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## Digital economy and global value chain restructuring from a cross-country sustainable industry analysis

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**Abstract:** The unprecedented expansion of the digital economy is fundamentally altering the architecture and operational dynamics of global value chains (GVCs). This study investigates the impact of digital economy development on the restructuring of GVCs. This analysis develops a theoretical framework and employs empirical analysis utilising cross-country industry data. These findings show that digital economy development catalyses GVC restructuring. This restructuring is mainly reflected in changes in network positions within GVCs, with notable heterogeneity across industries, input origins, and country classifications. Mechanism analysis shows that the digital economy promotes the restructuring of GVCs by improving production efficiency and innovation capabilities.

**Keywords:** GVC; global value chain restructuring; digital economy; production efficiency; innovation capability; mediation effect.

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## 1 Introduction

The proliferation and integration of global value chains (GVCs) has emerged as an inherent corollary of the intensifying international labour division in the contemporary economic globalisation epoch. Over the past three decades, this phenomenon has become increasingly prominent, marking a significant shift in the global economic landscape (Yang and Qu, 2021). The fragmentation of production processes is closely linked to multinational corporations' expansion of global sourcing and outsourcing (Arndt and Kierzkowski, 2001). Notably, the international division of labour pattern has evolved significantly: from traditional inter-industry division to intra-industry specialisation, ultimately extending to multiple stages of product manufacturing, forming a complex GVC system. The 2008 global financial crisis marked a critical turning point. Influenced by cyclical and structural factors, the dynamics driving value chain expansion shifted, leading to multidimensional restructuring trends in GVCs. This restructuring not only involves the disruption of existing value chains but also emphasises the importance of innovation (Lun, 2023).

As the world entered the 21st century, the rapid development of digital information technology (Chen et al., 2024) brought new transformative forces to GVCs. Breakthroughs in next-generation technologies such as big data, cloud computing, the internet, artificial intelligence, and blockchain have elevated data to the fourth major factor of production, following land, capital, and labour. Buckley (2020) show that applying these digital technologies profoundly alters GVC operations, enhancing production efficiency and restructuring value distribution patterns. In the face of digital transformation, countries' roles within GVCs are undergoing profound changes. Developed nations have led in formulating digital economy development strategies (Ran et al., 2024), such as Germany's Industry 4.0, the USA's Smart Manufacturing and Industrial internet Consortium, and Japan's New Robot Strategy. Meanwhile, developing countries are actively executing policies to encourage digital economic growth and promote deep integration between digital and traditional economies. These initiatives reflect the urgent need for countries to maintain competitiveness in restructuring GVCs.

Despite extensive research on GVC restructuring, significant gaps remain. First, a clear analytical framework and measurement system for digital economy development

and GVC restructuring have yet to be established. Second, studies on the impact of digital economy development on China's participation in GVC restructuring are largely theoretical or policy-oriented, lacking specific quantitative analysis. Finally, existing literature rarely discusses how digital economy development generates dynamic effects on GVCs and addresses potential inequities.

This paper constructs a theoretical framework for digital economy development and GVC restructuring to address these research gaps. Through empirical research on 35 industries across 25 countries, this investigation aims: to develop a theoretical framework for the impact of digital economy development on GVC restructuring, based on models by Hallak and Sivadasan (2008) and Kee and Tang (2016); to incorporate product quality and institutional factors to reveal how they influence the role of digital economy in GVC restructuring, providing important references for policy-making; and to employ GMM methodology to study GVC dynamic changes and potential inequities, offering insights for building a fairer and more reasonable GVC system.

## 2 Literature review

The concept of GVC restructuring lacks a unified definition. Beck et al. (2001) initially proposed the idea from an organisational behaviour perspective, describing the reorganisation phenomenon caused by network effects on various value chain stages. In 2005, the EU expanded this concept to encompass changes in company structures. As the research scope broadened from individual organisational behaviour to global structural changes, 'value chain restructuring' evolved into 'global value chain restructuring'. Stigler (1996) analysed vertical integration changes in GVC restructuring from an industry life cycle perspective, while Milberg and Winkler (2010) further explained horizontal GVC restructuring. Other scholars began exploring GVC restructuring drivers from the external environment, profit space, and enterprise competition.

The digital economy has recently gained attention as a crucial force driving GVC restructuring. Foster and Graham (2017) highlighted how new digital technologies reshape industry chain value distribution through data-driven, platform-supported, and service value-added approaches. Kondratiev (2018) focused on how digital technologies affect various businesses' operational arrangements and positioning within GVCs. Szalavetz (2019) studied how leading companies and manufacturing subsidiaries in the global automotive value chain use and are impacted by digital technologies. Yang et al. (2022) analysed the evolution trends, potential risks, and coping strategies of GVCs in the digital economy era, providing suggestions for Chinese enterprises' strategic adjustments in global competition.

The development of the digital economy has significantly altered GVC restructuring processes, necessitating a reassessment of traditional frameworks and methods. Lianos (2019) emphasised the need to understand new value generation and capture processes in the digital economy for better competition law design and execution. He (2020) revealed the internal mechanisms and pathways of digitalisation in promoting China's manufacturing value chain upgrade through rigorous empirical analysis. Liu and Pan (2020) constructed a comprehensive evaluation system for value chain restructuring efficiency, systematically assessing and analysing China's manufacturing performance in the value chain restructuring process.

Despite extensive discussions on GVC restructuring from various perspectives, research on how the digital economy impacts explicitly GVC restructuring and reforming pathways remains insufficient. This study conducts empirical analysis using panel data from 25 countries (or regions) and 35 industries from 2010 to 2021. This research uses weighted degree centrality as an indicator for the GVC restructuring index and the product of national-level digital economy development and industry-level digital economy development (total consumption coefficient) as the core explanatory variable to examine the impact of digital economy development on GVC restructuring.

This study makes four significant contributions to the existing literature: First, this exploration develops a theoretical framework that explains the mechanisms through which digital economy development influences GVC restructuring. Second, this study provides empirical evidence for this relationship by testing the impact of digital economy development on GVC restructuring using cross-national industry data. Third, this research discovers the critical role of institutional environments in mediating the digital economy's influence on GVC restructuring, emphasising the importance of context in this process. Finally, this investigation addresses potential digital divide issues and proposes coping strategies for middle and low-income countries, thereby addressing potential inequities in GVCs in the digital era.

Recent research on digital trade and 'third unbundling' provides an additional theoretical foundation for understanding GVC restructuring in the digital era. Baldwin (2016) introduced the 'third unbundling' framework, arguing that digital technologies enable the remote performance of service tasks, fundamentally altering labour market dynamics and value chain configurations beyond the previous 'unbundlings' driven by falling transportation and communication costs. Complementing this framework, Constantinescu et al. (2020) empirically demonstrated how digital technologies influence GVC participation and upgrading through trade cost reduction and productivity improvement channels.

The emerging literature on digital trade further depicts the transformation of value chains. López González and Jouanjean (2017) examined how digital technologies create new trade opportunities and alter traditional trade patterns through reduced coordination costs and improved service traceability. Similarly, Brynjolfsson et al. (2019) highlighted how artificial intelligence and machine learning technologies reshape comparative advantages and redefine value-creation mechanisms in global trade networks. Adding to this discourse, Goldfarb and Tucker (2019) analysed how digital technologies reduce verification costs and enable new forms of contract enforcement across borders, fundamentally altering the governance structures of GVCs.

These recent contributions emphasise the multidimensional impact of digitalisation on global production networks beyond traditional efficiency gains, encompassing transformations in governance structures, value capture mechanisms, and the geographic distribution of economic activities.

### **3 Theoretical mechanism analysis**

Drawing on the heterogeneous model of Hallak and Sivadasan (2008) and the model of Kee and Tang (2016), this analysis constructs a theoretical framework to examine the relationship between digital economy development and GVC restructuring. First, This

examination establishes a monopolistic competition demand model with constant elasticity of substitution:

$$Q_i = \frac{v_i^{-\epsilon} \eta_i^{\epsilon-1}}{(Z')^{1-\epsilon}} W \quad (3.1)$$

where  $Q_i$  is the demand for product  $i$ ,  $v_i$  is the price of product  $i$ ,  $\eta_i$  represents the quality of product  $i$ ,  $W$  denotes total consumer expenditure,  $\epsilon$  indicates the elasticity of substitution between products ( $\epsilon > 1$ ), and  $Z'$  is the aggregate price index.  $Z'$  satisfies:

$$Z' = \left( \int_i v_i^{1-\epsilon} \eta_i^{\epsilon-1} di \right)^{\frac{1}{1-\epsilon}} \quad (3.2)$$

For simplification, let  $Z = (Z')^{1-\epsilon}$ , then  $Q_i$  can be rewritten as:

$$Q_i = \frac{v_i^{-\epsilon} \eta_i^{\epsilon-1}}{Z} W \quad (3.3)$$

Firm heterogeneity is primarily reflected in two aspects: production efficiency and innovation capability (Melitz, 2003; Bustos, 2011). Higher production efficiency implies lower variable costs (VC), while higher innovation capability implies lower research and development costs (RC). Therefore, the variable cost of product  $i$  can be expressed as a function of  $\eta_i$  and  $\delta$ :

$$VC_i(\eta_i, \delta) = \frac{k}{\delta} \eta_i^{\beta_{vc}} \quad (3.4)$$

where  $\delta$  represents production efficiency; a larger  $\delta$  indicates lower variable costs.  $\beta_{vc}$  denotes the quality elasticity of variable costs, with  $\beta_{vc} > 0$ , and  $k$  is a constant. Similarly, the R&D cost can be expressed as a function of  $\eta_i$  and  $\omega$ :

$$RC_i(\eta_i, \omega) = \frac{h}{\omega} \eta_i^{\beta_{rc}} + RC_0 \quad (3.5)$$

in this equation,  $\omega$  represents innovation capability; a higher  $\omega$  indicates lower R&D costs.  $\beta_{rc}$  denotes the quality elasticity of R&D costs, with  $\beta_{rc} > 0$ ,  $RC_0$  represents the basic R&D cost, and  $h$  is a constant.

Combining the above expressions, when firms maximise profits,  $\eta_i$  can be expressed as a function of  $\delta$  and  $\omega$ :

$$\eta_i(\delta, \omega) = \left[ \frac{(1 - \beta_{vc}) / \beta_{rc} \cdot \omega / h \cdot ((\epsilon - 1) / \epsilon)^\epsilon \cdot (\delta / k)^{\epsilon-1} \cdot W / Z}{\beta_{rc} - (1 - \beta_{vc})(\epsilon - 1)} \right]^{\frac{1}{\beta_{rc} - (1 - \beta_{vc})(\epsilon - 1)}} \quad (3.6)$$

where  $\beta_{rc} - (1 - \beta_{vc})(\epsilon - 1) > 0$ .

To investigate the impact of digital economy development on  $\delta$  and  $\omega$ , this research introduces digital economy development factors:

$$\delta = \left( \int_0^1 Y_j^\tau dj \right)^{\frac{1}{\tau}}, \quad \omega = \left( \int_0^1 Y_j^\nu dj \right)^{\frac{1}{\nu}} \quad (3.7)$$

where  $Y$  represents the digital economy development that improves production efficiency  $\delta$  and innovation capability  $\omega$ .  $Y$  can be divided into two parts: digital economy development  $D$  and non-digital economy development  $N$ . Parameters  $\tau$  and  $\nu$  represent factor substitution parameters, satisfying  $\tau \leq 1$  and  $\tau \neq 0$ , as well as  $\nu \leq 1$  and  $\nu \neq 0$ .

Further, this investigation can express  $\delta$  and  $\omega$  as functions of  $D$  and  $N$ :

$$\delta = \left[ \alpha \left( \frac{D}{\alpha} \right)^\tau + (1-\alpha) \left( \frac{N}{1-\alpha} \right)^\tau \right]^{\frac{1}{\tau}} \quad (3.8)$$

$$\omega = \left[ \zeta \left( \frac{D}{\zeta} \right)^\nu + (1-\zeta) \left( \frac{N}{1-\zeta} \right)^\nu \right]^{\frac{1}{\nu}} \quad (3.9)$$

Substituting these two expressions into  $\eta_i(\delta, \omega)$ , this research obtains a function of product quality in terms of digital economy development  $D$ . To simplify the analysis, assume  $\tau \rightarrow 0, \nu \rightarrow 0$ , then this exploration gets:

$$\eta_i(D) = \left[ \left( \frac{1-\beta_{wc}}{\beta_{rc}} \right) \cdot (D^\zeta N^{1-\zeta}) \cdot \left( \frac{\epsilon-1}{\epsilon} \right)^\epsilon \cdot \left( \frac{D^\alpha N^{1-\alpha}}{k} \right)^{\epsilon-1} \cdot \frac{W}{Z} \right]^{\frac{1}{\beta_{rc}(1-\beta_{rc})(\epsilon-1)}} \quad (3.10)$$

Taking the partial derivative of this expression with respect to  $D$ , this analysis can prove that  $\frac{\partial \eta_i(D)}{\partial D} > 0$ , indicating that the improvement of digital economy development is conducive to enhancing product quality.

Based on the above model, this exploration can further analyse the impact of digital economy development on the restructuring of GVCs. The local value-added ratio of exports (GVC) is an important indicator for measuring a firm's position in the GVC. A substantial domestic value-added ratio in exports signifies a favourable position in reconfiguring GVCs. This assertion finds theoretical underpinning in the seminal works of Kee and Tang (2016) and Mao and Xu (2019), GVC can be expressed as:

$$GVC = 1 - \chi_M \left( \frac{v_i}{VC_i} \right)^{-1} \frac{1}{1 + \left( \frac{x^L}{V^F} \right)^{\epsilon-1}} \quad (3.11)$$

where  $\chi_M$  represents the output elasticity coefficient of intermediate inputs,  $0 < \chi_M < 1$ . After simplification, this research gets:

$$GVC = 1 - \frac{\psi}{\pi_i} \quad (3.12)$$

Substituting the simplified  $\eta_i(D)$  into the GVC expression and introducing auxiliary variables to simplify the expression, this investigation obtains:

$$GVC = 1 - \frac{\psi}{\left( \frac{v_i \delta_i}{kG(D^c N^{1-\alpha}) (D^\alpha N^{1-\alpha})^{c-1} H} \right)^s} \quad (3.13)$$

where  $G$ ,  $H$ , and  $N$  are simplified constants. Taking the partial derivative of GVC with respect to  $D$ , this analysis can prove:

$$\frac{\partial GVC}{\partial D} > 0 \quad (3.14)$$

This result suggests that developing the digital economy helps improve production efficiency and innovation capability to improve product quality, thereby enhancing firms' positions in GVCs. This provides a theoretical foundation for studying the impact of digital economy development on the restructuring of GVCs. Based on the above model derivation, this paper proposes the following hypotheses:

*Hypothesis 1: The development of the digital economy eases the restructuring of global value chains.*

*Hypothesis 2: The development of the digital economy restructures global value chains by influencing production efficiency and innovation capability.*

## 4 Empirical analysis

### 4.1 Model setting

Based on the theoretical framework established in Section 3, where this paper demonstrated that digital economy development positively influences GVC restructuring (as shown in equation (3.14):  $\partial GVC/\partial D > 0$ ), this study now empirically constructs an econometric specification to test this relationship. The theoretical model suggests that digital economy development ( $D$ ) improves production efficiency and innovation capability, thereby improving countries' positions in GVCs. To capture this effect empirically, the paper employs a panel fixed-effects model that relates the measures of GVC position ( $GVC\_CEN$ ) to digital economy development ( $DIG$ ) while controlling for country-specific, industry-specific, and time-specific factors that might influence GVC restructuring. This approach allows us to isolate the effect of digital economy development on GVC position, as predicted by the theoretical model while accounting for other potential determinants of GVC restructuring.

$$GVC\_CEN_{cit} = \beta_0 + \beta_1 DIG_{cit} + \beta_2 Controls + \lambda_c + v_i + \mu_t + \varepsilon_t \quad (4.1)$$

where  $c$  denotes country,  $i$  denotes industry, and  $t$  denotes year. The dependent variable  $GVC\_CEN_{cit}$  represents the GVC restructuring index for country  $c$ 's industry  $i$  in year  $t$ , measured by either weighted degree centrality or PageRank centrality in the GVC network. The key explanatory variable  $DIG_{cit}$  represents the level of digital economy development in country  $c$ 's industry  $i$  in year  $t$ . Controls are control variables,  $\lambda_c$ ,  $v_i$  and  $\mu_t$  are fixed effects,  $\beta_0$  and  $\varepsilon_t$  are the intercept and random error term, respectively, and  $\beta_1$  and  $\beta_2$  are the estimated coefficients. It is important to note that while the theoretical

model discusses GVC positioning in terms of domestic value-added ratio (as shown in equation (3.11)), the empirical strategy employs network centrality measures as the primary indicators of GVC restructuring. This methodological choice stems from the recognition that network-based measures better capture the multidimensional nature of countries' positions in increasingly complex global production networks. Network centrality metrics account for the value-added dimension and incorporate critical aspects of connectivity, influence, and strategic positioning within the entire production network. Throughout the remainder of this paper, the investigation consistently uses network centrality measures (specifically weighted degree centrality and PageRank centrality) as the operational definitions of GVC positioning to ensure conceptual clarity and methodological consistency.

## 4.2 Variable selection and data sources

### 4.2.1 Dependent variables

This study employs Weighted Degree Centrality to assess countries' positional status in interest distribution within GVC networks. This study denotes the weight matrix as  $W = [w_{ij}^m]$ , which represents the magnitude of domestic value-added trade exports between countries. The weighted degree centrality  $C_w(i)$  for node  $i$  is calculated using the following formula:

$$GVC\_CEN1(i) = \sum_j w_{ij} + \sum_j w_{ji} \tag{4.2}$$

where the first component  $\sum_j w_{ij}$  represents the out-strength of node  $i$  (the sum of all outgoing edge weights), and the second component  $\sum_j w_{ji}$  represents the in-strength of node  $i$  (the sum of all incoming edge weights). A higher weighted degree centrality indicates that a country occupies a more central position in the GVC network.

Furthermore, to ensure the robustness of these empirical results, this study also employs PageRank centrality as an alternative indicator for regression analysis. The formula for PageRank is calculated as:

$$GVC\_CEN2(i) = \alpha \sum_{p_j \in M_{pi}} \frac{PR(p_j)}{L(p_j)} + \frac{1-\alpha}{N} \tag{4.3}$$

where  $PR(p_j)$ , represents the PageRank centrality,  $\alpha$  is a constant between 0 and 1 which following Brin and Page (1998), this examination sets to 0.85, and  $L(p_j)$  is the out-degree centrality of country (or region)  $j$  in year  $t$ .

In subsequent empirical testing, GVC\_CEN1 represents the weighted degree centrality, which serves as the core explanatory variable in this study. GVC\_CEN2 denotes the PageRank centrality, which is used as the robustness check variable in this research.

#### 4.2.2 Explanatory variables

The core explanatory variable is the level of digital economy development:

$$DIG_{cit} = Digg_{cit} \times Digi_{cit} \quad (4.4)$$

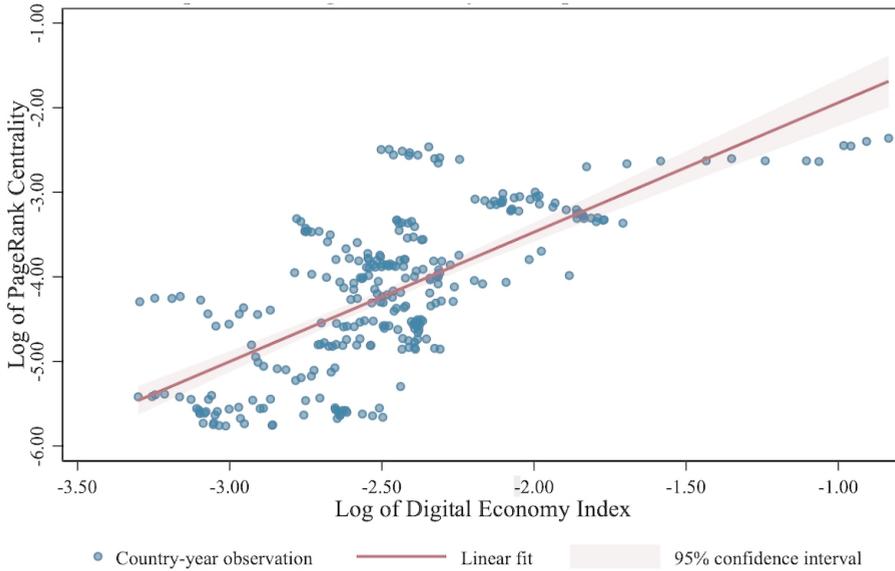
$DIG_{cit}$  represents the product of industry-level digitalisation and country-level digital economy development. Specifically, based on 23 indicators across five dimensions:

- i Digital Infrastructure and Connectivity (fixed/mobile telephone subscriptions, broadband access, internet bandwidth).
- ii Digital Adoption and Usage (internet penetration, digital service delivery).
- iii Innovation Capacity (ICT goods/services exports, R&D expenditure, scientific publications, researchers per million, patent applications).
- iv Human Capital and Education (education expenditure, tertiary enrollment).
- v Digital Economy Policy Environment.

The entropy weight method objectively determines each indicator's weight by calculating information entropy, giving higher weights to indicators with greater variation across countries. While  $Digi_{cit}$  represents the industry-level development of the digital economy, measured by the complete consumption coefficient. In subsequent empirical testing,  $DIG_{cit}$  is measured from the following two dimensions:  $DIG1$  is the product of country-level digital economy development (calculated using the entropy weight method) and the complete consumption coefficient, serving as the primary explanatory variable in this study.  $DIG2$  is the product of country-level digital economy development (calculated using the entropy weight method) and the direct consumption coefficient, serving as one of the robustness check variables in this research.

Figure 1 illustrates the relationship between digital economy development and GVC reconstruction. The horizontal axis represents the logarithm of the Digital Economy Index, while the vertical axis depicts the logarithm of PageRank Centrality. Each blue dot represents a country-year observation, the red line indicates the linear fit, and the light red shaded area represents the 95% confidence interval. Figure 1 reveals a significant positive correlation between these two variables. It suggests that as countries advance in digital economy development (moving rightward on the x-axis), they tend to occupy more central positions in GVCs (moving upward on the y-axis). The upward slope of the fitted line, combined with the relatively narrow confidence interval, provides robust evidence of this relationship. The scatter plot demonstrates considerable variation in both digital economy development and GVC centrality across countries and years. Yet, the overall pattern confirms the research hypothesis that digital transformation improves a country's position within global production networks. This finding contributes to the growing literature on the determinants of GVC participation and position by highlighting the transformative role of digitalisation in reshaping global production structures.

**Figure 1** Relationship between digital economy development and GVC reconstruction (see online version for colours)



Data source: Author’s calculation. Each point represents a country-year observation

#### 4.2.3 Control variables and data sources

This study employs three primary control variables: GDP, obtained from the World Bank’s World Development Indicators (WDI) database in current USD, which crucially shapes GVC network structures as higher GDP reflects more advanced production technologies and institutional environments that ease access to higher value-added segments; the human capital index (hc) from Penn World Table, calculated based on education years and returns, which serves as a core factor driving GVC formation while profoundly influencing national positioning in global economic specialisation by enabling knowledge-intensive industry development and upgrading; and total population (pop) from the World Bank’s WDI database, which substantially impacts both the degree and mode of GVC participation by providing larger domestic markets and abundant labour resources that offer unique advantages for countries engaging in GVCs.

This study uses data from the Asian Development Bank Multi-Regional Input-Output Database (ADB-MRIO) and analytical resources from the UIBE Global Value Chain Institute to conduct a comprehensive analysis. The ADB-MRIO database provides rich network structure data covering global economic input-output relationships from 2007 to 2021. Considering the availability and completeness of digital economy indicators, this analysis constructs a panel dataset encompassing 25 major economies and 35 industries (classified according to ISIC Rev.4), spanning from 2010 to 2021 – a critical period of GVC restructuring following the global financial crisis – yielding 10,500 observations. All variables undergo logarithmic transformation to reduce heteroscedasticity effects (Wooldridge, 2010), enabling an in-depth investigation of how digital economies are reshaping GVC structures and their underlying influence mechanisms.

### 4.3 Baseline regression results

Table 1 analyses digital economy development's impact on global value chain restructuring (GVC\_CEN1). This investigation employs a three-dimensional fixed effects model incorporating country, industry, and year fixed effects to address potential omitted variable bias. This study further adjusts the OLS regression using robust standard errors to reduce potential heteroscedasticity and model specification issues.

**Table 1** Baseline regression results

	(1)	(2)	(3)	(4)	(5)
Log of Entropy digital economy index × Total digital consumption (DIG1)	0.65127*** (0.01773)	0.02034*** (0.00260)	0.00567*** (0.00178)	0.00551*** (0.00179)	0.00598*** (0.00178)
Log of real GDP, output-side			0.93167*** (0.01379)	0.93030** (0.01374)*	0.93664*** (0.01402)
Log of human capital index				0.02073*** (0.00939)	0.02188** (0.00885)
Log of total population				0.10891	-0.38690*** (0.05262)
Country fixed	No	Yes	Yes	Yes	Yes
Industry fixed	No	Yes	Yes	Yes	Yes
Time fixed	No	Yes	Yes	Yes	Yes
Observations	9799	9799	8167	8167	8167
r2_a	0.13501	0.99425	0.99771	0.99771	0.99773

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Column (1) presents the baseline model without fixed effects or control variables, while column (2) incorporates country, industry, and year fixed effects. In both specifications, the coefficient for digital economy development (measured by the interaction between the entropy index and total digital consumption) is positive and statistically significant at the 1% level (0.65127 and 0.02034, respectively). These initial findings support the hypothesis that higher levels of digital economy development are associated with greater centrality in GVC networks. To address potential omitted variable bias, the research progressively introduces control variables in columns (3)-(5) while maintaining the three-dimensional fixed effect's structure. Column (3) introduces real GDP per capita (output-side), column (4) adds the human capital index, and column (5) further controls for population size. Across all specifications, the coefficient for digital economy development remains positive and statistically significant at the 1% level, with minimal variation in magnitude (ranging from 0.00551 to 0.00598).

The consistency of these results across multiple specifications emphasises the robustness of the relationship between digital economy development and improved

positioning within GVCs. The economic significance of these findings suggests that countries investing in digital transformation can strategically improve their integration into global production networks.

4.4 Robustness analysis

To further confirm the robustness of the findings, this study conducted multiple robustness tests, with results presented in Table 2, column (1), this analysis employed PageRank centrality as an alternative measure of global value chain restructuring (GVC\_CEN1), yielding a significant positive impact of digital economy development (coefficient 0.10011,  $p < 0.01$ ), confirming that these conclusions are not sensitive to the measurement approach for GVC restructuring.

**Table 2** Robustness test results

	(1)	(2)	(3)	(4)	(5)
Log of Entropy digital economy index × Total digital consumption (DIG1)	0.10011*** (0.00445)			0.12045*** (0.00463)	0.12133*** (0.00453)
Log of Entropy digital economy index × Direct digital consumption (DIG2)×		0.06334*** (0.00329)			
(Log of direct_digital_consumption)			0.03219*** (0.00331)		
Log of real GDP, output-side	1.06439*** (0.00714)	1.71229*** (0.00896)	1.74277*** (0.00886)	1.68448*** (0.00922)	1.68576*** (0.00906)
Log of human capital index	0.08733*** (0.02138)	-0.34250*** (0.02728)	-0.33258*** (0.02757)	-0.39190*** (0.02681)	-0.38906*** (0.02682)
Log of total population	0.53897*** (0.00204)	0.83432*** (0.00201)	0.84414*** (0.00203)	0.82305*** (0.00215)	0.82505*** (0.00200)
Country fixed	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes
Observations	8167	8167	8167	8032	8167
r2_a	0.91727	0.94773	0.94618	0.94519	0.94934

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Columns (2) and (3) use alternative digitalisation indicators: the product of entropy-weighted country-level digital economy development with direct digital consumption coefficient (0.06334,  $p < 0.01$ ) and direct digital consumption (0.03219,  $p < 0.01$ ), respectively. Both estimates remain significantly positive, confirming the robustness of

the finding that digital economy development promotes GVC restructuring across different digitalisation measures.

Column (4) presents regression results after excluding extreme values, with the core variable coefficient (0.12045,  $p < 0.01$ ) highly consistent with baseline results, eliminating potential interference from outliers. Column (5) excludes samples from 2020 and beyond to control for extreme event impacts, with the digital economy development coefficient (0.12133,  $p < 0.01$ ) remaining significantly positive, verifying that these findings are not affected by economic fluctuations during exceptional periods.

Notably, estimation results for control variables remain largely consistent across all robustness tests, further corroborating model stability and result reliability. These multi-dimensional robustness tests strongly support the core hypothesis that digital economy development drives GVC restructuring.

#### 4.5 *Endogeneity tests*

The empirical model faces three main types of endogeneity issues. First, omitted variable bias emerges as a critical issue; despite the well-developed theoretical foundation and rich empirical research in GVC theory, there may still be omissions in the selection of control variables. These omitted variables could enter the error term, leading to multicollinearity and biased estimates.

Furthermore, measurement error introduces additional uncertainty, as the construction of GVC network centrality indicators using input-output tables and social network analysis algorithms may not accurately reflect the characteristics of different countries and industries in GVC restructuring. Potential biases in the measurement process and missing data for key indicators could lead to deviations in estimation results.

Additionally, the research is complicated by potential reverse causality. For example, a bidirectional causal relationship may exist between digital economy development and GVC restructuring. This endogeneity issue could lead to the endogeneity of the digital economy development variable, affecting the reliability of estimation results.

To reduce these potential endogeneity problems, the research adopted a robust instrumental variable methodology to enhance causal identification. Specifically, the study uses instrumental variable estimation techniques to address potential endogeneity concerns surrounding digital economy development and its implications for GVC restructuring. Table 3 presents IV regression results using three different instruments for digital economy development and its impact on GVC restructuring. The undertaken research constructs three types of historically based instrumental variables: the interaction between electricity consumption and industry digitalisation (IV\_POWER), a triple interaction term of education, electricity, and industry digitalisation (IV\_EDUPOWER), and higher education enrolment rates from the 1970s (IV\_EDU70S). These historical variables satisfy the relevance and exclusion restrictions required of valid instruments, as historical infrastructure investments and human capital accumulation exert persistent influences on current digital economy development without directly affecting current GVC network centrality through other channels.

**Table 3** Endogeneity test results (1)

	<i>IV_POWER</i>		<i>IV_EDUPOWER</i>		<i>IV_EDU70S</i>	
	(1)	(2)	(3)	(4)	(5)	(6)
Log of Entropy digital economy index × Total digital consumption (DIG1)	0.15710*** (0.01144)	0.13187*** (0.01223)	0.19453*** (0.01380)	0.00906 (0.01377)	0.41469*** (0.02984)	0.31394*** (0.02676)
Log of real GDP, output-side	1.55699*** (0.01135)	1.02079*** (0.01038)	1.50388*** (0.01175)	0.98785*** (0.00862)	1.43226*** (0.01599)	0.88867*** (0.01260)
Log of human capital index	– 0.20809*** (0.02660)	0.11837*** (0.02234)	0.33884*** (0.02709)	0.09011*** (0.02119)	0.51691*** (0.04176)	0.15648*** (0.03603)
Log of total population	0.78222*** (0.00279)	0.52567*** (0.00253)	0.76805*** (0.00323)	0.53191*** (0.00258)	0.73459*** (0.00583)	0.48558*** (0.00478)
Country fixed	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7479	7479	6799	6799	6799	6799
r2	0.93816	0.89506	0.93592	0.91370	0.90708	0.87156

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

In Table 3, the first set of instrumental variables (*IV\_POWER*) yields a first-stage regression F-statistic of 709.4, substantially exceeding the critical value of 10 and firmly rejecting the weak instrument hypothesis. Second-stage regression results show that digital economy development coefficients for weighted degree centrality and PageRank centrality are 0.15710 and 0.13187, respectively, significantly positive at the 1% level. The second instrument set (*IV\_EDUPOWER*) shows an F-statistic of 740.941, similarly indicating strong instruments, with digital economy development's impact coefficient on weighted degree centrality at 0.19453 ( $p < 0.01$ ). In contrast, its coefficient on PageRank centrality, though positive (0.00906), remains insignificant. The third instrument set (*IV\_EDU70S*), despite a relatively lower but still robust F-statistic (252.421), yields even larger and significant ( $p < 0.01$ ) effect coefficients for both GVC centrality measures (0.41469 and 0.31394 respectively).

Notably, control variable effects across all three instrumental approaches exhibit high consistency: GDP consistently shows significant positive impacts on GVC restructuring (coefficients ranging from 0.88867 to 1.55699); human capital index predominantly displays adverse effects on weighted degree centrality while showing varying directional impacts on PageRank centrality depending on instrument selection, potentially reflecting

heterogeneous effects of different human capital types across value chain dimensions; population size shows robust positive relationships across all models (coefficients ranging from 0.48558 to 0.78222).

Based on Klein-Cragg-Donald statistics and first-stage F-statistics, all instrumental variables withstand weak instrument testing, confirming that the instruments effectively identify the causal effect of digital economy development on GVC restructuring. These three sets of instrumental variable results provide strong causal evidence supporting the core hypothesis that digital economy development drives GVC restructuring, further validating the reliability of the baseline regression findings. Historical instruments (electricity consumption, education enrollment, and their interactions) might affect current GVC positioning through channels beyond digitalisation. To address this issue, the investigation conducted additional tests to confirm the instrumental variable approach. The research performed placebo tests using artificial instruments constructed by randomly permuting the actual instruments across countries while maintaining the time-series structure. As expected, these placebo instruments showed no significant correlation with the endogenous variable in the first-stage regressions (F-statistics consistently below 10), and the second-stage results displayed no significant effects, confirming that spurious correlations or statistical artefacts do not drive the findings.

The current research introduced a two-way fixed effects model with time and individual fixed effects in the panel data regression analysis. This method helps control for factors that do not vary over time and are difficult to observe directly, partially alleviating the omitted variable bias problem. To further confirm the causal relationship between digital economy development and GVC restructuring, Table 4 presents estimation results from panel fixed effects and first-difference models. Like instrumental variable approaches, these methods reduce endogeneity concerns, particularly regarding unobserved heterogeneity and reverse causality. Column (1) displays panel fixed effects model results, eliminating time-invariant country-industry characteristics to control for potential omitted variable bias effectively. The estimated coefficient of digital economy development on GVC restructuring is 0.03583, significantly positive at the 1% level, consistent with the baseline model findings. Column (2) employs first-difference estimation, eliminating time-invariant factor influences by differencing all variables, further addressing serial correlation and potential non-stationarity issues. Results show that changes in digital economy development positively affect changes in GVC restructuring (coefficient 0.03329,  $p < 0.01$ ). Both alternative endogeneity treatment methods support the core hypothesis that digital economy development promotes GVC restructuring, reinforcing the instrumental variable findings and providing robust, multi-dimensional, and multi-methodological evidence for the causal nature of the research conclusions.

## 4.6 *Heterogeneity analysis*

### 4.6.1 *Industry heterogeneity analysis*

Based on the empirical results in Table 5, the research reveals significant industry heterogeneity in digital economy development's impact on GVC restructuring. Columns (1) and (2) show that digital economy development significantly and positively influences GVC restructuring in both manufacturing and service industries (coefficients 0.11772 and 0.11926 respectively, both  $p < 0.01$ ), indicating that digital economy

development effectively improves centrality positions within GVC networks across both sectors. When further disaggregating manufacturing by technological intensity into low-technology, medium technology, and high-technology manufacturing, columns (3)–(5) show positive but statistically insignificant coefficients (0.00558, 0.00332, and 0.00348, respectively), contrasting sharply with the significant positive effect observed for manufacturing. This phenomenon potentially reflects complex intra-industry interaction mechanisms in how digital economies influence manufacturing sectors, possibly requiring more granular classification or longer time series to capture such differences (Wang et al., 2024). Notably, regarding control variables, GDP consistently shows significant positive effects on GVC restructuring across all industry types. At the same time, population size exhibits positive coefficients in manufacturing and service industry regressions but negative coefficients in disaggregated manufacturing regressions, suggesting differential scale effect mechanisms across industry hierarchies.

**Table 4** Endogeneity test results (2)

	(1)	(2)
Log of Entropy digital economy index × Total digital consumption (DIG1)	0.03583*** (0.00856)	
δ(Log of Entropy digital economy index × Total digital consumption)		0.03329*** (0.00795)
Log of real GDP, output-side	0.93551*** (0.01994)	0.71264*** (0.02664)
Log of human capital index	0.01115 (0.01341)	0.22878*** (0.02227)
Log of total population	-0.41209*** (0.07647)	0.30283** (0.13669)
Country fixed	Yes	Yes
Industry fixed	Yes	Yes
Time fixed	Yes	Yes
Observations	8167	7350
r2_a	0.81137	0.70417

#### 4.6.2 Heterogeneity analysis of digital economy input sources

Table 6 investigates the heterogeneous effects of digital input sources on GVC restructuring. The empirical results show that both domestic and foreign digital inputs positively influence GVC restructuring, albeit with significant differences in magnitude. Specifically, columns (1) and (3) show that domestic digital inputs have positive impacts on weighted degree centrality and PageRank centrality (coefficients 0.01007 and 0.01057, respectively, both  $p < 0.01$ ). In contrast, columns (2) and (4) reveal substantially larger effects from foreign digital inputs (coefficients 0.12333 and 0.09825 respectively,  $p < 0.01$ ), approximately 10–12 times greater than domestic inputs.

Columns (5) and (6) further confirm this heterogeneity by simultaneously incorporating domestic and foreign digital inputs in regression models. In these comprehensive models, foreign digital inputs maintain significantly larger impacts on weighted degree centrality and PageRank centrality (coefficients 0.16050 and 0.13064,

respectively) compared to domestic digital inputs (coefficients 0.04150 and 0.03616), approximately 3.6–3.9 times greater, with all coefficients significant at the 1% level.

**Table 5** Heterogeneity test results for manufacturing industries

	(1)	(2)	(3)	(4)	(5)
Log of Entropy digital economy index $\times$ Total digital consumption (DIG1)	0.11772*** (0.00778)	0.11926*** (0.00574)	0.00558 (0.00526)	0.00332 (0.00660)	0.00348 (0.00355)
Log of real GDP, output-side	1.67944*** (0.01473)	1.69638*** (0.01214)	0.93637*** (0.03110)	0.93631*** (0.03685)	0.93872*** (0.04180)
Log of human capital index	-0.34186*** (0.04245)	-0.43587*** (0.03661)	0.02272 (0.01981)	0.02371 (0.02360)	0.02436 (0.02684)
Log of total population	0.82406*** (0.00320)	0.82618*** (0.00272)	-0.38373*** (0.11687)	-0.37663*** (0.13909)	-0.37174** (0.15711)
Country fixed	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes
Observations	3349	4338	1679	1200	950
r2_a	0.94867	0.94949	0.99769	0.99767	0.99760

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

This pronounced heterogeneity likely reflects advanced technologies, management expertise, and global network externalities embedded in foreign digital inputs, improving a country's position in GVCs more effectively. Foreign digital inputs represent more advanced digital technologies and services, facilitating better integration into global production networks and strengthening international competitiveness. Conversely, while domestic digital inputs also promote GVC participation, their effectiveness may be constrained by local digital technology development levels.

Control variable estimates consistently show robustness, with GDP and population size showing significant positive effects on GVC restructuring. Human capital exhibits varied impacts across centrality measures – negative for weighted degree centrality but positive for PageRank centrality – potentially reflecting different GVC participation characteristics captured by different centrality indicators.

#### 4.6.3 Country heterogeneity analysis

Table 7 presents a heterogeneity analysis of digital economy development's impact on GVC restructuring across countries with different income levels. Results reveal significant cross-income variations in this relationship. Specifically, for low-income countries (column 1), digital economy development has the most significant positive impact on GVC restructuring (coefficient 0.21475,  $p < 0.01$ ); for middle-income

countries (column 2), the impact remains positive but smaller (coefficient 0.08278,  $p < 0.01$ ); while for high-income countries (column 3), the impact becomes significantly negative (coefficient  $-0.07904$ ,  $p < 0.01$ ), indicating an inverse relationship between digital economy development and GVC restructuring.

**Table 6** Heterogeneity test results by digital input sources

	(1)	(2)	(3)	(4)	(5)	(6)
Log of Entropy index × Domestic digital consumption	0.01007*** (0.00164)		0.01057*** (0.00138)		0.04150*** (0.00175)	0.03616*** (0.00149)
Log of Entropy index × Foreign digital consumption		0.12333*** (0.00315)		0.09825*** (0.00308)	0.16050*** (0.00303)	0.13064*** (0.00296)
Log of real GDP, output-side	1.74417*** (0.00885)	1.68067*** (0.00862)	1.11127*** (0.00708)	1.06217*** (0.00688)	1.63552*** (0.00853)	1.02284*** (0.00674)
Log of human capital index	-0.34871*** (0.02759)	-0.26857*** (0.02550)	0.11823*** (0.02130)	0.18477*** (0.01960)	-0.29157*** (0.02449)	0.16474*** (0.01916)
Log of total population	0.84045*** (0.00207)	0.85715*** (0.00190)	0.55108*** (0.00206)	0.56506*** (0.00203)	0.85040*** (0.00183)	0.55918*** (0.00194)
Country fixed	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8167	8167	8167	8167	8167	8167
r2_a	0.94588	0.95369	0.91225	0.92305	0.95713	0.92887

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

This systematic heterogeneity pattern reveals a ‘late-mover advantage’ effect in how digital economy development influences GVC restructuring. For low income and middle-income countries, digital economy development helps better combine them into GVC networks, enhancing their GVC positions. This likely occurs because these countries can use digital technologies to reduce transaction costs in international trade and production coordination, overcoming geographical and institutional barriers to more effectively participate in the global division of labour systems. Conversely, the negative coefficient for high-income countries suggests that digital economy development may prompt these nations to readjust their GVC strategies, such as reshoring manufacturing or reorganising production networks, thereby decreasing their traditional GVC participation. While the reshoring of manufacturing activities may partially explain this phenomenon, several additional mechanisms likely contribute to this distinctive pattern.

**Table 7** Heterogeneity test results by countries

	(1)	(2)	(3)
Log of Entropy index × Total digital consumption (DIG1)	0.21475*** (0.00552)	0.08278*** (0.00546)	-0.07904*** (0.01036)
Log of real GDP, output-side	1.81838*** (0.02870)	0.47960*** (0.04148)	0.92615*** (0.02662)
Log of human capital index	-0.63370*** (0.05561)	-0.02730 (0.02857)	-0.45890*** (0.04596)
Log of total population	0.85193*** (0.00342)	0.83288*** (0.00305)	0.73790*** (0.00724)
Country fixed	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes
Observations	2707	2730	2730
r2_a	0.96960	0.97356	0.83489

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

First, high-income countries are increasingly specialising in the pre-production (R&D, design) and post-production (marketing, after-sales services) stages of value chains. These stages are more knowledge-intensive but may register lower traditional GVC network centrality despite potentially generating higher value-added. This ‘smile curve’ specialisation pattern sees these nations strategically withdrawing from manufacturing-focused middle segments of value chains while maintaining control of high-value activities.

Second, digital technologies enable high-income countries to execute ‘deindustrialisation’ strategies, whereby manufacturing activities are supplemented or replaced by service components. This leads to a structural transformation that may reduce traditional GVC participation measures while enhancing economic value. The negative coefficient may reflect this transition toward service-dominant business models rather than a diminished economic position.

Third, digital platforms and ecosystems in high-income countries may promote more localised production networks supported by advanced technologies like 3D printing and smart manufacturing. This reduces the necessity for geographically dispersed production while maintaining economic efficiency. These compact, technology-intensive value chains may register as lower GVC participation despite representing advanced forms of production organisation.

Control variable estimates also reflect significant cross-income group differences. GDP shows a substantially larger impact on GVC restructuring for low income countries (1.81838) compared to middle-income (0.47960) and high-income countries (0.92615), indicating greater marginal contributions of economic development to GVC participation for low-income countries. The human capital index shows significant negative impacts for low-income and high-income countries but insignificant effects for middle-income countries, potentially reflecting complex relationships between human capital structures

and GVC participation patterns across different development stages. Population size exhibits significantly positive effects across all income groups, with coefficients decreasing from low-income (0.85193) to high-income countries (0.73790). This suggests that scale effects are significant for low-income countries' GVC participation.

#### 4.7 Analysis of mechanisms

##### 4.7.1 Mediation effect model

Through empirical testing, this study confirms that digital economy development significantly improves countries' (or regions') central positioning in GVC networks, thereby strengthening their advantages in GVC restructuring. To deeply analyse the underlying mechanisms through which digital economy development influences GVC restructuring, the current study constructs the following mediation effect model:

First, the conducted analysis examines digital economy development's impact on mediating variables:

$$Mediator_{it} = \beta_1 DIG_{cit} + \gamma_1 * X_{it} + \lambda_t + \varepsilon_{it} \tag{4.5}$$

Second, the analysis verifies the total effect of digital economy development on GVC restructuring:

$$GVC_{it} = \beta_2 DIG_{cit} + \gamma_2 * X_{it} + \lambda_t + \varepsilon_{it} \tag{4.6}$$

Finally, the examination tests the direct effect of digital economy development after controlling for mediating variables:

$$GVC\_CEN_{cit} = \beta_3 DIG_{cit} + \delta * Mediator_{it} + \gamma_3 * X_{it} + \lambda_t + \varepsilon_{it} \tag{4.7}$$

where  $DIG_{cit}$  represents the product of industry-level digitalisation and country-level digital economy development,  $GVC\_CEN_{cit}$  represents the GVC restructuring index for country  $c$ 's industry  $i$  in year  $t$ ,  $Mediator_{it}$  encompasses mediating variables (including labour productivity and R&D innovation intensity, they are used to represent production efficiency and innovation capabilities),  $X_{it}$  represents the set of control variables,  $\lambda_t$  indicates year fixed effects, and  $\varepsilon_{it}$  is the random error term.

##### 4.7.2 Innovation capability

Table 8 presents empirical results testing the mechanisms through which the digital economy impacts GVC restructuring. This research constructs a comprehensive mediation framework, systematically examining digital economy development's effects on mediating variables, its total effects on GVC restructuring, and direct effects after controlling for mediators, providing a solid foundation for mechanism identification.

First, column (1) shows that digital economy development significantly and positively impacts labour productivity (coefficient 0.03897,  $p < 0.01$ ). This confirms that as digital economies develop, labour productivity increases effectively, supporting theoretical expectations that digital technologies improve productivity through improved production processes and resource allocation efficiency. Simultaneously, column (2) shows that the digital economy positively affects R&D innovation intensity (coefficient

0.23509,  $p < 0.01$ ), indicating digital technology applications significantly promote innovation activities at both firm and national levels.

**Table 8** Results of mechanism analysis and dynamic effects analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log of Entropy index $\times$ Total digital consumption (DIG1)	0.03897*** (0.00274)	0.23509*** (0.01058)	0.12133*** (0.00453)	0.09433*** (0.00462)	0.10885*** (0.00472)	0.07328*** (0.00472)	0.02449*** (0.00540)
L. Log of weighted degree centrality							0.95764*** (0.00747)
Log of labour productivity				0.48129*** (0.01711)		0.62037*** (0.01812)	
Research and development expenditure intensity					0.07683*** (0.00517)	0.13163*** (0.00554)	
Log of real GDP, output-side	1.09795*** (0.00619)	1.02517*** (0.01869)	1.68576*** (0.00906)	1.13608*** (0.02185)	1.63069*** (0.01036)	0.87552*** (0.02462)	0.04849*** (0.01146)
Log of human capital index	-0.583*** (0.01588)	0.156*** (0.05748)	-0.389*** (0.02682)	0.114*** (0.02820)	-0.408*** (0.02731)	-0.05540* (0.02919)	-0.02141* (0.01120)
Log of total population	0.03466*** (0.00217)	0.17318*** (0.00417)	0.82505*** (0.00200)	0.79855*** (0.00261)	0.81426*** (0.00209)	0.77778*** (0.00263)	0.02669*** (0.00578)
Country fixed	Yes						
Industry fixed	Yes						
Time fixed	Yes						
Observations	7828	7790	8167	7828	7790	7451	7351
r2_a	0.89641	0.48605	0.94934	0.94181	0.95278	0.94805	

Values in parentheses represent robust standard errors. The symbols \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively. Sobel-Goodman mediation tests shows that labour productivity ( $Z = 3.86$ ,  $p < 0.001$ ) and R&D intensity ( $Z = 2.94$ ,  $p < 0.01$ ).

Column (3) confirms digital economy development's significant positive total effect on GVC restructuring (coefficient 0.12133,  $p < 0.01$ ). When controlling for labour productivity (column 4), digital economy development's coefficient significantly

decreases to 0.09433 ( $p < 0.01$ ), while labour productivity itself exhibits significant positive effects on GVC restructuring (coefficient 0.48129,  $p < 0.01$ ). This indicates that labour productivity plays an important mediating role, with digital economies indirectly enhancing GVC restructuring through productivity improvements. Based on coefficient changes, labour productivity's mediating effect accounts for approximately 22.3% of the total effect. When controlling for R&D intensity (column 5), digital economy development's coefficient decreases to 0.10885 ( $p < 0.01$ ), with R&D intensity positively influencing GVC restructuring (coefficient 0.07683,  $p < 0.01$ ). This suggests that research and innovation constitute another important transmission channel, accounting for approximately 10.3% of the total effect, supporting innovation's critical role in digital-era value chain upgrading.

When simultaneously controlling for both mediating variables (column 6), digital economy development's direct effect further decreases to 0.07328 ( $p < 0.01$ ), with both R&D intensity and labour productivity showing significant positive coefficients (0.13163 and 0.62037, respectively, both  $p < 0.01$ ). This indicates that while the digital economy's direct impact on GVC restructuring persists after controlling for these two important mechanisms, its strength notably weakens, suggesting digital economies primarily influence GVC restructuring by enhancing labour productivity and promoting R&D innovation, with their combined mediating effects accounting for approximately 39.6% of the total effect.

The study conducted Sobel-Goodman mediation tests based on the regression results to confirm the mediating effects identified above. For labour productivity, the Sobel test statistic ( $Z = 3.86$ ,  $p < 0.001$ ) confirms the statistical significance of this indirect pathway, with its mediating effect accounting for 22.3% of the total effect. Similarly, for R&D innovation intensity, the Sobel test statistic ( $Z = 2.94$ ,  $p < 0.01$ ) indicates a significant mediation effect, representing 10.3% of the total effect. These formal statistical tests provide strong evidence supporting the mechanistic explanation that digital economy development improves GVC restructuring through improvements in production efficiency and innovation capability while acknowledging additional transmission channels that warrant further investigation.

While the findings confirm that labour productivity and R&D innovation intensity together intervene in approximately 39.6% of the digital economy's total effect on GVC restructuring, exploring potential mechanisms behind the remaining 60.4% of unexplained effects is crucial. Several additional pathways warrant consideration:

First, digital platforms and ecosystems likely ease value chain coordination by reducing transaction costs and information asymmetries. Digital platforms create multisided markets that connect different value chain participants more efficiently, lowering search, contracting, and monitoring costs while facilitating smoother coordination across geographically dispersed production networks.

Second, data as a production factor constitutes a critical channel through which digital economy development influences GVC restructuring. Collecting, analysing, and utilising massive data enable more precise demand forecasting, inventory optimisation, and personalised production, fundamentally altering how value is created and distributed in global production networks.

Third, network effects and digital externalities may increase the impact of digital technologies on GVC restructuring through non-linear scaling mechanisms. As digital adoption reaches critical thresholds, the value derived from connectivity increases

exponentially, potentially explaining why conventional linear mediation models capture only part of the total effect.

Fourth, institutional complementarities between digital development and policy environments likely influence GVC restructuring outcomes. The effectiveness of digital technologies in reshaping value chains depends on complementary institutions such as intellectual property protection, digital governance frameworks, and cross-border data flow agreements.

Fifth, organisational transformations enabled by digital technologies – including the shift from hierarchical to networked structures, the execution of agile methodologies, and the adoption of remote work models – fundamentally alter firm boundaries and reshape interfirm relationships within value chains.

Future research employing more granular firm-level data and alternative methodological approaches could further depict these additional transmission mechanisms, providing a complete understanding of how digital economy development drives GVC restructuring.

### 4.7.3 Dynamic effects

After verifying the influence mechanism of digital economy development on GVC restructuring, this study employs the System Generalised Method of Moments (System GMM) to examine potential dynamic effects. The model is specified as follows:

$$GVC\_CEN_{cit} = \alpha_2 + \beta_3 DIG_{cit} + hGVC\_CEN_{cit-1} + \beta_4 Controls + \lambda_t + v_i + \mu_t + \varepsilon_{it} \quad (4.8)$$

In this model,  $GVC\_CEN_{cit}$  represents the GVC restructuring index,  $DIG_{cit}$  denotes the digital economy development level. To execute the System GMM, this study used,  $GVC\_CEN_{cit}$  and its one-period lag as dependent variables, with first and second-order lags of,  $GVC\_CEN_{cit}$  and  $DIG_{cit}$  serving as instrumental variables. The results, presented in columns (7) of Table 8, strongly support the model's validity and robustness.

The Sargan and Hansen test p-values exceeded 0.1, confirming instrument exogeneity and the absence of over-identification issues. The AR tests met System GMM expectations, with AR(1) significant and AR(2) non-significant, indicating no significant serial correlation in residuals. These results held consistently when using second-order lags, further validating the model's robustness.

Key findings revealed that both the first-order lag of  $GVC\_CEN_{cit}$  and Log of Entropy index  $\times$  Total digital consumption (DIG1) was significantly positive at the 1% level. Notably. This indicates strong persistence in GVC restructuring, suggesting a 'Matthew effect' where stronger participants continually reinforce their positions.

## 5 Conclusion

This study provides a comprehensive examination of the impact of digital economy development on GVC restructuring. These findings reveal a significant positive correlation between digital economy development and GVC restructuring. However, this impact is characterised by notable heterogeneity across multiple dimensions, including industries, input sources, and national development levels.

One of the most striking findings is the different effects of digital economy development on countries at different income levels. These results show that digital economy development significantly improves low-income and middle-income countries' GVC network centrality while simultaneously reducing that of high-income countries. This phenomenon emphasises the 'late-mover advantage' effect in how digital economy development influences GVC restructuring.

Further analysis reveals that production efficiency and innovation capability are crucial pathways through which digital economy development influences GVC restructuring. This dynamic analysis discovers a significant persistent effect of digital economy development on GVC restructuring. This finding suggests the potential for a 'Matthew effect,' whereby initial advantages are amplified over time, potentially deepening inequalities in GVC positions. Based on these findings, particularly the significant heterogeneity across country income levels, this analysis proposes adapted policy recommendations for countries at different development stages:

For low-income countries, where digital economy development shows the most substantial positive impact on GVC positioning (coefficient 0.21475), policies should focus on fundamental digital infrastructure development and capability building. Specifically, governments should:

- i invest in basic connectivity infrastructure through public-private partnerships
- ii develop specialised digital skills training programs targeting export-oriented sectors with lower technological barriers to entry
- iii execute simplified digital customs and trade facilitation measures to reduce trade friction
- iv establish clear data governance frameworks that enable cross-border data flows while providing adequate protection.

For middle-income countries with a moderate positive effect (coefficient 0.08278), policies should emphasise industrial upgrading and value chain specialisation. Key recommendations include

- i developing sector-specific digital transformation roadmaps for strategic industries with existing comparative advantages
- ii establishing innovation hubs and knowledge transfer programs focused on digital technologies for manufacturing
- iii promoting the adoption of industry-specific digital platforms to ease integration with global production networks
- iv executing targeted incentives for digital technology adoption in export-oriented SMEs.

For high-income countries, which uniquely demonstrate a negative relationship (coefficient  $-0.07904$ ), policies should focus on strategic repositioning within GVCs. These countries should:

- i invest in frontier digital technologies that enable new forms of value creation beyond traditional manufacturing

- ii develop advanced educational and research frameworks for emerging digital fields like artificial intelligence, blockchain, and advanced robotics
- iii establish regulatory environments that promote data-driven innovation while addressing potential anti-competitive practices in digital markets
- iv execute proactive labour market policies to ease workforce transitions as digital technologies alter GVC structures.

International cooperation mechanisms should also be strengthened to address the potential ‘digital divide’ in GVC restructuring. Developed economies should support technology transfer and capacity building in lower-income countries, while multilateral institutions should work toward establishing common standards and interoperable frameworks for digital trade. Such collaborative approaches ensure that digital-driven GVC restructuring contributes to inclusive and sustainable global economic development.

As the digital economy continues to develop rapidly and penetrate deeply, research frameworks and methodologies will need continuous innovation and improvement. Future research should focus on improving theoretical, analytical frameworks to comprehensively grasp the multidimensional impacts of digital economy development on GVCs. In-depth studies on the differential impacts of emerging technologies such as artificial intelligence, robotics, industrial internet, and blockchain on GVC restructuring are also crucial.

Lastly, combining macroeconomic data with microenterprise data to construct more comprehensive analytical frameworks will be valuable. This approach can help explore the micro-mechanisms through which the digital economy influences GVC restructuring, contributing to a more comprehensive and deep understanding of the dynamic relationship between the digital economy and GVCs. Such research will provide stronger theoretical support and empirical evidence for relevant policy formulation in this rapidly evolving landscape.

## Conflicts of interest

The authors declare that there is no conflict of interest.

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