Measuring digitalization effects in China: A global value chain perspective

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ARTICLE INFO	ABSTRACT
	Measuring the digitalization effect, especially in traditional industries, is crucial for both economic researchers and policy makers. We quantify the effect and the rate of digitalization at the sectoral level in China from the perspective of production on the basis of the Inter-Country Input–Output (ICIO) accounting framework, which allows us to account for digitalization in traditional industries through value chains. Our results indicate that digitalization has developed rapidly in China and has become an important path for the transformation and upgrading of traditional industries. We show that global value chain (GVC) activities have significant digitalization characteristics in China and that digitalization promotes the sectoral reconstruction of China's GVCs. By constructing a GDP growth account that is consistent with our digitalization measure to capture the inter-temporal impact of digitalization through the investment channel, we find that the growth in digital capital input contributes to GDP growth in China and several world major economies and that the effect can be significant for developing countries that are experiencing rapid growth in investment.

1. Introduction

Over the past three decades, the digital economy has become a driving force behind China's economy. By 2021, the value of China's digital economy reached CNY 47.94 trillion (USD 7.1 trillion), ranking second worldwide after the digital economy of the USA. The share of the digital economy in China's GDP, as measured by the combined value of technology products and integrated digital inputs, reached 39.8% in 2021, up from 20.9% in 2012 (CAICT, 2022). In addition to China, the digital economy contributed to the growth of other main economies during the same time. From 2012 to 2017, the investment share of GDP from the information and communication technology (ICT) sector increased from 2.3% to 2.5% (OECD, 2023). Even though the contribution of the digital economy to GDP growth in developed countries is less than its contribution in developing countries such as China, it is sustainable and significant (Bukht & Heeks, 2017). Furthermore, the COVID-19 pandemic has accelerated digitalization, as an increasing number of people continue, to the greatest extent possible, to pursue their activities through online channels (UNCTAD, 2021). Given the increasingly important role of digital economic activities in the world, measuring the impact of the digital economy is crucial for both researchers and policy makers to have a greater understanding of the evolution of China's economy and its interaction with the global economy.

Although the importance of measuring the impact of digitalization has been increasingly realized, precisely quantifying the rate of digitalization and its impact is still challenging. Digitalization refers to the use of digital technologies to change a business model and

provide new revenue and value-producing opportunities (*Gartner Glossary*, 2022). The impact of digitalization can be understood as the product of its scale of diffusion and its depth of effect (Handel, 2016). Following these definitions as a starting point, we construct a measurement of the digitalization rate from the perspective of production. We further emphasize the connectedness of production to completely capture the impact of digitalization on non-digital firms. An input–output (IO) approach has been proposed to capture the effects of digitalization through the linkage of production. Despite many practical measurement issues raised by digital activities (Ahmad & Schreyer, 2016), it is conceptually straightforward to trace the value added as being driven by the production of digital industries to quantify the rate of digitalization and its impact. However, very few studies measure digitalization, especially the rate of digitalization in traditional industries based on the Inter-Country Input–Output (ICIO) database. More importantly, in addition to the easy accessibility of ICIO data, the IO approach makes it possible to capture both the direct and indirect effects caused by the use of digital technologies and digital data by accounting for the production interaction across industries and countries. In the framework of the ICIO model, the direct effects refer to the value and output directly created by digital industries, and the indirect effects refer to the additional amount of input available for non-digital industries as digital industries develop. By emphasizing this production interaction through value chain activities, our paper aims to measure the degree and impact of digitalization on the world economy based on the publicly available ICIO database.

This work draws on several lines of literature. First, this study is most closely aligned with the literature on digital economy measurement. Although a vast amount of literature focuses on measuring the scale of the digital economy itself (Ahmad & Schreyer, 2016; Barefoot, Curtis, Jolliff, Nicholson & Omohundro, 2018; Machlup, 1962; OECD, 2020; Porat & Rubin, 1977; UNCTAD, 2014, 2021; Xu & Zhang, 2020), only a small part of the literature tries to quantify the rate of digitalization. The World Bank (WB) developed the Digital Adoption Index (DAI) to measure countries' digital adoption from the perspective of final use (Worldbank, 2016). The China Academy of Information and Communication Technology (CAICT) measures digitalization by emphasizing the production side, and it measures the contribution of capital stock from ICT industries to each sector (CAICT, 2020). As mentioned previously, most existing research that focuses on GDP or the final demand for digital industries ignores the indirect effects of digitalization that can be seen through value chain activities. In fact, for many industries, their value added is highly driven by the change in their upstream industries' demand for digital industries. Ignoring the importance of digital industries, as seen through value chain activities, may lead to an underestimation of their impact on the economy. To overcome this limitation, our study focuses on quantifying the indirect effects through an IO approach using both forward and backward cross-border inter-industry linkages.

Second, this work is closely related to a strand of literature that studies the effects of digitalization. The critical role of ICT industries in explaining growth, welfare, and research and development (R&D) has been widely studied. O'Mahony and Vecchi (2003) show a positive and significant long-run impact of ICT on total factor productivity (TFP). Jorgenson (2001) provides a new framework of growth accounting to capture the contribution of the ICT sector to the growth of the United States. Cai and Niu (2021) applies a similar framework to measure the contribution of digital assets to the scale of value-added and its impact on TFP. Madsen (2007) notes that imports of knowledge, including ICT products, significantly contribute to the TFP increase in many countries. Venturini (2009) tests the long-run effect of ICT on economic growth and confirms the boosting effect of ICT on growth. Bouwman, Nikou, Molina-Castillo and de Reuver (2018) show that social media and big data robustly contribute to business model innovation. Ribeiro-Navarrete, Botella-Carrubi, Palacios-Marqués and Orero-Blat (2021) find that updating the use of digital technology can enhance company performance. Their work has shed light on quantifying the micro or aggregate-level change driven by the development of digital industries. However, due to the ignorance of the indirect impact of digitalization through inter-industry interconnection, the effect of digitalization can be seriously underestimated. To overcome this issue, we include the indirect impact of digitalization through cross-border inter-industry linkages in our analytical framework, especially the interaction between digital industries and traditional industries, which aligns with the trend of measuring digitalization. Then, we try to use our measurement to explain the diversification of growth around the world. In addition, to obtain the inter-temporal implications of digitalization for understanding the effects of digitalization on the basis of our proposed measures, this paper provides a growth accounting framework that is consistent with our proposed measures of digitalization to capture the indirect contribution of the digital sector to GDP growth by disentangling indirect digital capital input from non-digital capital input.

Finally, this paper contributes to the literature on the global value chain (GVC). Digital industries are highly involved in global production fragmentation, and different stages of production regularly occur in different countries. This feature naturally raises a question when we quantify the effects of digitalization: Can we use a well-defined IO framework to account for the cross-border effect of digitalization by economy? To answer this question, we follow the frameworks of Koopman, Wang and Wei (2014) and Wang, Wei, Yu and Zhu (2017). Koopman et al. (2014) suggest an accounting framework that traces value-added activities by their sources in gross trade flows. They identify which parts of the gross trade statistics are double counted relative to GDP statistics, and they provide a way to interpret gross trade transactions in value-added terms (relative to GDP) that are fully consistent with the System of National Accounts (SNA) standard. Wang et al. (2017) propose a framework to decompose total production into GVC and non-GVC activities at the country/sector level,[1] and they construct a new measure of GVC participation based on this decomposition. Our measurement follows the accounting framework of Koopman et al. (2014) and Wang et al. (2017) to comprehensively quantify the impacts of direct and indirect digitalization in a consistent manner. Our measurement classifies the embedded factor content into digital and non-digital activities to precisely capture the total value added contributed by both domestic and foreign digital industries. The major contributions of this paper are as follows: (1) A unified framework that can calculate the total effect of digitalization considering cross-border

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[1] The "country" here includes all economies. Since this is also expressed in Koopman et al. (2014), the term "country-sector level" is used here.

inter-industry linkages from the GVC perspective is constructed. (2) This paper defines and quantifies both the direct and indirect portions of digitalization, and it computes the digitalization rates of various value chain activities in China at the overall and sector levels. (3) This paper further provides a growth accounting framework to measure the inter-temporal impact of digitalization in China through the investment channel. This study classifies the embedded factor content into digital and non-digital activities to precisely capture the input of the digital industry in China's production activities.

The remainder of this paper is organized as follows. Section 2 presents the methodology. Section 3 shows the main results of measuring digitalization in China and analyses its effects at the overall and sector levels. Section 4 discusses the digitalization rate of different value chain activities in China and the relationship between GVC activities and digitalization in various sectors. Section 5 provides a new growth accounting framework that is consistent with our methodology to account for the impact of digital capital input on growth in China. Section 6 concludes.

2. Methodology

Before defining digitalization, we first define digital industries. The definition and measurement of digital industries are relatively mature. Following the definition proposed by the Bureau of Economic Analysis (BEA), digital industries are defined as "digital infrastructure, digital media and e-commerce". From the perspective of production, we define digitalization as the use of digital technologies and digitized data to impact how work is completed, transform how customers and companies engage and interact, and create new revenue streams (Chapco-Wade-Safina, 2018). In addition to digitalization, a closely related concept is industrial digitalization, which focuses more on non-digital industries. According to a report by the CAICT, industrial digitalization refers to "the process of digital upgrade, transformation and reconstruction of all factors in the upstream and downstream of the industrial chain by the application of digital technology and data, which is the integration of digital technology and the real economy" (CAICT, 2020). We use this definition as a reference and measure industrial digitalization by measuring the contribution of digital industries to both the value added and final goods production of non-digital industries. From the perspective of production, industrial digitalization is the indirect portion of digitalization; therefore, in this work, we assume that industrial digitalization and the indirect portion of digitalization are equivalent. The ICIO table is used as a unified accounting framework to analyse the digitalization of each economy from the perspectives of value added and final goods production. The detailed structure of the ICIO table is depicted in Table 1.

Suppose that there are G economies in the world and that each economy has N sectors. Z_{sr} is an N × N matrix of intermediate input flows that are produced in economy s and used in economy r. Y_{sr} is an N × 1 vector of final products produced in economy s and consumed in economy r. X_s is also an N × 1 vector of gross outputs in economy s. VA_s denotes a 1 × N vector of value added in economy s. In this ICIO account, the input coefficient matrix can be defined as $A = Z\widehat{X}^{-1}$, where $\widehat{X}$ denotes a diagonal matrix with total output vector X as its diagonal. The value-added coefficient vector can be defined as $V = VA\widehat{X}^{-1}$. ˆ denotes the diagonalization operation, and ′ denotes the transpose operation.

The digitalization effect can be measured using the hypothetical extraction method(Los, Timmer, & De Vries, 2016; Paelinck, De Caevel, & Degueldre, 1965). Suppose that the hypothetical extraction method is completed in two steps. The first step is to consider the industrial linkages in the whole economic system when extracting digital industries (deleting) from the system. The second step is to calculate the difference in various indicators by subtracting the value of the system without digital industries from the actual economic system, that is, the impact of digital industries on the whole economic system through industrial linkages. Accordingly, we first multiply both ends of the Leontief equation by the value-added coefficient to obtain the decomposition formula of GDP:

$$GDP = V(I - A)^{-1}Y = VBY \tag{1}$$

where $B = (I - A)^{-1}$ is the well-known (global) Leontief inverse matrix and represents the total requirement coefficients of output in the global economy of each extra unit of final products produced by a sector of a particular economy. Eq. (1) explains how the final output directly drives the value added of the industry and indirectly drives the value added of the upstream industry along the production chain, that is, the source of factor value along the production chain of the final output. It can also be explained by how value added is directly used for the final production of the industry and is indirectly used for the final production of the downstream industry.

Based on the hypothesis extraction method, after extracting digital industries from Eq. (1) by setting indices related to the digital industry to 0, a new GDP decomposition formula unrelated to digital industries is obtained.

Table 1
Structure of the ICIO table.

Output Input		Intermediate Use				Final Use				Total Output
		Economy 1	Economy 2	⋯	Economy G	Economy 1	Economy 2	⋯	Economy G	
Intermediate Input	Economy 1	Z_{11}	Z_{12}	⋯	Z_{1G}	Y_{11}	Y_{12}	⋯	Y_{1G}	X_1
	Economy 2	Z_{21}	Z_{22}	⋯	Z_{2G}	Y_{21}	Y_{22}	⋯	Y_{2G}	X_2
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Economy G	Z_{G1}	Z_{G2}	⋯	Z_{GG}	Y_{G1}	Y_{G2}	⋯	Y_{GG}	X_G
Value added		VA_1	VA_2	⋯	VA_G					
	Total Input	X_1'	X_2'	⋯	X_G'					

$$GDP_{\overline{D}} = V_{\overline{D}}[I - (A - A_D)]^{-1}Y_{\overline{D}} = V_{\overline{D}}B_{\overline{D}}Y_{\overline{D}} \tag{2}$$

where the subscript D indicates digital industries and the subscript $\overline{D}$ indicates non-digital industries. V_D is the value-added coefficient vector of digital industries; that is, the values of non-digital industries are set to 0. $V_{\overline{D}} = V - V_D$ is the value-added coefficient vector of non-digital industries. A_D and $A_{\overline{D}}$ are the direct input coefficient matrices of digital industries and non-digital industries, respectively. Specifically, the input coefficients of digital industries in A_D are not 0, and all others are set to 0. $B_{\overline{D}} = [I - (A - A_D)]^{-1}$ is the Leontief inverse matrix for non-digital industries. Y_D is the vector of final products produced by digital industries, where the values of all non-digital industries are set to 0. $Y_{\overline{D}} = Y - Y_D$ is the vector of final products produced by non-digital industries.

The digitalization effect is the difference between total GDP and GDP unrelated to digital industries. The formula is as follows:

$$GDP_D = GDP - GDP_{\overline{D}} = VBY - V_{\overline{D}}B_{\overline{D}}Y_{\overline{D}} \tag{3}$$

Eq. (3) explains the impact of digital industries on digital and non-digital industries through global industrial linkages. From the perspective of forward industrial linkages, it illustrates how the value added of digital industries (non-digital industries) is directly (indirectly) used for the production of digital industries. From the perspective of backward industrial linkages, it illustrates how the final output of digital industries (non-digital industries) directly (indirectly) drives the value added of digital industries.

Both backward and forward industrial linkages reflect the importance of digital sectors in the total economy. However, it is more instructive to dive into the backward industrial linkage when measuring digitalization. Compared to the allocation of output from digital industries, people may pay more attention to the use of digital technologies and data by non-digital industries, which in fact is the widely used definition of digitalization. Therefore, we define the digitalization effect from the perspective of backward industrial linkages. By diagonalizing the column vector of final products in Eq. (3), the digitalization effect from the perspective of backward industrial linkages can be obtained.[2]

$$Y\_TD = VB\widehat{Y} - V_{\overline{D}}B_{\overline{D}}\widehat{Y}_{\overline{D}} \tag{4}$$

Then, we can divide the digitalization effect into a direct effect and an indirect effect (Eqs. (5) and (6)). The direct portion of digitalization refers to the component of digitalization that is directly related to digital industries. From a backward perspective, it is the final goods and services produced by digital industries. The indirect portion of digitalization refers to the parts of non-digital industries that are related to the digital industry through upstream and downstream industrial linkages. From the perspective of backward industrial linkages (sink method), it is the input from digital industries in the final products or services of other non-digital industries (such as semiconductors or computers used in the chemical and energy sectors), representing the backward indirect effect of digitalization.[3]

$$Y_{Dir} = Y_D^{'} \tag{5}$$

$$Y_{Ind} = VB\widehat{Y} - V_{\overline{D}}B_{\overline{D}}\widehat{Y}_{\overline{D}} - Y_D^{'} = VB\widehat{Y}_{\overline{D}} - V_{\overline{D}}B_{\overline{D}}\widehat{Y}_{\overline{D}} \tag{6}$$

The backward digitalization rate is the ratio of the digitalization effect of an economy to its total final products, and it is used to reflect the level of digitalization of the economy. We can measure the backward digitalization rate as follows:

$$D\_backward = Y\_TD/Y^{'} \tag{7}$$

After defining our quantitative measures of digitalization and defining the rate of digitalization in the ICIO accounting framework, we further derive measures of digitalization from the GVC perspective to better understand the impact of digitalization in China. According to the decomposition presented in Wang et al. (2017); Wang, Wei, Yu, and Zhu (2022), production activities can be divided into pure domestic value chains, traditional trade value chains, and simple and complex GVCs. Therefore, the digitalization effect defined in Eq. (4) can be further decomposed into different value chain activities as follows:

$$Y\_TD = VB\widehat{Y} - V_{\overline{D}}B_{\overline{D}}\widehat{Y}_{\overline{D}}$$

$$= \underbrace{VL\widehat{Y}^L - V_{\overline{D}}L_{\overline{D}}\widehat{Y}_{\overline{D}}^L}_{\substack{\text{Digitalization of}\\\text{pure domestic}\\\text{value chains}}} + \underbrace{VL\widehat{Y}^E - V_{\overline{D}}L_{\overline{D}}\widehat{Y}_{\overline{D}}^E}_{\substack{\text{Digitalization of}\\\text{traditional trade}\\\text{value chains}}} + \underbrace{VLA^E L\widehat{Y}^L - V_{\overline{D}}L_{\overline{D}}A_{\overline{D}}^E L_{\overline{D}}\widehat{Y}_{\overline{D}}^L}_{\substack{\text{Digitalization of simple GVCs}}}$$

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[2] By diagonalizing the row vector of the value-added coefficient of Eq. (3), the forward digitalization effect can be obtained as follows: $V\_TD = \widehat{V}BY - \widehat{V}_{\overline{D}}B_{\overline{D}}Y_{\overline{D}}$.

[3] From a forward perspective, the direct effect is the value added created by digital industries. In addition, the indirect effect is the value added of non-digital industries driven by digital industries (for example, the production of ICT equipment requires intermediate inputs from the chemical and energy sectors). $V\_Dir = VA_D^{'} = \widehat{V}_D X_D V\_Ind = \widehat{V}BY - \widehat{V}_{\overline{D}}B_{\overline{D}}Y_{\overline{D}} - \widehat{V}_D X_D = \widehat{V}_{\overline{D}}BY - \widehat{V}_{\overline{D}}B_{\overline{D}}Y_{\overline{D}}$, where VA_D is the value-added vector of digital industries.

$$+ \underbrace{VLA^E\left(B\hat{Y} - L\hat{Y}^L\right) - V_{\overline{D}}L_{\overline{D}}A_{\overline{D}}^E\left(B_{\overline{D}}\hat{Y}_{\overline{D}} - L_{\overline{D}}\hat{Y}_{\overline{D}}^L\right)}_{\text{Digitalization of complex GVCs}} \tag{8}$$

where $L = \left(I - A^L\right)^{-1}$ is defined as the local Leontief inverse matrix. A^L and A^E are the diagonal block matrix and off-diagonal block matrix of A, which represent the local and foreign direct input coefficient matrices, respectively. The final demand matrix Y comprises Y^L and Y^E, which are the final products and services that satisfy domestic and foreign demands. The four items in Eq. (8) are all 1 by GN matrices, corresponding to the backward effects of the digitalization of various value chain activities.

The major data source of our empirical work is the 2021 version of the ICIO tables published by OECD, covering 67 economies and 45 industries from 1995 to 2018. Referring to the definition of digitalization provided by the BEA and combining it with the sector classifications published by the OECD, we define digital industries as "computer, electronic and optical products", "publishing, audiovisual and broadcasting activities", "telecommunications", "IT and other information services", and the e-commerce section of the "wholesale and retail" sector. Except for e-commerce, data for all four other core digital industries can be found directly in the OECD-ICIO tables. To separate e-commerce from the wholesale and retail industries, we use the percentage of the e-sales value by platform and customer in total turnover as published by the OECD for OECD members and the percentage of the international trade in digitally deliverable services in the total trade in services from UNCTAD for non-OECD members from 2005 to 2018. The average percentage of non-OECD members is used for the rest of the world (ROW). To achieve comparability between OECD and non-OECD countries, the percentages of the non-OECD economies are adjusted using both of the percentages of the United States from the two databases (since the data for the USA in both databases are calculated based on the internal method of the United States). We smooth the missing data using a simple time series technique. Due to the data limitations for e-commerce, we only measure the results from 2005 to 2018. This has some rationality in that since the beginning of the 21st century, digital transformation has begun to present the characteristics of "sharing and integration".

3. The effect and rate of digitalization in China at the overall and sector levels

Based on the definition of digitalization in Section 2, we can quantify two components of digitalization: the direct portion (digital industries) and the indirect portion (industrial digitalization). In this section, we numerically compute the rate of digitalization and analyse its effects in China by applying our methodology to the ICIO dataset.

In general, the digitalization effect in China is gradually increasing, which has greatly boosted China's economic growth (Fig. 1). Specifically, in 2018, the input from digital industries in final products reached USD 2.0 trillion, accounting for 14.3% of China's final products. Moreover, in the process of digitalization in China, the structure of China's digitalization is changing. From 2005 to 2018, the value of final goods and services produced by digital industries rose from USD 201.1 billion to USD 1016.2 billion, and the share in total final products decreased from 8.8% to 7.3%, showing a trend of first rising and then falling. At the same time, the effect of industrial digitalization increased from USD 150.7 billion to USD 983.5 billion, and its share in total final products increased from 6.6% in 2005 to 7.1% in 2018, showing a trend of first decreasing and then increasing. Importantly, during this period, the proportion of indirect effects (digital input in the final products of other non-digital industries) in final products gradually approached that of direct effects (final products produced by digital industries) in final products. Although digital industries have played a more obvious role in
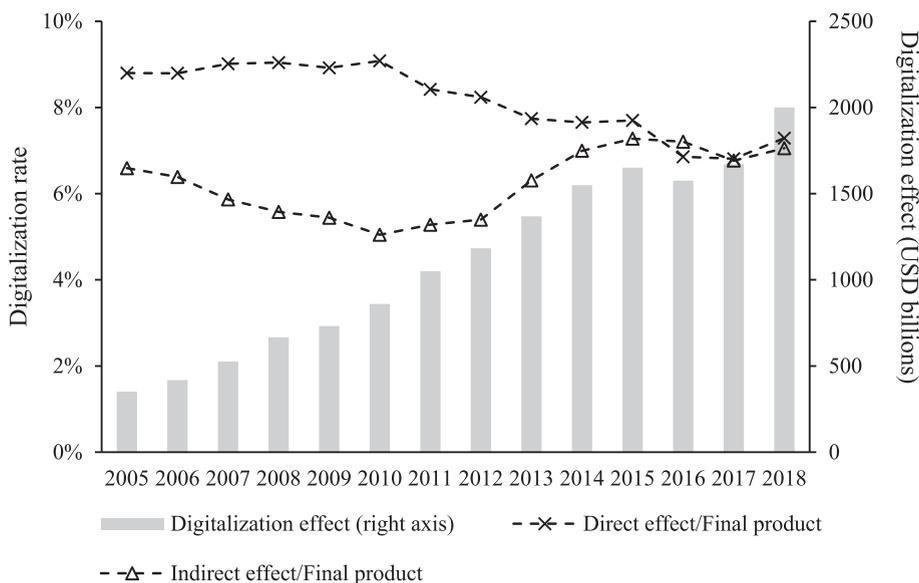

Fig. 1. Digitalization effect and digitalization rate in China, 2005–2018.

promoting China's digitalization at present, industrial digitalization may become the dominant form of digitalization in China in the future. Therefore, evaluating the industrial digitalization of non-digital industries (indirect portion of digitalization) is important for us to understand digitalization and its impact on China's economy.

We further evaluated the digitalization effect and digitalization rate in major economies and compared the results with those in China (Table 2). We found that digital transformation displayed obvious regional characteristics. **First**, in terms of scale, with the continuous improvement in digitalization, China has entered the forefront of major digital economy powers. As indicated in Table 2, the economies with the largest digitalization effects were the United States and China, which accounted for more than 40% of the global digitalization effect. The digitalization of China and the United States has become the top priority of the world's digital transformation in recent years. In comparison, the scale of the USA digitalization effect is higher than that of the Chinese digitalization effect. The digitalization effect in the United States reached USD 3350.4 billion in 2018, nearly 1.68 times that in China, which is roughly in line with the ratio of GDP of the two economies (1.46 times). In addition, some Asian economies (such as Japan, South Korea and India) and European economies (such as Germany, the UK and France) play important roles in global digital transformation. These developed economies tend to have very significant digitalization rates. **Second**, in terms of growth, the digitalization effects increased in all of these economies, with the growth rates in China and India being the highest. From 2005 to 2018, the digitalization effect in China increased by USD 1647.9 billion, with an average annual real growth rate of 13.4%, and such a trend also held true for India, which reached 12.0% during the study period. In contrast, the digitalization effects in the United States and other developed economies exhibited relatively flat growth. This finding indicates that China's digitalization has the development potential to catch up with fierce competition in the development of the global digital economy. Furthermore, digital transformation in China will have an increasing impact on promoting the development of global digitalization. **Third**, in terms of structure, the two rapid digitalization regions (i.e., China and the United States) differed substantially in their ways of realizing digitalization. The United States focused on integrating digital industries into the downstream production of traditional industries, which contributed more than 54.9% to its total digitalization effect. In contrast, China was more dependent on its digital industries, as most of its digitalization effect was a direct result of final products produced by digital industries. Although the scale of the USA digitalization effect was higher than that of the Chinese digitalization effect, the total amount of the direct digitalization effect between the two economies was very close, and the USA gained an advantage mainly in industrial digitalization. **Finally**, the digitalization rate in China was higher than the global average but lower than that in the USA and some developed Asian economies. As Table 2 shows, the digitalization rate in China in 2018 was only 14.3%, while that in the USA, Japan and South Korea reached 16.5%, 16.6% and 17.9%, respectively. Germany, France and Italy, the top three economies in the EU, did not show digital advantages, as these European economies were deeply concerned about the implicit infringement of digital sovereignty by digital operations. In contrast, some small EU economies, such as Ireland, Malta and Luxembourg, focused more on attracting greater investment from digital enterprises and expanding local employment, thus exhibiting

Table 2
Digitalization effects in China and other major economies, 2005 and 2018.

Year	Region	Income level	Digitalization effect (USD billions)					Total effect per capita ($/person)	Digitalization rate
			Direct effect	Indirect effect	Total effect	% Global	Growth rate		
2005	USA	High	886.0	921.7	1807.7	30.6%	–	6117.1	13.8%
	CHN	Upper middle	201.1	150.7	351.8	6.0%	–	269.9	15.4%
	JPN	High	358.0	311.3	669.3	11.3%	–	5238.4	14.3%
	DEU	High	165.4	159.8	325.2	5.5%	–	3943.2	12.4%
	GBR	High	139.6	161.9	301.6	5.1%	–	4992.6	12.7%
	FRA	High	116.4	156.3	272.7	4.6%	–	4316.6	13.0%
	IND	Lower middle	39.7	35.9	75.6	1.3%	–	65.9	9.2%
	KOR	High	108.8	48.0	156.8	2.7%	–	3254.3	16.7%
	CAN	High	50.5	76.6	127.0	2.2%	–	3939.7	11.7%
	ITA	High	69.5	119.9	189.3	3.2%	–	3265.8	10.4%
	GLOBAL		2932.8	2971.9	5904.7	100%	–	906.8	12.9%
2018	USA	High	1510.4	1840.0	3350.4	28.2%	4.7%	10,250.9	16.5%
	CHN	Upper middle	1016.2	983.5	1999.7	16.8%	13.4%	1425.5	14.3%
	JPN	High	395.7	412.0	807.7	6.8%	1.4%	6369.0	16.6%
	DEU	High	190.9	289.9	480.8	4.0%	3.0%	5799.3	13.2%
	GBR	High	161.3	226.8	388.2	3.3%	1.9%	5840.6	14.5%
	FRA	High	168.4	200.5	368.8	3.1%	2.3%	5496.9	13.8%
	IND	Lower middle	192.2	165.6	357.7	3.0%	12.0%	264.5	12.7%
	KOR	High	153.7	144.2	298.0	2.5%	4.9%	5775.9	17.9%
	CAN	High	83.1	142.5	225.5	1.9%	4.4%	6084.6	13.8%
	ITA	High	82.2	129.2	211.3	1.8%	0.8%	3497.8	10.5%
	GLOBAL		5514.3	6363.6	11,877.9	100%	5.4%	1562.3	14.3%

Note: The economies listed in Table 2 account for more than 70% of the global digitalization effect. For the income level, please see Appendix Table A.1.

a higher level of digitalization.

Comparing the digitalization effects between China and other economies, it can be verified that there is still a stark gap between China and developed countries. This phenomenon was more evident when considering the results of the total digitalization effect per capita. In 2018, the digitalization effect per capita in the USA, Japan and South Korea was USD 10,250.9, USD 6369.0 and USD 5775.9, respectively, much higher than that in China (USD 1425.5). Due to the rapid generational replacement of digital technology, the application of a new generation will completely replace that of the previous generation, making it difficult to realize gradient transfer between regions, as occurred in traditional technology. As a result, developed economies have a distinct technological advantage in digitalization. In recent years, China has narrowed its digital gap with high-income economies through independent R&D and innovation. For example, in 2005, the digitalization effect in China accounted for only 6.0% of the global digitalization effect, while this proportion rose to 16.8% in 2018. Although developed economies still exhibit a relatively high digitalization effect, China is playing an increasingly important role in global digitalization. The digital transformation of China is likely to become one of the major drivers of global digitalization reform in the future.

Digitalization can transform the existing production mode and become an important driving force for the development and upgrading of the traditional manufacturing industry in China (Table 3.1). The construction of digital infrastructure, including 5G, the industrial internet and artificial intelligence technology, is boosting the production of the manufacturing industry, especially technology- and knowledge-intensive sectors. As the largest developing economy, China has experienced a rapid development of manufacturing digitalization in recent years. In 2018, the digitalization effect of China's non-digital manufacturing industry was USD 331.2 billion, with a corresponding digitalization rate of approximately 9.1%. Considering the higher labour costs, China is improving the manufacturing automation level by continuously introducing new production modes, such as the "digital factory" (Li, 2018). This kind of production mode is mostly used in sectors with high technology intensity (such as electrical equipment, machinery and other transport equipment), thus driving the digitalization rate of these sectors in China and even exceeding the global level. For example, the digitalization rate of electrical equipment in China reached 13.8% in 2018, which is much higher than that of some low-tech manufacturing sectors, such as food products (5.8%) and textile products (8.6%). There are significant differences in digitalization rates between manufacturing sectors with different technical levels, and the phenomenon of the digital divide is obvious. At the same time, the relative digitalization rate of China's electrical equipment reached 1.15, indicating that the digitalization rate of this sector in China is higher than that of the world and fully demonstrating the determination of the digital transformation of traditional high-tech manufacturing sectors in China. However, although digital transformation in China has entered the third stage, in which the deep integration of digital technology with the real economy is realized with the help of the internet, many sectors have yet to explore powerful driving forces and appropriate digitalization paths. Based on the relative digitalization rate of manufacturing sectors in China, the relative digitalization rate of most sectors (except for textile products, which is China's traditional advantageous sector, and some high-tech sectors that easily carry out digital transformation) is less than 1, indicating that the digital transformation process of China lags behind that of the world. Thus, the integration of digital technology with the real economy still needs to be strengthened.

Compared with the manufacturing industry, the contribution of the service industry to industrial digitalization is far ahead (Tables 3.1 and 3.2). The average annual contribution of the primary industry to industrial digitalization was 2.7%, that of the manufacturing industry was 33.7%, and that of the service industry was 63.6%. Digitalization greatly promotes the vigorous development of the service economy and further promotes the globalization of the service industry in China. Among service sectors, "wholesale and retail trade" and "professional, scientific and technical activities" had relatively high digitalization rates, reaching 25.7% and 10.4%, respectively, in 2018. Digital industries promote the emergence and development of online scientific research, cross-border delivery, electronic logistics and other services in China through digital platforms, and they drive the production of trade,

Table 3.1
Digitalization results of traditional manufacturing sectors in China, 2018.

Sectors	Sector Group	Digitalization effect (USD billions)	% total effect in China	Digitalization rate	Relative digitalization rate
Food products	LTI	46.2	4.7%	5.8%	0.72
Textile products	LTI	37.8	3.8%	8.6%	1.07
Wood products	LTI	0.4	0.0%	5.6%	0.74
Paper and printing	LTI	2.9	0.3%	6.0%	0.71
Coke and refined petroleum products	LTI	2.6	0.3%	3.8%	0.75
Chemical products	HTI	3.4	0.3%	5.8%	0.67
Pharmaceuticals	HTI	9.7	1.0%	6.2%	0.77
Rubber and plastics	MTI	1.9	0.2%	6.9%	0.77
Other non-metallic mineral products	MTI	1.2	0.1%	5.2%	0.80
Basic metals	MTI	0.7	0.1%	5.0%	0.82
Fabricated metal products	MTI	10.1	1.0%	6.4%	0.89
Electrical equipment	HTI	34.9	3.5%	13.8%	1.15
Machinery	HTI	78.6	8.0%	13.0%	1.19
Motor vehicles	HTI	66.6	6.8%	10.5%	0.93
Other transport equipment	HTI	19.6	2.0%	13.7%	1.15
Other manufacturing	LTI	14.6	1.5%	7.1%	0.83
Total		331.2	33.7%	9.1%	1.01

Table 3.2
Digitalization results of traditional service sectors in China, 2018.

Sectors	Sector Group	Digitalization effect (USD billions)	% total effect in China	Digitalization rate	Relative digitalization rate
Electricity, gas and water supply	OSE	21.7	2.2%	7.1%	1.19
Construction	OSE	224.6	22.8%	6.9%	1.03
Wholesale and retail trade	FBS	172.0	17.5%	25.7%	1.00
Transportation and Postal	FBS	18.8	1.9%	6.4%	1.01
Accommodation and food	FBS	17.4	1.8%	5.6%	0.82
Financial and insurance	FBS	6.7	0.7%	1.9%	0.30
Real estate	OSE	11.4	1.2%	1.4%	0.55
Professional, scientific and technical activities	FBS	19.2	2.0%	10.4%	1.05
Administrative and support	FBS	16.2	1.6%	6.4%	0.89
Defense and social security	OSE	56.1	5.7%	6.5%	0.96
Education	OSE	23.8	2.4%	3.9%	0.92
Health and social work	OSE	24.8	2.5%	5.5%	0.94
Arts and entertainment	OSE	5.3	0.5%	4.4%	0.63
Other service	OSE	7.8	0.8%	3.3%	0.55
Total		625.7	63.6%	7.2%	0.88

Note: relative digitalization rate = digitalization rate in China/global digitalization rate. If the relative digitalization rate is greater than 1, then the digitalization rate of this sector in China exceeds the global level; if the rate is less than 1, then it is below the global level. For the detailed sector classification, please see Appendix Table A.2.

transportation and research activities. As a result, these sectors in China have undergone rapid digital transformation, with the digitalization rate being higher than the global level (the relative digitalization rate is greater than 1). In general, the application of digital technologies has greatly improved the tradability and efficiency of China's modern service sectors. It is necessary to continuously improve the adoption of ICT services to realize further digitalization and cyberization in the future.

4. The relationship between GVC participation and digitalization in China

GVC activities show obvious digitalization characteristics in China. The results of the digitalization of different value chain activities (Fig. 2) clearly show that the digitalization rates of GVC activities in China, especially those of complex GVC activities (reached 44.8% in 2018), are significantly higher than those of domestic value chain (10.7%) and traditional trade value chain activities (32.2%). This finding shows that digital industries have a great impact on the production process by embedding themselves into GVCs and that the application of digital technology is a means of increasing productivity and promoting development. Moreover, from 2005 to 2018, the digitalization rate of GVC activities in China was consistently higher than the world average. The concentration of multinational enterprises in China may be an important reason. Enterprises engaged in international production sharing activities have a higher need for digital technology to obtain greater production efficiency. They have stronger incentives and capacities to integrate
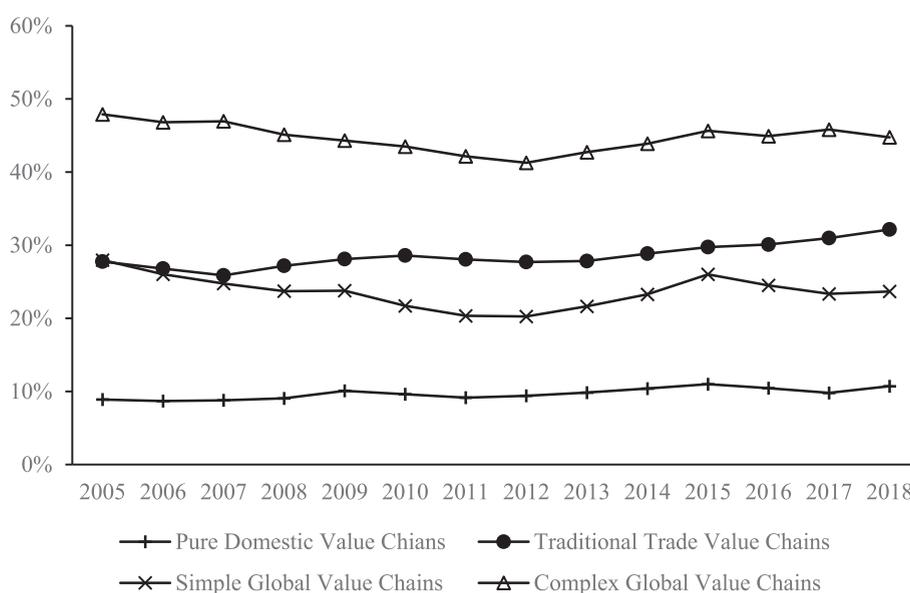

Fig. 2. Digitalization rate of different value chain activities in China.
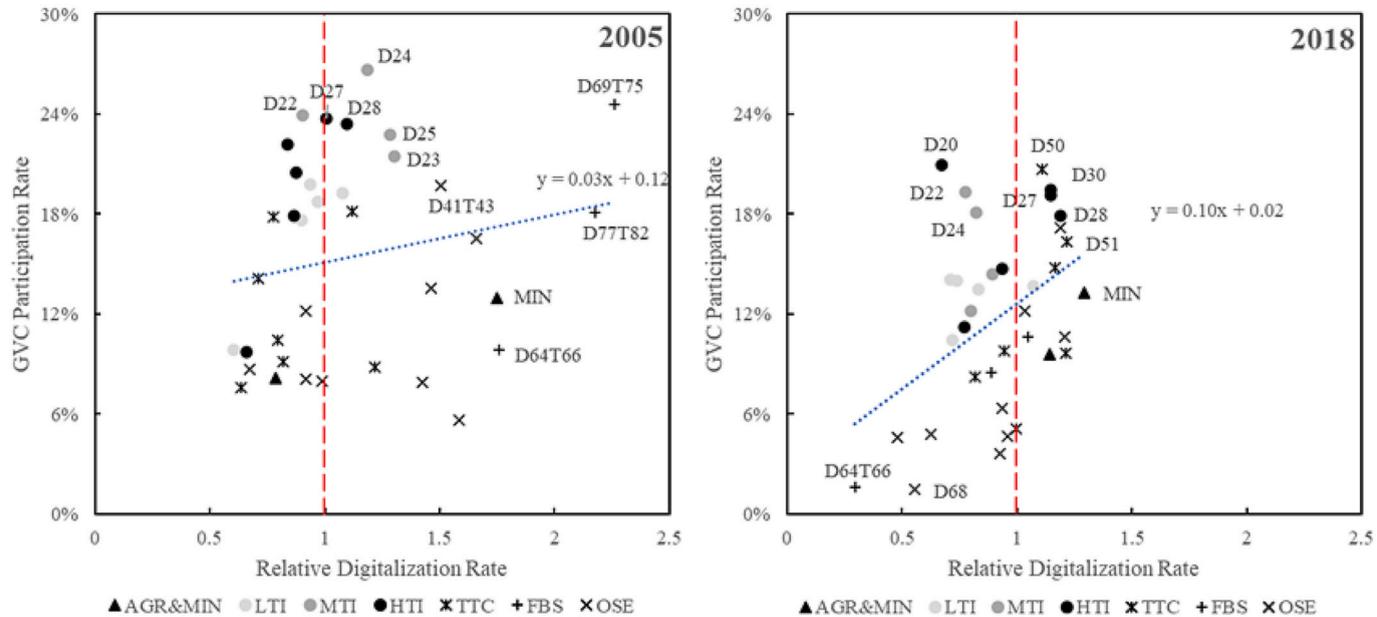
Fig. 3. The relationship between the relative digitalization rate and GVC participation rate at the sector level in China, 2005 and 2018.
Note: The GVC participation rate was calculated by the authors based on the method presented in Wang et al. (2017). The red lines are the lines with a relative digitalization rate equal to 1. On the right side of the red line, the digitalization rate of the sector in China exceeds the global level, and on the other hand, it is below the global level. For the legends, AGR&MIN represent agriculture and mining; LTI, MTI and HTI represent medium-low-tech, medium-tech and high-tech manufacturing sectors, respectively; TTC represents trade and transportation; FBS represents financial and business services; OSE represents other services. For the detailed sector classification, please see Appendix Table A.2.

more digital inputs through cross-border investment and trade, which drives their production activities to become more digitally intensive. However, from 2005 to 2018, the digitalization rate of GVC activities decreased, while the digitalization rate of pure domestic value chain activities increased. China is shifting to a development mode mainly based on domestic circulation, and the digitalization of domestic value chains has become the current focus that cannot be ignored.

Digitalization has a profound impact on China's participation in the international division of labour in production. The transnational flow of data, a production factor, reduces the trade cost of production, and it provides convenience and potential for China to participate in cross-border product cooperation. Fig. 3 illustrates the relative digitalization rate of each sector in China along the horizontal axis and the rate of GVC participation in the sector along the vertical axis. It displays a clear pattern: The higher the rate of digitalization is, the higher the GVC participation rate is. For example, many high-tech manufacturing sectors (such as electrical equipment, machinery and other transport equipment) and transportation services that have high relative digitalization rates tend to be highly integrated into GVCs. The machinery manufacturing sector is a good example. Owing to efforts to actively promote the development and application of digital technology, the relative digitalization rate of China's machinery equipment reached a very high level in 2018, much higher than the global average (relative digitalization rate reached 1.19). Digital transformation has inserted new growth points into the development of China's machinery manufacturing sector and created new advantages for China in the global division of labour in machinery production.

At present, digitalization is gradually promoting the GVC participation of industries in China as well as the sectoral reconstruction of China's GVC. In 2018, if a sector's relative digitalization rate was 1 percentage point higher than the rest, its GVC participation rate was 0.10 percentage point higher, compared with 0.03 percentage point higher in 2005. The slope of the trend line in Fig. 3 is increasing, indicating a deepening influence of the digitalization rate on sectoral GVC activities, which widens the differences between sectors. There are two reasons for this phenomenon. First, with the development of global digitalization, an increasing number of small firms have opportunities to participate in GVCs, which further enhances the depth and breadth of the division of labour of the highly digitalized sector in the GVC. Second, because digitalization can realize the specialization and standardization of different functions, sectors with a higher digitalization rate often have greater economic power to refine the functional division of the whole value chain, while sectors with a lower digitalization rate have insufficient power to go deeper into the international division of the labour system.

5. Measuring the impact of digital capital input in a growth account

The previous section describes the detailed results derived from measuring the rate of digitalization from the perspective of backward industrial linkage and discusses the association and potential causality between income level, GVC participation and the digitalization rate. In this section, we further identify the relationship between development and digitalization through a specific input channel, i.e., capital input. Digitalization refers to the transformation of the economy by using digital technology and data. One principle of this transition is the accumulation of knowledge and data through tangible and intangible digital assets. In previous research, only the economic shift and impact of digital assets is treated as the contribution of digital capital input. To be consistent with the methodology of measuring digitalization rate we proposed, the non-digital assets driven by the digital capital investment through the interconnection of investment across industries is treated as the indirect contribution of digital capital input in our accounting framework. By accounting for both the direct and indirect contributions of digital industries to capital accumulation, we can disentangle the inter-temporal effect of digitalization on the economy via both direct and indirect channels. We provide a growth accounting framework to analyse the contribution of capital input from the digital sector to growth at both the country and sector levels. Our method of constructing the growth account follows the work of Dale Jorgenson (Jorgenson, 2001; Jorgenson & Griliches, 1967). By assuming that each industry j has its own production function, we have $VA_{jt} = f(K_{jt}, L_{jt}, T_{jt})$ where VA, K, L, T are the indices of value added, capital input, labour input, and multifactor productivity (MFP), respectively. We further assume that the production function satisfies constant returns to scale. Distinguishing indirect digital capital input from non-digital capital input, we split the contribution of non-digital capital in previous research into two parts: the capital service does not relate to digital industries at all and the indirect digital capital, which its asset type belongs to non-digital but is driven by the growth in the investment of digital industries. Now the growth accounting framework can be summarized by the following equation:

$$\Delta lnVA_{jt} = \underbrace{\overline{v}_{K,jt}\left(\overline{\omega}_{\overline{D},jt}\Delta lnK_{\overline{D},jt} + \overline{\omega}_{\overline{DD},jt}\Delta lnK_{\overline{DD},jt} + \overline{\omega}_{D,jt}\Delta lnK_{D,jt}\right)}_{\text{Capital Account}} + \underbrace{\overline{v}_{L,jt}\Delta lnL_{jt}}_{\text{Labour Account}} + \Delta lnA_{jt} \tag{9}$$

where $\Delta lnVA_{jt}$ is the growth rate of the value added in sector j at time t; $\overline{v}_{K,jt}$ and $\overline{v}_{L,jt}$ are the two-period average capital share and labour share of total input between time t and t-1, respectively. $\overline{\omega}_{\overline{D},jt}$, $\overline{\omega}_{\overline{DD},jt}$ and $\overline{\omega}_{D,jt}$ denote the average value shares of different types of capital input. We first distinguish the capital input that is produced by digital industries directly from total capital input. We call it direct digital capital input and use $\overline{\omega}_{D,jt}$ to denote its share in total capital input. Then, we further decompose the remaining capital input into two parts based on the share of the capital input from digital industries for producing these assets. Now, each unit of the capital input of non-digital assets is divided into two parts: (i) The first part is capital input multiplied by the shares of its digital input; (ii) the second part is capital input multiplied by the share of its input from non-digital industries. We denote the share of the first part in total capital input $\overline{\omega}_{\overline{DD},jt}$ and call it the indirect digital capital input share since this part of input is produced through the backward linkage between the industry in which the non-digital asset is produced and the digital industry from which it purchases input. The share of the second part is denoted as $\overline{\omega}_{\overline{D},jt}$, and we call it the non-digital capital input share since this part of assets does not relate to digital industries at all. Further details on calculating the shares of capital input can be found in Appendix C. All shares are in nominal

values. Following Solow's method, A is a parameter of the production function, and $\Delta ln A_{jt}$ is the change in the residual used to capture the growth in the MFP index T.

The capital account warrants further discussion. We distinguish indirect digital capital input $K_{\overline{DD},jt}$ from non-digital capital input to further explore the total effects of development in digital industries. This approach to constructing the capital account allows us to capture the indirect effect through the backward linkage between non-digital and digital industries, which is consistent with the methodology provided in Section 2. Indeed, we argue that this approach provides a practical meaning: Many investments in non-digital industries are driven by the interconnection of investment growth in non-digital industries with upstream digital industries. Ignoring this backward linkage may underestimate the indirect effects of digitalization on the economy by contributing to the production of non-digital assets. For many new emerging countries such as China, because they experienced rapid growth in both non-digital and digital industries, this indirect effect could be very large. Ideally, labour input can also be decomposed into several parts on the basis of this approach. However, due to a lack of data, we only perform this decomposition for capital inputs.

We mainly rely on the World Input–Output Database (WIOD) Social Economics Accounts (SEA), China's capital input matrix for 2002, China's Statistical Yearbooks for 1997 to 2013, China's Investment in Fixed Assets Statistical Yearbooks for 1997 to 2013, China's official IO tables, and OECD ICIO tables as our major data sources to construct growth accounts for China. In addition to China, we report the results of 7 selected countries by using the Vienna Institute for International Economic Studies (Wiiw) Growth and Productivity Database as an additional data source. These countries cover the USA and several major countries in Europe and East Asia. Table 4 depicts the growth accounting results of these countries from 2000 to 2012. Even though we cannot cover a wider range of time series and more countries due to the lack of data, this period covers the large economic transition of China after it became a member of the World Trade Organization (WTO).

During this period, we see a positive contribution of direct digital capital input to GDP growth for all countries except Germany (DEU). We find that for China, the contribution of direct capital input to GDP is relatively small compared with other selected countries. For China, direct capital input contributed to 6.1% of its GDP growth during the 2000–2012 period. In other developed countries, such as Japan and the USA, the contribution of direct capital input was more than 20% of GDP growth. For all the selected countries with a positive correlation between GDP growth and capital input, direct capital input contributed the smallest percentage of GDP growth in China. Of course, given China's fast-growing GDP during this period, its value of the growth in direct capital input is still the largest among all the selected countries. In addition to the contribution of direct digital capital input, we examine the impact of indirect digital capital input. We see that for most countries, the contribution of indirect digital capital input is not very significant. However, for China, which experienced a rapid growth in non-digital capital input from 2000 to 2012, there was a significant impact of indirect digital capital input on GDP growth. China's indirect capital input contributed the largest percentage of its GDP growth among all countries, as shown in Table 4. China is a typical case that shows the significant effect of indirect capital input caused by the large co-movement between non-digital and digital industries through production linkage. During the 2000–2012 period, China's indirect digital capital input explained 2.9% of GDP growth. For the remaining selected countries, the contribution of indirect capital input explains less than 2% of their GDP growth.

We turn next to apply a similar methodology to elucidated the contribution of digitalization to the manufacturing sector, which experienced rapid development in China as China joined the WTO and became the "world factory". We perform our growth accounting analysis by classifying the two major groups in manufacturing sectors: (i) the manufacturing group with R&D intensity above the midpoint (high-tech) and (ii) the manufacturing group with R&D intensity below the midpoint (low-tech). A detailed classification can be found in Table A.2. To focus on the impact of digital capital input on non-digital sectors, we exclude the digital industries in the high-tech manufacturing sector. Tables 5.1 and 5.2 display the growth account results for these two groups. Comparing Table 5.1 to Table 5.2 and focusing on China, we see a larger contribution of both direct digital capital input and indirect digital capital input to the high-tech group than to the low-tech group. The contribution of direct digital capital input is 5.5% of total GDP growth in high-tech manufacturing sectors and 3.6% of the growth in the low-tech group. For other countries, the positive contribution of both direct and indirect digital capital input holds for most countries.

Unlike high-tech industries, low-tech manufacturing sectors show shrinking production during the 2000–2012 period for many countries. In addition, the results for low-tech industries show an opposite co-movement for GDP growth and direct digital capital input. Similar to the results of the overall economy, we see a significant impact of indirect digital capital input for both high- and low-tech groups in the manufacturing sector. For the high-tech manufacturing group, indirect digital capital contributes to 2.8% of total GDP growth, and it is 2.5% for industries in the low-tech group.

Table 4
Sources of GDP growth across world major economies, 2000–2012.

2000–2012	$\Delta ln GDP_t$	Direct D	Indirect D	Non D	Labour	TFP
CHN	123.93%	7.54%	3.54%	69.25%	19.84%	23.76%
USA	18.35%	3.72%	0.36%	5.80%	−1.00%	9.48%
JPN	5.80%	3.06%	0.05%	−0.60%	−1.55%	4.84%
KOR	45.97%	4.09%	0.82%	17.87%	19.38%	3.81%
DEU	12.18%	−0.10%	0.28%	2.38%	2.32%	7.30%
GBR	21.01%	1.50%	0.21%	3.99%	3.04%	12.28%
FRA	13.79%	1.97%	0.14%	1.88%	3.23%	6.57%
ITA	−0.09%	0.35%	0.37%	6.04%	3.23%	−10.08%

Note: *Direct D* refers to direct digital capital input; *Indirect D* refers to indirect digital capital input; *Non D* refers to non-digital capital input.

Table 5.1
Sources of value-added growth in high technology intensity manufacturing sectors, 2000–2012.

2000–2012	$\Delta lnVA_{jt}$	Direct D	Indirect D	Non D	Labour	TFP
CHN	231.47%	12.73%	6.48%	101.79%	29.72%	80.75%
USA	13.17%	0.17%	−0.01%	0.59%	−18.98%	31.41%
JPN	48.54%	1.64%	0.42%	4.71%	−4.23%	46.00%
KOR	81.01%	4.77%	1.16%	22.63%	6.27%	46.18%
DEU	24.47%	−0.14%	0.54%	4.18%	−0.22%	20.12%
FRA	3.58%	1.58%	0.69%	7.70%	−15.32%	8.93%
GBR	17.25%	0.10%	0.07%	−1.55%	−22.48%	41.11%
ITA	3.75%	0.06%	0.51%	7.25%	−2.63%	−1.44%

Table 5.2
Sources of value-added growth in low technology intensity manufacturing sectors, 2000–2012.

2000–2012	$\Delta lnVA_{jt}$	Direct D	Indirect D	Non D	Labour	TFP
CHN	163.38%	5.89%	4.17%	111.29%	15.53%	26.50%
USA	−4.61%	0.56%	0.88%	6.95%	−15.89%	2.88%
JPN	−27.17%	2.89%	0.11%	−2.28%	−14.89%	−13.00%
KOR	9.31%	−3.93%	1.02%	15.68%	0.61%	−4.07%
DEU	−1.56%	−1.04%	0.04%	−5.29%	−5.83%	10.55%
FRA	3.38%	1.32%	0.10%	−1.45%	−13.58%	17.00%
GBR	−10.10%	−0.42%	0.00%	−2.25%	−30.27%	22.83%
ITA	−13.22%	−0.08%	0.30%	2.05%	−8.72%	−6.77%

To summarize, our growth accounting framework confirms the positive contribution of digitalization to the growth of China and several other major economies in the world through the capital input channel. The direct digital capital input significantly contributed to the GDP growth of the selected countries from 2000 to 2012. Furthermore, for China, indirect digital capital input plays an important role in contributing to GDP growth through the investment linkages across sectors. This finding implies that we may not ignore the indirect contribution of digital capital input through the backward linkage in an emerging economy that has a high growth rate of investment in both digital and non-digital industries. At the sector level, manufacturing industries with high R&D intensity make a more positive contribution of direct digital capital input to value-added growth than manufacturing industries with low R&D intensity. From the perspective of production, the growth accounting results imply that the direct and indirect effects of digitalization can be partially explained by the linkage of investment across digital and non-digital industries. For many countries, rapid growth in digital industries leads to an increase in the demand of non-digital industries for capital input from digital industries. Iteratively, there will be an increase in the production of assets from these non-digital industries to benefit GDP growth over time.

We close this section with a brief note on the unusual results or shortcomings in our accounting work. First, we note that some countries experience an unusual decrease in TFP in some sectors even though the growth in digital capital input is positive. Because we calculate TFP as the residual, the opposite effect across TFP and digital input can be caused by some unobserved factors. In addition, our accounting framework assumes constant returns to scale, which may not be practical for all industries in all countries. Finally, due to the lack of data, we apply only a short time series in our growth accounting work, which may hamper its accuracy. Despite the potential challenges and inconsistencies in these cases, our growth accounting analysis supports the contribution of digitalization to GDP growth, and it can be used to quantify the indirect effects of digital industries through the production linkage.

6. Conclusions and discussion

In this paper, the ICIO accounting framework is applied to construct indices to measure digitalization in China and compare the results with other major economies in the world. Following the definition of digitalization from the perspective of production, we quantify both the direct and indirect portions of digitalization and compute the backward digitalization rate for country/industry pairs. In addition, we further construct GDP growth accounts by combining ICIO tables with other data sources to measure the intertemporal impact of digitalization through the investment channel.

Building on the above, our paper provides the following conclusions: (1) The digitalization effect in China increased rapidly from 2005 to 2018, propelling the economy to the forefront of major digital economy powers. (2) The structure of China's digitalization is changing. The development of digital industries is still the dominant form of digitalization in China, but the role of industrial digitalization is becoming increasingly significant. (3) There are significant differences in digitalization rates among traditional industries. The digitalization rates of the high-tech manufacturing industry and the modern service industry are relatively high, with some even exceeding the global average. (4) GVC activities have significant digitalization characteristics in China, and sectors that have higher relative digitalization rates tend to be highly integrated into GVCs, indicating that digitalization promotes the sectoral restructuring of China's GVCs. (5) The growth in both direct and indirect digital capital input contributed to GDP growth in China and several world major economies from 2000 to 2012, and the indirect effect is significant for developing countries that are experiencing rapid investment growth.

Based on our findings, we propose several policy implications as follows: Firstly, strengthen research on core technologies, strive to achieve independent innovation, and seize the initiative in the development of the digital economy. In terms of the digitalization effect per capita, there is still a stark discrepancy between China and developed economies. The government may gradually narrow the gap with developed economies by making breakthroughs in key core areas and continuously improving the stability and modernization of the production chain and supply chain. Secondly, promote the integration of the Internet, big data, artificial intelligence with the real economy, accelerate the digital transformation of traditional industries , and build a modern production chain. For the digitalization in most low-tech manufacturing industries and many service sectors such as finance and business services, China still lags behind the world. Besides consolidating the application of digital technology in industries with relatively high digitalization rates, it is beneficial for the government and firms to facilitate the integration of digital technologies in low-tech manufacturing sectors and service sectors, build intelligent industrial chains, to enhance trade capacity and efficiency, and accelerate industrial transformation and upgrading. Thirdly, accelerate the construction of digital platforms to facilitate the GVC participation of local firms. The development of digital platforms plays an important role in the restructuring of domestic and global value chains in the post-pandemic era. As a result, integrating into GVCs allows local firms to improve their digitalization rate and production efficiency through technology spillover. Finally, the government may encourage firms to utilize digital assets in both direct and indirect ways to accelerate digitalization continuously.

We round off our discussion by briefly discussing the limitation of our paper. At present, there is a lack of authoritative standards for measuring global digitalization, improvements in the level of data openness and sharing are needed, and the technical basis is relatively weak. A unified standard should be set so that all economies can measure their own degree of digitalization, compare them among each other and provide reliable data support to help governments set digitalization development goals and policies. Due to a lack of data support, it is difficult to separate the digital components of other services, such as those of digital finance and electronic logistics, from the original industry statistics. Therefore, this aspect is not included in the accounting methods used in this paper, which may underestimate the degree of digitalization. To accurately identify the digital components of non-digital industries, relevant data from other international organizations need to be further searched as auxiliary information.

Credit authorship contribution statement

Xuefan Guo: Data curation related to input–output data, formal analysis, and writing—original draft. Dingyi Xu: Data curation related to growth accounting and writing—original draft. Kunfu Zhu: Conceptualization, methodology, and writing—review and editing.

Data availability

Data will be made available on request.

Acknowledgements

Appendix A. Country and sector classification

Table A.1
Country classification.

Country code	Country name	Income group	Country code	Country name	Income group
AUS	Australia	High	CHE	Switzerland	High
AUT	Austria	High	TUR	Turkey	Upper middle
BEL	Belgium	High	GBR	United Kingdom	High
CAN	Canada	High	USA	United States	High
CHL	Chile	High	ARG	Argentina	Upper middle
COL	Colombia	Upper middle	BRA	Brazil	Upper middle
CRI	Costa Rica	Upper middle	BRN	Brunei Darussalam	High
CZE	Czech Republic	High	BGR	Bulgaria	Upper middle
DNK	Denmark	High	KHM	Cambodia	Lower middle
EST	Estonia	High	CHN	China	Upper middle
FIN	Finland	High	HRV	Croatia	High
FRA	France	High	CYP	Cyprus	High
DEU	Germany	High	IND	India	Lower middle
GRC	Greece	High	IDN	Indonesia	Lower middle
HUN	Hungary	High	HKG	Hong Kong, China	High
ISL	Iceland	High	KAZ	Kazakhstan	Upper middle

Table A.1 (*continued*)

Country code	Country name	Income group	Country code	Country name	Income group
IRL	Ireland	High	LAO	Lao People's Democratic Republic	Lower middle
ISR	Israel	High	MYS	Malaysia	Upper middle
ITA	Italy	High	MLT	Malta	High
JPN	Japan	High	MAR	Morocco	Lower middle
KOR	South Korea	High	MMR	Myanmar	Lower middle
LVA	Latvia	High	PER	Peru	Upper middle
LTU	Lithuania	High	PHL	Philippines	Lower middle
LUX	Luxembourg	High	ROU	Romania	Upper middle
MEX	Mexico	Upper middle	RUS	Russian Federation	Upper middle
NLD	Netherlands	High	SAU	Saudi Arabia	High
NZL	New Zealand	High	SGP	Singapore	High
NOR	Norway	High	ZAF	South Africa	Upper middle
POL	Poland	High	TWN	Chinese Taipei	High
PRT	Portugal	High	THA	Thailand	Upper middle
SVK	Slovak Republic	High	TUN	Tunisia	Lower middle
SVN	Slovenia	High	VNM	Viet Nam	Lower middle
ESP	Spain	High	ROW	Rest of the world	–
SWE	Sweden	High			

Notes: Country/region abbreviations come from ISO 3166-1 alpha-3 standard. For a complete list, see https://unstats.un.org/unsd/tradekb/knowledgebase/country-code. The country group classification based on income is from the World Bank; see https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

Table A.2
Sector classification.

Sector code	Sector description	ISIC Rev.4	Sector group	Sector type
D01T02	Agriculture, hunting, forestry	01, 02	AGR	$\overline{D}$
D03	Fishing and aquaculture	03	AGR	$\overline{D}$
D05T06	Mining and quarrying, energy producing products	05, 06	MIN	$\overline{D}$
D07T08	Mining and quarrying, non-energy producing products	07, 08	MIN	$\overline{D}$
D09	Mining support service activities	09	MIN	$\overline{D}$
D10T12	Food products, beverages and tobacco	10–12	LTI	$\overline{D}$
D13T15	Textiles, textile products, leather and footwear	13–15	LTI	$\overline{D}$
D16	Wood and products of wood and cork	16	LTI	$\overline{D}$
D17T18	Paper products and printing	17, 18	LTI	$\overline{D}$
D19	Coke and refined petroleum products	19	LTI	$\overline{D}$
D20	Chemical and chemical products	20	HTI	$\overline{D}$
D21	Pharmaceuticals, medicinal chemical and botanical products	21	HTI	$\overline{D}$
D22	Rubber and plastics products	22	MTI	$\overline{D}$
D23	Other non-metallic mineral products	23	MTI	$\overline{D}$
D24	Basic metals	24	MTI	$\overline{D}$
D25	Fabricated metal products	25	MTI	$\overline{D}$
D26	Computer, electronic and optical equipment	26	HTI	D
D27	Electrical equipment	27	HTI	$\overline{D}$
D28	Machinery and equipment, nec	28	HTI	$\overline{D}$
D29	Motor vehicles, trailers and semi-trailers	29	HTI	$\overline{D}$
D30	Other transport equipment	30	HTI	$\overline{D}$
D31T33	Manufacturing nec; repair and installation of machinery and equipment	31–33	LTI	$\overline{D}$
D35	Electricity, gas, steam and air conditioning supply	35	OSE	$\overline{D}$
D36T39	Water supply; sewerage, waste management and remediation activities	36–39	OSE	$\overline{D}$
D41T43	Construction	41–43	OSE	$\overline{D}$
D45T47	Wholesale and retail trade; repair of motor vehicles	45–47	TTC	DUAL
D49	Land transport and transport via pipelines	49	TTC	$\overline{D}$
D50	Water transport	50	TTC	$\overline{D}$
D51	Air transport	51	TTC	$\overline{D}$
D52	Warehousing and support activities for transportation	52	TTC	$\overline{D}$
D53	Postal and courier activities	53	TTC	$\overline{D}$
D55T56	Accommodation and food service activities	55, 56	TTC	$\overline{D}$
D58T60	Publishing, audiovisual and broadcasting activities	58–60	FBS	D
D61	Telecommunications	61	FBS	D
D62T63	IT and other information services	62, 63	FBS	D
D64T66	Financial and insurance activities	64–66	FBS	$\overline{D}$
D68	Real estate activities	68	OSE	$\overline{D}$
D69T75	Professional, scientific and technical activities	69–75	FBS	$\overline{D}$
D77T82	Administrative and support services	77–82	FBS	$\overline{D}$

Table A.2 (*continued*)

Sector code	Sector description	ISIC Rev.4	Sector group	Sector type
D84	Public administration and defense; compulsory social security	84	OSE	$\overline{D}$
D85	Education	85	OSE	$\overline{D}$
D86T88	Human health and social work activities	86–88	OSE	$\overline{D}$
D90T93	Arts, entertainment and recreation	90–93	OSE	$\overline{D}$
D94T96	Other service activities	94–96	OSE	$\overline{D}$
D97T98	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	97, 98	OSE	$\overline{D}$

Notes: The basis for sector classification comes from the OECD (the prefix "D" in the sector code is short for "Department"), and sectors are divided into 8 industry groups. See https://www.oecd.org/sti/inno/researchanddevelopmentstatisticsrds.htm. 1) AGR: agriculture, forestry and fishing (01T03 in the ISIC Rev4); 2) MIN: mining and quarrying (05T08 in the ISIC Rev4); 3) HTI: high-R&D-intensive industries, expressed as the high-tech manufacturing sector in the text (20T21, 26T29, 302, 304, 309, 303 in the ISIC Rev4); 4) MTI: medium-R&D-intensive industries, expressed as the medium-tech manufacturing sector in the text (22T25, 301, less 325 in the ISIC Rev4); 5) LTI: medium-low-R&D-intensive industries, expressed as the medium-low-tech manufacturing sector in the text (10T19, 31T32 in the ISIC Rev4); 6) TTC: trade and transportation (45T53, 55T56, 58T60 in the ISIC Rev4); 7) FBS: postal, telecommunication, financial and business services (61T66, 69T75 in the ISIC Rev4); and 8) OSE: real estate, public administration, construction and other services (35T39, 41T43, 68, 77T82, 84T88, 90T99 in the ISIC Rev4). Here, we define medium-low- and medium-R&D-intensity industries (LTI and MTI) in the OECD classification as the low-technology group and define high-R&D-intensity industries (HTI) as the high-technology group. The last column indicates whether the sector is a digital sector. D represents digital sector; $\overline{D}$ represents non-digital sector; and DUAL represents the sector including both digital and non-digital parts.

Appendix B. Sources and methodology for constructing growth accounting data

We construct growth accounts for China, the USA, Japan, South Korea, and 14 European countries from 2000 to 2012. The details are displayed as follows:

Table B.1
Information on the selected countries.

Alpha 3	Economy	Year	Sector
Outside Europe			
CHN*	China	2000–2012	Aggregated sector-level
JPN	Japan	2000–2012	Sector-level
KOR	South Korea	2000–2012	Sector-level
USA	United States	2000–2012	Sector-level
Europe			
CZE	Czech Republic	2000–2012	Sector-level
DEU	Germany	2000–2012	Sector-level
DNK	Denmark	2000–2012	Sector-level
ESP	Spain	2000–2012	Sector-level
FIN	Finland	2000–2012	Sector-level
FRA	France	2000–2012	Sector-level
GBR	United Kingdom	2000–2012	Sector-level
ITA	Italy	2000–2012	Sector-level
LTU*	Lithuania	2000–2012	No sector-level data for manufacturing sector
LUX*	Luxembourg	2000–2012	No sector-level data for manufacturing sector
NLD	Netherlands	2000–2012	Sector-level
SVK	Slovak Republic	2000–2012	Sector-level
SVN*	Slovenia	2000–2012	No sector-level data for manufacturing sector
SWE	Sweden	2000–2012	Sector-level

B.1. Breakdown of capital input into three parts

To break down capital input into three parts, we first need to identify the investments of digital industries from total investments. Sector-specific investment data distinguishing digital and non-digital assets are not available for China. To construct the sector-specific investment series, we updated the original investment matrix for 2002 by using a biproportional matrix balancing procedure (i.e., RAS). Other necessary data are from several types of Chinese statistical yearbooks and China's official IO tables. To guarantee inter-temporal consistency, we aggregated the detailed investment into 10 sectors (see Table B.2 for classification). For other countries, we rely mainly on the KELMS database and extract 11 types of gross fixed capital formation (GFCF) of 38 sectors in 22 economies, mapping these types to sectors in the OECD-ICIO tables. Finally, the GFCF data of 37 sectors divided into 9 types of the investment (GFCF) are obtained (see Table B.3). The classification of types of investment are different among China and other countries. However, the identification of the ICT manufacturing sector and ICT service sector follows the consistent standard. Therefore, the results of growth

accounting are still comparable across countries.

Table B.2
Types of investment for China.

No.	Sector	Type
1	Agriculture, forestry and fishing	$\overline{D}$
2	Mining	$\overline{D}$
3	LTI	$\overline{D}$
4	MTI	$\overline{D}$
5	HTI (Non-ICT)	$\overline{D}$
6	ICT manufacturing	D
7	Electricity, gas, steam, air conditioning and water supply	$\overline{D}$
8	Construction	$\overline{D}$
9	Non-ICT Services	$\overline{D}$
10	Telecommunication and ICT services	D

Notes: D represents digital input, and $\overline{D}$ represents non-digital input. See Table A.2 for more details on the definitions of LTI, MTI, and HTI.

Table B.3
Types of investment for other countries.

No.	Sector	Code	Type
1	Agriculture, forestry and fishing	A	$\overline{D}$
2	Computer, electronic and optical products	C26	D
3	Machinery and equipment, nec	C28	$\overline{D}$
4	Transport equipment	C29_C30	$\overline{D}$
5	Construction	F	$\overline{D}$
6	ICT services	J58-J60, J61, J62_J63	D
7	Professional, scientific, technical, administrative and support service activities	M_N	$\overline{D}$
8	Arts, entertainment and recreation	R	$\overline{D}$
9	Other industries	Other	$\overline{D}$

Notes: For detailed information, see http://www.euklems.net/.

Following Eqs. (2) and (4) we attempt to separate out the digital component. Digital capital input consists of two parts: direct digital capital input and indirect digital capital input. Direct digital capital input refers to the direct input of digital industries (D) in GFCF, which can be directly identified from *GFCF*:

$$GFCF_{direct} = GFCF_D \tag{C.1}$$

Indirect digital capital input refers to the digital input in the GFCF of non-digital industries, which needs to be fully extracted from the *GFCF* of non-digital industries.

$$GFCF_{indirect} = VBA_D B_{\overline{D}} \widehat{GFCF}_{\overline{D}} \tag{C.2}$$

B.2. Capital account

The main source used to construct the capital accounts for other countries is the KLEMS database. For China, we construct the capital data based on the investment matrix for 2002 provided by the National Bureau of Statistics (NBS) and the industry-specific investment data for other years from the China Statistical Yearbooks, the China Investment in Fixed Assets Statistical Yearbooks, and China's IO tables. The capital compensation share of value added is taken from WIOD SEA. To clarify, capital compensation ($P_{jt}^K K_{jt}$) equals the taxation on capital (T_j^K) plus the operating surplus (OS_{jt}) minus the self-employed compensation (LC_{jt}^S):

$$P_{jt}^K K_{jt} = T_j^K + OS_{jt} + LC_{jt}^S \tag{C.3}$$

As mentioned above, the asset type of indirect digital capital input ($K_{\overline{D}D\,jt}$) is the same as that of non-digital capital input ($K_{\overline{D}\,jt}$); therefore, the indirect digital capital compensation share of non-direct digital capital input and the corresponding capital stock shares are the same. We use OECD data to construct the share of direct digital capital in indirect digital capital input by following the method described in the previous section. Then, we follow King and Levine (1994) and assume that the initial period is in the steady state.

$$A_{k,t-1}^* = \frac{I_{k,t}}{\delta_K + g} \tag{C.4}$$

where *g* is the growth rate of GDP. We can use the indirect digital capital share of non-digital input to capture the initial capital stock.

The OECD data provide the GFCF by asset type beginning with 1995; thus, we use 1995 as the initial year. For countries other than China, we distinguish the indirect digital capital stock from the non-digital capital stock of 1995 based on the classification in Table B.3 For China, we rely on the GFCF and capital input data from China's official IO table for 1997 and the yearbooks for this year; 1997 is the initial year for China. Then, we can also construct a series of direct digital capital investment, indirect digital capital investment, and non-digital investment. We can use PIM to construct all the necessary capital stock series. For direct digital capital, we distinguish investment based on asset type. For indirect digital capital and non-digital capital, we first calculate the indirect digital investment share of non-digital investment $\alpha_{\overline{DD}}$ based on Eq. (C.2). Then, we construct the capital stock series as follows:

$$A_{\overline{DD}t} = \sum_{\tau=0}^{t} (1 - \delta_{\overline{D}})^{t-\tau} \alpha_{\overline{DD}} I_{\overline{D}\tau} \tag{C.5}$$

To construct the capital service, we first construct the rental price of capital service by following KLEMS' approach as follows:

$$P_{k,t}^{K} = r P_{k,t-1}^{I} + \delta_k P_{k,t}^{I} \tag{C.6}$$

For China, we do not have investment price and depreciation rate data regarding ICT. For the investment price, we use the producer price index for ICT manufacturing as a proxy. For the depreciation rate of China's ICT equipment, we use the value from Harry (2015). For digital service capital such as software, Harry gives a service average of only 5.2%, which is much lower than that of other countries. For the depreciation rate of software, we use South Korea's value of 24.7% as a proxy. This value is much closer to the world average. Then, weighted by the volume of assets, we obtain the depreciation rate of ICT in China. After all these steps, we can construct all types of capital compensation shares of capital input $\overline{\omega}_{\overline{D},jt}$, $\overline{\omega}_{\overline{DD},jt}$ and $\overline{\omega}_{D,jt}$. We also have all series of $\Delta ln K_{k,jt}$; therefore, we can construct the capital account.

B.3. Labour account

The labour account is simple. We use the labour compensation and employment data in WIOD SEA to obtain the labour compensation share of value added and the growth rate of labour.

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