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How does digital technology affect export in services?

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ABSTRACT

Based on the comprehensive measures of digital technology and cross-country services trade database, our study empirically examines the impacts of digital technology on export in services. We find that digital technology significantly promotes services export. However, the impact varies in different modes of supply. Digital technology significantly promotes service export in the mode of cross border delivery, consumption abroad, and commercial presence rather than the mode of the natural person movement. Heterogeneous analysis shows that the trade impact of digital technology is more pronounced in developed countries and the countries with higher levels of digital openness. Based on both the empirical analysis and the case studies, three main channels of the enhancement of tradability, the function of digital platforms, and innovation of new trade models are discussed for the influencing mechanisms of digital technology.

1. Introduction

In the face of increasing trade protectionism, the role of trade in services has gained prominence as a catalyst for accelerating international trade. Traditionally, cross-border trade in services faced several challenges, including the inherent non-tradability feature, inefficiency in supply and demand matching due to high transaction costs, and concerns related to performance security and risk management.[1] Addressing these constraints necessitates innovative solutions. Recent years have witnessed a rapid global development of digital technology, marked by the rise of digital industrialization and industrial digitization. Technologies such as artificial intelligence (AI), big data, cloud computing, Internet of Things (IoT), and blockchain have emerged. They offer innovative solutions to the long-standing challenges in cross-border trade of services, ushering in a new era of service provision and intellectualization. Digital technologies play a dual role in this transformation. On one hand, they provide crucial technical support for cross-border trade in services, enhancing the efficiency of service delivery across borders. On the other hand, digital platforms play an important role in improving global supply-and-demand matching, thereby bolstering the safety and credibility of cross-border services. To illustrate, consider the case of DiDi Global Inc., a leading mobile mobility technology platform. DiDi utilizes a range of digital

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[1] Service products are characterized by intangibility, inseparability of production and consumption, and non-storability. These attributes make it difficult to carry out increasing returns to scale and batch standardized production in the service industry, especially difficult in cross-border trade. The nonstandard characteristics of service products make the information matching cost between buyers and sellers high. The cognition, discovery, collection, processing and identification of information will incur costs. Resource mismatch and ineffective allocation may occur. Effective risk management is essential in the process of cross-border transactions of services to build reliable trust between supply and demand and to ensure product quality and performance security.

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technologies, including AI and big data, to offer diverse mobility services such as online taxi booking, chauffeur-driven services, and ride-hailing services across Asia Pacific, Latin America, and other markets. This case indicates the empowering potential of digital technology in driving export in services.[2] Importantly, the influence of digital technology extends beyond isolated examples and brings new opportunities for trade in services. Our paper represents one of the early studies delving into the far-reaching impacts of digital technology on international trade, with a specific focus on export in services.

To assess the impact of digital technology on services trade, we develop digital technology indicators from both narrow and broad perspectives. In the narrow context, we employ digital patents encompassing areas such as "artificial intelligence," "blockchain," "cloud computing," "big data," and the "Internet of Things" from 2005 to 2021. These patents serve as a proxy for measuring technological innovation. In a broad-sense perspective, we establish a comprehensive digital technology development index based on multiple digital components based on several databases of International Federation of Robotics (IFR), the World Bank Indicator (WDI), and the International Telecommunication Union (ITU).

In our empirical analysis, we examine the effects of digital technology on services export. Our findings reveal a substantial and positive impact of digital technology on service export. These results are robust after addressing potential endogeneity issues. Furthermore, our study investigates the heterogeneous impact of digital technology on the modes of service trade, countries in different economic development level and digital openness level. Based on the Trade in Services by Mode of Supply (TiSMoS) Database, we find that digital technology only increases service export in three modes: cross-border delivery, consumption abroad, and commercial presence, but a mute effect on the movement of natural persons. Utilizing the Digital Service trade Restrictiveness Index (DSTRI) published by the Organization for Economic Cooperation and Development (OECD), we find that digital technology development significantly fosters export in services, particularly in countries with higher digital openness. Moreover, our research indicates that the impact of digital technology on services export is more significant in developed countries than in developing countries.

We then investigate the underlying mechanisms through which digital technology exerts its influence on services export and propose three possible channels. The first is the tradability enhancement. Digital technology plays a pivotal role in boosting the tradability of services, dismantling conventional barriers and thus facilitating cross-border service trade. The second is the reduction of transaction costs and risk through digital platforms. Digital platform can effectively reduce transaction costs and mitigating risk in service transactions, along with enhanced efficiency and security, thus increasing export in services. The third is innovation in service trade models. Digital technology inspires innovation, leading to new trade models and formats. These innovations fundamentally facilitate the delivery and accessibility of services, thus promoting service export

This paper contributes to the literature in three dimensions. First, our paper focuses on the impact of digital technology on trade in services. Since the onset of the Fourth Industrial Revolution on a global scale, some studies have focused on the impact of digital technologies on economic growth, and some studies focus on particular digital technology and investigate the effect on goods trade, like the impact of 3D printing on international trade (Freund et al., 2022), impact of artificial intelligence on trade growth (Aghion et al., 2017; Brynjolfsson et al., 2019). However, few studies have examined the effects of digital technology on international trade in services, while our paper focus on export in services. From this perspective, we find that digital technology has a significant contribution to services trade and also boosts service export under three modes: cross-border, consumption abroad and commercial presence.

Second, we comprehensively measure digital technology. We measure digital technology in both a narrow and a broad perspective, with several sub-indicators which can reflect a country's digital technology development comprehensively. The literature lacks a unified standard or comprehensive measurement for digital technology, and measurements can typically be categorized into two main types. One is the direct measurement, which directly adopts indicators related to digital technology, often drawn from international organizations (Solomon and van Klyton, 2020). Researchers may utilize indicators such as the ICT Development Index (IDI), released by the International Telecommunication Union (ITU) as a measure of digital technology development (James, 2012). The other measurement is an indirect method, which employs a multidimensional set of indicators to construct a comprehensive digital technology development index through specific calculation methods (Katz et al., 2014; Zhang and Wang, 2022). Our paper introduces an indicator system to measure the digital technology at the country level, covering both narrow and broad aspects of digital technology. Specifically, in our approach, when measuring digital technology from a narrow sense, we focus on innovation only, using patent data for five specific digital technologies. Simultaneously, when measuring digital technology from a broad perspective, we consider different components of digital technology in various dimensions. These two approaches help to measure digital technology comprehensively, addressing the limitations of the existing one-dimensional approaches in the literature.

Third, our paper makes a contribution to the literature by investigating the mechanisms through which digital technology promotes export in services. While previous studies have primarily explained the impacts of digital technology on international trade, they often focus on trade in goods. We shift our attention to service trade. Previous research has highlighted the facilitative role of digital technology in trade by improving import and export conditions (Abeliansky and Hilbert, 2017) and expanding international trade volume through ICT and the Internet (Vemuri and Siddiqi, 2009). The Internet's influence on exports has also been explored (Clarke and Wallsten, 2006). However, our paper takes a different path by presenting three mechanisms of how digital technology impacts services export, such the tradability enhancement, the function of digital platforms and the drives of new trade models.

The paper is structured as follows: Section 2 provides a discussion of the mechanisms. Section 3 discusses the relevant literature on digital technology and international service trade, along with an overview of the current status of digital technology and services trade

[2] Digital technologies play a transformative role in services trade by enabling new forms of service delivery. This is evident in how companies like DiDi can operate across multiple countries, utilizing digital platforms to deliver services internationally. Such advancements in technology significantly increase the efficiency of service export and allow businesses to scale globally with ease.

development. Section 4 covers the empirical specification and data, while Section 5 presents the empirical findings. Mechanism analysis is carried out in Section 6, and Section 7 serves as the paper's conclusion.

2. Discussion of the mechanisms

The mechanisms through which digital technology influences trade in services are summarized by Yi and Jiang (2022) in Annual research report of China's services trade. As illustrated in Fig. 1, digital technology effectively addresses the challenges of traditional service trade, which is inherently intangible and non-storable. Digital technology, with the support of AI and other creative digital technologies, serves as the underlying technical backbone. This technology facilitates the integration of digital resources and elements, adapting them to a range of diverse application scenarios within the service trade domain. This transformative process results in an innovation-driven approach that empowers and enhances trade in services (Yi and Jiang, 2022).

Firstly, digital technology plays a pivotal role in improving the tradability of services. Traditionally, services present unique characteristics such as intangibility, inseparability of production and consumption, and non-storability, which pose significant obstacles to cross-border transactions. However, digital technology has driven a transformation in the service trade landscape. It enables the conversion of initially non-tradable services into tradable services by facilitating cross-border delivery. This innovation addresses the challenges associated with cross-border transactions in the service trade sector, effectively expanding the scope of tradable services.

Secondly, digital technology lowers transaction costs and mitigates risks within the service trade sector, largely through the emergence of digital platforms. As digital technology advances, digital platforms have emerged, seamlessly integrating production, circulation, services, and consumption. This integration enables the combination of online and offline resources and enables efficient division of labor. As a result, numerous new business models and formats have been spawned, laying the groundwork for innovative developments within the service trade domain.

Thirdly, digital technology serves as a catalyst for the creation of novel models and formats within the service trade. By providing a wide range of digital solutions and accelerating the digitization process, introducing new dynamics to the trade landscape. Digital technologies such as AI, blockchain, cloud computing, big data, and IoT contribute to this transformation from various angles. The continuous evolution and refinement of digital technology bring about significant changes in the provision and operation of service trade. This, in turn, leads to the standardization and modeling of service processes, marking a fundamental shift in the way services are delivered and accessed.

3. Facts on digital technology and trade in services

3.1. *The definition of digital technology*

Digital technology is an emerging scientific concept that is yet to be uniformly defined. Yoo et al.(2010) identified three key characteristics of digital technology: re-programmability, homogeneity of data, and self-referentiality. Originally, digital technology was defined with a focus on physical matter (Bharadwaj et al., 2013; Fitzgerald et al., 2014). However, it has evolved over time from its physical substance origins to being viewed as a service-oriented concept (Lyytinen et al., 2016). Recent developments have led to various approaches to defining digital technology, encompassing its constituent elements (Lyytinen et al., 2016; Nambisan et al., 2019; Von Briel et al., 2018) and representative technologies (Sturgeon, 2021; Urbinati et al., 2018). To ensure a comprehensive measurement, this paper adopts a dual definition of digital technology, addressing both narrow and broad interpretations.

In a narrow sense, Urbinati et al. (2018) and Sturgeon (2021) define digital technology using five main digital technologies: AI, blockchain, big data, cloud computing and the IoT. These technologies form the foundation for the variables examined in this paper. In a broad sense, digital technology is defined based on its constituent elements, comprising three main components: digital components, digital infrastructure, and digital platforms (Lyytinen et al., 2016; Nambisan et al., 2017; Nambisan et al., 2019; Von Briel et al., 2018), which facilitate the conversion of data and information into a computer-readable format for processing, analysis, and delivery. Digital components are software or hardware embedded in new products or services, providing specific functionality and value to users.

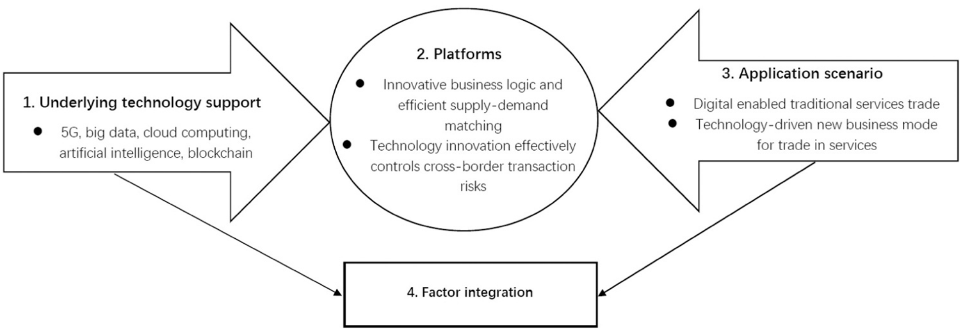

Fig. 1. Mechanisms for the impact of digital technology on international trade in services.
Source: Annual research report of China's service trade 2022: impact of digital transformation and innovation on service trade (Yi and Jiang, 2022)

Examples include mobile apps and electronic chips. Digital infrastructure includes tools and systems that facilitate communication, collaboration, and computing power to support the operation of digital technologies. It includes resources such as data analytics and 3D printing. Digital platforms are defined as a set of shared, common services and architectures for hosting complementary products, including digital offerings (Parker et al., 2016; Tiwana et al., 2010). Prominent examples include cross-border e-commerce platforms like Alibaba and eBay. Specifically, digital technology in a broad sense encompasses a comprehensive array of elements. This expansive perspective includes communication technology, information technology, and associated services and is an advanced information and communication technology or system, which includes physical parts such as digital hardware, logical parts such as network connections, access methods, and operational procedures that underpin the functioning of digital technology, and end results such as information, products, platforms, and infrastructures.

3.2. Measures of digital technology

Taking into account the need for comprehensive and accessible indicators, this paper establishes an indicator system for measuring the level of digital technology development. This system is founded on a dual definition that encompasses both the narrow and broad interpretations of digital technology.

3.2.1. Measures of digital technology in a narrow sense

In accordance with the narrow definition of digital technology, our study evaluates the level of digital technology development in each country by examining their patents related to five key digital technologies: “artificial intelligence”, “blockchain”, “cloud computing”, “big data” and “Internet of Things”. Here is the specific method used: we conducted searches in the “WIPO PATENTSCOPE”database using these keywords for each country and year. We then aggregated the total number of patents across these digital technology domains. Subsequently, we applied the natural logarithm to this count, creating a unique indicator that measures the level of digital technology development in a narrow sense. This indicator is crucial for our research, as it provides valuable insights into the technological landscape of each country in relation to digital innovation.

3.2.2. Measures of digital technology in a broad sense

To access the development of broadly defined digital technology, we devised an indicator system using the entropy method.[3] This system incorporates three key elements: digital components, digital infrastructure, and digital platforms, which we refer to as primary indicators (Level 1). Each of these primary indicators is further decomposed into six secondary indicators (Level 2). The three primary indicators and their respective six secondary indicators along with their data sources are presented in Table 1. To assess digital components (hardware), we employ robot stock data as a proxy obtained from lFR database. Digital infrastructure is constituted by three secondary variables, encompassing fixed broadband penetration (measured via fixed broadband subscriptions per 100 inhabitants), fixed telephone penetration (evaluated using fixed telephone subscriptions per 100 inhabitants), and mobile telephone penetration (assessed through mobile telephone subscriptions per 100 inhabitants), with data derived from the World Development Indicator (WDI) database. Digital platforms consist of two secondary indicators, including the mobile broadband activity rate (evaluated through active mobile broadband subscribers per 100 inhabitants) and subscriber network traffic (measured via network traffic per Internet user), with data sourced from ITU Database. This comprehensive measurement approach enables a multifaceted analysis of digital technology across these fundamental dimensions.

3.2.3. Facts of digital technology development

Based on our indicator construction for digital technology, we can reveal facts about digital technology worldwide both in a narrow sense and in a broad sense. Fig. 2 shows the trend for global digital technology measured in a narrow sense by digital technology patents. From 2005–2021, the number of digital technology patents worldwide grew from 244 to 63,237. It has been on an upward trend and began to surge in 2015. Fig. 3 shows the index of global digital technology in a broad sense. The broad-sense digital technology index exhibits an overall upward trend and peaks in 2017.

To gain a comprehensive insight into the global digital technology landscape, our indicator construction provides valuable insights into this evolving realm, examining digital technology both in a narrow and broad sense. In Figure2, we illustrate the evolving landscape of global digital technology as measured in a narrow sense through the lens of digital technology patents. From 2005–2021, we observe a remarkable surge in the number of digital technology patents worldwide, marking a transformative period in the digital technology landscape. Notably, this growth began to accelerate in 2015. In Fig. 3, we present the index of global digital technology in a broad sense, offering a holistic view of digital technology development. The broad-sense digital technology index demonstrates an overall upward trend, reaching its zenith in 2017. This comprehensive measurement encompasses the diverse facets of digital technology, laying the groundwork for our analysis of its impact on international service trade.

3.3. Development of trade in services

Global trade in services has witnessed a rapid and substantial expansion since the early 21st century, setting the stage for our

[3] The calculation steps of entropy method are shown in the Appendix.

Table 1
Indicator system for digital technologies in broad sense.

Level 1 Indicators	Level 2 Indicators	Content	Source	Year
Digital components	Hardware	Robot stock	IFR	2005–2019
Digital infrastructure	Fixed broadband penetration	Fixed broadband subscriptions per 100 inhabitants	WDI	2005–2021
	Fixed telephone penetration	Fixed telephone subscriptions per 100 inhabitants	WDI	2005–2021
	Mobile telephone penetration	Mobile telephone subscriptions per 100 inhabitants	WDI	2005–2021
Digital platforms	Mobile broadband activity rate	Active mobile broadband subscribers per 100 inhabitants	ITU	2007–2021
	Subscriber network traffic	Network traffic per Internet user	ITU	2007–2021

Notes: The units of the Subscriber network traffic are expressed in 1000 bit/s.

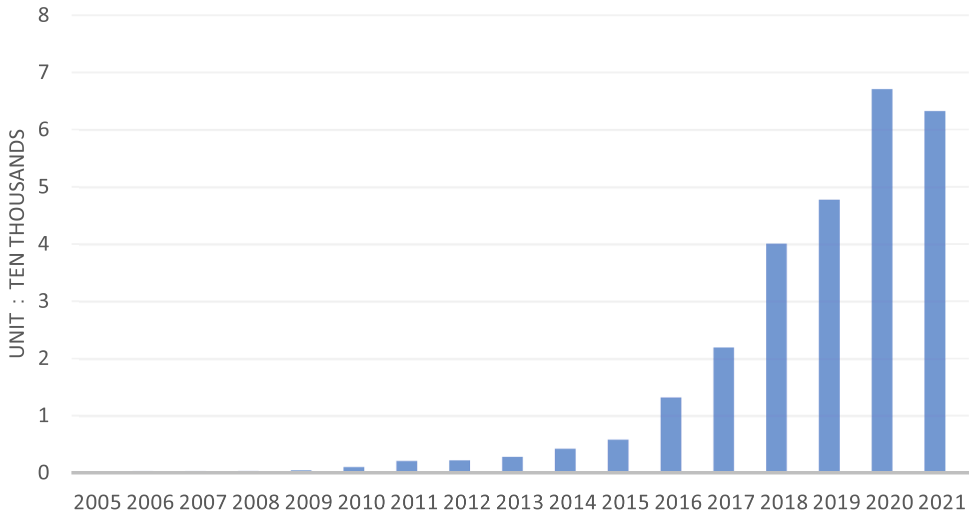

Fig. 2. The number of global digital technology patents.
Data source: World Intellectual Property Organization (WIPO)

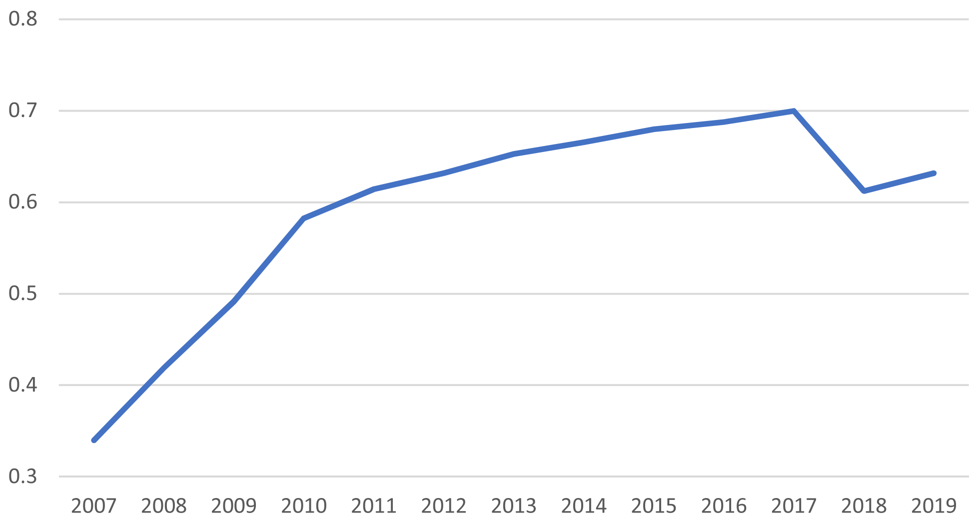

Fig. 3. The trend of global digital technology in broad sense.
Data source: Indicator system for digital technologies in broad sense calculated by the authors

exploration of the influence of digital technology on this dynamic landscape. From 2005–2021, the total value of global service exports surged from US$2.66 trillion to an impressive US$6.01 trillion,[4] marking a remarkable 126 % increase over a span of 16 years, as depicted in Fig. 4. Drawing on the database of Trade in services by mode of supply (TiSMoS), service exports via cross-border delivery experienced remarkable growth, surging from US$1.85 trillion to US$5.6 trillion,[5] marking an increase of 203 % as shown in Fig. 5. These trends provide a critical backdrop for our examination of how digital technology influences the dynamics of international service trade.

4. Empirical model and data

To identify the effect of digital technology on trade in services, we construct the estimation equation as follows:where $Service_{it}$ represents total exports in services for country i in year t; $Digital_{it}$ corresponds to the level of digital technology development, taking into account both the narrow and broad senses of digital technology. $Controls_{it}$ includes a series of control variables that may influence international trade in services, such as foreign direct investment (FDI_{it}), employment in services (EMP_{it}) and service value added (SVA_{it}). β_0 represents the intercept term, while $v_i$andv_t represent country fixed effects and year fixed effects, respectively, and ε_{it} is the random disturbance term. The explained variable $Service_{it}$ source from OECD-WTO BaTIS database. The core explanatory variables $Digital_{it}$ have mentioned in the Section 3.2, that is, as for the narrow definition of digital technology evaluates the level of digital technology development in each country by examining their patents related to five key digital technologies: "artificial intelligence", "blockchain", "cloud computing", "big data" and "Internet of Things" and aggregated the total number of patents across these digital technology domains and applied the natural logarithm to this count, creating a unique indicator that measures the level of digital technology development in a narrow sense. For the broadly defined digital technology, we devised an indicator system using the entropy method. This system incorporates three key elements: digital components, digital infrastructure, and digital platforms. Besides, the control variables are from the World Bank.

For our analysis of the impact of narrow digital technology indicators on international trade in services, we utilized a dataset comprising 49 sample countries and data from the years 2005–2021. Similarly, our analysis, based on the broad sense digital technology index, involved data from 59 countries covering the period from 2007 to 2019. To provide a comprehensive overview, we explore the main variables and their associated descriptive statistics, as presented in Table 2.

5. Empirical results

5.1. Baseline results

We present the estimation results for Eq. (1) in Table 3. In column (1), we assess the impact of narrow digital technology, while column (2) examines the impact of broad digital technology. Our results reveal statistically significant and positive coefficients for both narrow and broad digital technology development levels, highlighting the crucial role of digital technology in promoting service export.

5.2. Robustness checks

5.2.1. Endogeneity issues

To address potential endogeneity concerns, we employ a multifaceted approach. First, we include control variables such as FDI and service value added in our baseline regression model to account for the observables. Additionally, we introduce country fixed effects and year fixed effects to control for unobservable country characteristics and time trends. Second, to mitigate the issues of reverse causality, we construct instrumental variables to address the issue of endogeneity in examining the impact of digital technology on service trade. We construct two instrumental variables for digital technology respectively. In a narrow sense, digital technology refers to innovations based on digital technology. Therefore, the instrumental variable for the narrowly defined digital technology are created using the number of patents for digital chip,[6] as they are closely related to digital technology. In a board sense, we construct instrumental variable using postal and telecommunications data, as there's a close relationship between digital technology development and advancements in postal and telecommunication infrastructure. To ensure the effectiveness of our instruments, we use historical data, particularly the fixed telephone penetration rate in 1984, which reflects past postal and telecommunication development. In our instrumental variable construction, we multiply the per capita network traffic by the number of fixed-line telephones per 100 people in 1984 and take the natural logarithm of this cross-product as the instrumental variable (Tele). This rigorous approach helps address endogeneity concerns and enhances the robustness of our analysis.

In Table 4, columns (1) and (3) display the results from the first-stage estimation, while columns (2) and (4) provide insights into the second-stage outcomes. The coefficients of digital technology based on IV estimation remain statistically significant. The statistical values of Cragg-Donald Wald F (CD Wald F) Statistics are both larger than the cut-off value of the weak instrumental variable test at the

[4] Data source: Balanced International Trade in Services (BaTIS) EBOPS 2010, https://stats.wto.org/

[5] Data source: WTO, https://www.wto.org/english/res_e/statis_e/gstdh_mode_supply_e.htm

[6] The data of the number of digital chip patent comes from WIPO PATENTSCOPE database. By searching keyword "digital chip" and sum up the total number of the patent.

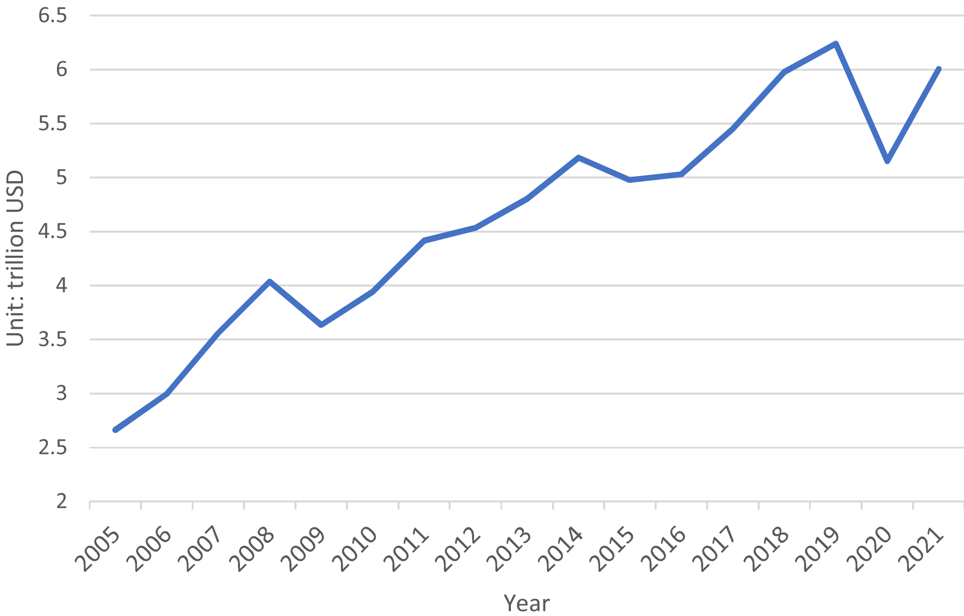

Fig. 4. Total service exports (Trillion USD).
Data source: OECD-WTO Balanced International Trade in Services (BaTIS) database

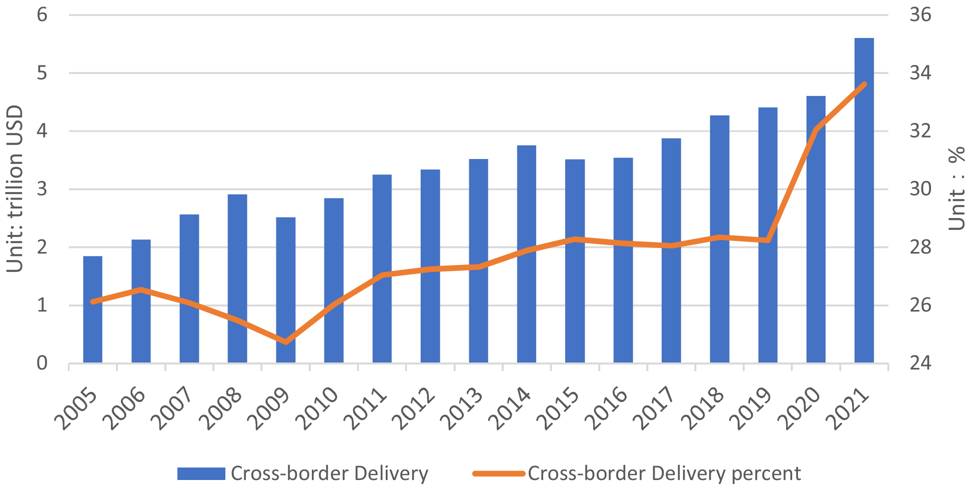

Fig. 5. Total value and proportion of services exports by cross-border mode of supply.
Data source: TiSMoS database

10 % level, indicating that there is a strong correlation between IVs and the digital technology. The problem of weak IV can be excluded. The Lagrange Multiplier (LM) statistic are also larger than the cut-off value, rejecting the hypothesis of insufficient identification of instrumental variables at the 1 % level. As a result, the results of IV estimation are effective. The trade effects of digital technology remain positive and significant, reinforcing the robustness of our baseline result.

5.2.2. Alternative measures for digital technology

Following Solomon and van Klyton (2020), we use the Network Readiness Index (NRI) as an alternative measure of digitization to evaluate a country's digital technology development. The NRI comprises three essential dimensions: infrastructure, overall business, and regulation. The regression results in column (1) of Table 5 are consistent with the direction of our baseline regression results, for both narrow and broad definitions of digital technology. We also investigated the influence of digital technology infrastructure and components, using them as the primary explanatory variables in place of the broad digital technology indicators, to test for robustness. The regression results in columns (2) and (3) of Table 5, which are consistent with the baseline results, reinforce the reliability of our findings.

Table 2
Descriptive Statistics.

Variables	Variable symbols	Variable Description	Observations	Mean	sd	min	max
Explained variables	Service export	Natural logarithm of total exports of trade in services	649	10.12	1.440	6.580	13.64
Core explanatory variables	Digital	Indicators of digital technologies in a narrow sense	539	1.050	1.710	0	9.740
		Indicators of digital technologies in a board sense	649	10.12	1.440	6.580	13.64
Control variables	FDI	Natural logarithm of total foreign direct investment inflow	614	6.720	1.780	1.210	11.20
	EMP	General government expenditure on education	649	4.140	0.230	3.250	4.430
	SVA	Annual growth rate for value added in services	646	4.060	0.170	3.440	4.350

Notes: The units of the explanatory variable Service are expressed in ten million USD, and the units of control variables FDI are expressed in ten million USD, the units of control variables EDU and SVA are expressed in percentage.

Table 3
Baseline Results.

	(1)	(2)
	Level of digital technology in narrow sense	Level of digital technology in abroad sense
Digital	0.043***	0.232**
	(0.010)	(0.108)
FDI	0.040***	0.051***
	(0.008)	(0.009)
SVA	0.804***	0.773***
	(0.234)	(0.141)
EMP	−0.088	−0.997***
	(0.233)	(0.220)
Country FE	YES	YES
Year FE	YES	YES
Observation	515	612
R^2	0.993	0.990

Notes: The covariates used for the OLS process with the WDI database include foreign direct investment inflow, percentage of employment in service and service value added of GDP. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *, **, *** denote the significance levels at 10 %, 5 %, and 1 %, respectively.

Table 4
Robustness Checks: IV estimations.

	(1)	(2)	(3)	(4)
	Level of digital technology in a narrow sense		Level of digital technology in a board sense	
	First stage	Second stage	First stage	Second stage
	Digital	Service	Digital	Service
Digital Chip	0.448***			
	(0.086)			
Tele			0.072***	
			(0.010)	
Digital		0.182***		1.278***
		(0.043)		(0.316)
Controls	YES	YES	YES	YES
Country FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
CD Walt F Statistics		27.025		53.056
LM statistic		28.608		54.703
Observations	397	397	629	629
R^2	0.910	0.985	0.833	0.988

Notes: The instrumental variable (Digital Chip) in column (1) and (2) is the number of digital chip patents and takes the natural logarithm of the total number. The instrumental variable (Tele) in in column (3) and (4) is multiplies the per capita network traffic in each country with the number of fixed-line telephones per 100 people in each country in 1984 and takes the natural logarithm of the total number. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 %, and 1 % respectively.

Table 5
Robustness checks: alternative of explanatory variables and the controls STRI.

	(1)	(2)	(3)	(4)	(5)
	Alternative of explanatory variables			More controls of STRI	
NRI	0.264*** (4.73)				
Digital Infrastructure Level		0.195*** (0.045)			
Digital Component Level			0.103*** (0.016)		
Digital				0.374*** (0.124)	0.028* (0.014)
STRI				−0.261 (0.755)	−0.548 (1.101)
Controls	YES	YES	YES	YES	YES
country FE	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES
Observations	420	608	593	209	222
R^2	0.992	0.990	0.990	0.998	0.993

Notes: The core explanatory variable in column (1) is the network readiness index (NRI) from the World Economic Forum (WEF). The core explanatory variables in column (2) and column (3) in this table are the data of the broad-sense digital technology indicators in Table 1. We take their natural logarithm and find their mean value as the indicator of the digital infrastructure level and digital component level. Column (4) and column (5) in this table are regressions with the added control variable of Service trade Restrictiveness Index (STRI). Based on the availability of data, the STRI data used in this paper is from 2014 to 2021. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 %, and 1 %, respectively.

5.2.3. More controls of STRI

Services trade policy has direct effects on services trade (World Trade Report, 2019) (And we add the controls of service trade restrictiveness index (STRI) from the OECD database to measures the level of restrictiveness policies in trade and investment in services from 2014 to 2021, with scores ranging from zero (complete openness) to one (complete closure). The results are presented in columns (4) and (5) in Table 5. With the controls of STRI,[7] the coefficients of digital technology are still positive and significant, and the service trade effects of digital technology are robust.

5.3. Heterogeneity analysis

5.3.1. Heterogeneity analysis by the supply mode

Heterogeneity analyses based on the mode of supply are presented in Table 6. Columns (1) to (4) show the impact of digital technology in narrow sense on the four modes of supply: cross-border delivery (mode 1), consumption abroad (mode 2), commercial presence (mode 3), and movement of natural persons (mode 4). Columns (5) to (8) depict the impact of digital technology development in broad sense on the services trade. Our findings indicate that digital technology has a significant and positive impact on international trade in services by the modes of cross-border delivery, consumption abroad, and commercial presence. However, it does not significantly impact trade in services involving the movement of natural persons. The ability of digital technology to reduce the need for physical presence in service provision may have a substitution effect on the movement of natural persons.

5.3.2. Heterogeneity analysis by development level

The relationship between digital technology and international trade in services is significantly influenced by exporting country's development level. To explore this relationship, we categorized the countries in our sample into two groups: developed and developing countries, using the United Nation and World Bank classification criteria. United Nation classification criteria mainly depends on Human Development Index (HDI)[8] as well as economic, social, and environmental factors. World Bank classification criteria depends on Gross National Income (GNI) per capita. To be specific, the countries with a per capita GNI of more than $13,845 are classified as the developed countries, otherwise are the developing countries.

For this analysis, we focus exclusively on broad-sense digital technology indicators. The columns (1) and (2) of Table 7 use the World Bank classification criteria, while columns (3) and (4) use the United Nations classification criteria. Both classification methods reveal notable differences in how digital technology impacts international trade in services for countries with different levels of development. Specifically, digital technology serves as a significant promoter of international trade in services in developed countries, while its impact on developing countries is not statistically significant. This outcome can be attributed to the superior conditions for

[7] Based on the availability of data, the STRI data used in this paper is from 2014. And the data source is: https://stats.oecd.org/Index.aspx?DataSetCode=STRI

[8] The United Nations Development Program (UNDP) uses the Human Development Index as a key measure of a country's development level. The HDI takes into account life expectancy, education level, and per capita income.

Table 6
Heterogeneity analysis in services export by supply mode.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Level of digital technology in narrow sense				Level of digital technology in broad sense			
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 1	Mode 2	Mode 3	Mode 4
Digital	0.040***	0.020*	0.083***	0.013	0.292***	0.269***	0.557***	0.125
	(0.010)	(0.011)	(0.017)	(0.018)	(0.083)	(0.104)	(0.181)	(0.183)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Observations	614	614	614	611	637	638	637	631
R^2	0.990	0.979	0.988	0.977	0.992	0.982	0.984	0.972

Notes: We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 %, and 1 %, respectively.

Table 7
Heterogeneity analysis based on development level.

	(1)	(2)	(3)	(4)
	World Bank's classification criteria		United Nations classification criteria	
	Developed Country	Developing Country	Developed Country	Developing Country
Digital	0.374**	−0.113	0.387***	0.153
	(0.145)	(0.166)	(0.093)	(0.188)
Controls	YES	YES	YES	YES
country FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES
Observations	345	267	393	262
R^2	0.989	0.988	0.994	0.983

Notes: The columns (1) and (2) use the World Bank classification of developed and developing countries. Columns (3) and (4) use the United Nation classification of developed and developing countries. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 % and 1 %, respectively.

digital technology development in developed countries, which often possess a knowledge-intensive and capital-intensive digital technology landscape. In such environments, the impact of digital technology on trade in services is more pronounced. Importantly, this result underscores the potential for digital technology to widen the development gap between developed and developing countries, thereby contributing to an overall imbalance in global development.

5.3.3. Heterogeneity analysis by digital trade policy

We employ the Digital Service trade Restrictiveness Index (DSTRI), an index published by OECD, to perform an analysis based on the level of national openness to digital trade. The DSTRI is an adaptation and extension of the STRI, designed to identify and measure policy impediments in countries that impede the development of digital service trade within the context of global digital service expansion. This index primarily focuses on assessing cross-border policy barriers that affect digital service trade. The DSTRI assigns values ranging from zero to one, where a score of zero indicates complete openness in terms of trade and investment in digital services, while a score of one represents complete closure to such trade and investment. We divide our sample into two groups based on the median DSTRI openness level[9]: high openness and low openness. The results, detailed in Table 8, demonstrate that digital technology significantly contributes to service trade in high digital openness countries, while showing no significant effect in low digital openness countries.

6. Mechanisms analysis

6.1. Tradability enhancement

Traditional trade in services can only be delivered "face-to-face", and many services are difficult to step across borders due to geographical distance, thus leading to a certain services trade restriction. Meanwhile, the stringent regulatory system for trade in services in various countries has further restricted the development of service trade. However, the emergence and evolution of digital technology have empowered services trade to overcome these challenges. Digital technology promotes trade in services by means of

[9] Based on the availability of data, the DSTRI data used in this paper is from 2014 to 2021. And the data source is: https://stats.oecd.org/Index.aspx?DataSetCode=STRI_DIGITAL

Table 8
Heterogeneity analysis based on the digital openness level.

	(1)	(2)
	Low DSTRI index countries	High DSTRI index countries
Digital	1.571*	0.185
	(0.858)	(0.244)
Controls	YES	YES
Country FE	YES	YES
Year FE	YES	YES
Observation	73	94
R^2	0.998	0.999

Notes: DSTRI is a dummy that indicates a country's DSTRI index, which equals one if the country's DSTRI index is above the median value. The DSTRI data used in this paper is from 2014 to 2021. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 % and 1 %, respectively.

Table 9
Mechanisms Analysis: tradability Enhancement.

	(1)	(2)	(3)	(4)
	Level of digital technology in narrow sense		Level of digital technology in broad sense	
VARIABLES	Cross-border delivery	Digital trade	Cross-border delivery	Digital trade
Digital	0.040***	0.033**	0.292***	0.249*
	(0.010)	(0.016)	(0.083)	(0.144)
Controls	YES	YES	YES	YES
country FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES
Observations	614	504	637	596
R^2	0.990	0.990	0.992	0.989

Notes: Cross-border delivery is the export value of mode 1 based on TiSMoS database, and digital trade is the export value of trade in service of BOP statistics. Their natural logarithm forms are taken. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 %, and 1 %, respectively.

transforming non-tradable services into tradable services through cross-border delivery mode, and broadens the scope of trade. In particular, some services in the target market, which were needed to be realized through the establishment of subsidiaries in the host country, mergers and acquisitions before, can be realized through cross-border delivery to lower the trade cost and greatly enhance the efficiency of services. Thus, this paper explores the mechanisms based on the fact that digital technology facilitates cross-border delivery. The specific regressions are presented in Table 9, which reports the impact of digital technology on services export under mode 1 in columns (1) and (3) in the narrow and broad sense of digital technology. The development of digital technology has promoted export in services provided by the mode of cross-border delivery, which expands the scope of service trade, thus promoting the overall development of service export.

The tradability enhancement mechanism can also be manifested by the increase of exports of digitizable services. According to WTO data, global exports of digitizable services grew 2.4-fold between 2005 and 2022, with a share of global service exports increasing from 45 % to 57.1 % and a predicted 1.2 % points increase of the average annual growth rate of trade in services. To verify the tradability enhancement mechanism through exporting digitizable services, we identify how digital technology affects digital trade. Based on the definition and industry classification of digital trade,[10] we identify specific service sectors of insurance and pension, finance, intellectual property rights, ICT, and personal, cultural, and recreational services. For these five sectors, we aggregate the value of service exports and subsequently take the natural logarithm form. Regression analysis is then conducted following Eq. (1).

We regress digital technology development on the digital trade. The results are presented in Table 9. There is a significantly positive effect of digital technology on digital trade, as observed in columns (2) and (4).

[10] As for the definition of trade in services, according to the BOP statistics, encompasses 12 sectors, including manufacturing services on physical inputs owned by others, maintenance and repair services, transport, travel, construction, insurance and pension services, financial services, intellectual property rights, telecommunications, computer and information services (ICT), computer and information services, other business services, personal, cultural and recreational services and government goods and services. As for the definition of digital trade, in 2020, the OECD/WTO/IMF jointly published the "Handbook for Measuring Digital Trade", where digital trade was defined as "all transactions that are ordered digitally and/or delivered digitally". This widely recognized definition categorizes digital trade into three main types: digital ordering trade, digital delivery trade, and digital intermediary platform-enabled trade. Furthermore, the United States Bureau of Economic Analysis (USBEA) in 2018 introduced sector categories known as "digitizable services". These categories are based on the definition of digital trade, taking into account the degree of digitization of the services sector and the mode of service delivery.

Table 10
Mechanisms Analysis: the function of digital platforms.

	(1)	(2)	(3)
VARIABLES	Cross-border delivery	Service trade	Digital trade
platform	0.058***	0.027**	0.061**
	(0.010)	(0.011)	(0.026)
Controls	YES	YES	YES
country FE	YES	YES	YES
year FE	YES	YES	YES
Observations	1033	1078	971
R^2	0.995	0.993	0.979

Notes: The explained variable cross-border delivery is mode 1 in TiSMoS database. The explained variables Service and digital trade are the export value of trade in service of BOP statistics, and we take the natural logarithm of the total of the value. The explanatory variable platform is the data of the broad-sense digital technology indicator. We take their natural logarithm and find their mean value as the indicator of the digital platform level. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 %, and 1 %, respectively.

The tradability enhancement mechanism can be manifested by the growth of service outsourcing. The rapid expansion of digital technologies and the emergence of novel service outsourcing models have contributed to the steady increase in the scale of global service outsourcing with a growth rate exceeding 20 %.[11] For example, in the traditional service industry, consider a Beijing-based enterprise that offers security services to communities in the United States. Its employees are tasked with monitoring surveillance footage from American communities via display screens in Beijing. They notify local police officers in the United States whenever they detect any abnormalities. Through cross-border delivery, this Beijing-based security company can provide its services to the United States without the need to physically relocate. This approach maximizes the utilization of labor resources in countries with abundant labor, simultaneously expanding employment opportunities. Moreover, it results in cost savings for the recipient country. In the contemporary business landscape, many large enterprises are increasingly turning to external companies that specialize in operating and managing noncore aspects of their business operations. They leverage the benefits of service outsourcing. For instance, prior to Sony Electronics' collaboration with Hewitt (Hewitt Associates LLC),[12] Sony's human resource department faced challenges. Only 18 % of their human resource applications were standardized across different locations, posing a significant management hurdle for an enterprise with a vast workforce. Sony needed to address its human resource issues through technological solutions, improve cost-effectiveness in HR services, and elevate the strategic importance of the HR function. Consequently, Sony Electronics opted to enter into an outsourcing agreement with Hewitt to transform its human resource operations. With Hewitt managing human resource functions, Sony Electronics embarked on a comprehensive overhaul of its HR department. This transformation extended beyond the implementation of new technologies; it provided an opportunity to streamline management processes, enhance service quality, and restructure HR work schedules to boost overall business performance. Sony Electronics has already begun to realize substantial benefits from its outsourcing initiative.

6.2. *The function of digital platforms*

The widespread adoption of digital technology has led to the emergence of numerous digital platforms, driven by a distinct "network effect". Leveraging the internet's cross-temporal nature, digital platforms have expanded their boundaries infinitely, transforming into convenient hubs for traditional economic transactions. This shift has moved various activities from traditional methods to online platforms. The "network effect" increases users' utility. This integration of production, circulation, service, and consumption on digital platforms can use both the online and offline resources, fostering efficient labor division and giving rise to various new business models and formats. This transformation has led to the emergence of a platform economy (Hukal et al., 2020), laying the groundwork for innovative developments in service trade. According to the 2020 Global Digital Governance White Paper by the China Institute of Information and Communication, over 50 % of global service trade now takes place on digital platforms. These platforms encompass a variety of types, including trading platforms, knowledge sharing platforms, crowdsourcing platforms, crowdfunding platforms, virtual spaces, digital creator spaces, and social media (Parker et al., 2016; Storz, 2008).

To test the digital platform function, we use the platform component indicator of our digital technology indicator in a broad sense as a proxy and investigate the effect on service trade. The results of this analysis are presented in Table 10. Column (1) of Table 10 shows the positive effect of digital platforms on cross-border delivery of services export. Additionally, digital platforms exert a positive influence on service export, as depicted in column (2) of Table 10. Furthermore, the result in column (3) indicates a significantly positive effect of digital platforms on digital trade.

With the ongoing improvement of digital platforms, the cost associated with trade activities has noticeably decreased. On the one hand, digital platform reduces the cost of information asymmetry. For example, social networking platforms like WeChat and Facebook, as well as e-commerce giants such as Alibaba, Amazon, and eBay, have significantly accelerated information flow, dismantling

[11] Data source: China Service Outsourcing Development Report 2021

[12] Hewitt(Hewitt Associates LLC): one of the world's largest integrated human resources management consulting firms.

Table 11
Mechanism Analyses: the innovation of new models and forms.

	(1)	(2)	(3)	(4)	(5)
AI	0.039***				
	(0.014)				
Bigdata		0.038***			
		(0.013)			
Cloud computing			0.024***		
			(0.009)		
IoT				0.029***	
				(0.009)	
Blockchain					0.009
					(0.010)
Controls	YES	YES	YES	YES	YES
country FE	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES
Observations	515	515	515	515	515
R^2	0.992	0.992	0.992	0.993	0.992

Notes: The explanatory variables AI, blockchain, cloud computing, big data, and IoT are the number of their patents, and we take their natural logarithm form. We control for the year and country fixed effects in all regressions. Standard errors are in parentheses, and *,**,*** denote the significance levels at 10 %, 5 %, and 1 %, respectively.

information barriers. Additionally, under the steady improvement of digital platforms, the cost associated with trade activities has seen a noticeable reduction. Take eBay, a major e-commerce platform that provides a convenient, fast, and secure channel for transactions. Lendle et al. (2016) found that eBay significantly reduced search costs, decreasing the distance's impact on trade flows by an average of 65 %. Moreover, eBay's machine translation program has been instrumental in reducing search costs related to language barriers, resulting in a 17.5 % increase in export trade on the platform. In 2014, eBay facilitated more than $14 billion in international trade across over 200 countries solely through machine translation (Brynjolfsson et al., 2019).

Apart from e-commerce platforms, digital platforms in various industries have shown significant advantages. For example, the WTO's World Trade Report 2019 underscores the role of online work platforms in boosting professional service trade. Digital platforms have transformed traditional professional services, serving as hubs for experts who no longer need physical offices. This shift lowers fixed costs for service providers and benefits clients. For example, online accounting and legal service platforms no longer necessitate physical offices for offering consulting services to clients. Instead, clients can easily access these services through online platforms. This not only saves costs for service providers but also empowers customers to choose the most suitable services through the platform.

Besides, digital platforms have significantly impacted the education industry through the transformation of off-line to online. A prime example of this transformation is New Oriental, an established and trusted name in the education sector. With the rapid advancement of digital technology, renders traditional teaching models inadequate for the contemporary demands for high-quality human resources, the way people acquire knowledge has been shifting toward online platforms. In response to this evolving landscape, New Oriental, which originally focused on offline educational services, made the strategic move to expand its offerings into the online realm. Recognizing the need to transcend the constraints of time, space, and learning scenarios, New Oriental embarked on the development of an online education platform. To date, New Oriental Online has offered users a comprehensive range of educational products catering to diverse age groups, including preschool, K12, and adult learners. Furthermore, they have developed unique and groundbreaking solutions for an array of customers, extending their reach to university libraries, public libraries, and children's homes. Beyond educational products, New Oriental has also ventured into e-commerce through the establishment of Oriental Selection in 2021. Capitalizing on their educators' proficiency in knowledge and culture dissemination, they have pioneered a distinctive "knowledge live" approach, fusing the realms of knowledge and cultural explanation.

6.3. *The innovation of new models and forms by different digital technologies*

In this context, we examine how digital technology improves service trade by innovation of new trade models and forms. As mentioned earlier, our focus is based on five key digital technologies: AI, blockchain, cloud computing, big data, and IoT. They can independently or together promote service export and enlarge new mode of service trade. Thus, we first estimate the baseline model by separately adding the patent number of each technology and the regression results are shown in Table 11. Columns (1) to (4), clearly demonstrate the positive impact of AI, big data, cloud computing, and IoT on improving service export. Blockchain is related with data encryption security technology that, on its own, may not significantly impact service export. However, when combined with other technologies, it can foster the development of service export. These results highlight the strong connection between the growth of service export and digital technologies.

To investigate how these technologies enlarge the new models and forms of services trade, we give some practical examples. AI applications have significantly improved operational efficiency in the service industry. Intelligent production and order matching have effectively reduced service trade errors, enhancing the overall consumer experience. Moreover, AI-powered interactive voice systems offer uninterrupted service to users worldwide. Furthermore, AI-driven epidemic prevention and control systems provide accurate screening of high-risk populations, real-time epidemic trend analysis, and swift infection pathway tracing.

The application of big data has ushered in a new era of precision in service supply. By collecting, cleaning, and analyzing vast volumes of transaction data, enterprises gain valuable insights into the behavioral patterns of distinct user groups. This enables businesses to tailor their research, design efforts, and market engagement to specific target groups. The combination of big data and cloud computing can be described as "data + computing power + algorithm", providing crucial technical support for international trade in services. This approach empowers the enterprises with high-precision data, facilitating research and development, design, and market engagement. These technologies also serve as the foundation of digital infrastructure, equipping all industries with digital capabilities for comprehensive perception and intelligent services. An exemplary case illustrating this transformation is the pilot project for the innovative development of trade in services in the Guizhou Guian New Area. Starting in June 2018, the region actively harnessed big data to attract businesses, foster industrial integration, and pioneer new business models.

Blockchain technology efficiently verifies transaction attributes at minimal cost. This adoption of blockchain helps reduce information asymmetry, facilitating service delivery on online platforms. The combination of blockchain and AI technologies reduces the time spent on customs and logistics procedures. Additionally, the synergy between blockchain and IoT technologies simplifies verification and authentication, while real-time translation and online platform services bridge language barriers. Innovations in cross-border payments and financial services further streamline transactions.

During the period of COVID-19 pandemic, digital technology has notably influenced the healthcare industry. AI, in particular, is transforming healthcare by enabling online services, earlier interventions, and personalized treatments. It simplifies medical processes, cuts costs, and enhances the patient experience. AI in healthcare also benefits medical practitioners with data-driven patient records, improving diagnosis and management. The integration of big data and cloud computing enhances precise healthcare delivery. Internet hospitals and digital matchmaking between patients and doctors have reduced geographical limitations, making specialized healthcare more accessible. Blockchain technology revolutionizes data storage and security. Digital healthcare services, powered by IoT, facilitate remote surgery and medical robotics, promising more efficient and secure healthcare delivery for users and organizations. In summary, digital technology has reduced costs, improved service efficiency, personalized treatments, and expanded healthcare access, ultimately enhancing patient outcomes and experiences. Digital technology has had a profound impact on the healthcare industry, offering a range of benefits. It has led to cost reductions by streamlining administrative processes and enabling more efficient healthcare delivery. Additionally, it has improved service efficiency, allowing for better patient management, personalized treatment options, and streamlined access to healthcare services. These advancements are enhancing the quality of healthcare and expanding its reach, ultimately improving patient outcomes and experiences.

7. Conclusions

It is clear from the research presented in this paper that digital technology has a substantial and positive impact on export in services. The development of digital technology, both measured in a narrow and broad sense, significantly enhances services export. This impact is observed across various modes of service supply, including cross-border delivery, consumption abroad, and commercial presence. In addition, the findings suggest that digital technology development has a more significant impact on services export in developed countries and countries with high levels of digital openness. In summary, digital technology acts as an enabler for export in services by streamlining cross-border delivery, providing digital platforms for global interactions, and enlarging the new mode of service trade through its unique characteristics. As digital technology continues to advance, it will continue to play an increasingly pivotal role in shaping the landscape of trade in services. Overall, this research contributes valuable insights into the relationship between digital technology and trade in services and underscores the importance of harnessing digital innovations to enhance global trade in the service.

The paper underscores the critical importance of bolstering a country's digital technology proficiency to secure a prominent position in the digital economy and elevate its competitiveness in services trade. To realize this objective, it is imperative to implement a multifaceted approach. This involves fostering increased integration of digital technologies across various sectors, modernizing digital infrastructure components, such as high-speed internet access, data centers, and cloud resources, and strategically defining industries where digital technologies can make the most significant impact. Furthermore, it is essential to create a friendly environment for digital technology experts through educational and immigration policies. Encouraging digital technology-fueled innovation and entrepreneurship, supporting startups, and establishing collaborative digital technology platforms are also vital steps. Last but not least, continuous optimization of digital platforms, including e-commerce, data sharing, and communication networks, is crucial to meet evolving global service trade demands and standards. These measures collectively empower a nation to enhance its digital prowess, foster innovation, and emerge as a leader in the worldwide digital economy, thus propelling international trade in services and elevating its global economic standing.

However, when comparing the development of trade in services in developing countries with that of some advanced economies, it becomes apparent that many developing countries lag behind. The introduction and advancement of digital technology can potentially exacerbate the existing disparities between developed and developing countries. Therefore, it is imperative for developing countries to expedite the transformation and modernization of their traditional trade in service industries while providing robust support for the burgeoning modern trade in service sectors. While striving to enhance the efficiency of trade in services, it is equally crucial to maintain the commitment to opening up the service and digital industry, foster multilevel international cooperation, and actively integrate into the global service trade network.

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Bingjie Wong: Data curation, Methodology. **Yan Zhang:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Writing – original draft, Writing – review & editing. **Nan Kong:** Data curation, Methodology, Software, Writing – original draft, Writing – review & editing. **Nianli Zhou:** Investigation, Resources, Supervision.

Declaration of Competing Interest

The authors of this paper declare that they have no conflicts of interest to disclose that may have influenced the research, analysis, or the reporting of results in this paper.

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Data Availability

Data will be made available on request.

Appendix 1

The calculation steps of the entropy method:

1. Standardization of data.
   To quantify the individual indicators, for positive indicators, the normalized values of the data for each indicator are:

$$Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \quad , i = 1, 2\ldots\ldots n;\ j = 1, 2\ldots\ldots m \tag{2}$$

   where i represents the year and j represents the indicator.
2. Calculating the weight of indicator j in year i, we obtain

$$p_{ij} = \frac{X_{ij}}{\sum_i^m X_{ij}} \tag{3}$$

   where m is the sum of indicators.
3. According to the definition of information entropy in information theory, the information entropy of a set of data is

$$E_j = -\frac{1}{lnn}\sum_i^m (p_{ij} \times \ln p_{ij}) \tag{4}$$

4. Determination of the weights of the indicators
   According to the formula of information entropy, the information entropy of each indicator is calculated as $E_1, E_2\ldots, E_m$.
5. Calculating information entropy redundancy

$$D_j = 1 - E_j \tag{5}$$

6. Calculating indicator weights

$$w_i = D_j \bigg/ \sum_{j}^{m} D_j \tag{6}$$

7. Calculation of digital technical indicator composite scores,

$$digital_{ij} = \sum_{i=1}^{m} w_i \times D_{ij} \tag{7}$$

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