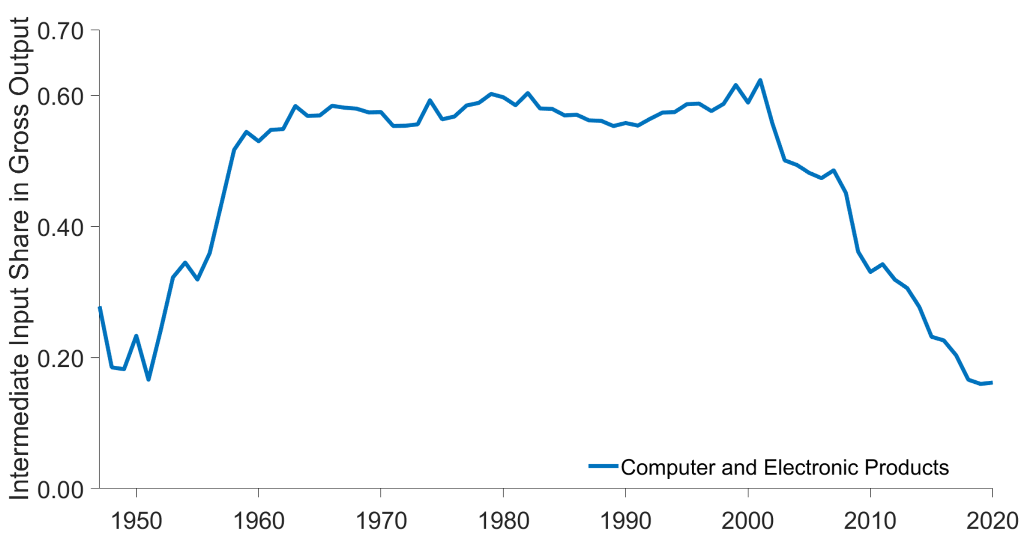
Table 13: Computers and Peripheral Equipment Production: US

	1997	**2021**
Computer and Electronic Products	0.74	0.46
Computer Systems Design and Related Services	0.07	0.34

Notes: The numbers show the shares of the industries in the production of the computers and peripheral equipment capital. The data source is the bridge tables from the BEA.

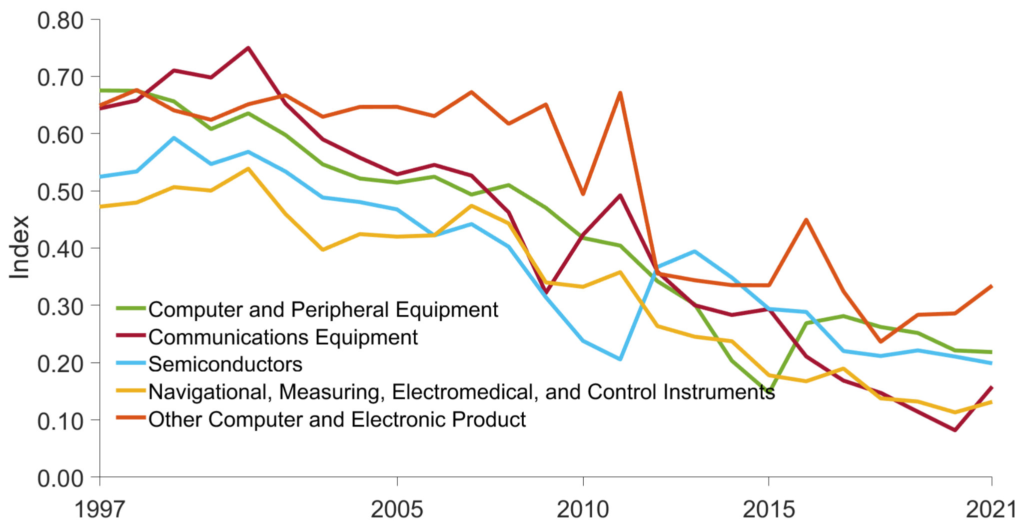
Third, and most importantly, since the early 2000s, the computer and electronic products industry has become increasingly value-added intensive (Figure 6). The numbers are striking: while the share of intermediate inputs in gross output was around 60% before the 2000s, by 2020 this share had decreased to nearly 10%. It is crucial to note that this phenomenon is observed across all sub-industries within the computer and electronic products sector, as further illustrated in Figure 7.

Figure 6: Intermediate Input Intensity in the Computer and Electronic Products Industry



Notes: The data source is the Experimental BEA-BLS integrated Industry-Level Production Account.

Figure 7: Intermediate Input Intensity in the Sub-Industries of the Computer and Electronic Products Industry



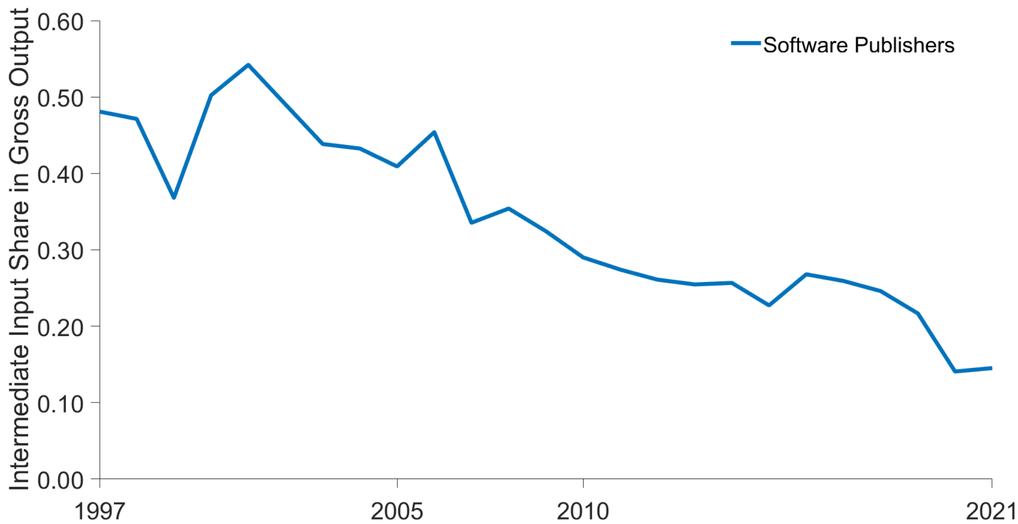
Notes: The data source is the BEA.

A further exploration of this value-added intensification in the computer industry reveals an even more curious fact: Figure 8 shows that the same trend is observed in the software publishing industry. How can we account for this change? The value added in these digital-producing industries primarily consists of labor and labor-intensive R&D costs. These figures suggest that labor costs play a larger role in determining the price dynamics within digital-technology-producing industries.

To explore this idea more formally, I estimate the elasticity of substitution between value added (comprising labor and mostly R&D capital) and intermediate inputs in digital-technology-producing industries. The results confirm that perfect complementarity characterizes production in all digital-technology-producing industries, including computer and electronic products, publishing industries, motion picture and sound recording industries, broadcasting and telecommunications, data processing, and computer systems design.

In the case of the computer and electronic products industry, assuming that production shares remained at their pre-2002 levels implies no slowdown in the TFP growth rate for this industry. Therefore, the slowdown in computer-specific technical change can be entirely attributed to the perfect complementarities in computer production.

Figure 8: Intermediate Input Intensity in Software



Notes: The data source is the BEA.

6 Conclusion

In this paper, I analyze the productivity growth slowdown and the role of digitalization within a production network framework. My results attribute the recent productivity growth slowdown observed in the US and the UK to a deceleration in computer-specific technical change, which is amplified through the network structure of the economy. This effect alone accounts for approximately half of the aggregate productivity growth slowdown, with the remaining portion explained by other capital goods-producing industries. Furthermore, my findings suggest that the slowdown in computer-specific technical change can be entirely attributed to perfect complementarities in production. Since the early 2000s, the weakest links in production have shaped the productivity dynamics in the computer sector, a characteristic observed in all digital-technology-producing industries.

The results of this paper have both positive and negative implications for the future productivity effects of digital technologies. On the positive side, the increasing intermediate input intensity in service industries reflects a substitutability between labor and digital services, suggesting that productivity growth will improve in stagnant services as digitalization progresses. Second, the general favorability of digitalization toward service industries indicates that technical change has become increasingly service-biased through capital-embodied technical change. More importantly, technological advances are targeting the bottleneck industries that are central in production networks.

It is worth noting that digital-intensive service industries, such as finance, business services, and administrative and support services, experienced almost zero productivity growth before the late 1970s. Without capital deepening, these industries would have seen no productivity growth since then, highlighting the importance of developing new technologies that target these sectors.

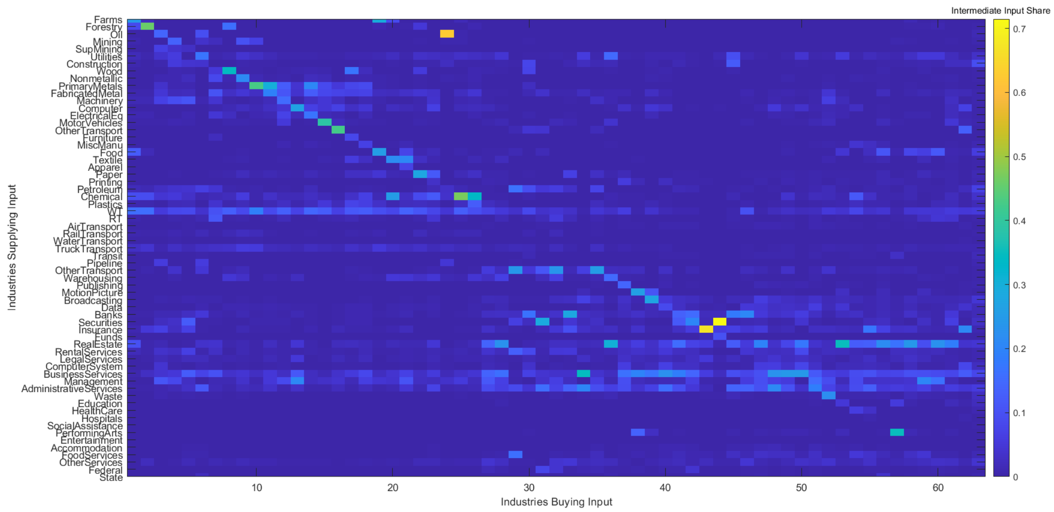
Another key characteristic of digital technologies is their ability to diffuse easily compared to historical standards. Additionally, the dynamics of productivity in these technologies often exhibit exponential growth, at least up to a certain point. Lastly, the network structure of the economy amplifies the positive effects of digital technologies.

On the negative side, digital technologies possess two fundamental characteristics that are detrimental to productivity growth. First, digital capital goods have high depreciation rates. More importantly, digital technologies have increasingly been embodied in intermediate inputs. Since capital deepening is the primary driver of productivity growth in central industries, productivity improvements in these industries depend heavily on technical progress in digital capital producers. However, due to their high depreciation rates, digital capital goods do not induce much persistence in the productivity growth of industries that use these goods intensively. In this context, a sudden decline in aggregate productivity growth is not surprising.

Second, and more importantly, the results strongly suggest the presence of a cost disease in digital technology production, meaning that it is a natural tendency for these technologies to slow down as complementarities in production eventually take hold. These two forces imply that another period of high productivity growth is unlikely to persist for long. It remains an open question to what extent artificial intelligence can overcome the bottlenecks in digital technology production.

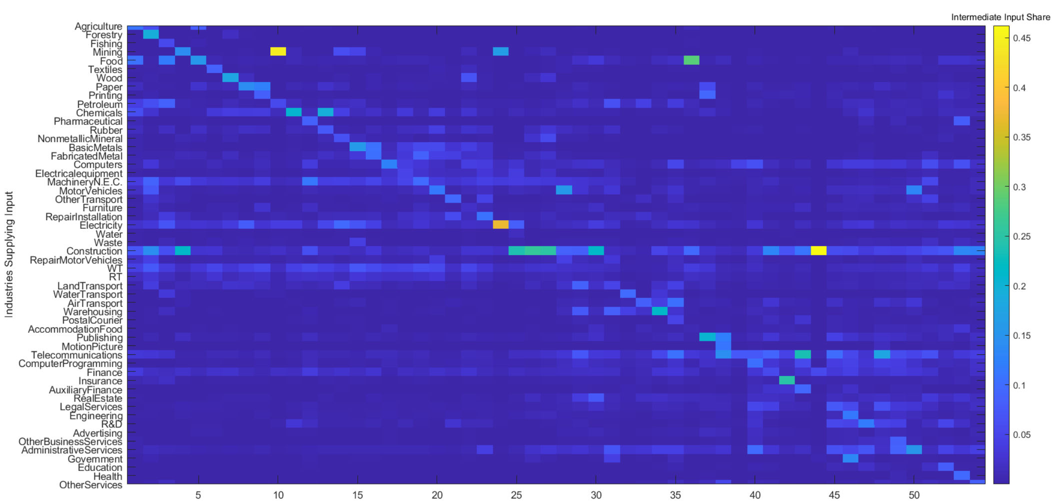
Appendix: Production Networks in the US and the UK

Figure 9: Production Network: US



Notes: The data source is the BEA.

Figure 10: Production Network: UK



Notes: The data source is the ONS.

7 References

Aghion, P., Bergeaud, A., Boppart, T., Klenow, P., & Li, H. (2023). A theory of falling growth and rising rents. *Review of Economic Studies 90(6)*, 2675–2702.

Aum, S., Lee, S.Y., & Shin, Y. (2018). Computerizing industries and routinizing jobs: Explaining trends in aggregate productivity. *Journal of Monetary Economics, 97(C)*, 1-21.

Baumol, W. J. (1967). Macroeconomics of unbalanced growth: The anatomy of urban crisis. *American Economic Review, 57(3)*, 415-426.

Casal, L., & Caunedo, J. (2024). On the investment network and development. Cornell University Working Paper.

Caunedo, J., & Keller, E. (2023). Capital embodied structural change. Working Paper.

De Ridder, M. (2024). Market power and innovation in the intangible economy. *American Economic Review, 114 (1)*, 199–251.

Ding, X. (2023). Capital services in global value chains. Georgetown University Working Paper.

Fadinger, H., Ghiglino, C., & Teteryatnikova, M. (2022). Income differences, productivity, and input-output networks. *American Economic Journal: Macroeconomics, 14(2)*, 367-415.

Fernald, J. (2015). Productivity and potential output before, during, and after the great recession. *NBER Macroeconomics Annual 29 (1)*: 1–51.

Foerster, A. T., Hornstein, A., Sarte, P.-D. G., & Watson, M. W. (2022). Aggregate implications of changing sectoral trends. *Journal of Political Economy, 130(12)*, 3286–3333.

Gaggl, P., Gorry, A., & vom Lehn, C. (2023). Structural change in production networks and economic growth. CESifo Working Paper No. 10460.

Giannoni, M., & Mertens, K. (2019). Outsourcing, markups and the labor share. Working paper.

Goldin, I., Koutroumpis, P., Lafond, F., & Winkler, J. (2024). Why is productivity slowing down? *Journal of Economic Literature, 62 (1)*, 196–268.

Gourio, F., & Rognlie, M. (2020). Capital heterogeneity and investment prices: How much are investment prices declining. Northwestern University Working Paper.

Greenwood, J., Hercowitz, Z., & Krusell, P. (1997). Long-run implications of investment-specific technological change. *American Economic Review, 87(3)*, 342-362.

Grobovsek, J. (2018). Development accounting with intermediate goods. *The B.E. Journal of Macroeconomics, 18(1)*, 20160223.

Jorgenson, D. (2007). 35 Sector KLEM. Harvard Dataverse, VI, http://hdl.handle.net/1902.1/10684.

Jorgenson, D., Ho, M., & Stiroh, K. (2005). Growth of U.S. industries and investments in information technology and higher education. In Corrado, C., Haltiwanger, J. and Sichel, D. ed., Measuring Capital in the New Economy, Chicago: University of Chicago Press for the National Bureau of Economic Research, pp.403-478.

Miranda-Pinto, J. (2021). Production network structure, service share, and aggregate volatility. *Review of Economic Dynamics 39*, 146–73.

Moro, A. (2012). The structural transformation between manufacturing and services and the decline in the US gdp volatility. *Review of Economic Dynamics 15 (3)*, 402–415.

Moro, A. (2015). Structural change, growth, and volatility.*American Economic Journal:Macroeconomics 7 (3)*, 259–94.

Ngai R., & Samaniego R. (2009). Mapping prices into productivity in multisector growth models. *Journal of Economic Growth 14*, 183–204.

Oulton, N. (2001). Must the growth rate decline? Baumol's unbalanced growth revisited. *Oxford Economic Papers 53*, 605–627.

Poirier, C., & Vermandel, G. (2023). Reallocation dynamics in production networks with heterogeneous elasticities. Working paper.

Stiroh, K.J. (2002). Information technology and the U.S. productivity revival: what do the industry data say? *American Economic Review 92 (5)*, 1559–1576.

Takahashi, Y., & Takayama, N. (2023). Global technology stagnantion. Working paper.

Triplett, J.E., & Bosworth, B.P. (2004). Productivity in the US services sector: new sources of economic growth. The Brookings Institution, Washington, DC

Vom Lehn, C., & Winberry, T. (2022). The investment network, sectoral comovement, and the changing US business cycle. *The Quarterly Journal of Economics, 137(1)*, 387-433.