Essays on Global Value Chains: Trade, Participation, and Positioning in the Context of Digitalization and Sustainable Development

Peiyu Xu

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Department of Economics and Finance

School of Business, Economics and Law

Abstract

Digitalization is reshaping global production and trade systems, it enables real-time coordination across borders, allowing firms to optimize global production and participate more efficiently in international trade. This thesis investigates how digital technologies affects global value chains (GVCs) and trade outcomes, using both econometric models and computable general equilibrium (CGE) simulation. Together these methods quantify both direct and economy-wide impacts, yielding a comprehensive assessment of the digitalization–GVC nexus. The three papers in this thesis provide complementary perspectives on the interaction between digitalization, GVCs, and trade performance, with a particular focus on manufacturing and environmental goods, which addresses critical gaps hitherto not addressed in empirical research on this topic.

The first paper employs a structural gravity model to examine how digitalization interacts with geographic distance and RTAs in shaping bilateral manufacturing GVC trade. This holds relevance as policymakers should have insights into the main drivers of GVCs, i.e., digitalization and regional trade agreements (RTAs), and how they interact to impact GVC trade flows. It contributes by way of estimating sectoral digital intensity measures based on the Asian Development Bank (ADB)'s Multi-Regional Input-Output (MRIO) tables, with the analysis covering 62 countries from 2007 to 2019. The results show that digitalization increases GVC exports and mitigates distance-related trade barriers. However, RTAs do not enhance—and may even dampen—the positive impact of digitalization, with significant heterogeneity observed across sectoral and income levels.

Having established the trade-promoting role of digitalization on manufacturing GVC trade, in the second paper of the thesis, the paper employs an economy-wide model to assess not only the economy-wide impacts of digitalization but also its impacts on both backward and forward GVC participation across regions. By introducing digitalization shocks through a sectoral digital input index and multi-regional input-output framework hitherto not attempted earlier in the empirical literature, the simulation quantifies the impact of digital transformation on manufacturing GVC linkages. The findings suggest that while digitalization significantly improves the macroeconomic effects on welfare, output and gross trade. In addition, digitalization enhances backward participation—particularly in simpler forms of GVC involvement—thereby contributing to a structural reorganization of regional production networks.

Furthermore, sustainability in trade and GVCs is an important issue for policymakers to consider. The third paper uses panel data methods to analyze the relationship between GVC positioning and trade in environmental goods across 75 countries. The findings suggest that GVC positioning enhances green trade through a nonlinear channel, and that digitalization acts as a moderator by shifting the structure and strength of this relationship. These are novel empirical findings that hold significant relevance in the current policy debate on green trade and the role of GVCs. Heterogeneity is also evident across different types of environmental goods.

The thesis provides a multi-layered analysis of the technological, and policy factors that shape GVCs and trade outcomes. The thesis contributes to the literature by bridging digitalization and GVC studies, providing novel empirical evidence on how sectoral digital intensity interact with GVC trade, participation, and positioning. It also demonstrates the complexity of interactions between digitalization, GVCs, and sustainable trade outcomes. The results have practical implications for policymakers seeking to modernize RTAs and improve digitalization to promote the development of GVCs and leverage GVCs to support sustainable and inclusive trade development.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Student's signature: ………………………………………….. Date: 12/08/2025 …………………

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Chapter 1 Introduction

This thesis investigates how digitalization reshapes global value chains (GVCs) across multiple dimensions. It examines role of digitalization in influencing GVC trade and participation and further explores how a country's GVC positioning affects green trade outcomes. By combining econometric techniques with CGE modelling, the thesis offers new empirical insights into the interplay between digital technology, trade policy, and environmental sustainability within GVCs, thereby contributing to the existing empirical literature.

The three standalone papers that constitute this thesis are unified by a central theme: how the structure and functioning of GVCs are being transformed by digital and policy-related forces, and what implications this transformation holds for sustainable trade. While each paper addresses a distinct research question, together they form a coherent narrative that spans country-sectoral level dimensions of GVCs.

The first paper, "Navigating Trade Barriers: The Interplay of Digitalization, Distance, and Regional Trade Agreements in Global Value Chains", investigates the impact of digitalization on bilateral manufacturing GVC trade using a structural gravity model. Using sectoral digital intensity indicators (Zhang & Yu, 2020) derived from the Asian Development Bank Multi-Regional Input-Output (ADB MRIO) database [1]and panel data from 62 countries over the period 2007–2019, the paper estimates the trade-enhancing effects of digitalization. It shows that digitalization significantly promotes GVC trade and mitigates the negative effects of geographical distance. However, contrary to expectations, RTAs do not amplify the positive effect of digitalization and may even constrain it due to trade costs caused by potential digital protection. This paper also uncovers heterogeneity across countries and sectors, with low-income economies and medium-high digital intensity sectors gaining more from digitalization, hitherto not explored in existing research published in this space.

The second paper, "The Impact of Digitalization on Global Manufacturing Value Chains: Regional Dynamics in the Age of Industry 4.0", shifts the analytical lens from GVC trade flows to GVC participation across regions. It employs the latest Global Trade Analysis Project (GTAP) model (Corong et al., 2017), the GTAP 11 Data Base (Aguiar et al., 2023), a multi-regional input-output framework (Peters et al., 2011), and GVC accounting methodologies (Wang et al., 2017). Contributing to a new empirical framework to compute GVC impacts using MRIOS, the paper quantifies how digital transformation alters backward and forward participation in manufacturing GVCs across different regions. The study provides evidence that digitalization facilitate economic development and promotes backward participation and regionalization of value chains.

The third paper, "Leveraging Value Chains for Green Trade: The Moderating Role of Digitalization and Participation", turns attention to the green trade dimension of GVC positioning. By harmonizing data from diverse sources, the study applies high-dimensional fixed effects model to examine how a country's GVC positioning affects the cross-border trade in environmental goods. Results show that GVC positioning

[1] Retrieved from https://data.adb.org/.

enhances green trade, but the relationship is nonlinear and varies across categories of environmental goods. Furthermore, digitalization is shown to moderate this relationship by shifting the inflection points of the GVC–trade nexus, suggesting that digitalization is an influencer in the potential of GVCs in promoting green trade.

The thesis is organized as follows. Chapter 2 provides a prelude to the first paper, which explores how digitalization, distance, and RTAs interact in shaping manufacturing GVC trade. Chapter 3 presents the first paper. Chapter 4 offers a prelude to the second manuscript, followed by Chapter 5 which applies a CGE-based analysis of digitalization's impact on manufacturing GVCs. Chapter 6 presents a prelude to the third paper. Chapter 7 introduces the third paper, which empirically examines how GVC positioning affects trade in environmental goods. Chapter 8 concludes with a synthesis of results and directions for future research.

By bringing together three distinct yet connected strands of research, this thesis offers a comprehensive view of how GVCs are being reshaped, and how they interact with digitalization in the era of digital transformation. The results have practical implications for policymakers seeking to modernize trade agreements, leverage digitalization, and use GVC integration as a tool for green and inclusive development.

Prelude to Navigating Trade Barriers: The Interplay of Digitalization, Distance, and Regional Trade Agreements in Global Value Chains

The first paper in this thesis investigates how digitalization interacts with geographic distance and regional trade agreements (RTAs) to influence bilateral manufacturing trade embedded in global value chains (GVCs). While digital technologies could reduce trade costs, it remains unclear how these benefits vary across countries and the joint effects of digitalization and existing RTAs on GVC trade, especially when accounting for sectoral digital intensity.

Using a structural gravity model estimated with Poisson Pseudo Maximum Likelihood (PPML) estimator, the paper estimates sector-level digital intensity data from the ADB Multi-Regional Input-Output (MRIO) database, covering 62 countries between 2007 and 2019. The analysis includes robustness checks and instrumental variable techniques to ensure the validity of the results.

The results show that digitalization significantly promotes GVC trade and mitigates the trade-reducing effect of distance. However, existing RTAs do not appear to amplify these benefits and may even limit them. The analysis also finds heterogeneity in the impact of digitalization across income groups and sectors, with lower-income countries and medium-low digital intensive sectors gaining the most.

This study provides new empirical evidence on the interaction between digitalization, trade policy, and production networks, offering insights for modernizing RTAs to better align with the realities of the digitalization.

Chapter 2 Navigating Trade Barriers: The Interplay of Digitalization, Distance, and Regional Trade Agreements in Global Value Chains

Abstract

This study aims to empirically investigate the impact of digitalization on bilateral manufacturing GVC trade by utilizing ADB data from 2007 to 2019. Employing sectoral digital intensity as a proxy for digitalization and utilizing a structural PPML estimator to effectively address heteroscedasticity and zero trade flows, this paper examines how digitalization influences GVC trade in the context of RTAs. The findings reveal that digitalization significantly enhances GVC exports, particularly by mitigating the negative effects of geographic distance. However, existing RTAs do not fully exploit the potential benefits of digitalization, suggesting that RTA provisions should be updated to better support the digital economy. Furthermore, the results indicate that the combined effects of digitalization and RTAs are more influenced by sectoral digital intensity, while the interaction between digitalization and distance is more significantly affected by the income levels of trading partners. Robustness checks, including instrumental variable (IV) techniques to address endogeneity, alternative measures of digital intensity, and re-estimations excluding major economies, confirm the reliability of these findings. Important policy implications are discussed.

Additional Information

This paper is under review and submitted to the journal *Singapore Economic Review*.

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2.1 Introduction

The expansion of global value chains (GVCs) has been one of the most defining features of international trade over the past three decades (World Bank, 2020). Production processes are increasingly fragmented across borders, with intermediate goods and services crossing national boundaries multiple times before final assembly. While this fragmentation has generated substantial efficiency gains, it has also increased firms' exposure to trade frictions related to geographic distance, coordination costs, and institutional barriers (Antràs, 2020). Understanding the forces that shape GVC trade has therefore become a central concern in both academic research and trade policy.

In parallel with the rise of GVCs, digitalization has fundamentally transformed the organization of production and trade. Digital technologies, encompassing information and communication technologies (ICTs), artificial intelligence, cloud computing, and internet-based services, facilitate real-time information exchange, enhance coordination across geographically dispersed production stages, and reduce transaction costs (UNCTAD, 2021). A growing body of empirical literature documents that digitalization is associated with higher trade volumes (Yang et al., 2023), deeper GVC participation (Gopalan et al., 2022), and improved export performance (Qi et al., 2022). These findings suggest that digitalization could mitigate the potential frictions that traditionally constrain cross-border production networks.

Nevertheless, the implications of digitalization for GVC trade are not unambiguous. Digital technologies have been described as a "double-edged sword" for GVC development (Dollar et al., 2019). On the one hand, digitalization may encourage reshoring and shorten value chains by reducing the need for geographically dispersed production. On the other hand, by enhancing efficiency and facilitating coordination and knowledge exchange, digitalization may enable firms and countries to participate more deeply in GVCs. Which of these effects dominates remains an open empirical question.

More broadly, despite the growing consensus that digitalization matters for trade, important questions remain unanswered. Much of the existing literature treats digitalization as a uniform trade-enhancing factor and focuses on estimating its average effect on trade outcomes. Less attention has been paid to the conditions under which digitalization matters more or less, and to the specific transmission channels through which it affects GVC trade. In particular, two dimensions are highly relevant yet remain insufficiently explored.

First, geographic distance has long been recognized as a primary determinant of trade costs. However, the rapid proliferation of digital technologies has fundamentally challenged the traditional "tyranny of distance" (Clarke & Wallsten, 2006). By streamlining information flows and mitigating transaction-related frictions, including market entry, communication, and negotiation costs, digital technologies enhance market competitiveness and efficiency (Nath & Liu, 2017). While digital technologies are often argued to weaken the trade-reducing effect of distance, empirical evidence typically relies on interaction effects between digitalization and distance without explicitly identifying the underlying mechanism. It remains unclear whether the distance-attenuating effect of digitalization reflects genuine reductions in communication and coordination costs, or whether it captures other correlated factors. Particularly, the joint effects of digitalization and distance on GVC trade is under-researched.

Second, institutional arrangements governing trade have evolved alongside digitalization. Regional trade agreements (RTAs) have long played a central role in facilitating trade and supporting GVC integration (Antràs, 2020). However, traditional RTAs were primarily designed to address tariffs and border measures, whereas many of the frictions relevant in the digital era relate to data flows, digital services, and regulatory compatibility (Mitchell & Mishra, 2020). As a result, it is not obvious whether RTAs complement digitalization, substitute for it, or potentially constrain its trade-enhancing effects. Empirical evidence on how digitalization interacts with RTAs in shaping GVC trade remains limited and mixed.

Against this backdrop, this paper examines how digitalization affects manufacturing GVC trade according to sectoral digital intensity, with a particular focus on spatial and institutional channels. We first establish the baseline relationship between digitalization and manufacturing GVC trade. We then explore how this relationship varies with geographic distance and RTA membership by estimating interaction effects between digitalization, distance, and RTAs. While these interaction effects document important conditional heterogeneity, they do not, by themselves, identify the underlying mechanisms.

To address this issue, the paper conducts a structured mechanism analysis. Specifically, we examine whether the distance-attenuating effect of digitalization operates through communication-related channels by introducing traditional communication infrastructure as a channel-specific control. In addition, we assess whether the interaction between digitalization and RTAs reflects institutional overlap by distinguishing between conventional RTAs and those containing explicit digital trade provisions. Attenuation of the interaction effects once these channel-specific variables are accounted for provides direct evidence on the mechanisms through which digitalization reshapes GVC trade.

This study contributes to the literature in several ways. First, it provides new empirical evidence on the relationship between digitalization and manufacturing GVC trade using sector-level measures of digital intensity. Second, it advances the literature by explicitly distinguishing between conditional interaction effects and underlying transmission mechanisms. Third, by jointly examining digitalization, geographic distance, and RTAs, the paper offers policy-relevant insights into how digital and institutional reforms interact to shape the evolution of GVCs.

2.2 Literature Review

2.2.1 Digitalization and GVC Trade

A growing body of literature has examined the relationship between digitalization and participation in global value chains (GVCs), generally pointing to a positive association between the two. The diffusion of digital technologies—including information and communication technologies (ICTs), automation, and data-driven production processes—has fundamentally reshaped the organization of cross-border production. By reducing transaction costs, improving information flows, and facilitating coordination across geographically dispersed production stages, digitalization is widely regarded as an important enabler of international production fragmentation and GVC integration (Amador and Cabral, 2016; Antràs, 2020).

Early conceptual contributions emphasize that GVC participation depends on firms' ability to manage complex inter-firm relationships and coordinate activities across borders. Within this broad perspective, digital technologies can be viewed as productivity-enhancing inputs that lower the costs of organizing and governing fragmented production processes. ICTs improve transparency and real-time communication between buyers and suppliers (Gereffi, Humphrey, and Sturgeon, 2005; Grant, 1991). These mechanisms suggest that digitalization may expand the set of firms and countries capable of being involved in GVCs by alleviating coordination frictions and reducing barriers to entry.

At the macro and industry levels, studies document a positive link between digitalization and GVC participation. Using country- and industry-level data, Amador and Cabral (2016) highlight the role of technological capabilities in shaping countries' positions within GVCs. Subsequent studies show that digital infrastructure and ICT intensity significantly enhance both backward and forward GVC participation across developed and developing economies. For example, Gniniguè et al. (2023) provide evidence from a large sample of developing countries that ICT adoption promotes participation in international production sharing. Guo, Xu, and Zhu (2023) construct an industry-level measure of digitalization for China and show that more digitally intensive industries are more deeply embedded in GVCs. Similarly, Ha (2022), focusing on European economies, documents a non-linear relationship between digitalization and GVC participation, suggesting that the benefits of digital technologies may vary with the level of digital development.

Complementary evidence at the firm level further supports the view that digital technologies facilitate engagement in GVC-related activities. Empirical studies consistently find that firms adopting ICTs—such as broadband internet, websites, and digital communication tools—are more likely to import intermediate inputs, export goods, and engage in cross-border production relationships (Fort, 2017; Gopalan, Reddy, and

Sasidharan, 2022; Banga, 2022; Reddy and Sasidharan, 2023). Digital technologies enable firms to identify foreign suppliers and customers more efficiently, customize products to meet buyer-specific requirements, and respond more quickly to changes in demand (Fernandes et al., 2019; Li, Frederick, and Gereffi, 2019). While these studies rely on firm-level data and specific country contexts, their findings are broadly consistent with macro- and industry-level evidence on the trade-enhancing role of digital technologies.

Beyond differences in analytical focus, the literature also varies considerably in how digitalization is measured and operationalized. Existing studies examine the interaction between digital technologies and manufacturing performance from multiple perspectives, including GVC participation (Gopalan et al., 2022), structural transformation of manufacturing value chains (Zhou et al., 2022), production upgrading (Banga, 2022), and domestic value-added generation (Qi et al., 2022). Correspondingly, digitalization is captured using a wide range of indicators. Some studies rely on firm- or country-level measures related to e-commerce activity and online transactions (Ha, 2022), while others adopt input–output approaches to construct sectoral indicators of digital intensity that reflect inter-industry linkages and digitally enabled services (Zhang and Yu, 2020; Yang et al., 2023; Chiappini and Gaglio, 2024). While this diversity of approaches has enriched our understanding of how digital technologies interact with trade, it also underscores the fragmented nature of the existing evidence.

Taken together, the literature provides robust support for a positive association between digitalization and GVC trade across different levels of analysis. Digital technologies facilitate international fragmentation by lowering transaction and coordination costs, improving access to foreign markets, and enhancing productive capabilities (Amador and Cabral, 2016; Antràs, 2020). Importantly, this body of work establishes digitalization as a key determinant of GVC participation rather than a peripheral factor, highlighting its central role in shaping the evolution of global production systems.

However, despite this broad consensus, important limitations remain. Much of the existing literature focuses on estimating the average effect of digitalization on GVC participation, often treating digitalization as a uniform trade-enhancing force. Although some studies document non-linearities or heterogeneity across countries, industries, or firms (Ha, 2022), these differences are rarely linked systematically to specific spatial or institutional conditions. Moreover, empirical analyses typically rely on reduced-form relationships and provide limited insight into how digital technologies interact with other fundamental determinants of trade.

As a result, less is known about the circumstances under which digitalization matters more or less for manufacturing GVC trade. In particular, the interaction between digitalization and geographic as well as institutional factors has received limited attention in the GVC literature, especially based on sectoral digital intensity. Understanding how digital technologies interact with spatial frictions and trade-related institutions is therefore essential for moving beyond average effects and for identifying the conditions under which digitalization reshapes global production networks. The following sections build on this literature by examining geographic distance and regional trade agreements as key conditioning factors shaping the relationship between digitalization and manufacturing GVC trade.

2.2.2 Digitalization, Distance, and Communication Costs

Geographic distance has long been recognized as a fundamental determinant of international trade costs. A large body of empirical literature identifies distance as a key barrier to trade, reflecting not only transportation costs but also a range of informational and coordination frictions associated with spatial separation (Hummels, 1999; Limao and Venables, 2001; Rauch, 1999; Chaney, 2011). In particular, remoteness between trading partners exacerbates search costs, limits information availability, and increases uncertainty in cross-border transactions.

Against this background, the development of ICTs has been widely viewed as a potential force mitigating distance-related trade frictions. From a theoretical perspective, ICTs reduce transaction and coordination costs by enabling real-time information exchange and lowering the costs of communication across geographically dispersed partners (Malone et al., 1987; Benjamin & Wigand, 1995). Improved digital infrastructure facilitates the search for foreign buyers and suppliers, reduces fixed market entry costs, and enhances coordination along international supply chains, thereby weakening information-related barriers to trade (Yadav, 2014; Liu & Nath, 2013).

A substantial empirical literature provides evidence that ICT adoption is associated with higher trade volumes, largely through reductions in information and communication costs. Early studies show that improvements in telecommunications infrastructure significantly promote bilateral trade flows (Limao & Venables, 2001; Fink et al., 2002; Freund & Weinhold, 2004). Using international telephone call cost data, Fink et al. (2005) demonstrate that higher information costs exert a negative and significant effect on bilateral trade, while subsequent studies employing indicators such as internet usage and broadband penetration generally confirm the trade-enhancing role of digital connectivity (Clarke & Wallsten, 2006; Choi, 2010).

However, evidence on whether digital technologies systematically attenuate the trade-depressing effect of geographic distance remains mixed. Several studies find that ICT adoption reduces the importance of non-geographic frictions, such as language barriers, rather than physical distance itself. For example, Visser (2019) shows that broadband penetration weakens the impact of language distance on trade, while Kitenge & Lahiri (2022) report similar effects for linguistic frictions but find no robust evidence of a mitigating effect on geographic distance. By contrast, Akerman et al. (2022), using firm-level data, show that broadband internet adoption may increase the sensitivity of trade patterns to distance, suggesting that digital technologies can reinforce spatial concentration under certain conditions.

Importantly, much of this literature focuses on aggregate trade flows and reduced-form relationships, without explicitly considering the specific context of global value chains. In GVCs, production stages are fragmented across locations and require intensive coordination and information exchange across borders. Distance-related frictions in this setting are therefore likely to operate primarily through communication and coordination costs rather than transportation costs alone. Yet existing studies rarely examine how digitalization interacts with geographic distance in shaping GVC trade.

Overall, while digital technologies clearly reduce information and communication costs in international trade, existing evidence provides no consensus on whether digitalization systematically weakens the trade-depressing effect of geographic distance. This gap is particularly salient in the context of manufacturing GVCs, where coordination across spatially dispersed production stages is critical. The present study builds on this literature by examining how digitalization interacts with geographic distance in shaping manufacturing GVC trade, with a particular focus on communication-related channels.

2.2.3 Regional Trade Agreements, Digital Rules, and Institutional Frictions

As regional trade agreements have evolved, their focus has increasingly shifted from tariff reductions at the border to the regulation of behind-the-border policies that are critical for the operation of global value chains. In particular, recent RTAs increasingly incorporate provisions related to digital trade, such as e-commerce, data flows, and regulatory cooperation, which are central to facilitating coordination-intensive GVC activities (Blanchard et al., 2016; Mitchell & Mishra, 2020). According to recent evidence, a large majority of contemporary trade agreements now include e-commerce-related provisions that fall under the WTO dispute settlement framework, reflecting the growing importance of digital rules in governing cross-border economic interactions (Burri & Polanco, 2020).

This shift has been accompanied by a relocation of digital trade rule-making from the multilateral arena toward bilateral and regional agreements. González & Ferencz (2018) document that digital trade negotiations are increasingly conducted through RTAs, where countries seek to address regulatory and institutional frictions not adequately covered by existing multilateral frameworks. A key component of this process is digital trade facilitation, including cross-border paperless trade and the electronic exchange of trade-related documents

(Duval & Mengjing, 2017; Mitchell & Mishra, 2020). These measures are shown to reduce trade costs, enhance transaction speed, and improve efficiency in international supply chains (Duval et al., 2018).

At the same time, the expansion of digitalization has generated new forms of regulatory fragmentation and protectionism. Panchenko et al. (2020) argue that digitalization may give rise to “digital neo-protectionism,” particularly through data governance regimes and restrictions on cross-border data flows. As international production increasingly depends on the seamless movement of data across borders, regulatory interventions related to data localization, cybersecurity, and privacy can become significant sources of trade frictions (González & Jouanjean, 2017; Ferencz & González, 2019). Such measures, often justified under the notion of digital sovereignty, may impose compliance costs and uncertainty for firms engaged in cross-border production and trade (Ferracane & Marel, 2019; Mitchell & Mishra, 2020).

Taken together, this literature suggests that while RTAs have the potential to complement digitalization by reducing institutional and regulatory frictions relevant to GVC trade, they may also interact with digitalization in more complex ways when digital regulations are incomplete, uneven, or restrictive. This ambiguity highlights the need for empirical analysis that distinguishes between traditional RTAs and those incorporating explicit digital trade provisions when assessing the joint effects of digitalization and institutional arrangements on GVC trade.

Overall, the literature shows that digitalization, geographic distance, and institutional arrangements are central to shaping trade and GVC participation, yet their joint impacts remain insufficiently understood. Existing studies largely focus on average effects or reduced-form relationships, providing limited evidence on how digitalization conditions distance-related and institutional frictions in fragmented production networks. In particular, it remains unclear whether digital technologies systematically mitigate distance-induced trade costs and how their effects depend on the design of RTAs, especially the inclusion of digital trade provisions. These unresolved issues motivate an empirical analysis that jointly examines digitalization, geographic distance, and RTAs, while explicitly distinguishing between conditional interaction effects and underlying transmission mechanisms.

2.3 Data and Methodology

2.3.1 Model Settings

The structural gravity model of trade is effective in explaining bilateral trade flows through key factors like economic size and distance and is a popular tool to quantify the impacts of ICT on trade. Its flexibility allows for the inclusion of control variables and fixed effects, improving the robustness of empirical results. (Anderson & Wincoop, 2003; Yotov et al., 2016; Rodriguez- Crespo et al., 2021; among others).

Anderson and Wincoop (2003) address the importance of accounting for relative trade costs in trade models, as trade flows between two countries are influenced not only by the bilateral trade barriers but also by the average trade barriers that each country faces with all its trading partners—commonly referred to as 'multilateral resistance.' Baldwin and Taglioni (2006) further caution that neglecting to account for multilateral resistance can result in what they describe as the "gold medal mistake," a critical error in trade flow estimation.

Head & Mayer (2014) emphasize that incorporating fixed effects is crucial for accurately specifying structural gravity equations. Omitted variable bias arises when the error term correlates with unobservable country-specific policy variables (Baier & Bergstrand, 2007) or time-invariant bilateral trade costs (Agnosteva et al., 2019; Egger & Nigai, 2015). These unobserved variables are often the source of endogeneity in trade models. Fixed effects help address this potential endogeneity by controlling for unobservable characteristics that could otherwise bias the estimates (Yotov et al., 2016; Laget et al., 2020).

The country-pair fixed effects account for all the factors that remain constant over time between the two trading partners, such as distance or historical ties. On the other hand, country- time fixed effects capture time-varying characteristics specific to each country, such as GDP (Baldwin & Taglioni, 2006; Rose & Van Wincoop, 2001). As a result, control variables that are collinear with these fixed effects—such as GDP or distance—are excluded from the equations to avoid multicollinearity.

In the core analysis, the following baseline empirical models are specified to explain the effects of digitalization on GVC trade in manufacturing:

$$X_{ij,t} = \propto_0 + \theta_1 lnDI_{ij,t} + \gamma_{i,t} + \delta_{j,t} + \varphi_{ij} + \varepsilon_{ij,t} \qquad (1)$$

Equation (1) investigates the role of digitalization in promoting GVC exports. In equation (1), $X_{ij,t}$ refers to the value of bilateral manufacturing GVC exports between country i and country j in year t. $lnDI_{ij,t}$ denotes the variable of digitalization, showing the average digitalization level between exporters and importers at time *t*. The variable is measured by capturing digital inputs (e.g., ICT-enabled services: the data processing related activities and ICT devices: computers and peripheral equipment) embodied in the manufacturing industry. Section 2.2.2 provides more details on the construction of the digital input index as an explanatory variable in the model.

$\gamma_{i,t}$ denotes the vector of exporter-time fixed effects, $\delta_{j,t}$ denotes importer-time fixed effects, and φ_{ij} refers to the symmetric pairwise fixed effect, respectively. The exporter-time and importer-time fixed effects can control for observable and unobservable country-specific characteristics that may vary for each exporter and importer. The pairwise fixed effects comprehensively cover more systematic information about trade costs. $\varepsilon_{ij,t}$ is the error term, and θ estimates the impact of digital intensity on international trade and is the parameter of interest.

The interaction of digitalization with bilateral distance is specified by extending equation (1) as follows:

$$X_{ij,t} = \propto_0 + \beta_1 lnDI_{ij,t} + \beta_2 lnDist_{ij} + \beta_3 lnDist_{ij} * lnDig_{i,t} + \beta_4 Z + \gamma_{i,t} + \delta_{j,t} + \varepsilon_{ij,t} \quad (2)$$

Wherein $lnDist_{ij} * lnDig_{i,t}$ is the key explanatory variable, presenting the role of digitalization interacting with distance in bilateral GVC manufacturing trade. $\ln Dist_{ij}$ is the natural logarithm of distance between the country i's capital and the country j's capital, Z is a vector that contains control variables such as $Comlang\_ethno$, $Contig_{ij}$. $Comlang\_ethno$ takes a value of 1 if trading partners share the common language (at least 9% of the population) and 0 otherwise. $Contig_{ij}$ takes a value of one if countries i and j are adjacent and 0 otherwise. β_3 are variables of interest, showing how digitalization could affect GVC trade by overcoming the effect of the distance. Due to the collinearity, control variables are dropped.

The effects of digitalization interacting with RTAs membership and the joint effects on bilateral GVC exports are estimated through the following specification:

$$X_{ij,t} = \propto_0 + \lambda_1 lnDI_{ij,t} + \lambda_2 RTA_{ij} + \lambda_3 RTA_{ij} * lnDI_{ij,t} + \gamma_{i,t} + \delta_{j,t} + \varphi_{ij} + \varepsilon_{ij,t} \quad (3)$$

In Equation (3), RTA_{ij} take a value of one if the origin country or destination country is involved in a specific regional trade agreement. The key variables are the interaction terms between variables of RTAs and digitalization ($RTA_{ij} * lnDI_{ij,t}$). These interaction terms analyze the role of digitalization combined with RTAs, showing that if RTAs could enlarge the benefits of digitalization. The equation contains country-pair, exporter-time, and importer-time fixed effects. λ_3 is the key parameter of interest in this model.

Models incorporating equations (1)-(3) are estimated using the Pseudo-Poisson Maximum Likelihood (PPML) estimator. The empirical justification for this follows Santos Silva & Tenreyro (2006, 2011) who have observed that the PPML estimator effectively addresses zero values and heteroscedasticity issues. Fally (2015) further indicates the similarity between PPML and the roots of the structural gravity equation using fixed effects to control for multilateral resistance, and researchers can use the PPML estimator to perform iterative estimations closer to the structural gravity equations (Beverelli et al., 2018). Kabir et al. (2017) further stresses the importance of PPML for consistent gravity estimation.

2.3.2 Identification & Instrumental Variable Construction

Endogeneity and Identification

Estimating the impact of digitalization on bilateral manufacturing GVC exports raises endogeneity concerns. Reverse causality may arise if sectors that successfully upgrade into higher value-added segments of global value chains subsequently invest more in digital technologies. In addition, omitted factors, such as time-varying managerial capability, institutional effectiveness, or unobserved policy reforms, may jointly affect digital adoption and GVC outcomes. To mitigate these concerns, we implement a two-stage least squares

(2SLS) strategy that instruments bilateral sectoral digitalization with exogenous variation from global ICT shocks and regional digital spillovers.

2.3.3 Bartik-style Instruments based on Global ICT Shocks

Our first identification approach follows a shift–share (Bartik-style) design that combines predetermined exposure with aggregate shocks (Bartik, 1993; Goldsmith-Pinkham et al., 2020; Borusyak et al., 2022). Specifically, we construct instruments by interacting the baseline (pre-sample) digital exposure of each country-pair–sector cell with the annual growth of global ICT exports:

$$Bartik\_IV = Z_{k,ij,s,t} = DI_{ij,s}^{2007} * \Delta\ln\left(ICT_{k,world,t}\right), k \in \{goods, services\} \quad (4)$$

The base-year term, $DI_{ij,s}^{2007}$, captures cross-sectional differences in initial digital intensity that are fixed prior to the sample period and therefore unlikely to reflect contemporaneous responses to post-2007 GVC outcomes. As digitalization contains both ICT service and ICT goods (Calvino et al., 2018). We construct two distinct shift components within the Bartik instrumental variable framework. The shift component, $\Delta\ln\left(ICT_{k,world,t}\right)$, is measured as the global growth rate of ICT goods exports and ICT services exports, respectively, capturing worldwide technological progress and demand conditions that are common across country–sector cells.

Identification relies on differential exposure to common global shocks. Conditional on high-dimensional fixed effects (including country-pair fixed effects and exporter-year and importer-year fixed effects), the identifying variation comes from cross-cell differences in baseline exposure intensity, $DI_{ij,s}^{2007}$, interacted with aggregate ICT growth. These fixed effects absorb time-invariant bilateral determinants of trade and country-specific macroeconomic and policy changes, so that remaining variation is driven by heterogeneous exposure to global ICT expansion.

This design is justified on three grounds. First, relevance: cells with higher baseline digital exposure are more likely to experience stronger digital upgrading when global ICT goods and services expand, generating a strong first-stage relationship between $Z_{k,ij,s,t}$ and current digitalization. Second, exogeneity: global ICT export growth reflects worldwide technology evolution and demand conditions, which are implausibly driven by GVC outcomes in any single country–sector pair. Third, exclusion: conditional on the fixed effects structure, global ICT growth affects bilateral GVC exports primarily through its impact on domestic digitalization rather than through alternative direct channels, supporting the exclusion restriction.

2.3.4 Alternative Instrument based on Regional Digital Intensity

To reinforce the identification strategy, we construct an alternative instrumental variable based on regional digital intensity. Following Acemoglu et al. (2019) and Chiappini & Gaglio (2024), the objective is to exploit variation that is strongly correlated with domestic digital intensity but plausibly exogenous to country–sector GVC trade outcomes. Digital transformation often diffuses geographically, generating regional waves of technological adoption similar to historical patterns observed in other structural transformations. Within global value chains, countries participating in related production networks are exposed to common technological environments, making domestic digitalization responsive to developments in neighbouring economies.

Conditional on country–time fixed effects, the lagged digital intensity of the same sector in other countries within the region is unlikely to directly influence sectoral exports in the focal country, except through its effect on domestic sectoral digital intensity. The instrument is constructed using a leave-one-out approach that excludes the focal country, ensuring that the variation reflects regional digital spillovers rather than domestic export conditions. This supports the exclusion restriction required for valid instrumental variable estimation. Therefore, we define the average domestic digital intensity in a region r (Appendix 1 presents details for classification) as:

$$R_{ikt} = \frac{1}{N_r} \sum_{j \neq i}^{J} DI_{jkt}^{d} \quad (5)$$

Where N_r is the number of countries in region *r*, leaving out *i*, the country under scrutiny. To further mitigate concerns about unobserved confounding factors, we introduce both spatial and temporal lags by using the two-year lagged regional digital intensity. This approach reduces the possibility that contemporaneous shocks simultaneously affect digital adoption and trade outcomes. Similar spatial–temporal instrumental variable strategies have been employed in prior studies examining the effects of globalization on inequality (Lang & Tavares, 2018) and foreign direct investment on health outcomes (Chiappini et al., 2022).

Table 3 reports the corresponding 2SLS estimates and standard identification diagnostics for both instrument sets.

2.3.5 Variables and Data Sources

2.3.5.1 Dependent Variables

Our study uses the Asian Development Bank (ADB) Multiregional Input-Output (MRIO) database[2] (2021) consisting of 62 economies, 35 industries (14 manufacturing industries), and spanning 13 years (2007-

[2] The data is available at http://mrio.adbx.online/

2019). The database was constructed by Borin & Mancini (2019) and is publicly available on the World Bank's World Integrated Trade Solution (WITS)[3].

Gross trade (E_{sr}) between country s and country r consists of both direct [($DAVAX_{sr}$), i.e., value-added crosses border once, and indirect trade (i.e., value-added crosses at least two borders). Borin & Mancini (2019)[4] propose a method to distinguish the directly absorbed value-added components, traded goods immediately absorbed and used as inputs in the production process entirely in the importing country. The residual value (E_{sr}-$DAVAX_{sr}$) is trade flows involved in GVCs, value-added components for re-exporting. Our study uses GVC trade flows in manufacturing goods as the dependent variable.

2.3.5.2 Independent Variables

As observed in our specified models that estimate equations (1)-(3), Digitalization is the critical variable of interest. Digitalization contains ICT devices and ICT-enabled services, blurring the boundary between goods and services (Calvino et al., 2018). The raw data for measuring digitalization in the manufacturing industry at the sub-sectoral level comes from the ADB MRIO (2021) database.

The methodology to measure the digital intensity follows Zhang & Yu (2020). While Zhang & Yu (2020) primarily focuses on digital pervasiveness in China's manufacturing industry, this paper contributes to the empirical literature by extending this methodology to 62 countries[5]. The digitalization index captures ICT devices and ICT-enabled services as an intermediate input for digitalizing the manufacturing industry. Following Zhang & Yu (2022), our study classifies four digital intermediate inputs according to the International Standard Industrial Classification of All Economic Activities (ISIC Rev.4). These sectors are manufacturing of computers, electronic, and optical products (C-26);[6] telecommunications (J-61);[7] computer programming, consultancy, and related activities (J-62); and information service activities (J-63)[8].

The index shows the degree of utilization of digital technologies in the manufacturing industry by covering direct and indirect digital inputs. Direct inputs are inputs from those four digital sectors immediately consumed by the manufacturing industry (e.g., digital inputs required for producing one unit of transportation equipment). Indirect digital inputs are embedded in other intermediate inputs used by a particular sector. The digital intensity index captures total embodied digital technology in the manufacturing industry by combining direct and indirect digital inputs.

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[3] Retrieved from https://wits.worldbank.org/gvc/gvc-data-download.html.
[4] Global Value Chain (GVC) trade is measured using Inter-Country Input-Output (ICIO) tables to decompose gross trade flows into their domestic and foreign value-added components. GVC-related trade specifically accounts for traded items that cross at least two international borders before being absorbed into final demand. It is calculated by subtracting the domestic value-added directly consumed by the importing country from total gross exports, which isolates both the "backward" linkages (imported inputs embedded in exports) and "forward" linkages (exported intermediates that are subsequently re-exported).
[5] Refer to Appendix A for details.
[6] Manufacture of electronic components and boards, manufacture of computers and peripheral equipment, manufacture of communication equipment, and manufacture of consumer electronics (C-26).
[7] Wired-, wireless-, satellite-, and other telecommunications activities (J-61).
[8] Data processing, hosting and related activities (J-63).

The direct digital index is calculated by:

$$a_{gj} = \frac{q_{gj}}{Y_g} \qquad (6)$$

Where a_{gj} is the proportion of the digital sector j's output that is directly consumed by sector g in the manufacturing industry for producing one unit of product g. Y_g is the total output value of sector g, and q_{gj} is the input value of sector g to sector j.

The total digital input index reflects the indirect economic and technological links between various sub-manufacturing sectors. The index for total digital input, b_{gj}, is calculated by:

$$b_{gj} = a_{gj} + \sum_{m=1}^{N} a_{gm}a_{mj} + \sum_{n=1}^{N}\sum_{m=1}^{N} a_{gn}a_{nm}a_{mj} + \cdots \qquad (7)$$

where a_{gj} refers to the direct consumption of digital output by sector g, as defined above. $\sum_{m=1}^{N} a_{gm}a_{mj}$ is the indirect digital sector j's output consumed by the manufacturing sector g via manufacturing sector m (e.g., machinery). $\sum_{n=1}^{N}\sum_{m=1}^{N} a_{gn}a_{nm}a_{mj}$ represents the additional indirect consumption of manufacturing sector g to digital sector j through manufacturing sectors m (e.g., machinery) and n (e.g., Rubber and Plastics) (and so on) until it covers indirect digital inputs in all relevant sub-manufacturing sectors.

Following the OECD taxonomy proposed by Calvino et al. (2018), we classify manufacturing sub-sectors into four groups—low, medium-low, medium-high, and high digital intensity (see Appendix 2 for the sector mapping). The taxonomy is based on a composite measure capturing ICT capital, the use of ICT intermediate inputs, ICT specialist intensity, and robot adoption. The taxonomy of sectors provides an operational tool for assessing whether digitalization affects trade differently across digital-intensive and less digital-intensive sub-manufacturing sectors. We use this classification to examine industry heterogeneity in the interaction analyses reported in Tables 9-10.

In the core regressions of equations (1)–(3), we use the total embodied digital intensity measure, and we assess robustness using the direct digital input measure.

2.3.6 RTAs and Other Controls

We include RTA membership and standard bilateral controls commonly used in structural gravity models. These variables are drawn from the Centre D'études Prospectives et D'informations Internationals

(CEPII)[9] Gravity Database, including bilateral distance, contiguity, and other dyadic characteristics. To capture the digital orientation of trade agreements, we use the Trade Agreement Provisions on Electronic Commerce and Data (TAPED) dataset[10] (Burri and Polanco, 2020), which codes the presence of digital trade–related provisions and dedicated digital trade chapters in preferential trade agreements. We construct a dummy variable DTA that equals one if the RTA governing a country pair contains at least one digital trade (e-commerce/data-related) provision as coded in TAPED, and zero otherwise.

Table 1 Variables and Data Sources

Variable	Abbreviation	Source
Value of bilateral GVC manufacturing exports	$X_{ijs,t}$	WITS
Distance between capital cities of trading partners	$Dist_{ij}$	CEPII
Common language (country i and country j)	$Comlang\_ethno_{ij}$	CEPII
Common border (country i and country j)	$Contig_{ij}$	CEPII
Common religion (country i and country j)	$Com\_religon_{ij}$	CEPII
Regional Trade Agreement	RTA_{ij}	CEPII
Digitalization variable (sector s in country i)	DI_{ij}	ADB MRIO
Regional Trade Agreement with Digital Provisions	DTA_{ij}	TAPED
Fixed-Line Telephone subscription	$Telephone_{ij,t}$	WDI

Source: Author's elaboration

2.3.7 Mechanism Analysis

Furthermore, we conduct two mechanism-oriented extensions while maintaining the same PPML estimator and fixed-effects structure as in the baseline. First, to examine whether the RTA-related heterogeneity depends on the digital orientation of agreements, we jointly estimate $RTA_{ij} * DI_{ij}$ and $DTA_{ij} * DI_{ij}$ (with DTA coded from TAPED). Second, to probe a spatial channel, we estimate specifications including $DI_{ij} * Dist_{ij}$ and, as a benchmark communication channel, $Telephone_{ij,t} * Dist_{ij}$.

[9] See Conte et al. (2022). Retrieved from CEPII - Gravity - Presentation.
[10] Retrieved from https://www.unilu.ch/en/faculties/faculty-of-law/professorships/burri-mira/research/taped/.

Telephone is measured as fixed-line telephone subscriptions per 100 people (World Bank Indicator[11]). Table 1 summarises definitions and data sources for all variables.

2.4 Empirical Results

2.4.1 Core Results

Column (1) of **Error! Reference source not found.** presents empirical results from the estimation of models estimated by equations (1) to (3). Column (2), column (3), and column (4) repeat the analysis in column (1) using alternative variables or methods to test the robustness of the results.

Table 2 Core Regression Results and Robustness Checks

	(1) GVC Trade	(2) GVC Trade	(3) GVC Trade	(4) GVC Trade
$\boldsymbol{DI_{ij}}$	0.721***		0.376***	
	(0.0376)		(0.016)	
$\boldsymbol{DI_{ij}2}$		0.417***		
		(0.026)		
$\boldsymbol{Adjusted\_DI_{ij}}$				0.424***
				(0.022)
Constant	8.724***	6.338***	-0.615***	5.962***
	(0.0865)	(0.094)	(0.001)	(0.017)
$\boldsymbol{N}$	672361	631844	604806	567930
pseudo $\boldsymbol{R^2}$	0.776	0.763		0.769
$\boldsymbol{R^2}$			0.775	
Exporter-Year FE	**Y**	**Y**	**Y**	**Y**
Importer-Year FE	**Y**	**Y**	**Y**	**Y**
Exporter-Importer FE	**Y**	**Y**	**Y**	**Y**

Notes: Estimation results reported by the PPML method. Results in column (3) is reported by the OLS method. ***, ** and * 1%, 5% and 10% levels of statistical significance respectively. The standard errors in parentheses are those clustered by country pairs.

The coefficient of the primary variable of interest, DI_{ij}, is positive and statistically significant at the 1% level. Specifically, the estimated elasticity of 0.721 indicates that, on average, a 1% increase in the average digitalization intensity of manufacturing sectors between exporting and importing countries leads to a 0.721% increase in bilateral manufacturing GVC exports. These results are obtained while controlling for exporter-year, importer-year, and symmetric country-pair fixed effects, which account for multilateral resistance terms and time-invariant bilateral trade costs. Columns (2)–(5) present alternative specifications, which are discussed in Section 2.3.

[11] Retrieved from https://data.worldbank.org/indicator/IT.MLT.MAIN.P2.

2.4.2 Robustness and Endogeneity Checks

2.4.2.1 Replacement Digitalization Index

To assess measurement robustness, we replace the baseline digitalization variable DI_{ij} with the direct digital intensity measure, $DI_{ij}2$, constructed in equation (6). As reported in Column (2) of **Error! Reference source not found.**, the estimated coefficient on digitalization remains positive and statistically significant, with a comparable magnitude to the baseline specification.

2.4.2.2 Regressions using the OLS estimator

As a benchmark, Column (3) of **Error! Reference source not found.** re-estimates the baseline gravity specification using OLS. The coefficient on digitalization remains positive and statistically significant, although the estimated magnitude is smaller than in the PPML specification.

2.4.2.3 Exclusion of Major Economies

To ensure that the baseline results are not driven by large economies, we re-estimate the model excluding China, the United States, Japan, and India. Column (4) of **Error! Reference source not found.** shows that the effect of digitalization remains positive and statistically significant; a 1% increase in digitalization is associated with a 0.424% increase in manufacturing GVC exports.

2.4.2.4 Endogeneity and IV Estimates

Table 3 reports 2SLS estimates that address potential endogeneity of digitalization using two instrument sets. Column (1) presents results based on the Bartik-style instruments constructed from baseline digital exposure interacted with global ICT goods and services export growth, while Column (2) uses the alternative instrument based on lagged leave-one-out regional sectoral digital intensity. Across both IV specifications, the second-stage coefficient on digitalization remains positive and statistically significant, consistent with the baseline estimates.

Table 3 Endogeneity Check

	(1) GVC Trade	(2) GVC Trade
DI_{ij}	108.475***	
	(35.765)	
$Regional\_DI_{ij}$		1.632***
		(0.453)
Constant	-1.736***	-1.688***
	(0.174)	(0.242)
N	131,438	342599
Exporter-Year FE	Y	Y
Importer-Year FE	Y	Y
Exporter-Importer FE	Y	Y
Kleibergen-Paap rk LM	55,210.04(P-value=0.000)	174.097(P-value=0.000)
Cragg-Donald Wald F	905.82	1540.698
Hansen J Statistic	0.263	2.5(P-value=0.114)

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Identification diagnostics support the IV specifications. The Kleibergen–Paap rk LM test rejects underidentification, and the Kleibergen–Paap rk Wald F statistic exceeds Stock–Yogo critical values, indicating no weak-instrument concerns. The Hansen J test does not reject the null of instrument exogeneity, suggesting that the overidentifying restrictions are valid. Overall, the IV results are consistent with the baseline findings.

2.4.3 Exploring Digitalization's Influence on GVC Trade Through Interactions with Distance and RTAs

Error! Reference source not found. reports estimate from specifications that introduce interaction terms between digitalization and (i) bilateral distance and (ii) RTA membership, as defined in equations (2) and (3).

In Column (1) of **Error! Reference source not found.**, the coefficient for bilateral distance is -0.352, suggesting that a 1% increase in distance between trading partners leads on an average, to a 0.352% decrease in bilateral manufacturing GVC exports, and the result is statistically significant at 1%. However, column (2) shows that the negative effect of distance is mitigated by digitalization, as evidenced by the positive and statistically significant coefficient for the interaction term ($DI_{ij}\&Dist_{ij}$), which is 0.059. Furthermore, the robustness of this result is confirmed by the results in Column (3), where the coefficient for $DI_{ij}\&Dist_{ij}$ remains stable even after accounting for country-pair fixed effects, addressing potential endogeneity caused by omitted variables.

es.

Table 4 Extended Core Analysis of Trade Effects of Digitalization: Interaction with Distance and RTAs

	(1) GVC Trade	(2) GVC Trade	(3) GVC Trade	(4) GVC Trade	(5) GVC Trade
$\boldsymbol{DI_{ij}}$		-0.00337	-0.102		0.515***
		(0.120)	(0.121)		(0.035)
$\boldsymbol{Dist_{ij}}$	-0.352***	-0.401***			
	(0.060)	(0.061)			
$\boldsymbol{DI_{ij}}$&$\boldsymbol{Dist_{ij}}$		0.059***	0.072***		
		(0.015)	(0.015)		
$\boldsymbol{Contig_{ij}}$	1.124***	1.120***			
	(0.141)	(0.142)			
$\boldsymbol{Comlang\_ethno_{ij}}$	0.502***	0.504***			
	(0.119)	(0.121)			
$\boldsymbol{Com\_religon_{ij}}$	-0.016	-0.024			
	(0.174)	(0.174)			
$\boldsymbol{RTA_{ij}}$				0.076***	0.163***
				(0.021)	(0.049)
$\boldsymbol{DI_{ij}}$ & $\boldsymbol{RTA_{ij}}$					-0.092*
					(0.047)
$\boldsymbol{Constant}$	9.933***	8.659***	6.281***	6.429***	6.163***
	(0.505)	(0.527)	(0.018)	(0.014)	(0.037)
N	658713	636876	611318	651489	631844
pseudo $\boldsymbol{R^2}$	0.646	0.695	0.777	0.728	0.776
Exporter-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**
Importer-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**
Exporter-Importer FE			**Y**	**Y**	**Y**

Notes: Estimation results reported by the PPML method. *** ,** and * 1%, 5% and 10% levels of statistical significance respectively. The standard errors in parentheses are those clustered by country pairs.

In column 4 the coefficient of RTAs is positive and statistically significant, consistent with the existing literature. Being a member of RTAs is observed to promote manufacturing GVC exports by around 8% [($e^{0.076}$-1) *100]. In column (5), the coefficient for the interaction term between digitalization and RTA ($\boldsymbol{DI_{ij}}$ & $\boldsymbol{RTA_{ij}}$) is found to be negative, although weakly statistically significant, at 10%. The results indicate that a 1% increase in digitalization reduces the trade-promoting effect of GVC trade by 0.092% for countries participating in RTAs, compared to non-member countries.

2.4.4 Mechanism Analysis

2.4.4.1 Digitalization, Distance, and Communication Costs

Table 5 reports PPML estimates that examine whether digitalization operates through a spatial (distance-related) channel in GVC trade. In Column (1), the interaction between distance and digitalization is positive and statistically significant ($Dist_{ij} * DI_{ij}$ = 0.093), while the level effect of digitalization is statistically insignificant.

Column (2) introduces a benchmark communication channel by interacting distance with telephone infrastructure. The telephone level variable is omitted due to collinearity with exporter-year and importer-year fixed effects. The distance–digitalization interaction remains positive and highly significant (0.092). In addition, the interaction between distance and telephone infrastructure is positive and statistically significant (0.079). Distance is negative and statistically significant in Column (2) (−1.447).

Table 5 Mechanism Analysis: The Role of Communication Infrastructure

Variables	(1) Distance x Digitalization	(2) Distance x Digitalization & Communication
$Dist_{ij}$	-0.132	-1.447***
	(0.086)	(0.534)
DI_{ij}	-0.016	-0.012
	(0.189)	(0.179)
$Dist_{ij} * DI_{ij}$	0.093***	0.092***
	(0.024)	(0.022)
$Dist_{ij} * Telephone_{ij,t}$		0.079**
		(0.034)
Constant	8.598***	8.449***
	(0.734)	(0.770)
Exporter-Year FE	Yes	Yes
Importer-Year FE	Yes	Yes
Pair FE	No	No
Observations	633,429	631,900
Clusters (pair)	3,600	3,600

Pseudo R2	0.695	0.697

Note: This table reports Poisson Pseudo-Maximum Likelihood (PPML) estimates examining distance-related mechanisms in GVC trade. The dependent variable is bilateral GVC trade flows. All specifications include exporter-year and importer-year fixed effects. Robust standard errors clustered at the country-pair level are reported in parentheses. The variable *telephone* is omitted due to collinearity with exporter-year and importer-year fixed effects. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

2.4.4.2 RTAs, Digital Trade Provisions, and Digitalization

Table 6 reports PPML estimates that distinguish between conventional RTA membership and RTAs with digital trade provisions (DTA). Across all specifications, the coefficient on digitalization is positive and statistically significant, ranging from 0.705 to 0.806 (all $p<0.01$).

In Column (1), the interaction term between digitalization and RTA membership ($RTA_{ij} * DI_{ij,t}$) is negative and weakly significant (−0.144). When both interaction terms are included jointly (Column 4), the estimate remains negative and becomes statistically significant (−0.146). By contrast, digital trade provisions are positively associated with GVC trade (DTA_{ij}= 0.454 in Column 3 and 0.494 in Column 4). Moreover, the interaction between digitalization and digital trade provisions ($DTA_{ij} * DI_{ij,t}$) is positive and statistically significant (0.187 in Column 3 and 0.200 in Column 4).

Table 6 Mechanism Analysis: RTAs, Digital Trade Provisions, and Digitalization

Variables	(1) Baseline RTA × DI	(2) RTA only	(3) DTA × DI	(4) RTA & DTA × DI
RTA_{ij}	−0.247	0.080***		−0.247
	(0.169)	(0.021)		(0.167)
Digitalization (DI)	0.806***		0.705***	0.803***
	(0.055)		(0.038)	(0.055)
$RTA_{ij} * DI_{ij}$	−0.144*			−0.146**
	(0.074)			(0.073)
DTA_{ij}			0.454***	0.494***
			(0.175)	(0.167)
$DTA_{ij} * DI_{ij,t}$			0.187**	0.200***
			(0.077)	(0.074)
Pair FE	Yes	Yes	Yes	Yes
Exporter-Year FE	Yes	Yes	Yes	Yes
Importer-Year FE	Yes	Yes	Yes	Yes
Observations	628,341	627,171	628,341	628,341
Pseudo R^2	0.777	0.727	0.777	0.777

Notes: Standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All models are estimated using the PPML method. DTA refers to Digital Trade Agreements or specific digital trade provisions within RTAs.

2.4.4.3 Country Heterogeneity

Examining the impact of digital intensity on trade flows further requires accounting for country and industry heterogeneity in our sample data. This requires considering any differential impacts that may result due to income levels of trading partners. Table 7 presents these results, which are categorized by four different types of trade flows: (1) exports from high-income countries to high-income countries (columns 1-2); (2) exports from high-income countries to low-income countries (columns 3-4); (3) exports from low-income countries to high-income countries (columns 5-6); and (4) exports from low-income countries to other low-income countries (columns 7-8). The classification of countries follows the World Bank's income classification system. Countries with a gross national income (GNI) per capita greater than $3,995 are categorized as high-income, while those with a GNI per capita of $3,995 or less are classified as low-income.

The coefficients of variable of interest (i.e., interaction between digitalization and distance) are positive in all groups, but its statistical significance varies. For high-income-to-high-income trade, the interaction term ($\boldsymbol{DI_{ij}}$&$\boldsymbol{Dist_{ij}}$) is positive and significant (0.069). The corresponding interaction is smaller and statistically insignificant for high-income to low-income flows (0.045). For low-income exporters, the interaction term remains positive and statistically significant both for exports to high-income destinations (0.093) and for low-income-to-low-income flows (0.077).

Table 7 Trade Effects of Digitalization: Interaction with Distance (Income Level)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	H to H GVC Trade	**H to H GVC Trade**	**H to L GVC Trade**	**H to L GVC Trade**	**L to H GVC Trade**	**L to H GVC Trade**	**L to L GVC Trade**	**L to L GVC Trade**
$\boldsymbol{DI_{ij}}$		-0.137		0.105		-0.205		-0.199
		(0.131)		(0.240)		(0.212)		(0.213)
$\boldsymbol{Dist_{ij}}$	-0.472***	-0.503***	-1.032***	-1.073***	-0.941***	-1.034***	-0.249**	-0.321***
	(0.091)	(0.090)	(0.044)	(0.051)	(0.057)	(0.069)	(0.082)	(0.084)
$\boldsymbol{DI_{ij}\&Dist_{ij}}$		0.069***		0.045		0.093**		0.077**
		(0.019)		(0.027)		(0.029)		(0.026)
$\boldsymbol{Constant}$	9.391***	9.572***	14.31***	14.42***	13.99***	14.46***	7.693***	7.989***
	(0.768)	(0.765)	(0.345)	(0.412)	(0.447)	(0.527)	(0.700)	(0.713)
$\boldsymbol{N}$	123298	121681	167717	162641	165788	160738	223988	160738
pseudo R^2	0.553	0.591	0.699	0.750	0.712	0.778	0.568	0.778
Exporter-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
Importer-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**

Notes: Estimation results reported by the PPML method. *** ,** and * 1%, 5% and 10% levels of statistical significance respectively. The standard errors in parentheses are those clustered by country pairs. H refers to high-income countries, and L stands for low-income countries.

Table 8 reports heterogeneous effects of digitalization and RTA membership on manufacturing GVC exports across income-pair trade flows (H to H, H to L, L to H, and L to L). Across all income groups, the coefficient on digitalization is positive and statistically significant, ranging from 0.377 to 0.555.

The estimated effect of RTA membership varies by income pair. RTA membership is positively associated with GVC exports for high-income-to-high-income flows (0.0938) and for low-income-to-low-income flows (0.251), while it is not statistically significant for high-income to low-income or low-income to high-income trade flows.

Turning to the interaction terms ($\boldsymbol{DI_{ij}}$ & $\boldsymbol{RTA_{ij}}$), coefficients are negative in all income-pair groups. However, it is statistically insignificant for H to H (−0.0833), H to L (−0.0884), and L to H (−0.0495) flows. In contrast, for low-income-to-low-income trade (Column 8), the interaction term is negative and statistically significant (−0.142). Overall, Table 8 indicates that the interaction between digitalization and RTAs is not statistically distinguishable from zero for most income-pair flows, with an exception for L-to-L trade where the interaction term is negative and significant.

Table 8 Trade Effects of Digitalization: Interaction with RTAs (Income Level)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	H to H GVC Trade	**H to H GVC Trade**	**H to L GVC Trade**	**H to L GVC Trade**	**L to H GVC Trade**	**L to H GVC Trade**	**L to L GVC Trade**	**L to L GVC Trade**
$\boldsymbol{DI_{ij}}$	0.377***	0.433***	0.454***	0.517***	0.535***	0.555***	0.473***	0.510***
	(0.026)	(0.0567)	(0.034)	(0.0453)	(0.0532)	(0.0813)	(0.0421)	(0.0562)
$\boldsymbol{RTA_{ij}}$		0.0938*		0.164		0.126		0.251*
		(0.0447)		(0.0893)		(0.120)		(0.114)
$\boldsymbol{DI_{ij}}$ & $\boldsymbol{RTA_{ij}}$		-0.0833		-0.0884		-0.0495		-0.142*
		(0.0583)		(0.0645)		(0.112)		(0.0712)
Constant	6.319***	6.253***	6.366***	6.233***	6.484***	6.438***	5.929***	5.734***
	(0.00944)	(0.0370)	(0.027)	(0.0616)	(0.0470)	(0.0853)	(0.045)	(0.0851)
N	116981	116981	164972	160272	158995	154295	212726	200296
pseudo R^2	0.777	0.777	0.779	0.781	0.802	0.803	0.744	0.740
Exporter-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
Importer-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
Exporter-Importer FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**

Notes: Estimation results reported by the PPML method. ***, ** and * 1%, 5% and 10% levels of statistical significance respectively. The standard errors in parentheses are those clustered by country pairs. H refers to high-income countries, and L stands for low-income countries.

2.4.4.4 Industry Heterogeneity

Table 9 reports estimate from specifications that interact digitalization with bilateral distance, separately for sub-manufacturing sectors grouped by digital intensity (high, medium-high, medium-low, and low). Across all sector groups, distance enters with a negative and statistically significant coefficient ($p<0.01$). The interaction term (**DI_{ij}&$Dist_{ij}$**) is positive in all groups, but statistical significance differs by sectoral digital intensity. The interaction term is positive and statistically significant for medium-high digital-intensity sectors (0.089), while it is statistically insignificant for high (0.0568), medium-low (0.0384), and low (0.0455) digital-intensity sectors.

Table 10 examines heterogeneity in the estimated effects of digitalization and RTA membership across sectoral digital-intensity groups. The coefficient on digitalization is positive and statistically significant for high (0.096, $p<0.10$; 0.359, $p<0.01$), medium-high (0.956 and 1.055, both $p<0.01$), and medium-low sectors (0.338, $p<0.01$; 0.207, $p<0.10$). For low digital-intensity sectors, the estimated coefficient on digitalization is small and statistically insignificant in Column (7) (−0.019), while it is negative and statistically significant in Column (8) (−0.158, $p<0.05$).

Turning to the interaction terms, the **DI_{ij} & RTA_{ij}** coefficient is negative and statistically significant for high digital-intensity sectors (−0.285, $p<0.10$) and medium-high sectors (−0.147), while it is positive and statistically significant for medium-low sectors (0.200). For low digital-intensity sectors, the interaction term is positive but statistically insignificant (0.181). RTA membership is positive and statistically significant for high and low digital-intensity sectors (Columns (1) and (8)), but statistically insignificant for medium-high and medium-low sectors.

Table 9 Digitalization & Distance (Sectoral Digital Intensity)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	H GVC Trade	**H GVC Trade**	**MH GVC Trade**	**MH GVC Trade**	**ML GVC Trade**	**ML GVC Trade**	**L GVC Trade**	**L GVC Trade**
$\boldsymbol{DI_{ij}}$		-0.342		0.258		0.0313		-0.356
		(0.673)		(0.195)		(0.269)		(0.314)
$\boldsymbol{Dist_{ij}}$	-0.450***	-0.476***	-0.429***	-0.552***	-0.543***	-0.559***	-0.561***	-0.582***
	(0.0836)	(0.104)	(0.0638)	(0.0730)	(0.0582)	(0.0604)	(0.0600)	(0.0588)
$\boldsymbol{DI_{ij}\&Dist_{ij}}$		0.0568		0.0890***		0.0384		0.0455
		(0.0878)		(0.0248)		(0.0340)		(0.0417)
$\boldsymbol{Constant}$	10.90***	11.04***	9.632***	9.784***	10.07***	10.10***	9.945***	10.09***
	(0.704)	(0.851)	(0.554)	(0.609)	(0.488)	(0.505)	(0.485)	(0.474)
N	48375	48498	243143	238446	340400	323007	48629	48629
pseudo R^2	0.836	0.829	0.644	0.800	0.608	0.609	0.789	0.777
Exporter-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
Importer-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**

Notes: Estimation results reported by the PPML method. ***, ** and * 1%, 5% and 10% levels of statistical significance respectively. The standard errors in parentheses are those clustered by country pairs. H, MH, ML, and L represent sectors with high, medium-high, medium-low, and low levels of digital intensity, respectively

Table 10 Digitalization & RTA (Sectoral Digital Intensity)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	H GVC Trade	**H GVC Trade**	**MH GVC Trade**	**MH GVC Trade**	**ML GVC Trade**	**ML GVC Trade**	**L GVC Trade**	**L GVC Trade**
$\boldsymbol{DI_{ij}}$	0.096*	0.359***	0.956***	1.055***	0.338***	0.207*	-0.019	-0.158*
	(0.046)	(0.099)	(0.035)	(0.050)	(0.054)	(0.082)	(0.025)	(0.078)
$\boldsymbol{RTA_{ij}}$		1.914***		0.174		0.0202		1.587***
		(0.168)		(0.113)		(0.060)		(0.109)
$\boldsymbol{DI_{ij}}$ & $\boldsymbol{RTA_{ij}}$		-0.285*		-0.147*		0.200*		0.181
		(0.133)		(0.0670)		(0.101)		(0.102)
$\boldsymbol{Constant}$	7.311***	6.165***	5.865***	5.743***	6.256***	6.239***	5.584***	4.642***
	(0.081)	(0.113)	(0.046)	(0.080)	(0.020)	(0.042)	(0.053)	(0.076)
$\boldsymbol{N}$	48498	48498	227773	227773	324566	309441	50228	48629
pseudo R^2	0.792	0.865	0.921	0.922	0.751	0.752	0.708	0.791
Exporter-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
Importer-Year FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
Exporter-Importer FE	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**

Notes: Estimation results reported by the PPML method. *** ,** and * 1%, 5% and 10% levels of statistical significance respectively. The standard errors in parentheses are those clustered by country pairs. H, MH, ML, and L represent sectors with high, medium-high, medium-low, and low levels of digital intensity, respectively.

2.5 Discussion

This study provides four core pieces of evidence on how digitalization shapes manufacturing GVC trade. First, digitalization is robustly associated with higher bilateral manufacturing GVC exports, and the IV estimates suggest that this relationship is unlikely to be driven primarily by reverse causality or omitted variables. Second, the interaction results support a clear trade-cost channel: digitalization significantly attenuates the inhibitory effect of distance on GVC trade. Third, the institutional environment matters in a conditional way. Conventional RTAs do not automatically amplify digital gains, whereas RTAs with explicit digital provisions interact positively with digitalization, indicating that agreement design is more consequential than membership per se. Fourth, the effects are heterogeneous: the distance-mitigating role of digitalization is stronger for low-income exporters, and the magnitude of the effect varies systematically with sectoral digital intensity, delineating the boundary conditions under which digitalization translates into GVC gains.

A consistent theme in our empirical results is that digitalization promotes GVC participation by reducing distance-related frictions. In fragmented production networks, geographic separation generates sizable coordination, search, monitoring, and contracting costs. These costs become especially salient when production stages span multiple borders and time zones. Our evidence is consistent with Keita (2016), who argues that greater ICT intensity lowers the sensitivity of trade costs to distance. It also accords with Herman and Oliver (2023), who highlight the role of internet bandwidth in expanding trade margins. Imbruno et al. (2025) show that digital connectivity lowers firms' entry thresholds into GVCs; we add that this channel operates in part through the systematic easing of geographic barriers. In our estimates, the Digital $\times$ Distance interaction term is attenuated, which is consistent with a "cost-substitution" mechanism whereby digital capabilities offset distance-related trade costs. This mechanism implies particularly large gains for developing economies and for firms located far from major markets.

Additional mechanism tests unpack the distance-mitigating channel and help identify the role of communication costs. We proxy traditional communication capacity using fixed-line telephone penetration and interact this measure with distance. The estimates show a clear pattern: after including the $Dist_{ij} * Telephone_{ij,t}$ interaction, the $Dist_{ij} * DI_{ij}$ coefficient remains positive and statistically significant, but its magnitude declines. This attenuation indicates that part of digitalization's distance-ameliorating effect operates through lower communication-related trade costs. Consistent with Bellucci et al. (2025), the results are in line with the notion of "virtual proximity," whereby digital connectivity partly substitutes for physical interaction. This mechanism is particularly relevant for GVC trade, where coordinating and synchronizing fragmented production stages across borders requires real-time information exchange and high contractual precision—requirements that are typically less stringent in trade in final goods.

However, the results also indicate that digitalization does more than substitute for voice communication. The remaining effect of digitalization is consistent with a broader reduction in informational and transactional frictions, including real-time inventory management, platform-based partner matching, reputation-based verification, and the cross-border delivery of digitally deliverable services. These functions are central to the tight coordination required in modern GVCs but are not fully provided by traditional telecommunications infrastructure. Overall, the evidence suggests that digital technologies facilitate deeper organizational integration across global networks by aligning firms' informational capabilities with the demands of modular production.

Turning to the institutional dimension, this research finds a negative interaction between digitalization and conventional RTAs in manufacturing GVC trade. This pattern implies that RTA membership does not necessarily amplify—and may even weaken—the trade-enhancing effect of digitalization. We interpret this result as evidence of an institutional–technological mismatch. Digitalization can streamline coordination and reduce information frictions, but many traditional RTAs are still primarily designed around trade in physical goods. In practice, reliance on paper-based procedures and complex rules of origin can raise administrative and compliance costs, thereby offsetting part of the efficiency gains from digital transformation (Wu, 2017; Tingvall et al., 2024). Moreover, regulatory heterogeneity and limited alignment of domestic policy objectives across members can slow or dilute the implementation of trade-facilitation commitments even after ratification (Du et al., 2023). Finally, when agreements lack clear disciplines on cross-border data flows, behind-the-border measures—such as data-localization requirements—can fragment the regulatory environment and limit firms' ability to scale digitally enabled value-chain transactions (Panchenko et al., 2020; Duval & Mengjing, 2017).

To distinguish whether the dampening effect reflects RTA membership per se or the design of specific disciplines, this study extends the baseline specification by interacting digitalization with RTAs that contain explicit digital trade provisions. The estimates show a clear pattern: digitalization interacts negatively with conventional RTAs but positively with digitally deep RTAs. Moreover, after accounting for this complementarity, the negative digitalization–conventional RTA interaction becomes larger in magnitude. This contrast suggests that targeted digital rules—rather than preferential market access alone—are central to translating digitalization into GVC trade gains.

These findings suggest that digital trade rules help convert technological capabilities into GVC gains by increasing legal certainty and limiting digital protectionism. Following López González and Ferencz (2018), we argue that digital chapters can strengthen the effects of trade agreements, but the magnitude of this complementarity depends on the depth and enforceability of the provisions. Digitally deep RTAs enhance institutional predictability and reduce regulatory risk, which can otherwise deter firms from investing in digital-intensive value-chain activities (Wu, 2017). In addition, as governments increasingly introduce restrictive digital measures under privacy or security rationales, provisions that improve transparency and discipline discriminatory practices can lower policy-induced frictions and facilitate cross-border digital transactions. This can support a more efficient allocation of digital inputs across production nodes (Panchenko et al., 2020). Overall, the evidence indicates that the GVC benefits of digitalization are institutionally contingent; realizing digital dividends requires policy frameworks to evolve in step with technological investment.

The empirical findings indicate that digitalization plays a heterogeneous role in manufacturing GVCs. Splitting the sample by partners' income levels, we show that digitalization not only mitigates distance-related trade frictions but may also generate institutional frictions in certain development contexts.

At the country level, the distance-ameliorating effect of digitalization is substantially stronger for low-income exporters. This pattern is consistent with higher marginal returns to digital adoption and with "technological leapfrogging." In low-income countries (LICs), where opaque information environments and weak physical infrastructure have historically raised entry barriers to GVCs, digital tools can help narrow informational gaps and reduce reliance on costly intermediaries. Herman and Oliver (2023) similarly argue that digital platforms enable firms in LICs to connect more directly with lead firms in advanced economies. The larger effects for LIC-to-HIC exports suggest that the scope for trade-cost savings is greatest when digitalization links partners with highly unequal technological capabilities. By contrast, the smaller incremental effects in high-income country (HIC) pairs are consistent with diminishing marginal returns: when digital infrastructure is already widespread, additional digitalization yields smaller trade gains (Yin & Choi, 2024).

Furthermore, the insignificant effects for exports from high-income to low-income countries point to a "digital bottleneck." Although exporters in advanced economies may have strong digital capabilities, these advantages may not translate into higher trade volumes when the importing partner lacks complementary inputs, such as reliable electricity, basic digital skills, and efficient last-mile logistics (Ismail, 2020). This interpretation is consistent with Bellucci et al. (2025), who emphasize that digital dividends depend on bilateral complementarities and the partner country's absorptive capacity.

The study also finds a significantly negative interaction between digitalization and RTA membership within the LIC subsample. This pattern is consistent with a crowding-out mechanism in which overlapping technological requirements and institutional procedures raise overall trade frictions rather than reducing them. We consider two plausible drivers: (i) a compliance trap and (ii) value-chain capture. First, when complex (digital) rules of origin are layered onto legacy paper-based processes, administrative duplication can arise and compliance costs may erode part of the efficiency gains from digitalization (APEC, 2022; Tingvall et al., 2024). Taken together, these institutional frictions and distributional asymmetries suggest that, for Global South members, regional cooperation accompanied by uneven implementation capacity may inadvertently create new barriers to GVC upgrading.

At the industry level, we find that both the direct effect of digitalization and its distance-ameliorating role vary systematically with sectoral digital intensity. This heterogeneity implies that digitalization does not uniformly eliminate the relevance of geography; instead, its ability to weaken the distance penalty in manufacturing GVC trade depends on industry characteristics. Digital technologies can exert opposing forces on the spatial organization of GVCs. On the one hand, they reduce the cost of coordinating tasks across dispersed locations, strengthening centrifugal incentives. On the other hand, they can increase the value of proximity to large consumer markets or innovation hubs by enabling real-time data use and knowledge spillovers, thereby reinforcing centripetal incentives. The observed net effect on the distance–trade relationship therefore reflects the balance between these countervailing forces (WTO, 2018).

This heterogeneity is consistent with early empirical scepticism that the internet does not uniformly weaken the role of distance. In line with Bellucci et al. (2025), we argue that the realization of digital dividends depends on sector-specific technological characteristics and the regulatory environment. In particular, the stronger distance-mitigating effect in medium-high-digital-intensity sectors is consistent with the OECD's (2023) "double dividend" argument. In manufacturing GVCs, digitalization therefore should not be viewed as a universal distance-reducing force; rather, it operates as a targeted enabler whose effects depend on technical alignment and threshold conditions. By showing that the distance channel varies with sectoral digital intensity, our results provide an industry-level explanation that can help reconcile the persistence of the "distance paradox" in global trade.

The sectoral heterogeneity analysis also points to an asymmetric interaction between digitalization and RTA membership. In high-digital-intensity sectors, digitalization is associated with stronger GVC trade, yet the digitalization–RTA interaction is negative, indicating a substitutive relationship. In these industries, the gains from digitalization plausibly arise from lower coordination costs and improved supply-chain visibility within regional production networks (Nayyar, 2022). At the same time, this pattern is consistent with a regulatory mismatch in which traditional trade rules lag behind technology. Fragmented digital regulation—including data-localization requirements and inconsistent standards—can raise compliance costs and uncertainty, thereby offsetting some of the technology-driven gains in data-intensive sectors (Wu, 2017; Panchenko et al., 2020).

By contrast, medium-low-digital-intensity sectors show stronger complementarities between digitalization and RTA membership. In these industries, RTAs appear to reinforce firms' catch-up gains from digital adoption by reducing non-tariff barriers, supporting paperless trade, and streamlining administrative procedures (López González & Ferencz, 2018; Kunkel et al., 2024). Under such conditions, incremental digital upgrading is more likely to translate into higher GVC participation because preferential agreements can improve institutional stability and transparency.

Overall, these results indicate that the effectiveness of the digitalization–institution nexus is not uniform but depends on sectoral regulatory sensitivity and technological maturity. Traditional RTAs may still facilitate GVC integration in transitioning industries, yet they appear less suited to governing frontier, data-intensive manufacturing activities. This contrast points to the need for trade rules that are better aligned with digital production and cross-border data-dependent transactions.

The findings imply that policies to foster GVC trade should go beyond technology investment alone and instead support a coordinated digital ecosystem. First, easing "digital bottlenecks"—especially in low-income economies—requires investment in complementary inputs, including reliable electricity and last-mile logistics, alongside high-speed connectivity. Without these complements, the marginal gains from digitalization are likely to remain limited. Second, to address the institutional–technological mismatch, trade rules need to evolve toward frameworks that incorporate operational digital provisions in RTAs, thereby reducing regulatory frictions and increasing legal certainty for data-intensive activities. Third, regional cooperation should remain inclusive by providing technical assistance that lowers compliance burdens for low-income members and reduces the risk of value-chain capture by technologically dominant hubs. Finally, governments should align policy instruments with sectoral digital intensity: for high-intensity industries, priorities include behind-the-border regulatory coherence and interoperability; for sectors still in digital transition, conventional trade facilitation and administrative simplification may yield larger gains. Overall, aligning technological upgrading with institutional reform can help countries leverage digitalization for sustainable competitiveness in global production networks.

2.6 Conclusion

This paper examined the impact of digitalization on bilateral manufacturing GVC trade using data from 2007 to 2019. Unlike previous studies, this paper 1) examines the effects of digitalization both in the presence and absence of RTAs and distance; 2) measures digitalization through sectoral digital intensity; 3) differentiates manufacturing sectors by their digital intensity and trading partners by their income levels, and 4) focuses specifically on bilateral manufacturing GVC trade. The structural PPML estimation is employed to account for multilateral resistance and mitigate heteroskedasticity in trade flows, and we further supplement our analysis by checking for endogeneity using an IV estimation approach.

The results confirm that digitalization significantly enhances aggregated bilateral manufacturing GVC exports. Furthermore, digitalization mitigates the adverse effects of geographical distance and existing RTAs fail to fully leverage digitalization, indicating that the current design of RTAs may need improvement to better accommodate digital trade. The study also reveals that the joint effects of RTAs and digitalization are more sensitive to a sector's digital intensity than to the income levels of trading partners, indicating that sectoral digital intensity is a more reliable indicator for capturing the variability in the interactive impact on trade.

These findings have critical implications for economic policy. Digitalization plays a pivotal role in enabling countries, particularly low-income nations, to participate in manufacturing GVCs and to narrow the gap with high-income countries. Comparing the effects of digitalization on GVC trade with and without RTAs suggests that countries should aim to harmonize digital trade rules within RTAs, ensuring that the rapid adoption of digital technologies is not undermined by existing agreements. As digital technologies evolve faster than the regulatory frameworks that govern them, interoperable standards and mutual recognition mechanisms are needed to address inconsistencies in digital trade regulations (Du et al., 2023).

Moreover, the impact of digitalization varies across industries based on their digital intensity. Policies should focus on enhancing digitalization in medium-low and medium-high digitally intensive manufacturing sectors to boost GVC trade. The development of digitalization should be tailored to reflect the digital intensity of specific sectors to maximize the benefits of digital integration.

This analysis, however, is subject to certain limitations that could guide future research. First, the measurement of digitalization remains a challenge, as there is no universally agreed-upon definition, and the concept continues to evolve. Future studies could incorporate broader dimensions of digitalization, such as artificial intelligence (AI) and blockchain technologies. Second, the current study employs an aggregated RTAs dummy variable. As digital trade-only agreements and specific digital trade chapters within RTAs play an increasingly important role, future research could explore the interaction between digitalization, digital trade-only agreements, and digital trade provisions in RTAs.

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Appendix A

1	AUS	Australia
2	AUT	Austria
3	BAN	Bangladesh
4	BEL	Belgium

5	BGR	Bulgaria
6	BHU	Bhutan
7	BRA	Brazil
8	BRU	Brunei Darussalam
9	CAM	Cambodia
10	CAN	Canada
11	CYP	Cyprus
12	CZE	Czech Republic
13	DEN	Denmark
14	EST	Estonia
15	FIJ	Fiji
16	FIN	Finland
17	FRA	France
18	GER	Germany
19	GRC	Greece
20	HKG	Hong Kong, China
21	HRV	Croatia
22	HUN	Hungary
23	IND	India
24	INO	Indonesia
25	IRE	Ireland
26	ITA	Italy
27	JPN	Japan
28	KAZ	Kazakhstan
29	KGZ	Kyrgyz Republic
30	KOR	Republic of Korea
31	LAO	Lao People's Democratic Republic
32	LTU	Lithuania
33	LUX	Luxembourg
34	LVA	Latvia
35	MAL	Malaysia
36	MEX	Mexico
37	MLD	Maldives
38	MLT	Malta

39	MON	Mongolia
40	NEP	Nepal
41	NET	Netherlands
42	NOR	Norway
43	PAK	Pakistan
44	PHI	Philippines
45	POL	Poland
46	POR	Portugal
47	PRC	People's Republic of China
48	ROM	Romania
49	RUS	Russia
50	SIN	Singapore
51	SPA	Spain
52	SRI	Sri Lanka
53	SVK	Slovak Republic
54	SVN	Slovenia
55	SWE	Sweden
56	SWI	Switzerland
57	THA	Thailand
58	TUR	Turkey
59	TAP	Taipei,China
60	UKG	United Kingdom
61	USA	United States
62	VIE	Viet Nam

Source: Author's elaboration

Appendix B

Classification of digital-intensive sectors	
Sector Name (Manufacturing Industries)	Digital Intensity
3-Food, beverages, and tobacco	Low
4-Textiles and textile products	Medium-Low
5-Leather, leather products, and footwear	Low
6-Wood and products of wood and cork	Medium High
7-Pulp, paper, paper products, printing, and publishing	Medium High
8-Coke, refined petroleum, and nuclear fuel	Medium-Low
9-Chemicals and chemical products	Medium-Low
10-Rubber and plastics	Medium-Low
11-Other nonmetallic minerals	Medium-Low
12-Basic metals and fabricated metal	Medium-Low
13-Machinery, nec	Medium High
14-Electrical and optical equipment	Medium High
15-Transport equipment	High
16-Manufacturing, nec; recycling	Medium High

Source: Author's elaboration

Appendix C

Country Name	Country Abbreviation	Geographic Region
China	CHN	East Asia
Hong Kong	HKG	East Asia
Japan	JPN	East Asia
South Korea	KOR	East Asia
Mongolia	MNG	East Asia
Taiwan	TWN	East Asia
Brunei Darussalam	BRU	Southeast Asia
Cambodia	CAM	Southeast Asia
Indonesia	INO	Southeast Asia
Lao People's Democratic Republic	LAO	Southeast Asia
Malaysia	MAL	Southeast Asia
Myanmar	MYA	Southeast Asia
Philippines	PHI	Southeast Asia
Singapore	SIN	Southeast Asia
Thailand	THA	Southeast Asia
Viet Nam	VIE	Southeast Asia
Bangladesh	BAN	South Asia
Bhutan	BHU	South Asia
India	IND	South Asia
Maldives	MLD	South Asia
Nepal	NEP	South Asia
Sri Lanka	SRI	South Asia
Pakistan	PAK	South Asia
Kazakhstan	KAZ	Central Asia
Kyrgyzstan	KGZ	Central Asia
Tajikistan	TAJ	Central Asia
Turkmenistan	TKM	Central Asia
Uzbekistan	UZB	Central Asia
Australia	AUS	Pacific
Fiji	FIJ	Pacific
New Zealand	NZL	Pacific
Papua New Guinea	PNG	Pacific

Canada	CAN	North America
United States	USA	North America
Argentina	ARG	Latin America
Brazil	BRA	Latin America
Chile	CHI	Latin America
Colombia	COL	Latin America
Mexico	MEX	Latin America
Peru	PER	Latin America
Austria	AUT	Europe
Belgium	BEL	Europe
Bulgaria	BUL	Europe
Croatia	CRO	Europe
Czech Republic	CZE	Europe
Denmark	DEN	Europe
Finland	FIN	Europe
France	FRA	Europe
Germany	GER	Europe
Hungary	HUN	Europe
Italy	ITA	Europe
Netherlands	NLD	Europe
Norway	NOR	Europe
Poland	POL	Europe
Portugal	POR	Europe
Romania	ROM	Europe
Russia	RUS	Europe
Slovakia	SVK	Europe
Slovenia	SVN	Europe
Spain	SPA	Europe
Sweden	SWE	Europe
United Kingdom	UKG	Europe

Source: Author’s elaboration

Appendix D

Panel A: Baseline Estimate	
Coefficient on DI	0.7212
Panel B: Placebo Distribution (300 permutations)	
Mean	-0.0001
Standard deviation	0.0130
1st percentile	-0.0291
5th percentile	-0.0209
95th percentile	0.0226
99th percentile	0.0315
Number of permutations	300
Panel C: Randomization-Inference Test	
Two-sided RI p-value	0.0033

Notes: The placebo distribution is obtained from 300 within-year permutations of the digitalization index. In each draw, the baseline PPML-HDFE specification with pair fixed effects and exporter-year and importer-year fixed effects is re-estimated, clustering standard errors at the country-pair level. The randomization-inference p-value is computed as (k+1)/(R+1), where k is the number of placebo draws satisfying $|\beta\_placebo| \geq |\beta\_true|$ and R is the total number of permutations.

This study conducts a randomization-inference (placebo) test to verify that the baseline result is not mechanically induced by the high-dimensional fixed-effects structure. Specifically, within each year we randomly reshuffle the digitalization index across observations while keeping the sample and baseline specification unchanged. Repeating this procedure 300 times yields a placebo distribution tightly centered around zero (mean = −0.0001; s.d. = 0.0130). The baseline estimate (β = 0.721) lies far outside the support of the placebo distribution, and the two-sided randomization-inference p-value equals 0.0033. This evidence indicates that the estimated effect is not driven by spurious correlation or common trends but by the non-random alignment between digitalization and bilateral GVC trade.

Prelude to The Impact of Digitalization on Global Manufacturing Value Chains: Evidence from a Global-Economy Wide Model

The second paper in this thesis extends the first by shifting the focus from trade flows to the structural transformation of global manufacturing value chains (GVCs) under digitalization. While the first paper examined how digital technologies influence bilateral GVC trade, this study estimates how digitalization reshapes GVC participation across regions.

To conduct this analysis, I utilized the computable general equilibrium (CGE) model, multi-regional input-output framework, and GVC accounting methodology to quantify the effects of digitalization on regional GVC participation rates. This is a novel empirical approach to analyzing the effects of digital technologies on GVC participation. While the analysis provides economy-wide impacts, the focus is on how digital transformation affects both forward and backward GVC participation, with a particular emphasis on simple and complex GVC participation.

This work is motivated by the growing interest in how Industry 4.0 technologies are altering production structures. While existing literature often highlights the benefits of digitalization for trade facilitation, less is known about how it restructures value-added flows and regional competitiveness in manufacturing. Employing a global CGE model, enables a comprehensive assessment of these structural shifts under the digitalization scenarios.

The results provide new evidence that digitalization intensifies backward GVC linkages—especially in simpler forms of participation—and contributes to a regional reorganization of manufacturing networks. These results have important implications for economies aiming to integrate into GVCs under the evolving digital landscape.

Chapter 3 The Impact of Digitalization on Global Manufacturing Value Chains: Evidence from a Global-Economy Wide Model

Abstract

The impacts of Industry 4.0 on manufacturing GVC remains as an open question. To this end, this paper attempts to investigate the questions through empirical research on the interplay between Industry 4.0 and manufacturing GVCs, focusing on how different regions with varying levels of technological advancement, integrate digitalization into their manufacturing sectors. By utilizing a global economy-wide model and integrating it with a multi-regional input-output (MRIO) framework for the first time in the empirical literature, the study provides new empirical evidence on the economic impacts and sector-specific changes in GVC participation due to Industry 4.0. Specifically, the paper constructs MRIO data before and after the incorporation of digitalization, to estimate the corresponding GVC indices. Comparing changes in GVC development caused by digitalization, this study observes whether digitalization promotes or impedes countries' involvement in manufacturing GVCs. The results reveal that digitalization improves regions' welfare, increases GDP, and boosts international trade, and enhances share of foreign content in countries' exports, facilitating greater integration in GVCs. However, its effects on countries' exports for re-exports are more nuanced. The results also suggest that intermediate goods imported for domestic final goods production with only one cross-border transaction benefit from greater efficiency, while those involved in at least two cross-border transactions face challenges. Overall, the empirical evidence points to the fact that digitalization is reshaping the structure of GVCs, promoting regionalization, and altering the dynamics of global production. The results provide insights into the future of manufacturing GVCs, particularly in the context of uneven digital technological adoption across regions.

Additional Information

This paper has been presented at *28th Annual Conference on Global Economic Analysis (GTAP)* held on 27 June 2025 in Kigali, Rwanda.

3.1 Introduction

The growth of global value chains (GVCs) has significantly shaped international trade over recent decades. GVCs have altered the foundation of international trade by fragmenting production activities across countries based on comparative advantages (Baldwin, 2018). The allocation of labor across countries has progressively transitioned from inter-industry and intra-industry specialization to division within products and 'task' specialization. Products are increasingly “made in the world”. After the explosive growth during the early 2000s, GVCs have gradually become the backbone of the global economy. The large flows of goods, services, capital and technology moving across borders within GVCs have resulted in a growing interconnectedness between countries (WTO, 2018).

Since the 1980s, GVCs have expanded in length and complexity. Production processes for a growing range of goods, including traditional products like textiles and more technology-intensive items like electronics, as well as services, are increasingly distributed across multiple locations worldwide. This has led to a rise in trade and transportation flows over time. Organizing production within long and intricate GVCs allows firms to capitalize on the most advantageous location-specific factors for different production stages, resulting in benefits such as increased productivity, efficiency, and economies of scale (OECD, 2017).

To accurately discern a nation's contribution to international trade division, Hummels et al. (2001) pioneered the concept of vertical specialization [(VS (vertical specialization), i.e., a country’s share of imports included in its exports or the share of exports produced by a country that is used as intermediates for exports by other countries (VS1)] and devised the Hummels, Ishii and Yi (HIY) model to quantify a country or region's participation in GVCs. HIY classified GVC involvement as either ‘forward participation’ or ‘backward participation’. Forward participation in GVC refers to the domestic value added by a country-sector that is exported and used by other countries, particularly as intermediate inputs that contribute to foreign goods for domestic consumption. Industries with high forward participation typically focus on activities like research and product design. Backward participation in GVC occurs when foreign value added is included in intermediate inputs. In this case, foreign suppliers contribute to the domestic production process. Industries with high backward participation generally engage in low value-added activities, such as processing and assembly.

Nevertheless, the seminal model of HIY overlooked instances where importing nations could employ a country's exports for subsequent processing rather than immediate final consumption, thereby biasing the evaluation for developing countries primarily engaged in intermediate processing trade. In response, Koopman et al. (2012) introduced the Koopman, Wang, and Wei (KWW) method. This novel export decomposition technique categorizes a nation's total GVC exports into four distinct value-added components, and those components could be further subdivided into nine parts according to the final destination of exports (Koopman et al., 2012). The framework precisely delineates the relationship between components of officially reported trade statistics (measured in gross terms) and GDP (in net terms).

Further, Wang, Wei, Yu, and Zhu (2017) (hence force WWYZ) track GDP component absorption through forward linkages and the origins of value-added in final goods production via backward linkages, allowing precise identification and measurement of GVC activities. Both forward and backward GVC participation can be decomposed into simple and complex activities. Simple value chains refer to intermediate goods that are used by the direct importing country to produce final goods for domestic consumption, involving only a single cross-border transaction. Complex value-added activities cross the border at least twice, and thus involve more production links and higher GVC positions than simple activities (Wang et al., 2017).

Technological advancements have historically been pivotal in influencing the organization of production, both domestically and internationally. Baldwin (2016) highlights how the emergence of specific technologies has transformed global production processes, leading to distinct waves of unbundling: the steam revolution facilitated the first unbundling, separating production from consumption, while information and communication technologies (ICTs), drove the second unbundling by enabling the fragmentation of production activities.

Moreover, some experts claim that globalization will continue to accelerate due to the development of digital technologies (Hofmann & Rusch, 2017; Lee et al., 2014). An example of this trend is the Fourth Industrial Revolution, also known as Smart Manufacturing or Industry 4.0 (Kagermann et al., 2013). Scholars tend to categorize Industry 4.0 technologies into groups according to their impacts and use. For example, advanced robotics and augmented reality are adopted to improve working-related activities (Frank et al., 2019). Additive manufacturing and flexible machinery can support digital manufacturing, improving firms' flexibility and allow for customization (Weller et al., 2015; Ardanza et al., 2019). Technologies such as cloud services, internet of things (IoT), big data analytics are directly linked to the concept of 'smart factory' (Strozzi et al., 2017). The most significant feature of Industry 4.0 is that machines and components exchange information independently, trigger actions, and control each other (UNCTAD, 2017; Brennan et al., 2015; OECD, 2017).

Although the concept of Industry 4.0 lacks a commonly agreed definition, it is recognized that it has resulted in a high level of automation in manufacturing (Stock & Seliger, 2016; Alexopoulos et al., 2016), and represents the development of the direction of the manufacturing industry (Xu et al., 2018). In manufacturing, Industry 4.0 concerns the integration and adaption of digital technologies, such as ICTs (Ghobakhloo & Fathi, 2019). Given that ICTs are the key elements of Industry 4.0, studies tend to use ICTs to capture the development of Industry 4.0 (Schwab, 2016; Nagy et al., 2018; Atik & Ünlü, 2019).

Significantly, digitalization in manufacturing industries could be a "double-edged" sword for developing manufacturing GVCs (Dollar, 2019). On the one hand, Industry 4.0, the automation of manufacturing processes reduces the reliance on low-cost labour, a key advantage for these economies, leading to the reshoring of production to developed countries and the loss of manufacturing jobs in labour-intensive sectors. Thus, the "reshoring effect"[12] could potentially shorten the GVCs and shrink the GVC trade. On the

[12] Digital technologies are reducing the worldwide work force. Nations with low wages lose their competitive advantage. In industrialized countries, production is moving closer to sales markets.

other hand, Industry 4.0 can boost the development of GVCs by increasing efficiency and knowledge spill over effects, which motivates firms to expand their geographic scope and reduces coordination costs along the value chain (Chen & Kamal, 2016; Antràs,2020). As a result, Industry 4.0 can affect the distribution of value-added and the division of production within GVCs (Wu et al., 2021; Li & Yang, 2021). The impacts of Industry 4.0 on manufacturing GVC remains as an open question.

To this end, this paper investigates the questions through empirical research on the interplay between Industry 4.0 and manufacturing GVCs. This work contributes to the existing literature in following ways. First, it examines the sectoral and economy-wide impacts of Industry 4.0 (as captured by digitalization-induced productivity shocks). Second, considering the varying levels of economic development among countries, the degree of Industry 4.0 implementation is expected to differ, this research studies whether its effects on manufacturing GVCs vary accordingly. Particularly, this paper investigates the potential of Industry 4.0 to drive manufacturing upgrades within GVCs. Third, different manufacturing industries demonstrate distinct levels of digital intensity, which may affect their sensitivity to digitalization and consequently influence the overall impact of Industry 4.0 on manufacturing GVCs. To address this, the paper analyses the effects by categorizing manufacturing sectors according to their digital intensity. Fourth, the research classifies manufacturing GVC participation based on methods of involvement and complexity, distinguishing between forward and backward participation as well as simple and complex GVC participation. In light of the heterogeneous levels of digital development among countries and the varying digital intensity across manufacturing sectors, this study seeks to explore the effects of Industry 4.0 on different types of manufacturing GVCs.

This analysis is investigated using an economy-wide model, which provides insights into the overall economy, specific industries, and facilitates "what-if" analyses. The economy-wide model links sectors and industries involved in economic change, depicting the actual landscape of manufacturing GVC across countries.

Several studies have used the Global Trade Analysis Project (GTAP) database for multi-regional input-output (MRIO) analysis. For example, Peters & Hertwich (2008) utilizes GTAP database to establish MRIO for calculating embodied carbon dioxide in international trade for examining implications of emission on global climate policy. Davis & Caldeira (2010) employs data from the GTAP Database to conduct a MRIO analysis on CO2 emissions based on consumption across global nations in 2004. Antimiani et al. (2018) extend the GTAP model by incorporating a value-added trade accounting framework, enabling value chain analysis in counterfactual simulations to measure value-added content in total trade flows. These studies demonstrate the GTAP models' potential to analyze the complex dynamics of GVCs. Thus, this research develops an economy-wide model built on MRIO tables to estimate the impacts of digitalization on manufacturing GVCs.

Augmenting existing methodologies, this work utilizes the economy-wide model and GVC accounting approach to estimate impacts of digitalization on manufacturing GVCs across regions. Specifically, this research employs the GTAP model to conduct counterfactual analyses, simulating the effects of digitalization on manufacturing industries. In the simulation, productivity shocks induced by digitalization are positively correlated with sectoral digital intensity. Additionally, based on the GTAP database and existing methodology [i.e., Peters et al. (2011) & Wang et al. (2017)], this research constructs MRIO tables before and after the digitalization shock to estimate the corresponding GVC indices. Comparing changes in GVC development caused by digitalization, this paper can observe whether digitalization promotes or impedes countries' involvement in manufacturing GVCs.

The analysis reveals several noteworthy results. First, digitalization boosts GDP, welfare, and international trade by increasing exports and reducing imports across regions. However, China is an exception, showing an increase in imports alongside a decline in exports. Second, digitalization in the manufacturing sector primarily enhances backward GVC participation while reducing forward GVC involvement across regions. Third, digitalization enhances simple GVC participation but constrains complex GVC participation. Results suggest that while impacts of digitalization vary across industries due to differences in sectoral digital intensity, the digital intensity alone is not the only determining factor. Each regions' role within GVCs also significantly influences how digitalization affects its manufacturing GVC participation. Despite variations in each region's role within GVCs, digitalization has generally facilitated the upgrading of manufacturing value chains across regions. There is also evidence that digitalization tends to shorten manufacturing value chains and promote the development of regional value chains.

The rest of the paper proceeds as follows: Section 5.2 undertakes the literature review, Section 5.3 details the used methodology, Section 5.4 presents results. Concluding remarks are offered in Section 5.5.

3.2 Literature Review

The links between Industry 4.0 and GVCs are multi-faceted and complex. Lichtblau et al. (2015) find that the goal of Industry 4.0 is to enable the manufacturing process to achieve high flexibility and high efficiency, allowing firms to manufacture individualized products in the economic condition of mass production. Strange & Zucchella (2017) express that the wide adoption of Industry 4.0 technologies can affect the spatial distribution of GVCs. Additionally, digital technologies, as upstream inputs, spread their effects through trade, with GVCs enhancing their role. Digitalization embedded in GVCs has reshaped the distribution of value-added (i.e., domestic value added in exports). This transformation alters the location of value chains and the production chains through GVCs (Gao et al., 2023).

However, Industry 4.0 could simultaneously be a driver and a barrier to GVCs. On the one hand, historical experience shows that new technologies favor the fragmentation of production across regions, and Industry 4.0 is no exception (Qin et al., 2024). Strange & Zucchella (2017) argue that Industry 4.0 (e.g., ICTs, an elementary part of Industry 4.0) increases GVC involvement by reducing trade costs and increasing efficiency. Firms improve production and logistical efficiency by using digital technologies to minimize transportation and inventory costs (World Bank, 2020). Accordingly, Backer & Flaig (2017) find that international fragmentation reduces transportation and coordination costs more than specialization and economies of scale.

Further, Opazo-Basáez et al. (2022) indicate that Industry 4.0 reduces GVC production phase geographical restrictions, delays, and uncertainties. Firms can 'fine slice' value-adding activities and arrange them to the optimal location (Buckley, 2011). Therefore, Industry 4.0 promotes GVCs.

On the other hand, Industry 4.0 could "make the international fragmentation of production less attractive" and is "the biggest game-changer, reversing the importance and length of GVCs and reshoring global production and trade back towards OECD economies" (De Backer & Flaig, 2017, P.6). Kagermann et al. (2013) and Bauernhansl et al. (2014) show that Industry 4.0 technologies can increase a firm's output by increasing productivity and capacity utilization and lowering production costs. Intensive usage of Industry 4.0 technologies may decrease labor input and change the capital-labor ratio (in favor of capital). Therefore, Industry 4.0 may diminish the appeal of labor arbitrage in low-wage countries and emphasize the significance of economies of scale in developed countries by compensating the locational advantages of low-wage countries. Similarly, according to De Backer & Flaig (2017), the international fragmentation of production is becoming less appealing due to the technologically feasible lower share of labor in production, high productivity potentials, and an increasing demand for customized products in developed countries. There is a trend toward the rebalancing of the world economy toward the developed economies.

Additionally, the digital integration of manufacturing processes has the potential to facilitate the development of more vital regional value chains. Strange & Zucchella (2018) advocate that the technology enhances human-machine and machine-machine interaction, enabling improved product adaptation and individualization. Consequently, firms will prioritize proximity to customers over production costs when making location decisions. This will accelerate the transition from centralized to decentralized supply chains, with greater emphasis on accessibility and localization. For example, while Kinkel (2014) points out that the 're-shore' effects are more significant in industries with high complexity and customization, Bornert & Musolino (2024) indicate that firms have a greater propensity to reshore in industries that have been investing more in contract manufacturing. As a result, Industry 4.0 may shorten GVCs and reduce GVC trade.

Furthermore, existing literature shows that digitalization can promote the upgrade of GVCs. Forster et al. (2018) assesses the impact of digital transformation on the enhancement of the value chain through qualitative lenses, such as through case analyses. A study by Oliveira et al. (2021) within the Brazilian digital gaming sector demonstrates that digitalization is instrumental in the value chain advancement of small and medium-sized enterprises (SMEs). Over time, researchers shift towards utilizing industry-level data to evaluate the implications of digitalization. He (2020) utilizes the World Input-Output Database (WIOD) to scrutinize the trade value added across various sectors within the manufacturing industry. Through empirical analysis, the study examined the transformative impact of digital technology on the restructuring and enhancement of the manufacturing sector. Yong et al. (2022) demonstrates that the digital economy plays a pivotal role in the structural advancement of the manufacturing sector. The research employs the mediation effect model, revealing that the digitalization significantly enhances the manufacturing structure. The study identifies that both innovation capacity and total factor productivity (TFP) serve as substantial partial mediator in this enhancement process. The findings underscore the significance of the digitalization in driving innovation and productivity, which are key in the structural upgrading of the manufacturing industry. Guo et al. (2023) used an inter-country input-output accounting model to measure the degree of industrial digitalization, finding that digitalization provides Chinese industries with a competitive advantage in the division of labor within GVCs.

Yet, these investigations have two limitations. First, these studies primarily focus on direct impacts of digital transformation on GVCs, failing to capture a comprehensive view of its economy-wide influence. Second, the analysis of digitalization's effects on GVCs according to the sectoral digital intensity is under-researched. As a result, based on the sectoral digital intensity, this research employs an economy-wide model to analyze the interaction between digitalization and manufacturing GVCs, while also assessing its macro- and microeconomic impacts.

3.3 Data and Methodology

This section presents the data and methodology used to analyze the impacts of Industry 4.0 on manufacturing GVCs, using digitalization as a proxy for Industry 4.0, consistent with existing literature. This work simulates the impact of digitalization effects in the GTAP model by introducing productivity gains in regional manufacturing sectors. The methodology consists of three primary components: measurement of digitalization in the manufacturing industry, calculation of GVC participation indices, and the construction of a MRIO database. First, this section introduces the estimation of manufacturing digital intensity across regions to capture Industry 4.0 progress (Section 5.3.1). Second, this section details the calculation of manufacturing GVC participation indices both before and after the digitalization simulation (Section 5.3.2). The changes present the impacts of digitalization. Third, given that MRIO tables are essential for calculating both digital intensity and GVC indices, this section introduces the construction of these tables using GTAP data for both baseline and simulated scenarios (Section 5.3.3). Finally, this section details the scenarios used in the simulations (Section 5.3.4).

3.3.1 Measurement of Digitalization

Following the approach of Zhang & Yu (2020), this study estimates digital pervasiveness within sub-manufacturing sectors using MRIO tables. By considering sectoral linkages, this method provides an accurate reflection of digitalization in each sector. The digitalization index measures the presence of ICT devices and ICT-enabled services to transform the manufacturing sector into a digitalized state. This research categorizes four digital intermediate inputs based on the International Standard Industrial Classification of All Economic Activities (ISIC Rev.4), as outlined by Zhang & Yu (2020). These four digital sectors are manufacturing of computers, electronic, and optical products (C-26);[13] telecommunications (J-61);[14] computer programming,

[13] Manufacture of electronic components and boards, manufacture of computers and peripheral equipment, manufacture of communication equipment, and manufacture of consumer electronics (C-26).

[14] Wired-, wireless-, satellite-, and other telecommunications activities (J-61).

consultancy, and related activities (J-62); and information service activities (J-63)[15]. The index measures the extent to which digital technologies are used in each manufacturing sector, considering both direct and indirect digital inputs. Direct inputs refer to the inputs obtained from the four digital sectors that are directly used by each industry. Indirect digital inputs are included in the inputs used by each manufacturing industry. The digital intensity index quantifies the overall presence of digital technology in the manufacturing sector by including both direct and indirect digital inputs (Xie & Wang, 2022).

The digital index for the use of digital input j in sector g, b_{gj}, is:

$$b_{gj} = a_{gj} + \sum_{m=1}^{N} a_{gm}a_{mj} + \sum_{n=1}^{N}\sum_{m=1}^{N} a_{gn}a_{nm}a_{mj} + \cdots \qquad (1)$$

Where a_{gj} refers to the direct consumption of digital output by sector g, as defined above. $\sum_{m=1}^{N} a_{gm}a_{mj}$ is the indirect digital sector j's output consumed by the manufacturing sector g via manufacturing sector m (e.g., machinery). $\sum_{n=1}^{N}\sum_{m=1}^{N} a_{gn}a_{nm}a_{mj}$ represents the additional indirect consumption of manufacturing sector g to digital sector j through manufacturing sectors m (e.g., machinery) and n (e.g., Rubber and Plastics) (and so on) until it covers indirect digital inputs in all relevant sub-manufacturing sectors.

3.3.2 Global Value Chain Participation Indices

This study follows the production activity decomposition framework proposed by Wang et al. (2017) to measure GVC participation indices. In Wang et al. (2017), the country-sector level production activities are decomposed into GVC and non-GVC components. The approach traces the sources and destinations of value added from both producer and user perspectives, differentiating forward and backward linkages. GVC participation measures the extent to which a country or sector is integrated into the global production system, with higher values indicating a greater degree of involvement in GVCs.

Wang et al. (2017) categorizes a country's total production activities into four distinct segments: purely domestic production, conventional international trade, simple GVC activities, and complex GVC activities. Specifically,

$$\hat{V}B\hat{Y} = \hat{V}L\widehat{Y^D} + \hat{V}L\widehat{Y^F} + \hat{V}LA^F B\hat{Y} = \hat{V}L\widehat{Y^D} + \hat{V}L\widehat{Y^F} + \hat{V}LA^F L\widehat{Y^D} + \hat{V}LA^F(B\hat{Y} - L\widehat{Y^D})$$
(2)

Where each element in the $\hat{V}B\hat{Y}$ matrix represents the value added from a source country-sector directly or indirectly used in the production of final goods and services in a particular country/sector. $\hat{V}$ represents diagonal matrix with elements of V at the diagonal, and V is the value-added coefficient vector. While Y is the

[15] Data processing, hosting and related activities (J-63).

final goods and services production vectors, $\hat{Y}$ is the diagonal matrix of final production of each country/sector. Y^D and Y^F are for domestic and foreign final goods and services production vectors, $\widehat{Y^D}$ and $\widehat{Y^F}$ are the diagonal matrixes accordingly. B is the global Leontief inverse, reflecting the industrial linkages among all countries; $L = (I - A^L)^{-1}$, is the local Leontief inverse, reflecting linkages among various industries within each individual country. A^F refers to foreign or imported input coefficient matrix.

Summing up Equation (2) along row direction, the work can decompose country-sector final goods production in terms of where the value added comes from:

$$va' = \hat{V}BY = \underbrace{\hat{V}LY^D}_{V\_D} + \underbrace{\hat{V}LY^F}_{V\_RT} + \underbrace{\hat{V}LA^F LY^D}_{V\_GVC\_S} + \underbrace{\hat{V}LA^F(BY - LY^D)}_{V\_GVC\_C} \quad (3)$$

Summing up Equation (2) along column direction, the work can decompose country-sector final goods production in terms of where the value added comes from:

$$Y' = VB\hat{Y} = \underbrace{VL\widehat{Y^D}}_{Y\_D} + \underbrace{VL\widehat{Y^F}}_{Y\_RT} + \underbrace{VLA^F L\widehat{Y^D}}_{Y\_GVC\_S} + \underbrace{VLA^F(B\hat{Y} - L\widehat{Y^D})}_{Y\_GVC\_C} \quad (4)$$

The first terms in both equations (3) and (4) represent value-added produced at home and absorbed by domestic final demand without involving international trade; it is labelled as V_D and Y_D, respectively. The second terms are domestic value-added embodied in final product exports, and are labelled as V_RT and Y_RT, respectively. Both of them are domestic production activities, but V_D and V_RT from are the sum of value added from a country-sector used in all downstream sectors. Y_D and Y_RT are the value added in a country sector that sums up the value added from all upstream sectors.

Thus, a country's forward and backward GVC participation can be expressed as follows:

$$GVCPt_f = \frac{V\_GVC\_S}{Va'} + \frac{V\_GVC\_C}{Va'} = \frac{\hat{V}LA^F BY}{Va'} \quad (5)$$

$$GVCPt_b = \frac{Y\_GVC\_S}{Y'} + \frac{Y\_GVC\_C}{Y'} = \frac{VLA^F B\hat{Y}}{Y'} \quad (6)$$

Forward GVC participation is measured by the share of a sector's value added that is part of GVC activities, reflecting a country's ability to provide intermediate goods for global production. Backward GVC participation, on the other hand, is measured by the contribution of both domestic and foreign production factors to the value added of a country's final products, indicating the extent of involvement in globally segmented production activities.

3.3.3 GTAP Model and MRIO Conversio

This research employs the latest version of the GTAP model (Corong et al., 2017) and the GTAP 11 Data Base (Aguiar et al., 2023), which uses 2017 as the reference year and distinguishes 65 sectors in each of 141 countries and 19 aggregated regions. The GTAP model is a multi-country, multi-sector general equilibrium model. The GTAP model explicitly models sectoral production, household and government consumption, and investment, in each country/region. The standard GTAP model assumes perfect competition and constant returns to scale. Each country in the model is interconnected via bilateral trade in each commodity. bilateral trade among regions using the Armington assumption (i.e., good produced in different regions are imperfect substitutes). The study utilizes the GTAP model to simulate and analyze the effects of Industry 4.0 on the economies of 11 regions and the dynamics within manufacturing GVCs.

The GTAP database is a consistent global database that contains harmonized input-output tables and bilateral trade data (Narayanan & Walmsley, 2008; Aguiar et al., 2023). Since the GTAP database is already balanced, the MRIO analyst can manipulate the GTAP data into an MRIO without the need to perform additional balancing (Peters, 2008). Therefore, the database can be used for many MRIO applications (Su et al., 2010). For example, Daudin et al. (2011) examined cross-country input-output data from GTAP and found that China's forward participation is lower than its backward participation. Wen et al. (2021) utilizes the GTAP database to construct MRIO and GTAP model to assess the impact of RCEP tariff reductions on GVCs and find that RCEP strengthens the GVC position and participation of signatories. This research constructs a MRIO database based on the GTAP database and analyze the impact of Industry 4.0 on development of manufacturing GVCs.

Following Peters et al. (2011), this paper converts the GTAP database into a MRIO database based on the following equation:

$$X_i^r = Z_i^{rr} + Y_i^{rr} + t_k^r + \sum_s e_i^{rs} = Z_i^{rr} + Y_i^{rr} + t_k^r + \sum_s Z_i^{rs} + Y_i^{rs}) \qquad (7)$$

Where X_i^r is the total output of industry *i* in region *r*, Z_i^{rr} is domestic firm purchases in industry *i* within region *r*, Y_i^{rr} is domestic consumer purchases of final goods in industry *i* within region *r*, t_k^r is the export of international transport service *k* from region *r*. e_i^{rs} is total export of industry *i* from region *r* to region *s*, the sum of exported intermediates and final goods. Z_i^{rs} is the exports of intermediates in industry *i* from region r to region s, and Y_i^{rs} refers to exports of final goods in industry *i* from region r to region s (Appendix B shows details).

3.3.4 Model aggregation and scenarios

This research aggregates the GTAP database into 7 sectors (Table 5-1) and 11 regions (Table 5-2). The regional aggregation includes China, Japan, Korea, U.S., EU, New Zealand, Australia, Singapore, ASEAN, India and Rest of the World (RoW). The 65 industrial sectors are grouped into Agriculture, Mining, Services, and four manufacturing industries, which differ with respect to digital intensity. Industry digital intensity classification follow Calvino et al., (2018) and are based on various factors, including ICT industry investment, procurement of ICT intermediate products, robotics utilization, ICT specialists, and online sales. The four manufacturing industries are: low-digital-intensity manufacturing sectors (LDIS), medium-low-digital-intensity manufacturing sectors (MLDIS), medium-high-digital-intensity manufacturing sectors (MHDIS), and high-digital-intensity manufacturing sectors (HDIS). Note that although the classification of manufacturing digitalization is based on Calvino et al., (2018), sectoral digital intensities for each sector are calculated using the GTAP Database and the methods of calculations Zhang & Yu (2020) (as described in Section 5.3.1).

Table 5-1 Industry Aggregation and Concordance

INDUSTRY AGGREGATION	GTAP CLASSIFICATION	ISIC.REV4 Sector
AGRICULTURE	PDR,WHT,GRO,V_F, OCR, OSD, C_B, PFB, CTL, OAP, RMK, WOL, FRS, FSH	
MINING	COA, OIL, GAS, OXT	
MANUFACTURING INDUSTRY SEGMENTS		
LOW DIGITAL INTENSIVE MANUFACTURING INDUSTRY	B_T, CMT, OMT, VOL, OFD, MIL, PCR, SGR, LEA	C10, C11,C12
MEDIUM LOW MANUFACTURING INDUSTRY	TEX, WAP, P_C, CHM, BPH, RPP, NMM, I_S, NFM, FMP,	C13,C14,C15, C19,C20,C21,C22,C23,C24,C25
MEDIUM HIGH DIGITAL INTENSIVE MANUFACTURING INDUSTRY	LUM, PPP, OME, EEQ, OMF	C16,C17,C18,C26,C27, C28
HIGH DIGITAL INTENSIVE MANUFACRTURING INDUSTRY	MVH, OTN	C29, C30
SERVICES	OTHERS	

Source: Author’s elaboration

Table 5-2 Aggregation of Regions

Abbreviation	Region Name	Nations Included
USA	United States	United States
CHN	China	China
JPN	Japan	Japan
KOR	Korea	Korea
AUS	Australia	Australia
NZL	New Zealand	New Zealand
SGP	Singapore	Singapore
ASEAN	Association of Southeast Asian Nations	Indonesia, Philippines, Thailand, Cambodia, Laos, Myanmar, Viet Nam, Malaysia, Brunei
EU	European Union	The EU has 27 countries now
IND	India	India
RoW	Other regions or nations in the world	Remaining countries in GTAPAgg

Source: Author's elaboration

Digitalization is expected to increase productivity in sectors that it is used. Because digitalization's impacts are broad and could be disruptive, detailed estimates are not widely available. In order to model the impacts of digitalization in manufacturing across countries, this study measures the digital intensity to represent the digitalization of each sector. These digital inputs are derived from four key digital industries (as mentioned in section 3.1). Moreover, the estimated digital intensities serves as a proxy for the productivity gain in each sector due to digitalization. (i.e., digitalization-induced productivity improvement will be large in sectors with higher digital intensity that sectors with lower digital intensity).

This analysis implements digitalization as technical change in the manufacturing sectors of each region. The technical progress is simulated as an increase in manufacturing productivity (i.e., a positive shock would be applied to the GTAP variable *aoall*), and it implies that more output will be produced for the same quantities of inputs (Appendix A presents the details). Furthermore, for the EU, ASEAN, and RoW, this study calculates productivity multipliers at both the sectoral and regional levels, accounting for each country's contribution to the region's total manufacturing output and the impact of its digitalization, with variations based on digital intensity. Specifically, a weighted average approach is employed, where each country's share of manufacturing value added, relative to the regional total, determines its influence on the region's overall digitalization level.

Table 5-3 presents the digitalization productivity shocks simulated in the model. The estimates range from 0.02% - 0.27%. On one hand, it demonstrates the existence of a digital divide, with varying paces and levels of digitalization in manufacturing across regions. On the other hand, it reveals that some developed regions could have relatively low digital levels, for example, the digitalization level in the United States is lower than that in Korea and China. Additionally, it shows that some MHDIS have a higher digital intensity than HDIS, as in Singapore and ASEAN, where the MHDIS digital intensity exceeds that of HDIS. This is because, as noted above, the classification of sectors and the calculation of digital intensity uses different methodologies.

Table 5-3: Simulated Settings: Productivity Shocks in Manufacturing Sectors Induced by Digitalization, Based on Digital Intensity

	China	Japan	Korea	Australia	New Zealand	Singapore	India	EU	USA	ASEAN	RoW
Low digital-intensive sectors	0.04	0.03	0.06	0.03	0.02	0.08	0.02	0.04	0.04	0.03	0.03
Medium-Low digital-intensive sectors	0.09	0.05	0.09	0.04	0.02	0.07	0.03	0.05	0.05	0.05	0.06
Medium-High digital-intensive sectors	0.27	0.14	0.24	0.24	0.04	0.25	0.11	0.14	0.09	0.18	0.21
High digital-intensive sectors	0.25	0.14	0.26	0.26	0.05	0.16	0.12	0.13	0.13	0.13	0.16

Source: Author's elaboration

In the next section, the results from the digitalization shock are presented, and GVC participation indexes before (i.e., baseline scenario) and after this shock (i.e., simulated scenario) are calculated and compared to measure the impact of digitalization on manufacturing GVCs.

3.4 Results

3.4.1 Economy-Wide Change and Gross Trade

This section presents changes in GDP, welfare, and gross trade due to digitalisation (relative to the baseline scenario), and explores how digitalization has impacted GVCs.

The impact of digitalization on GDP in each region in the Industry 4.0 scenario is shown in column (1) of Table 5-4. The productivity improvement in manufacturing industries induced by digitalization increased GDP by varying degrees across regions. Interestingly, higher productivity shocks do not necessarily translate into higher GDP changes. For example, the productive shocks for Australia are, on average, larger than those for the EU and USA; however, the proportional increase in GDP in Australia is lower than in those countries. This can be attributed to the smaller scale and specialized nature of Australia's manufacturing sector, which is concentrated in high-tech and resource-intensive industries. In contrast, the United States and Europe have larger and more diverse manufacturing sectors, encompassing industries such as automotive, aerospace, and electronics, enabling digitalization to have a greater impact on economic growth.

Table 5-4 Simulated changes in GDP and welfare in Industry 4.0 scenario relative to the benchmark

	(1)	(2)	(3)	(4)
	GDP (U.S.$ billion)	GDP (in %)	Social Welfare (U.S. $ billion)	Changes in Social Welfare Relative to Changes in GDP (in %)
China	26.986	0.22	34.452	1.277
Japan	2.889	0.06	1.780	0.616
Korea	2.914	0.18	2.365	0.812
Australia	0.127	0.01	0.135	1.063
New Zealand	0.016	0.01	0.035	2.188
Singapore	0.407	0.12	0.613	1.506
India	0.854	0.03	0.206	0.241
EU	7.447	0.05	5.513	0.740
USA	5.054	0.03	2.657	0.526
ASEAN	2.090	0.09	1.397	0.668
RoW	8.650	0.04	8.282	0.957

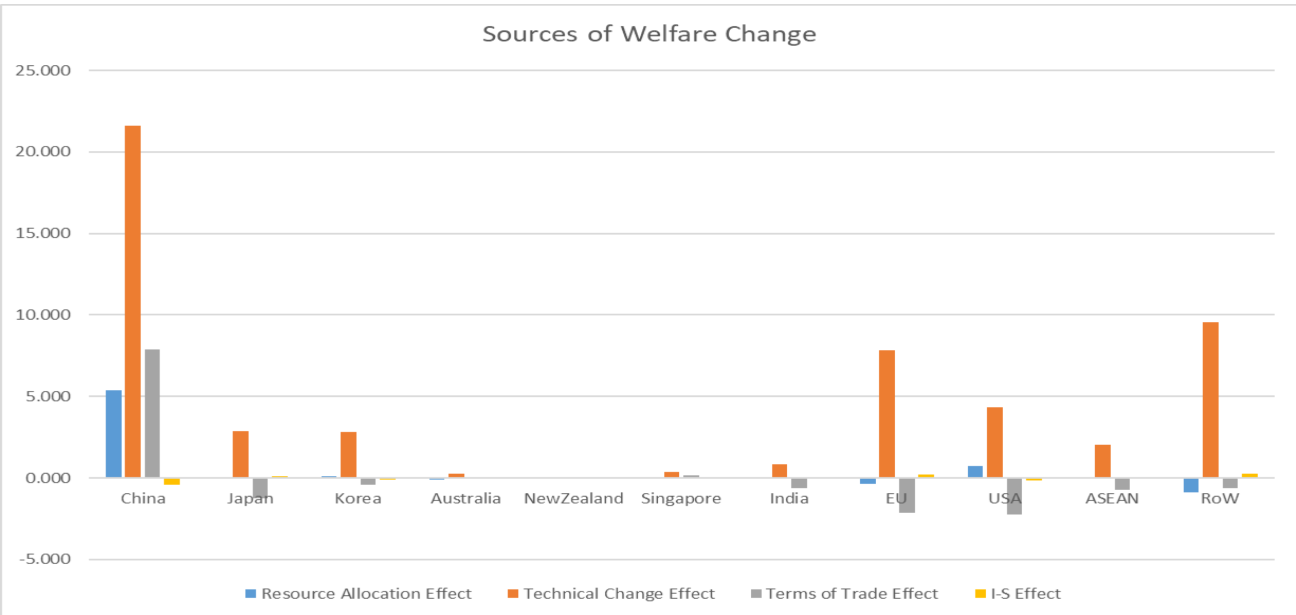
Source: Author's calculation

Change in welfare due to digitization are reported in column (3) of Table 5-4. Welfare changes are quantified using equivalent variation (EV) in income. Changes in welfare as a proportion of GDP are displayed in column (4), highlighting the combined impact of digital technologies on economic growth and social welfare. The welfare-to-GDP change ratio (W/G ratio) quantifies the extent to which GDP growth translates into welfare gains, providing a measure of the efficiency of economic growth in enhancing societal well-being, particularly in the context of digital technology adoption.

The results indicate that regions with a welfare-to-GDP change ratio exceeding 1% include New Zealand (2.188%), Singapore (1.506%), China (1.277%), and Australia (1.063%). In contrast, India exhibits a ratio below 0.5% (i.e., 0.241%), while all other regions fall within the range of 0.5% to 1%. Regional variations in this ratio are likely influenced by factors such as the quality of digital infrastructure, policy frameworks, social welfare systems, and stages of economic development (Oloyede et al., 2023). For example, according to the New Zealand's Strategic Intentions 2023-2028, the country aims to harness digitalization to drive economic growth and social well-being. This strategy emphasizes advancements in key areas such as cloud computing, cybersecurity, and artificial intelligence, while promoting R&D funding for start-ups and small-and-midsize enterprises (SMEs) to foster projects with substantial social and economic impact (Ministry of Business, Innovation and Employment, 2023).

Following Huff & Hertel (2001) and Hanslow (2001), this study conducts a welfare decomposition of the aggregate welfare changes due to digitalization. The sources of welfare change in the decomposition are changes in allocative efficiency, technology productivity, terms of trade, and investment/savings. Figure 5-1 displays the contribution of each category to the overall welfare change. The technical change effect is the dominated source of welfare gains for all regions, contributing around 91% of total welfare gains (i.e., $52.395 billion net welfare gains out of $57.434 billion). Changes in welfare in other categories are not uniform across regions. For instance, the resource allocation effect results in a welfare gain for China, whereas it leads to welfare losses for the EU and the RoW. Similarly, terms of trade leads to welfare gains for China, New Zealand, and Singapore, but caused welfare losses in other regions. Nevertheless, these effects are relatively minor compared to the impact of technical change.

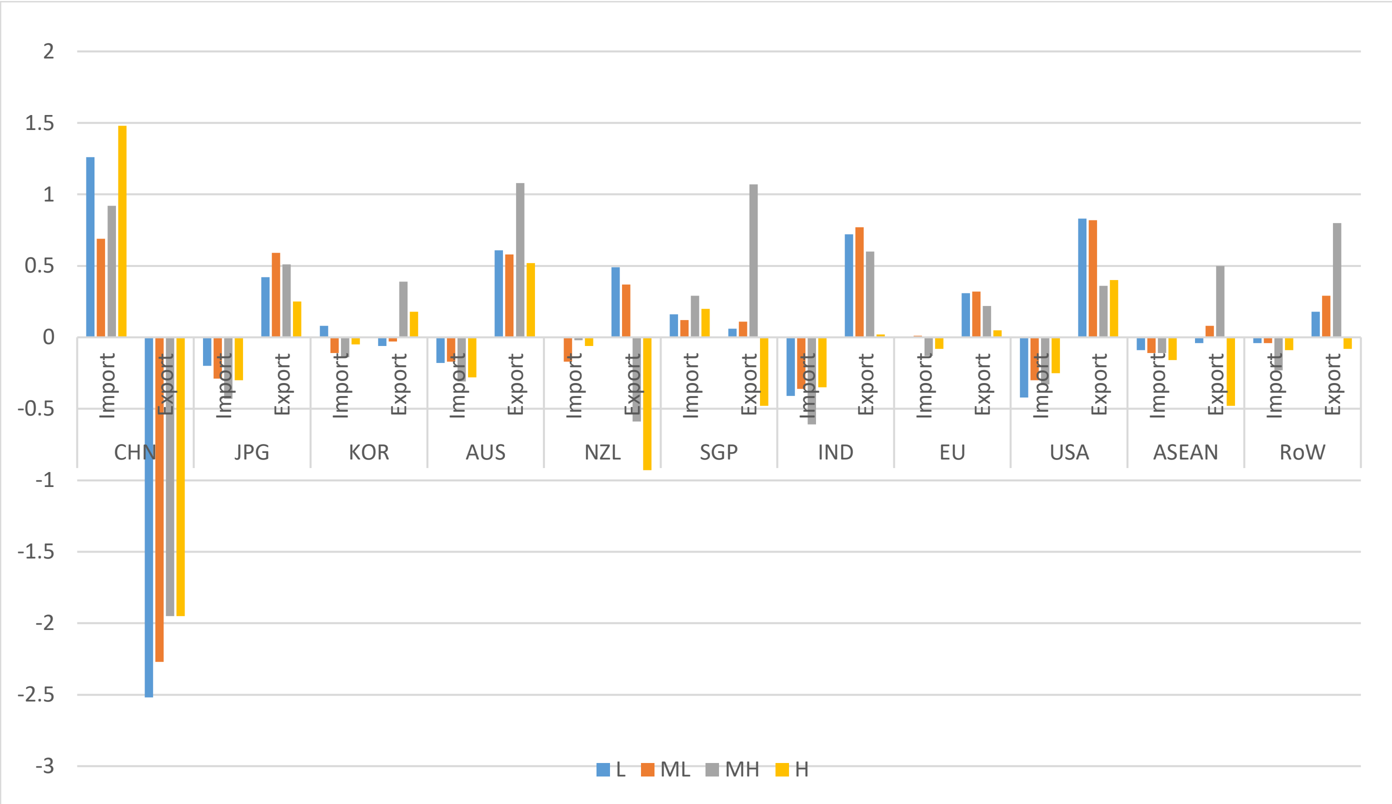
Figure 5-1 Decomposition of Welfare Changes Induced by Digitalization



Source: Author's calculation

Figure 5-2 presents aggregated changes in exports and imports for sectors of interest in the simulated scenario across regions. In all regions except China, manufactured exports increase (ranging from 0.02% to 1.08%) and imports decrease (ranging from -0.02% to -0.61%) across regions. China's manufactured exports decline by between 1.95% to 2.52%, and its imports increase by between 0.69% to 1.48%.

Figure 5-2 Change in Manufacturing Exports and Imports due to Digitalization (%)

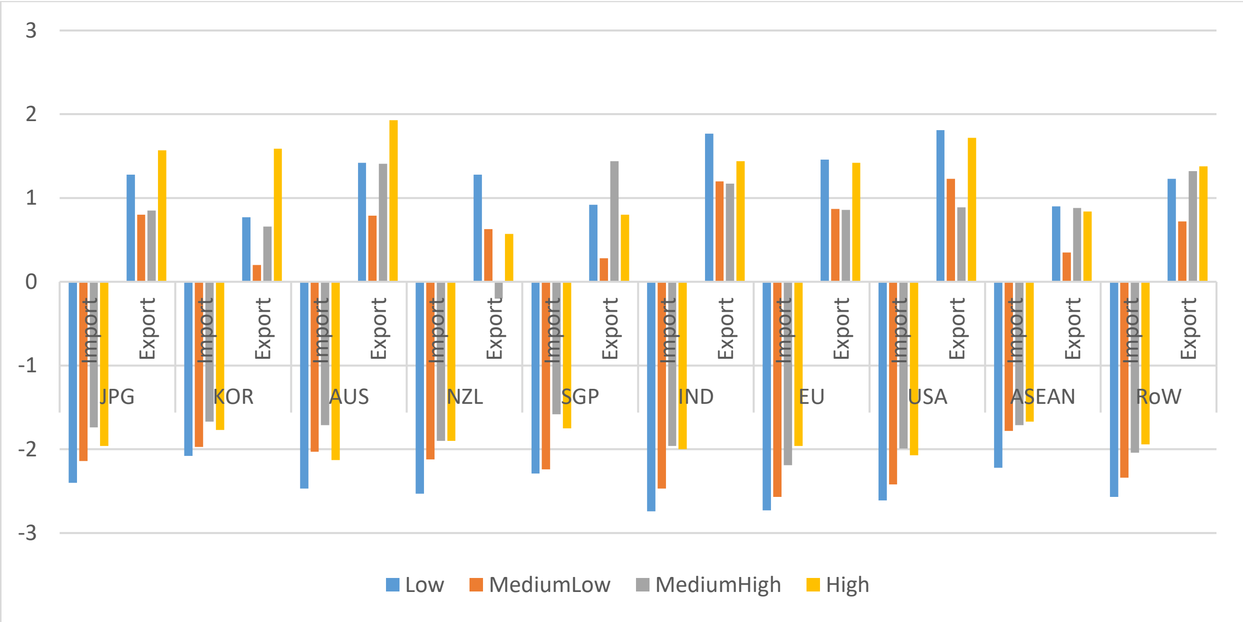


Source: Author's calculation.

Notes: H, MH, ML, and L represent sectors with high, medium-high, medium-low, and low levels of digital intensity, respectively.

Figure 5-3 illustrates the changes in imports from China and exports to China for each region. The most significant change occurs in exports of Australia (high digital-intensive sectors), USA (low digital-intensive sectors), and India (low digital-intensive sectors). Substitution from domestic to foreign goods in China could drive the increase in exports to China. The digitalization shocks cause an increase in the market price (*pms*) for Chinese manufactured goods relative to those produced in other countries. In other words, the digitalization shock reduces China's comparative advantage.

Figure 5-3 Changes in Regions' imports from and exports to China caused by Digitalization (%)



Due to the Armington assumption in the GTAP model, which differentiates products by their country of origin, the impact of digitization on terms of trade varies across regions, as shown in Column (3) of Appendix C.

Conversely, China, Singapore, and New Zealand have seen improvements in their terms of trade due to digitalization. China experiences the largest positive gains across all manufacturing sectors, while New Zealand benefits specifically from medium-high to high digital-intensive sectors. Singapore sees gains in most sectors except those with medium-high digital intensity.

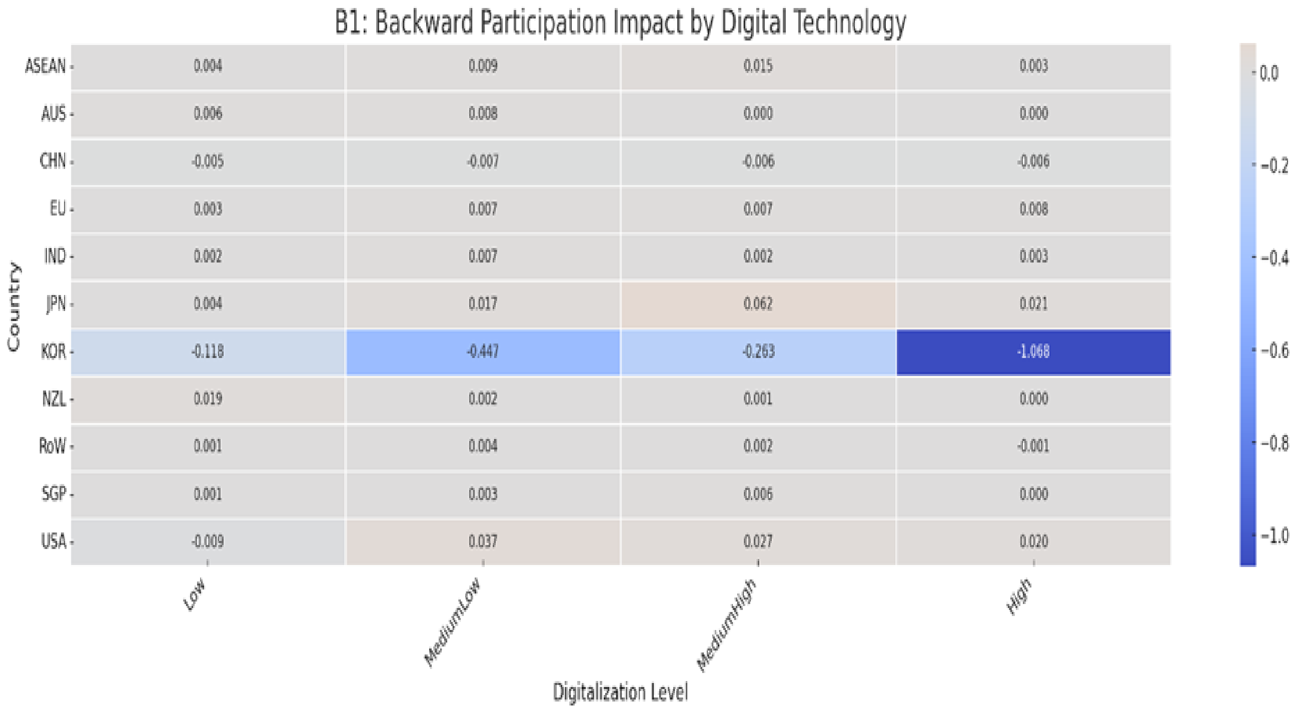
Despite digital advancements, many countries face increased global competition, leading to faster declines in export prices relative to import prices, resulting in modest terms of trade losses. Nonetheless, these regions achieve overall net welfare gains as terms of trade loss are relatively modest.

3.4.2 Global Value Chain Changes

3.4.2.1 Impacts on Forward Participation and Backward Participation

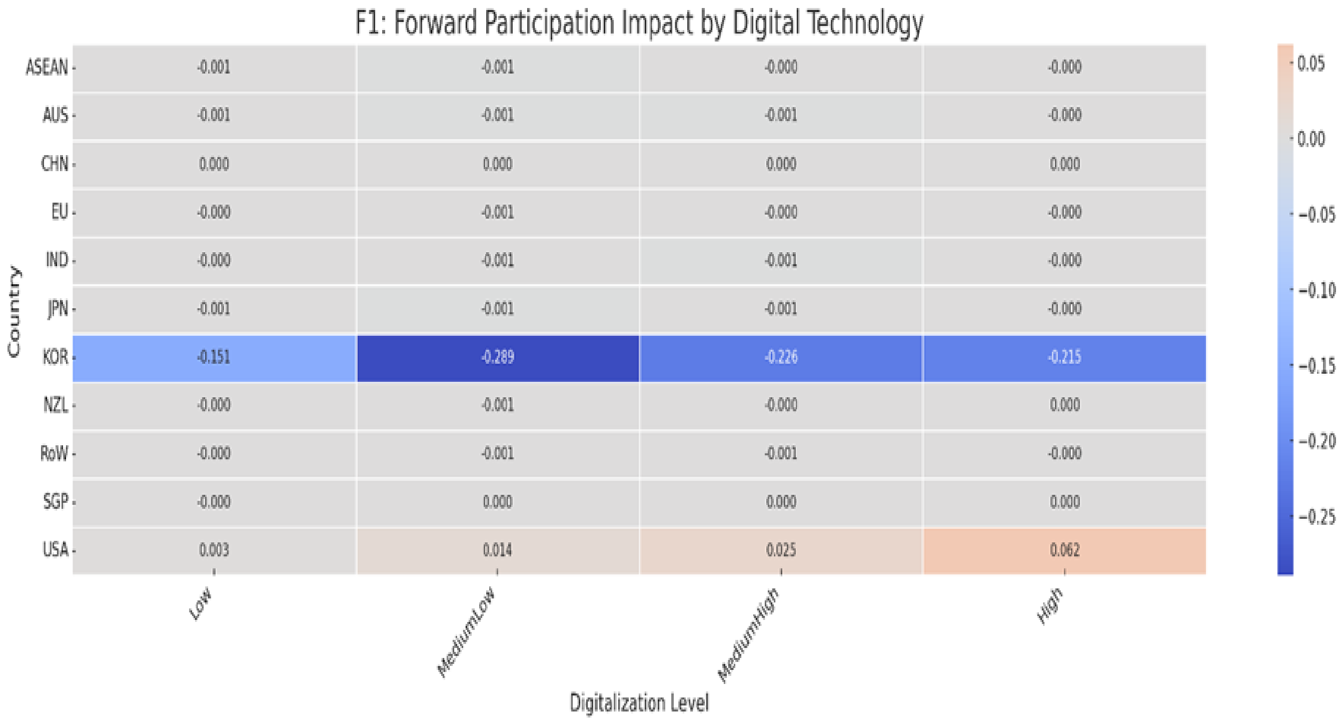
Upgrading within GVCs is driven by firms' adoption of digitalization in manufacturing. Following Wang et al. (2017), this analysis estimates and compares forward and backward GVC participation rates before and after the incorporation of Industry 4.0, capturing its direct impact on GVC participation. Notably, this analysis assumes that digitalization does not influence other factors, such as technologies or governance structures, which could further shape manufacturing GVCs. Figure 5-4 and Figure 5-5 illustrate the impacts of digitalization on backward participation and forward participation, respectively.

Figure 5-4 Changes in Backward Participation Index by Country



Source: Author's Calculation.

Figure 5-5 Changes in Forward Participation Index by country



Source: Author's Calculation.

These results are discussed separately for two different groups of economies. This enables a more detailed analysis of the factors influencing the impact of digitalization on the manufacturing value chain, while considering the specific developmental contexts of the regions involved.

The first group of economies are so-called latecomer countries. These countries learn from the experiences of developed nations, gradually accumulating capabilities within GVCs to achieve industrial upgrading and technological advancement, thereby enhancing their global competitiveness (Andreoni et al., 2021). As noted by Mehta (2022), productivity growth leads to GVC upgrading. This means that the degree of forward and backward GVC participation is influenced by a country's productivity level. Specifically, the GVC upgrading process consists of four stages. In the initial stage, low backward and forward linkages limit productivity growth. In stage two, as firms advance, backward linkages increase while forward linkages remain low, risking a low-value-added trap. In stage three, with the accumulation of technological capabilities, forward linkages rise and backward linkages decline, enabling a transition to high-value-added production. Finally, in the stage four (the advanced stage), both linkages decrease further, allowing firms to achieve high productivity through effective management of globally distributed production processes within the GVC (Mehta, 2022).

Latecomer countries/regions in the model are China, Korea, ASEAN, India, and Singapore. Latecomer countries tend to leverage their comparative advantages for specialized production and processing in manufacturing GVCs. The second group includes developed regions/nations such as the U.S., EU, Japan, Australia, and New Zealand. These countries hold a leading position in GVCs, with established industries and relatively advanced technologies.

Figures 5-4 and 5-5 illustrate the changes in backward and forward GVC participation due to digitalization, respectively. Positive values indicate an increase, while negative values indicate a decrease in participation. For instance, India's forward participation in medium-low digital-intensive sectors decreases by 0.001 (i.e., 0.2%), while backward participation increases by 0.007 (i.e., 3.5%). This suggests that, relative to the baseline, India's forward participation has decreased and backward participation has increased due to digitalization. Meanwhile, for reference, Appendix D and Appendix E provide the forward and backward GVC participation indices in baseline scenario, respectively.

For latecomer countries, digital technologies primarily enhance backward value chain participation while reducing forward value chain participation. These findings align with the stages of value chain upgrading discussed by Mehta (2022), demonstrating that digitalization facilitates status improvement within GVCs, even though countries are at different stages of GVC integration.

Specifically, the industrial structures of ASEAN, and India remain relatively traditional, dominated by less advanced manufacturing industries. In the presence of digitalization[16], these regions are increasingly involved

[16] This study examines only the direct impact of digitalization on manufacturing value chains, assuming that all other potential influencing factors remain fixed.

in backward manufacturing GVCs and less involved forward manufacturing GVCs (i.e., stage two: backward linkages increase while forward linkages remain low).

The results in Figure 5-4 show that the index for backward participation increased by less than 0.02 for these regions, and results in Figure 5-5 indicate that index for forward participation is reduced by around 0.001. These results indicate digitalization facilitates the transition of these regions from simple assembly and manufacturing to the production of more complex products and the accumulation of technological capabilities. Firms in these regions increasingly rely on external suppliers for components or intermediate goods. Thus, the backward linkages are increased. However, digitalization reduces forward linkages, indicating that easier access to and reliance on external technologies and components can lead firms to remain entrenched in certain production stages, stifling their capacity for independent innovation and hindering their ability to transition to higher-value-added activities (e.g., R&D and design). Consequently, this dependence may inhibit their development of forward participation (Araújo et al., 2021).

China and Korea stand out as exception. Backward GVC participation in China decreases while forward participation increases (i.e., stages three: forward linkages rise and backward linkages decline), whereas both types of GVC participation decline in Korea (i.e., stage four: both backward and forward linkages decrease further). This suggests that digitalization promotes manufacturing upgrade within GVCs for both China and Korea. For China, digital technologies allow firms to accumulate technological capabilities and resources to upgrade from low-value to high-value production processes. The patterns are consistent with stage three of upgrading within GVCs, that is, a reduction in reliance on external suppliers (i.e., decreased backward linkages) and an increase in influence over downstream markets (i.e., increased forward linkages).

In the case of Korea, productivity gains from digitalization result in a decline in both forward and backward linkages, aligning with the advanced stage described by Metha (2022). In Stage Four, Korean firms transition to high-value-added activities, creating advanced global production networks. Dependence on external suppliers and customers declines as firms restructure value chains to optimize resources and internalize key operations, enhancing control and efficiency. By focusing on core competencies and outsourcing non-core functions, firms reduce the quantity of forward and backward linkages while improving their quality. Long-term partnerships with high-calibre collaborators emerge, ensuring that these streamlined linkages are more aligned and value-driven, reinforcing the resilience and efficiency of the network (Mehta, 2022; Andreoni et al., 2021).

For the group of developed countries, results show that the impacts of digitalization on manufacturing GVC participation vary across regions and sectors. Overall, digitalization tends to reduce forward participation and increase backward participation, except in the U.S. (i.e., U.S. has seen an increase in both forward and backward linkages). The possible underlying reason for this phenomenon could be attributed to the distinct industrial development strategies and technological foundations of the regions in question.

For example, Europe and Japan have accumulated significant expertise in advanced manufacturing sectors. Europe excels in industries such as automotive and aerospace (i.e., HDIS) (De Concini & Toth, 2019), while Japan specializes in the manufacturing of computers, electronics, and optical products (i.e., MHDIS) (Intralink Limited, 2024). This technological and industrial prowess may explain why digitalization has the most pronounced positive impact on backward value chain participation in Europe’s HDIS and Japan’s MHDIS. As for Australia and New Zealand, these regions may place greater emphasis on leveraging their natural resources endowment. Firms in these areas may rely on the adoption and assimilation of advanced international technologies and base their economic development on resource-driven industries. For example, New Zealand's comparative advantage in agricultural commodities explains why backward participation in its LDIS have seen the most significant increase.

The United States and Singapore represent notable exceptions, as their manufacturing industries are characterized by a strong orientation toward service-oriented manufacturing. Firms in these countries increasingly provide value-added services, such as product design and customized solutions, which are deeply reliant on advanced digital technologies. The digital transformation of manufacturing has reenforced the competitive advantage of these nations in these areas.

Additionally, digital technologies may enhance backward linkages by improving supply chain management, allowing manufacturers to efficiently source resources on a global scale. The results also suggest that digitalization enhances the role of U.S. and Singapore in the high-value segments of the value chain, such as knowledge-intensive products and services. This could be due to the reason that as the center for technological innovation and the production of high-value-added products, their manufacturing uses digital tools to enhance connections with downstream customers, offering customized products that enhance forward linkages.

3.4.2.2 Disaggregated Analysis on Impacts of Digitalization on Simple and Complex Participation

This paper further examines the impacts of digitalization on forward and backward GVC participation by analysing simple and complex components of this participation. Simple forward participation in GVCs refers to goods or services crossing borders once during production, such as raw materials exports with minimal processing. Complex forward participation involves multiple border crossings, with intermediate goods being processed in several countries before final assembly or export, as seen in high-tech electronics production. Digitalization affects these differently: in simple GVCs, it enhances efficiency through automation, optimizing single-stage processes. In contrast, complex value chains benefit from digital technologies, which improve coordination across multiple production stages, facilitating real-time data sharing, logistics management, and collaboration across global firms (Institute of World Economics and Politics, CASS, & Research Center for Hongqiao International Economic Forum, 2023).

Consistent with changes in overall forward and backward GVC participation, South Korea shows simultaneous declines in both simple forward (Appendix F) and simple backward GVC participation (Appendix G). In other regions, while digitalization impacts vary due to industry-specific characteristics, its influence generally leads to positive growth in GVCs. Appendices I and H provide further insights into complex GVC participation. With digitalization, regions tend to reduce their involvement in both complex forward and complex backward GVC participation. Notably, only the results for the United States and South Korea align closely with those in Appendix F and Appendix G: the United States exhibits sustained positive growth, while South Korea shows negative growth. This confirms that digital technologies are strengthening the United States' influence within GVCs, while driving significant changes in South Korea’s role in manufacturing value chains.

Moreover, the results indicate that, in general, digitalization tends to boost simple GVC participation and impede complex GVC participation. This indicates that, in the presence of digitalization, GVCs are increasingly exhibiting patterns of regionalization and the formation of shorter supply chains (Lundquist & Kang, 2021).

There are several potential reasons for this result. First, the advancement of digital technology reshapes the relative importance of traditional production factors within GVC activities. For instance, the deep integration of digital technologies across manufacturing industries has reduced the relative significance of labor, making labor costs less decisive in the structuring of complex GVCs.

Second, while digitalization has generally improved overall production efficiency, its impact on participation in complex value chains appears to be more intricate. Complex value chains demand deeper technological innovation and closer partnerships, which may not be fully realized in the current stages of digitalization adoption. Thus, participation in these more intricate value chains could be constrained, as firms may struggle to meet the higher demands for innovation and collaboration that these chains require.

Overall, the results are consistent with Baldwin & Okubo (2019) who conclude that digitalization will lead to the development of production hubs, e.g., factory Asia and factory Europe.

3.5 Conclusion

This study explored the impact of Industry 4.0, particularly digitalization in manufacturing GVCs, highlighting both the opportunities and challenges associated with digital transformation across regions. In contrast to existing literature, this research 1) used sectoral digital intensity across regions as a proxy for manufacturing productivity improvements, 2) examined the economy-wide effects of digital technology adoption in manufacturing industries, and 3) investigated the simultaneous adoption of digitalization across regions at different stages of progress, considering their varying sectoral digital sensitivities and role within GVCs, thus providing a more nuanced and realistic perspective.

The results revealed that digitalization generates broad economic benefits, including enhanced welfare, economic growth, and increased cross-border trade. By influencing forward and backward GVC participation, digitalization has also facilitated the upgrading of manufacturing sectors within GVCs. However, its impacts varied across regions, depending on levels of development, sectoral digital intensity, and industrial capabilities. Additionally, the effects differ between simple and complex GVCs: while simple GVCs with fewer cross-border production stages gain from efficiency improvements, complex GVCs—characterized by multiple production stages and extensive international collaboration—become less prevalent. This trend reflected a regionalization and shortening of manufacturing GVCs.

Overall, results underscored the transformative role of digitalization in reshaping manufacturing GVCs and offered several important policy implications for governments aiming to harness the benefits of digitalization in manufacturing GVCs. First, as digitalization fostered greater backward GVC participation, policymakers in those regions should focus on improving access to digital technologies and strengthening their digital infrastructure. This will facilitate their integration into manufacturing GVCs and support their transition from low-value-added manufacturing to more technologically advanced production processes. However, the dependence on external suppliers for intermediate goods highlights the need for policies that encourage domestic innovation and reduce reliance on foreign technologies.

Second, policies should continue to support digitalization, particularly in regions where digitalization enhances both forward and backward GVC participation. This could include further investment in digital infrastructure, workforce upskilling in digital technologies, and incentives for firms to adopt advanced manufacturing technologies that can enhance competitiveness in global markets.

Third, while digitalization promotes regionalization and shorter supply chains, it also increases global competition. Policymakers should consider strategies to mitigate the risks associated with reshoring, such as enhancing the resilience of domestic manufacturing ecosystems through robust industrial policies and strategic investments in digital capabilities.

Despite providing insights into the impact of digitalization on manufacturing GVCs, this analysis is subject to certain methodological limitations inherent to the standard GTAP framework. First, the assumption of perfect competition and constant returns to scale abstracts from the economies of scale and network effects typical of Industry 4.0, which may lead our model to underestimate the concentration of value-added and monopolistic rents among early-adopting digital hubs. Second, the reliance on the Armington assumption—which treats goods from different regions as imperfect substitutes—might dampen the volatility of trade flow shifts, as digital components become increasingly standardized globally. Furthermore, simulating technological progress as a neutral productivity shock captures broad efficiency gains but obscures the factor-biased nature of digital transformation (e.g., skill- or capital-biased), potentially masking redistributive effects between capital and labor within manufacturing sectors. Finally, employing a static GTAP model provides a comparative static assessment without capturing the dynamic adjustments and high transition costs required for technological adaptation. This suggests that the immediate welfare and GDP gains reported herein may represent an upper bound of short-term benefits. Future research could overcome these limitations by utilizing dynamic computable general equilibrium models with firm heterogeneity to better account for long-term structural and redistributive effects.

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3.6 Appendix A

This paper implements digitalization as Hicks-neutral technical change in the manufacturing sectors of each region. For example, if output, Q, is a function of two inputs, X1 and X2, exogenous technical change is modelled as :

$$\frac{Q}{A_0} = f(X_1 * A_1, X_2 * A_2) \quad (1)$$

Parameters $A_0, A_1,$ and A_2 model technical change. The output and inputs are measured in market units (i.e., Q, X_1, and X_2) or augmented unites (i.e., $\frac{Q}{A_0}$, $X_1 * A_1, X_2 * A_2$). Hicks-neutral technical progress is simulated by an increase in parameter A_0 (i.e., a positive shock would be applied to the GTAP variable *aoall*), and it implies that more output will be produced for the same quantities of both inputs. Parameters $A_1,$ and A_2 represents Hick-input augmenting technical change.

In the GTAP model, the sequence equations that connect percent change in output (*qo*) with *aoall* is as follows:

Market clearing equation ensures output equals domestic consumption *qds* and exports *qxs*:

qo(i,r) = SHRDM(i,r)**qds*(i,r)+sum(*s*, REG, SHRXMD(i,r,s)**qxs*(i,r,s))+tradeslack(i,r); (2)

Domestic consumption is a sum of consumption by firms (*qfd*), households (*qpd*), and government(*qgd*):

qds(i,r)=sum(j,PROD_COMM,SHRDRM(i,j,r)**qfd*(i,j,r))+SHRDPM(i,r)**qpd*(i,r)+SHRDGM(i,r)**qgd*(i,r) (3)

Each type of consumption above has a CES nest, with an elasticity of substitution between domestic and imports (Armington) dictating the extent of pass through from prices to demand for domestic consumption by each agent. The following is the example equation for domestic private consumption being a function of total private consumption(*qp*), and private consumption prices-domestic(*ppd*) and aggregated(*pp*).

qpd(i,s)=*qp*(i,s)+ESUBD(i)*[*pp*(i,s)-*ppd*(i,s)] (4)

Each of the prices in the equations like the above are linked to the market prices (pm)-the following shows the example of the private domestic consumption price:

ppd(i,r)=*atpd*(i,r)+*pm*(i,r) (5)

The following equation links the market price with the supply price, the only difference being the output tax (*to*), which remains unchanged in our simulations:

ps(i,r)=*to*(i,r)+*pm*(i,r) (6)

The following equation links supply price with TFP, i.e., the variable *ao*, and other prices of intermediate inputs (*pf*), their associated productivity changes (*af*) as well as those of primary factors (pfe) and their associated productivity changes (*afe* and *ava*):

ps(j,r)+*ao*(j,r)=sum(i,ENDW_COMM,STC(i,jr)*[*pfe*(i,j,r)-*afe*(i,j,r)-*ava*(j,r)])+sum(i,TRADE_COMM, STC(i,j,r)*[*pf*(i,j,r)-*af*(i,j,r)])+profitslack(j,r) (7)

At last, the equation below shows how the total change in TFP may come from the sector-specific TFP *aosec*, region-speicfic TFP *aoreg* and TFP that is specific to a sector and region *aoall*:

ao(j,r)=*aosec*(j)+*aoreg*(r)+*aoall*(j,r) (8)

3.7 Appendix B

Following Peters et al. (2011), the total output of country *r* is calculated by:

$$X_i^r = Z_i^{rr} + Y_i^{rr} + t_k^r + \sum_s e_i^{rs} \quad (9)$$

$$e_i^{rs} = Z_i^{rs} + Y_i^{rs} \quad (10)$$

Where X_i^r is the total output of industry *i* in region *r*, Z_i^{rr} is the domestic firm purchases of industry *i* in region *r*, Y_i^{rr} is domestic purchases of final goods in industry *i* in region *r*, t_k^r is the export of international transport service *k* from region *r*, e_i^{rs} is total export of *i* from region *r* to region *s* (valued in market prices of *r*). Additionally, e_i^{rs} is the sum of exported intermediates and final goods in industry *i* from region *r* to *s*.

Substituting equation (10) into equation (9):

$$X_i^r = Z_i^{rr} + Y_i^{rr} + t_k^r + \sum_s Z_i^{rs} + Y_i^{rs}) \quad (11)$$

Where in equation (11),

$$Z_i^{rr} = vdfm_{ij}^r$$

$$Y_i^{rr} = vdpm_i^r + vdgm_i^r + vdkm_i^r$$

$$t_k^r = vst_k^r$$

the exports of intermediates in industry *i* from region r to region s are obtained by (valued in the market price of region *r*) :

$$Z_{ij}^{rs} = \frac{(z^m)_{ij}^s}{vim_i^s} e_i^{rs} \quad (12)$$

In addition, the exports of final goods from region r to region s in industry *i* are obtained by (valued in market price of region *r*):

$$y_i^{rs} = \frac{(y^m)_i^s}{vim_i^s} e_i^{rs} \quad (13)$$

In equation (12), $(Z^m)_{ij}^s$ is import firm purchase of *i* by *j* in region *s* (valued in price of region s), and $(y^m)_i^s$ is the import purchase of final goods of industry *i* in region *s* (valued in price of region s). $\frac{(Z^m)_{ij}^s}{vim_i^s}$ in equation (12) is import structure in importing countries (in prices of consuming countries) and provides the inter-industry shares, and $\frac{(y^m)_i^s}{vim_i^s}$ in equation (13) is for final consumption. vim_i^s is the total import of i into region *s*.

For more information,

$$vim_i^s = \sum_r vims_i^{rs} = \sum_j vifm_{ij}^s + vipm_i^s + vigm_i^s + vikm_i^s \quad (14)$$

$$e_i^{rs} = vxmd_i^{rs}$$

$$(Z^m)_{ij}^s = vifm$$

$$(y^m)_i^s = vipm_i^s + vigm_i^s + vikm_i^s$$

Where vim_i^s is import of *i* from region *r* to region *s*, $vifm_{ij}^s$ is import firm purchase of *i* by *j* in region *s*, $vipm_i^s$ is import household purchase of *i* in region *s*, $vigm_i^s$ is import government purchase of *i* in region *s*, $vikm_i^s$ is import investment purchase of *i* in region *s*, $vxmd_i^{rs}$ is export of *i* from region *r* to region *s*.

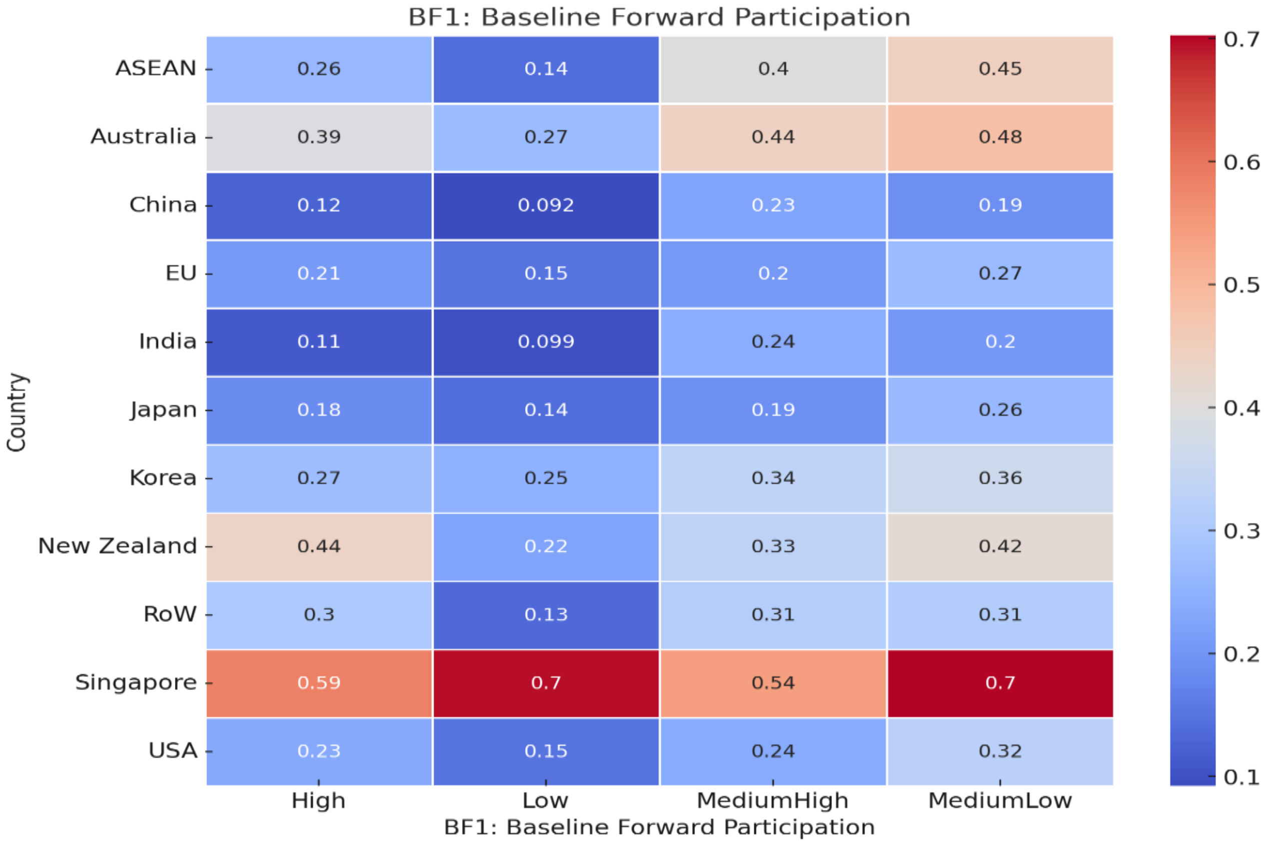
3.8 Appendix C

Sources of Welfare Changes (U.S. $ billion)

	(1)	(2)	(3)	(4)	(5)
	Resource Allocation Effect	Technical Change Effect	Terms of Trade Effect	I-S Effect	Total
China	5.387	21.599	7.862	-0.396	34.452
Japan	0.035	2.854	-1.234	0.125	1.780
Korea	0.110	2.804	-0.444	-0.105	2.365
Australia	-0.108	0.235	-0.023	0.031	0.135
New Zealand	-0.005	0.021	0.010	0.009	0.035
Singapore	0.045	0.362	0.174	0.032	0.613
India	0.039	0.816	-0.619	-0.030	0.206
EU	-0.357	7.804	-2.130	0.196	5.513
USA	0.734	4.320	-2.220	-0.177	2.657
ASEAN	0.056	2.035	-0.735	0.041	1.397
RoW	-0.895	9.545	-0.641	0.273	8.282

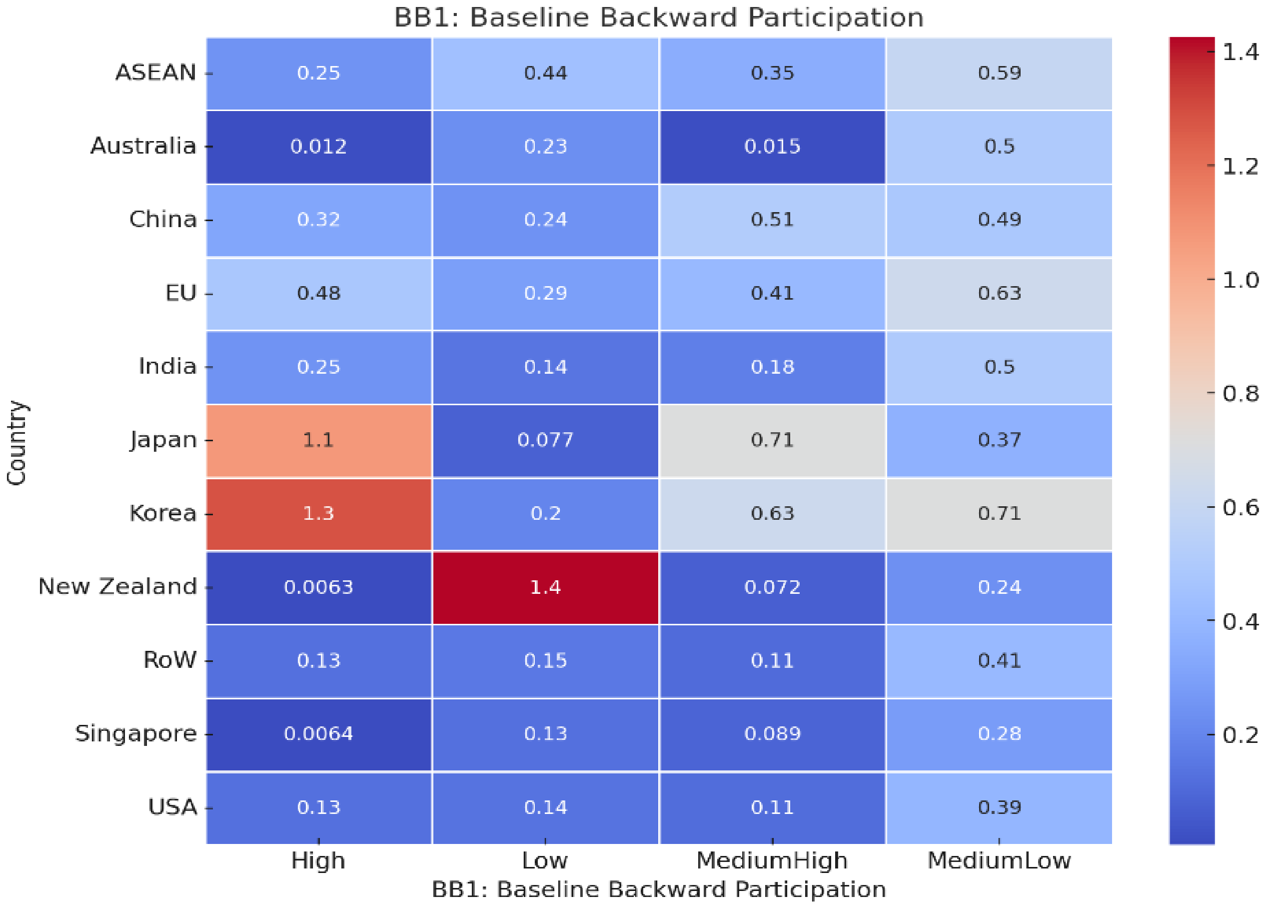
Source: Author's Calculation

3.9 Appendix D



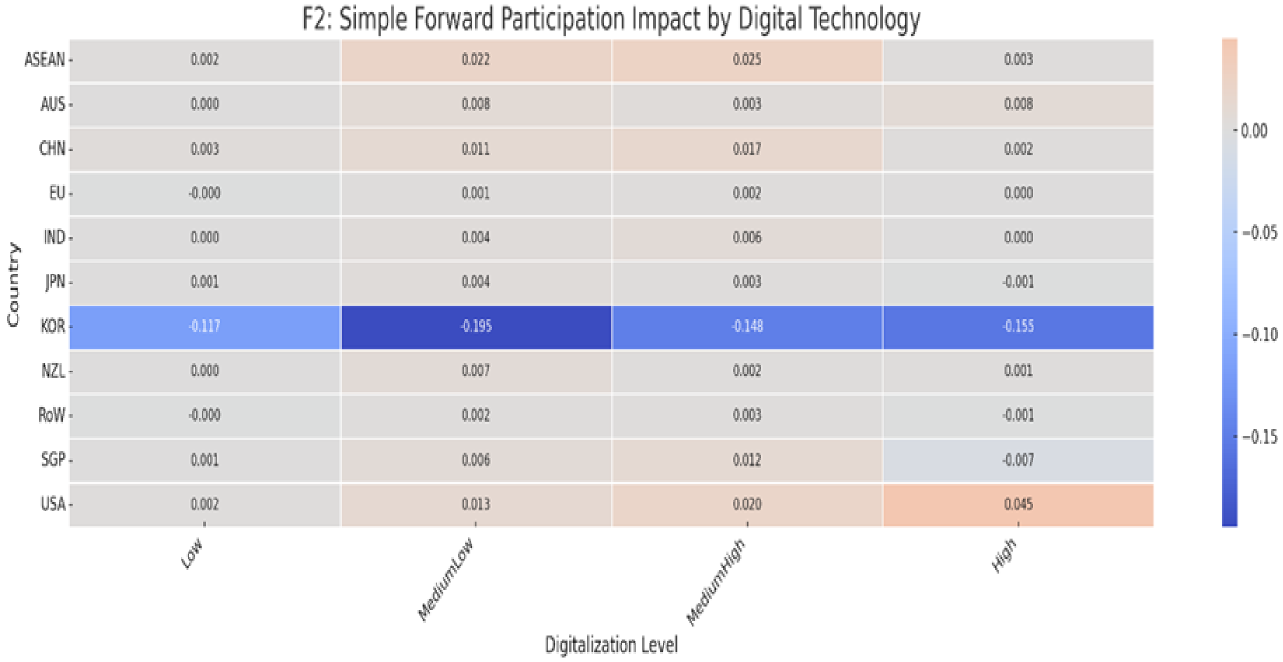
Source: Author's Calculation

3.10 Appendix E



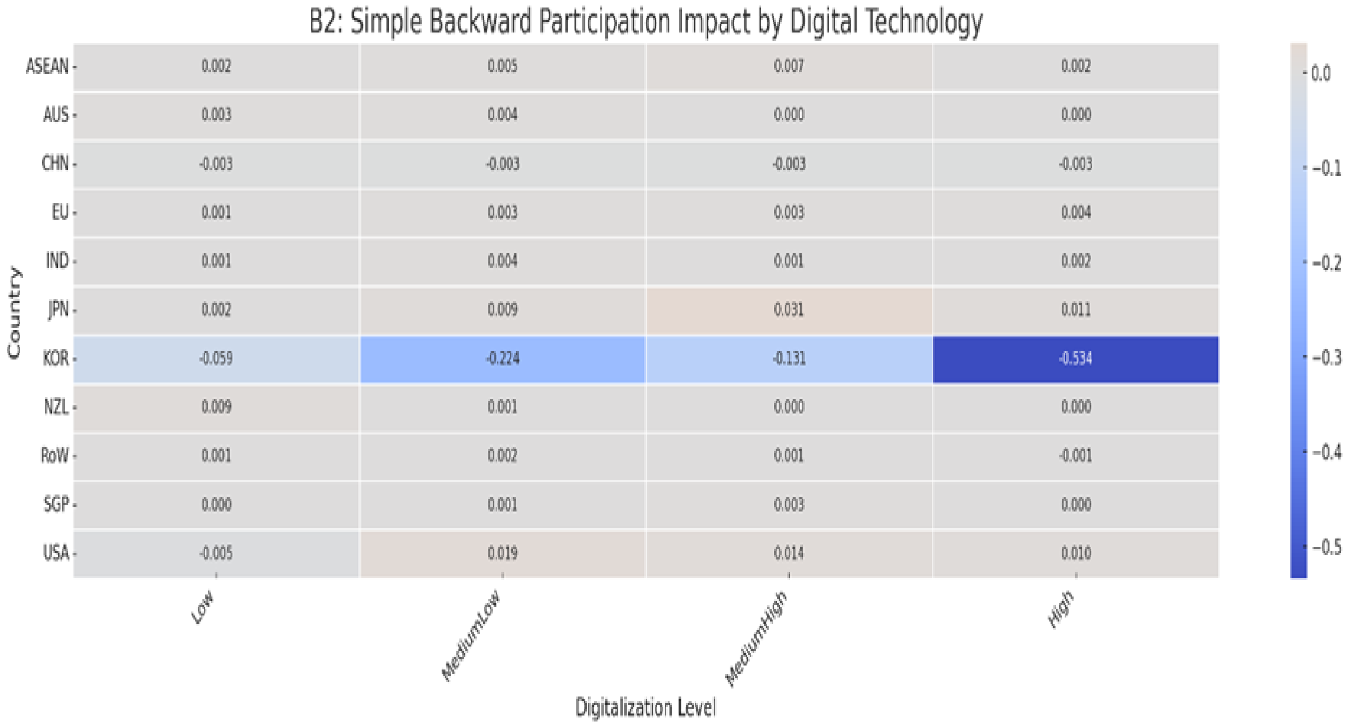
Source: Author's Calculation

3.11 Appendix F



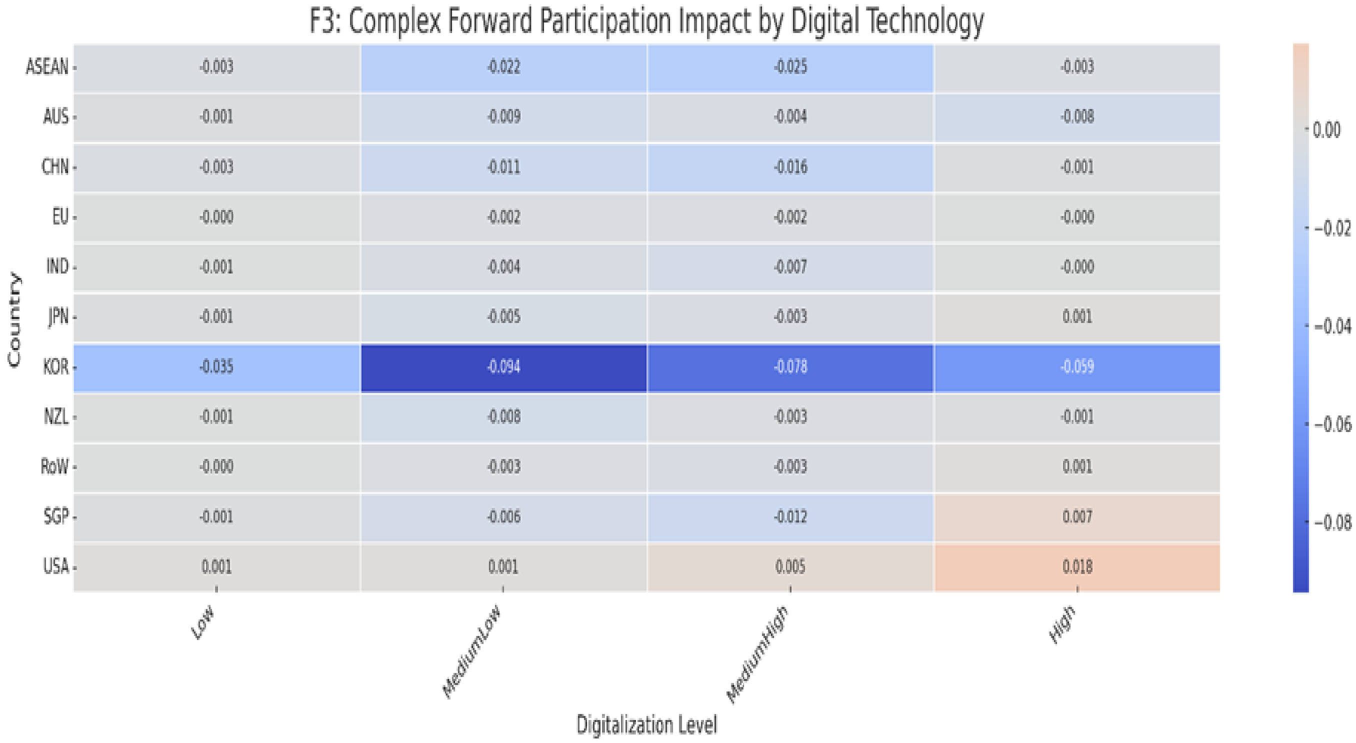
Source: Author's Calculation

3.12 Appendix G



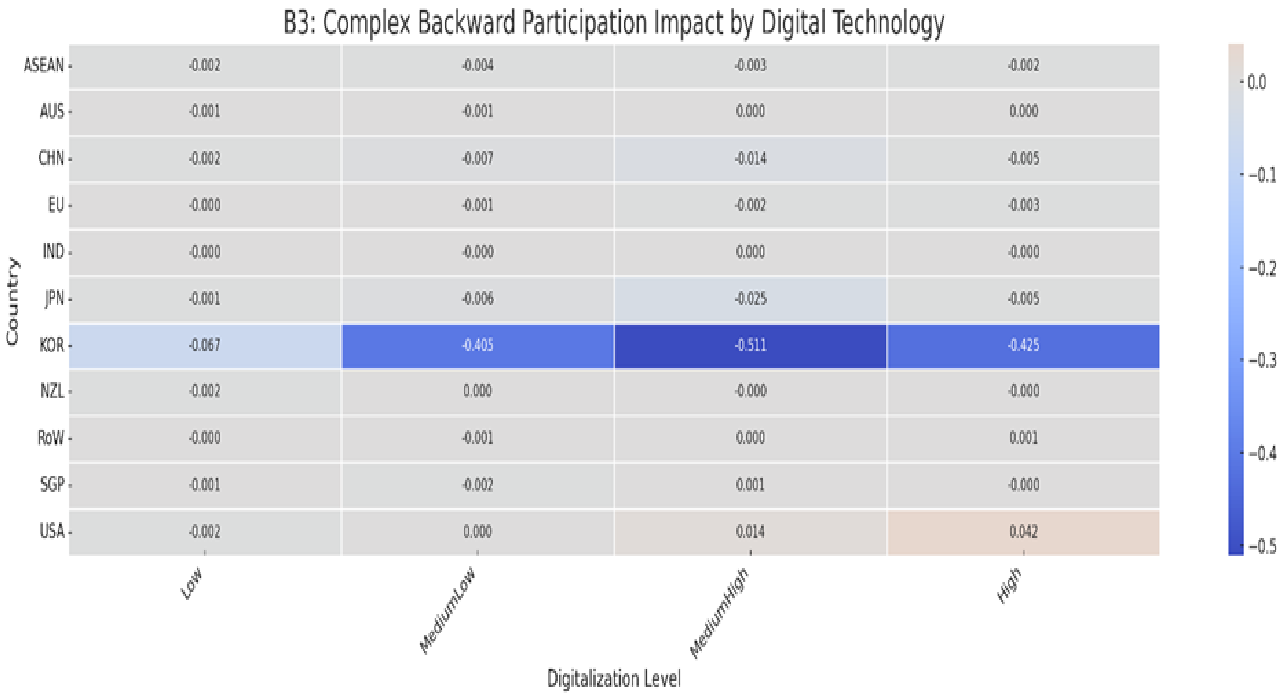
Source: Author's calculation

3.13 Appendix H



Source: Author's calculation

3.14 Appendix J



Source: Author's Calculation

Prelude to Leveraging Value Chains for Green Trade: New empirical evidence on the Moderating Role of Digitalization

The third manuscript in this thesis builds upon the previous two manuscripts by shifting the focus from manufacturing GVCs to the trade in environmental goods (EGs). While the first two studies examine how digitalization shapes GVC participation and GVC trade flows, this paper investigates whether a country's position in global value chains can enhance its exports of environmental goods—and how digitalization moderates this relationship.

The research employs a panel data analysis using a high-dimensional fixed effects model. The dataset covers bilateral trade in environmental goods across 75 countries, incorporating both linear and nonlinear measures of GVC positioning. The analysis further includes interaction terms to account for unobserved heterogeneity.

The results reveal a nonlinear, often convex, relationship between GVC positioning and environmental trade performance, with digitalization acting as a significant moderator. The interactions between GVC participation and digital capacity generates a U-shaped relationship, suggesting that digitalization can shift the trade benefits of GVC integration, as countries move on to higher end of the value chain involving green trade. However, these results vary across categories of these goods.

This analysis contributes to the growing literature on sustainable trade by linking GVCs with environmental performance and identifying digitalization as a critical enabler. The study provides new empirical evidence for policymakers seeking to promote green trade through value chain integration and development of digitalization.

Chapter 4 Leveraging Value Chains for Green Trade: New empirical evidence on the Moderating Role of Digitalization

Abstract

Understanding how countries can leverage global value chains (GVCs) to promote green trade is critical for advancing global sustainability. This study investigates the impact of GVCs positioning on green trade, with a particular emphasis on the moderating roles of GVC participation and digitalization. Using a harmonized dataset covering 75 countries from 1995 to 2020, the analysis combines HS 6-digit product-level trade data with GVC indicators and digitalization indices at the country-sector level, hitherto not attempted in the empirical literature. A high-dimension fixed model is employed for estimations and supported by robustness checks.

The results reveal that advancements in GVC positioning significantly boost cross-border green trade, following a convex pattern where higher GVC positions yield increasingly substantial marginal effects. Furthermore, the results uncover heterogeneous effects across different EGs (Environmental Goods) categories, with both linear and nonlinear dynamics emerging depending on product characteristics, which also shape the moderating roles of GVC participation and digitalization.

These results highlight the importance of aligning GVC strategies with digital transformation and GVC participation policies to maximize green trade benefits. This study contributes to the literature on green trade and offers actionable insights for policymakers aiming to achieve global environmental objectives.

4.1 Introduction

In the face of escalating global environmental challenges, achieving sustainable development has emerged as an urgent global consensus. Nations worldwide are now shifting their focus towards sustainable transformation and green growth. Central to this endeavor is the crucial role of global multilateral environmental cooperation, with trade in environmental goods taking center stage as a vital avenue for international environmental collaboration (Can et al. 2021). Environmental goods (EGs) are goods used for pollution control and environmental improvement (UNCTAD, 1995). Climate change mitigation can be enhanced by developing, adopting and deploying environmental technologies (ET). International trade in environmental goods can enable access to ET embodied in environmental products, and can help diffuse these technologies. Opening up trade in EGs further could potentially benefit the environment (World Trade Report, 2022).

Promoting trade in environmental goods holds immense potential to drive the transformation of development mode and foster green economic growth by optimizing trade structures and facilitating the dissemination of green environmental technologies (Cantore & Cheng 2018; Fraccascia et al. 2018). Specifically, the trade of EGs plays a significant role in fostering cleaner production practices (Dijkstra & Mathew, 2016). It can also contribute to welfare gains, especially in nations with relatively low internal demand for such goods (Wan et al., 2018). These benefits are particularly evident in scenarios where the environmental costs of producing polluting inputs are minimal, or where the societal emphasis on environmental enhancement is strong (Zugravu-Soilita, 2018). Notably, international negotiations, such as the Doha Round, have sought to promote the liberalization of trade in EGs, aiming to expand markets and promote the use of EGs, thereby mitigating environmental pressures (Mao & Wang 2022; Mealy & Teytelboym 2022).

Moreover, in the last decades, the pursuit of ever-better economic opportunities has pushed industrial organizations to delocalize: this process has built fragmented and functionally integrated chains of production and commercialization, also known as Global Value Chains (GVCs), in which firms and industries contribute to the final productions by assembling parts and components (Geref & Korzeniewicz, 1994).

Countries leverage their comparative advantages by integrating into specific positions within the production process. This involves extensive input and output of intermediates both domestically and internationally, forming the foundation of global production networks. Countries are involved in distinct roles within GVCs, undertaking diverse tasks in the international division of labor. Shifts in their positions within these chains can alter the direction of firms' technological advancements (Antràs & Chor, 2013).

GVC positioning, on the other hand, describes a country's or industry's position within the GVCs, reflecting its level of participation and value-added contribution. The promotion of the embedding position of GVC mainly refers to the gradual transfer from the downstream to the upstream and from the low value-added to the high value-added link of the industry, allowing economic upgrading. Specifically, specializing in upstream (e.g., producing key components or innovating in design and R&D) rather than downstream (e.g., assembly and production) stages of GVCs is generally associated with higher value-added shares and greater technological sophistication (Meng & Ye, 2022; Hummels et al., 2001; Baldwin & Yan, 2016; Hagemejer & Ghodsi, 2017).

Different positions demand varying product qualities and R&D priorities, prompting firms to adapt as their value chain roles shift. The technological advancements of partners influence domestic firms through the production network, shaping national technological progress (Coe & Helpman, 1995). Green technologies, defined by their complexity and incorporation of novel elements, often exert far-reaching impacts on subsequent innovations (Barbieri et al., 2020). Additionally, countries at higher GVC positions face stricter environmental standards, alongside greater social responsibilities, making environmental technology essential for competitiveness. In this context, advancing a country's position within GVCs serves as a critical factor in enhancing the efficiency of green technology innovation. It functions not only as a key driver but also as a catalyst for fostering an enabling environment that supports sustained technological progress (Hu et al., 2021) and, in turn, promotes cross-border trade in environmental products.

Further, being involved in GVCs not only facilitates general knowledge diffusion (Jona-Lasinio et al., 2019) and learning opportunities but also support the transfer of "green" knowledge. This occurs directly through technologies (Glachant et al., 2013) or indirectly by encouraging competition in green strategies (De Marchi et al., 2013; 2020). GVC integration can drive economies to upgrade production techniques to enhance competitiveness (De Marchi et al., 2020) or leverage these networks to adopt green technologies (Dechezleprêtre et al., 2013). For example, De Marchi et al. (2013) emphasize that opportunities within GVCs facilitate the sharing of green practices, enabling industries to maintain or strengthen their competitive advantages. Greater integration into GVCs not only amplifies the benefits of participation (Jurowetzki et al., 2018; Lema et al., 2019) but also accelerates advancements in green technologies as countries move up the position within GVCs. Understanding the combined effects of GVC participation and positioning on environmental products trade is therefore essential, offering insights into how GVC integration drives the cross-border diffusion of green technologies, ultimately shaping sustainable trade dynamics.

The distribution of value along the value chain exhibits a nonlinear pattern, often conceptualized and described using the "smile curve." (Shih, 1996). Based on the 'smile curve' hypothesis[17], differential benefits are found in the two tails of the production chains (Shin et al., 2012; Meng & Ye, 2022). Accordingly, impacts of GVC positioning on green technologies could potentially follow a nonlinear trajectory due to evolving challenges and opportunities at different stages. For example, in the early stages, firms invest in green technologies to meet international standards and boost competitiveness. At intermediate stages, progress may stall due to bottlenecks, competition, and path dependence. Over time, accumulated expertise, policy support, and market demand drive green technology development and commercialization, enhancing competitiveness

[17] The "Smiling Curve" is a conceptual model used to illustrate the distribution of value-added across different stages of a value chain. It depicts a nonlinear pattern where value-added is higher at both ends—such as R&D and marketing—and lower (such as manufacturing) in the middle, resembling the shape of a smile. This hypothesis highlights the increasing importance of knowledge-intensive activities in value creation amidst globalization and technological advances (Shin et al., 2012; Meng & Ye, 2022).

at advanced GVC stages. Therefore, it is significant to investigate whether the non-linear relationship exists between GVC position and trade in EGs[18].

Furthermore, the rapid advancement and pervasive adoption of information technology have transformed global trade, driving a shift toward digital trade and the digital economy (Jiang et al., 2024). In this evolving landscape, technology serves as the backbone, data provides the foundation, and knowledge fuels growth. The digitalization of GVCs has introduced a new mechanism for trade expansion (Mao et al., 2023; Miao, 2021; Zhu & Zhou, 2023).

Digitalization drives both industrial digitalization and digital industrialization, fostering sustainable development in the industrial sector (Wen et al., 2023; Yin, Liu, & Mahmood, 2023). This process promotes industrial structural optimization and upgrading, reshaping the global division of labor and trade structures as countries participate in GVCs. These shifts enhance a country's GVC positioning, leading to greater value-added gains.

From the perspective of digital industrialization, data—an essential input in digitalization—boosts productivity, redefines production relationships, and spurs the development of new technologies, products, and business models. This transformation establishes new production functions and opens pathways for efficient, sustainable economic growth (Bao & Lin, 2020). By altering production intensity factors, digital innovations can drive industrial transformation through incremental advancements.

In terms of industrial digitalization, the integration of digital technology with traditional industries introduces advanced technological solutions, products, and services, facilitating intelligent upgrades in conventional sectors. These advancements reshape cost structures and production functions, accelerating the evolution of traditional industries (Zhan & Li, 2020).

Digitalization drives industries toward higher-value segments of the GVCs by integrating digital technologies into research, production, transportation, and other operations. This transformation optimizes internal production structures and enables flexible production processes, facilitating an upward shift in GVC positioning. As a result, digitalization not only enhances traditional production functions but also establishes new ones, allowing countries and regions to overcome the constraints of the existing global labor division and escape the "low-end lock-in" trap. Understanding the interplay between digitalization and GVC positioning is thus essential for crafting policies that accelerate the diffusion of environmental technologies[19].

[18] EG trade is not simply high-tech trade: high-tech goods are defined by Eurostat/OECD as R&D-intensive product groups (SITC Rev.4; Eurostat, n.d.; Hatzichronoglou, 1997), whereas EG lists (OECD/APEC) are function-based HS sets targeting environmental uses. APEC shows most APEC EG lines concentrate in renewable energy, environmental monitoring/analysis, and waste/recycling (APEC Policy Support Unit, 2021), and APEC–OECD EG overlap is limited (≈27% of tariff lines), indicating different emphases rather than a high-tech bundle (Steenblik, 2005). This treatment is standard in the EG-trade gravity literature (Cantore & Cheng, 2018).

[19] While R&D and education expenditures are vital for general economic upgrading, this study isolates digitalization due to its unique network-driven capacity. Unlike localized capability-building investments, digitalization acts as a cross-border catalyst that directly reduces coordination costs within fragmented global value chains. Crucially, in the context of environmental goods, digital technologies uniquely enable the real-time monitoring, traceability, and resource optimization essential for verifying international green compliance.

This study addresses three key research questions: (1) How does a country's position within GVCs influence cross-border trade in EGs? (2) What are the combined effects of GVC positioning and GVC participation/digitalization on the trade of environmental goods? (3) Do these impacts vary across different categories of EGs?

The study makes several contributions to the existing literature. First, it integrates data from multiple sources, combining environmental product trade data at the Harmonized System (HS) 6-digit level with country-sectoral digitalization indices and GVC indicators derived from OECD input-output tables. To ensure consistency, the datasets are harmonized using the International Standard Industrial Classification of All Economic Activities (ISIC) Rev.4. Second, the analysis examines both linear and non-linear effects of GVC positioning on green trade by incorporating the square term of GVC position. Third, it investigates the mediating roles of GVC participation and digitalization in shaping the relationship between GVC positioning and EG trade. Finally, the study delves into the heterogeneous effects of GVC positioning across different categories of EGs, highlighting the moderating roles of GVC participation and digitalization in influencing trade dynamics.

The rest of the paper proceeds as follows: Section 7.2 is about data and methodology, section 7.3 presents results, and section 7.4 concludes.

4.2 Data and Methodology

This section presents the methodology and data utilized in this study. Specifically, Section 7.2.1 discusses the methodological approach, while section 7.2.2 focuses on the data employed in the analysis.

4.2.1 Empirical Specification

This paper adopts the gravity model of trade for estimation, which is a theory-consistent approach, focusing on quantifying the impact of determinants on international trade flows. Since Anderson's (1979) foundational work, the gravity equation has become a central tool for examining the relationship between trade flows and key policy variables (Head & Mayer, 2014). Anderson and Wincoop (2003) further advances this model by deriving it from a framework featuring a constant elasticity of substitution demand function and the Armington (1969) assumption of product differentiation. They emphasize the critical need to account for relative trade costs, as trade flows are influenced not only by bilateral trade barriers but also by each country's average trade costs with all other partners, referred to as "multilateral resistance." Baldwin and Taglioni (2006) highlighted the significance of including these multilateral resistance terms, describing their omission as the "gold medal mistake," particularly in long-panel data where multilateral resistance evolves over time. Additionally, Arkolakis et al. (2012) demonstrate that the gravity model is highly versatile, as it can be derived from various structural trade theories, such as Ricardian models (Eaton & Kortum, 2002) or frameworks with firm heterogeneity (Chaney, 2008; Melitz, 2003).

To capture the effect of GVC position on the distribution of green products, this paper follows Anderson & Yotov (2010) to construct the structural gravity model for sector *s* of country *i* and country *j* at time t of the following form:

$$EG_{ijst} = \beta_0 + \beta_1 GVCPosition_{ijst} + \beta_2 GVCPosition^2_{ijst} + \beta_3 Z + \gamma_{ij} + \varphi_{ij} + \delta_{ijs} + \varepsilon_{ijt} \quad (1)$$

Equation (1) is used to investigate the role of GVC position in promoting cross-border EGs trade. Where EG_{ijst} refers to bilateral trade in environmental goods between country *i* and country *j* at sector *s* at time *t*. According to the ISIC Rev.4 classification, EG_{ijst} is aggregated into sectoral level from 6-digit product level. $GVCPosition_{ijst}$ is the variable of sectoral GVC position, measuring countries' location within GVCs, and $GVCPosition^2_{ijst}$ is the square term to capture if non-linear relationship exists. These are variables of interest. To mitigate potential multicollinearity issues, the data has been standardized. Additionally, this work utilizes the average sectoral GVC position level between exporters and importers at time *t*. Z is the vector of control variables. Additionally, this paper controls for different types of fixed effects. As suggested by Baldwin & Taglioni (2006) and Yotov et al. (2017), γ_{ij} indicates the country-time fixed effects (i.e., accounts for MRTs) and φ_{ij} represents the country-pair fixed effects. δ_{ijs} is the sectoral fixed effects that reflects the long-term characteristics of each sector, and β_1 to β_3 are the coefficients associated with variables. ε_{ijt} is the error term.

$$EG_{ijst} = \beta_0 + \beta_1 GVCPosition_{ijst} + \beta_2 GVCPosition^2_{ijst} + \beta_3 GVCParticipation_{ijst} + \beta_4 \left(GVCParticipation_{ijst} * GVCPosition_{ijst}\right) + \beta_5 Z + \gamma_{ij} + \varphi_{ij} + \delta_{ijs} + \varepsilon_{ijt} \quad (2)$$

Equation (2) is primarily to analyze the role of GVC position combined with GVC participation on trade in EGs. Following Koopman et al. (2010), this paper measures one's GVC participation rate at country-sectoral level. Specifically, $GVCParticipation_{ijst}$ is the average sectoral GVC participation level between exporters and importers at time *t*. $GVCParticipation_{ijst} * GVCPosition_{ijst}$ is the key variables, and β_4 capture the interactions between GVC participation and GVC position.

$$EG_{ijst} = \beta_0 + \beta_1 GVCPosition_{ijst} + \beta_2 GVCPosition^2_{ijst} + \beta_3 Digitalization_{ijst} + \beta_4 \left(Digitalization_{ijst} * GVCPosition_{ijst}\right) + \beta_5 Z + \gamma_{ij} + \varphi_{ij} + \delta_{ijs} + \varepsilon_{ijt} \quad (3)$$

Equation (3) is constructed to study the joint effects of digitalization and GVC position on trade in EGs. Specifically, $Digitalization_{ijst} * GVCPosition_{ijst}$ is the key variables. β_4 reflects the impacts of GVC position on EGs in the presence of digitalization. $Digitalization_{ijst}$ is the average sectoral digitalization level between exporters and importers at time *t*.

4.2.2 Data

This study covers data from 1995 to 2020 for 75 countries. The dependent variable, trade flows in environmental products, is derived at the HS 6-digit product level using Base pour l'Analyse du Commerce International (BACI) data, while independent variables, such as digitalization and GVC position indices, are calculated from OECD input-output tables. Due to differences in classification standards between BACI and OECD input-output tables, ensuring coherence across datasets is essential. To address this, the study employs a concordance approach to harmonize the data. Trade flows are mapped to ISIC industry classifications from HS 6-digit product level for regression analysis, and digitalization and GVC position indices are similarly converted to align with ISIC sectors. This harmonized framework resolves inconsistencies between data sources, ensuring analytical compatibility.

4.2.3 Dependant Variable

The list of EGs used in this paper is derived from the OECD Consolidated List of EGs CLEG, consisting of 255 goods and 11 main categories in total (Sauvage, 2014). For details, the categories are 1) air pollution control 2) Cleaner or more resource-efficient technologies and products 3) Environmentally preferable products based on end-use or disposal characteristics 4) Heat and energy management 5) Environmental monitoring, analysis, and assessment equipment 6) Natural resource protection 7) Noise and vibration abatement 8) Renewable energy plant 9) Management of solid and hazardous waste and recycling systems 10) Clean up or remediation of soil and water 11) Wastewater management and potable water treatment.

Based on the 255 HS 6-digit environmental products classified by OECD, this paper utilizes the BACI provided by the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII) to obtain bilateral trade at product level. BACI covers bilateral values (in thousands of US dollars) and quantities (in tons) of world trade flows at HS 6-digit product disaggregation for more than 200 countries and 5000 products from 1995. BACI is updated every year and offers data with different revisions. This research utilizes the 1996 version and aggregates the 6-digit product trade flow at 2-digit industry classification level. Then, this analysis converts the HS 2-digit into country-sectoral level according to the ISIC Rev.4 classification.

4.2.4 Independent Variables

Digitalization Index

With the advent of the digital era, digital technology and the “digital dividend” have attracted extensive attention in academia. Digital sectors such as the production and provision of information technology hardware, software, IT consulting services, information services, and ICT products are the core of digitalization (Corejova and Madudova, 2019).

Adopting the methodology proposed by Zhang & Yu (2020), this research quantifies the extent of digital integration within discrete manufacturing sub-sectors through the application of OECD Multi-Regional Input-Output (MRIO) tables. This approach, attentive to inter-sectoral connections, yields a nuanced depiction of digital transformation across individual sectors. The constructed digitalization index gauges the prevalence of Information and Communication Technology (ICT) hardware alongside ICT-driven services, signifying the transition towards a digitized landscape.

Aligned with the ISIC Rev.4 and following the framework outlined by Zhang & Yu (2020), this study identifies four key categories of digital intermediate inputs: manufacturing of computers, electronic, and optical products (C-26);[20] telecommunications (J-61);[21] computer programming, consultancy, and related activities (J-62); and information service activities (J-63)[22]. The index measures the extent of digital technology adoption across sectors, capturing both direct and indirect contributions of digital inputs. Direct digital inputs refer to resources directly supplied by the four identified digital sectors and utilized by industries. Indirect digital inputs, on the other hand, represent digital components embedded within the broader supply chains of these sectors. By integrating both aspects, the digital intensity index provides a holistic view of digital technology diffusion, highlighting its multifaceted role in sectoral integration.

The digital index for the use of digital input j in sector g, b_{gj}, is:

$$b_{gj} = a_{gj} + \sum_{m=1}^{N} a_{gm} a_{mj} + \sum_{n=1}^{N} \sum_{m=1}^{N} a_{gn} a_{nm} a_{mj} + \cdots \qquad (4)$$

Where a_{gj} refers to the direct consumption of digital output by sector g, as defined above. $\sum_{m=1}^{N} a_{gm} a_{mj}$ is the indirect digital sector j's output consumed by the sector g via sector m. $\sum_{n=1}^{N} \sum_{m=1}^{N} a_{gn} a_{nm} a_{mj}$ represents the additional indirect consumption of sector g to digital sector j through sectors m and n (and so on) until it covers indirect digital inputs in all relevant sectors.

GVC Participation Index

Existing research has been conducted both domestically and internationally on the measurement of GVC integration. Hummels et al. (2001) was among the first to propose the vertical specialization analysis framework within the context of GVCs, introducing the Vertical Specialization Share (VSS) index. However, the VSS index is limited in scope, as it primarily measures the level of vertical specialization in an industry

[20] Manufacture of electronic components and boards, manufacture of computers and peripheral equipment, manufacture of communication equipment, and manufacture of consumer electronics (C-26).

[21] Wired-, wireless-, satellite-, and other telecommunications activities (J-61).

[22] Data processing, hosting and related activities (J-63).

within a country, without capturing the value-added contributions of different countries and sectors or distinguishing between various production stages within the GVC.

To address these limitations, researchers have increasingly turned to input-output tables for calculating GVC-related indicators. Koopman et al. (2010) relaxes the assumptions underlying the vertical specialization framework and developed the value-added trade accounting method, providing a more comprehensive approach to analyzing GVC integration.

For more information, Koopman et al. (2010) decomposes the value-added components of a country's exports. Assuming G countries and N sectors, a multi-country, multi-sector analysis is conducted using the direct value-added coefficient diagonal matrix $\hat{V}$ and the export diagonal matrix $\hat{E}$. By multiplying the direct value-added coefficient matrix $\hat{V}$ with the Leontief inverse matrix B and the export matrix $\hat{E}$, the value-added decomposition of exports across countries can be achieved.

$$V\hat{B}E = \begin{bmatrix} V_1 \sum_r^G B_{1r}E_{r1} & V_1 \sum_r^G B_{1r}E_{r2} & \cdots & V_1 \sum_r^G B_{1r}E_{rG} \\ V_2 \sum_r^G B_{2r}E_{r1} & V_2 \sum_r^G B_{2r}E_{r2} & \cdots & V_2 \sum_r^G B_{2r}E_{rG} \\ \cdots & \cdots & \cdots & \cdots \\ V_G \sum_r^G B_{Gr}E_{r1} & V_G \sum_r^G B_{Gr}E_{r2} & \dots & V_G \sum_r^G B_{Gr}E_{rG} \end{bmatrix}_{(GN*GN)} \quad (5)$$

Equation (5) shows the sum of the off-diagonal elements in the corresponding row of matrix $V\hat{B}E$ represents the indirect value-added exports of country *r*. The sum of the off-diagonal elements in the corresponding column of matrix $V\hat{B}E$ represents the foreign value-added $FV_r (FV_r = \sum_{s \neq r} V_s B_{sr} E_{r^*})$ to the exports of country r. This reflects the portion of country *r*'s exports that consists of value added by other countries in the GVCs. The diagonal elements of matrix $V\hat{B}E$ reflect the domestic value-added portion $DV_r (DV_r = V_r B_{rr} E_{r^*})$ in the exports of each country. Based on this decomposition in Koopman et al. (2010), this paper constructs the GVC participation index to measure a country's degree of involvement in GVCs. A higher value of the index indicates a greater degree of participation by the country in GVCs:

$$GVC\ Participation = \frac{IV_{ir}}{E_{ir}} + \frac{FV_{ir}}{E_{ir}} \quad (6)$$

In equation (6), IV_{ir} represents the indirect value-added exports of industry i in country r, capturing the value of intermediate goods exported to other countries and subsequently re-exported to a third country after processing. This measures the extent to which value-added from r's industry i is embedded in its intermediate exports. FV_{ir} denotes the foreign value-added embedded in the exports of final goods by industry i in country r, representing the value of imported intermediates contained in its final goods exports. Lastly, E_{ir} indicates the value-added exports of industry *i* in country *r*. **Table 0-1** summarizes the data.

Table 0-1 Descriptive Statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
EG_{ijst}	10217899	10.568	3.066	0	23.698
$GVCPosition_{ijst}$	10217899	0	1	-4.635	2.822
$GVCPosition^2_{ijst}$	10217899	1	1.819	0	21.481
$Digitalization_{ijst}$	10206989	0	1	-3.704	3.431
$GVCParticipation_{ijst}$	10208186	0	1	-13.563	2.171

Source: Author's elaboration

GVC Position Index

Koopman et al. (2010) assesses the international division of labor position of an industry within GVCs, known as the GVC position index. The GVC position index gauges a country's relative role as an importer versus an exporter of intermediates, thereby reflecting its capacity to generate value added within the GVCs division of labor. It compares the logarithm of the value of intermediate goods exported by an industry (used by other countries to produce and export final goods) to the logarithm of the value of imported intermediate goods utilized in domestic production and export of final goods. In essence, it measures the difference between the log value of an industry's intermediate goods exports and the log value of imported intermediate goods embedded in its exports. The index is measured as follows:

$$GVC\_Position_{ir} = \ln\left(1 + \frac{IV_{ir}}{E_{ir}}\right) - \ln\left(1 + \frac{FV_{ir}}{E_{ir}}\right) \qquad (7)$$

In equation (7), the $GVC\_Position_{ir}$ reflects the role of country r and industry i in the international division of labor within GVCs. IV_{ir}, FV_{ir}, and E_{ir} indicate the same content with those in the equation (6).

The positive value of GVC position means that the country is relatively located in upstreamness while the negative one denotes the position in downstreamness. According to Koopman et al. (2010), when a country operates in the 'upstream' segment of an industry's GVC (characterized by activities such as innovation, R&D, design, branding, and the production of components), it primarily contributes to GVC production by supplying intermediates to other countries. For such countries, the share of indirect value-added (IV_{ir}) in total exports (E_{ir}) tends to exceed the share of foreign value-added (FV_{ir}) in total exports. Conversely, countries engaged in the downstream segment of a GVC, such as final product assembly, rely heavily on imported intermediates to produce final goods. In these cases, IV_{ir} is typically lower than FV_{ir}. Therefore, the higher the $GVC\_Position_{ir}$ value, the higher the country's industry position in the GVC's international division of labor. Conversely, a lower $GVC\_Position_{ir}$ indicates a lower position within the GVC.

4.3 Results

This section presents the results for empirical analysis. Section 7.3.1 presents results for the baseline analysis, section 7.3.2 presents robustness and endogeneity check, section 7.3.3 presents results for extended analysis and section 7.3.4 presents heterogeneity analysis.

4.3.1 Baseline Analysis Results

Column (1) of Table 0-2 presents the baseline analysis results. The coefficients for the key policy variables, GVC positioning and its quadratic term, are both positive and statistically significant, confirming a convex relationship between GVC positioning and the diffusion of EGs. This indicates that the trade-enhancing impact of GVC positioning on EG trade becomes more pronounced as countries advance further along the GVC spectrum. Specifically, a 1% increase in GVC positioning corresponds to an approximate increase in the growth rate of EG trade by 0.166% + 0.01772% * (GVC positioning). This accelerating effect suggests that countries in higher GVC positions not only participate in greater volumes of EG trade but also experience a more substantial growth rate in trade as their GVC positioning improves.

Table 0-2 Baseline Analysis Results

	(1) EGs
$GVCPosition_{ijst}$	0.166^{***}
	(0.0112)
$GVCPosition_{ijst}^2$	0.00886^{*}
	(0.00358)
$Constant$	10.56^{***}
	(0.00358)
N	10217877
R^2	0.367
Country-pair FE	Yes
Country-Time FE	Yes
Sectoral FE	Yes

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

These results can be attributed to the distinct positioning of countries within GVCs. Developed countries typically occupy higher-end segments of GVCs, where high-value-added activities are concentrated, while developing countries are often positioned at the lower end, primarily supplying raw materials or engaging in basic production processes. High-end GVC countries leverage their technological expertise to play a central role in the global trade of EGs, facilitating the international diffusion of these goods and technologies. Their strategic position within the trade ecosystem allows them to significantly influence global dialogues on environmental standards and technology transfer, thereby reinforcing their dominance in the global EG market (Wang et al., 2024).

4.3.2 Robustness and Endogeneity Check

4.3.2.1 Re-estimate the Model Using Different Samples

Column (1) and column (2) of Table 0-3 present results for robustness check by re-estimating the model using different samples. Specifically, in column (1), the results are obtained by re-run the model using data from 2005 to 2020, excluding the data from 1995 to 2004. Results in column (2) are estimated by re-estimating the model while excludes USA, i.e., the country with the largest GDP. Overall, results show that the signs and significance of coefficients are the not changed compare to those in the baseline analysis, confirming robustness of the conclusions drawn from Table 0-2.

Table 0-3 Robustness Check

	(1) EG_{ijst}	(2) EG_{ijst}	(3) EG_{ijst}
$GVCPosition_{ijst}$	0.142***	0.160***	0.0159***
	(0.0123)	(0.0116)	(0.00108)
$GVCPosition_{ijst}^2$	0.00886*	0.0144***	0.000967**
	(0.00391)	(0.00366)	(0.000350)
$Constant$	10.60***	10.45***	2.372***
	(0.00361)	(0.00334)	(0.000356)
N	7145161	9611833	10217877
R^2	0.370	0.349	
pseudo R^2			0.063
Country-Pair FE	Yes	Yes	Yes
Country-Year FE	Yes	Yes	Yes
Sectoral FE	Yes	Yes	Yes

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.3.2.2 Regressions Using the PPML Estimator

This paper further re-estimates the model using a structural Poisson Pseudo-Maximum Likelihood (PPML) estimator given that the estimator can effectively address heteroscedasticity and zero trade flows in cross-border trade (Silva & Tenreyro, 2011). Column (3) of Table 0-3 presents results estimated by PPML estimator.

The PPML results closely align with those of the baseline regression, exhibiting similar coefficient magnitudes, signs, and statistical significance. This consistency suggests that the core results are not sensitive to the choice of estimation technique. The robustness of the results underscores the reliability of the identified relationships between GVC position and trade in EGs, ensuring that the conclusions drawn are methodologically sound and empirically stable.

4.3.2.3 Endogeneity Check

A potential endogeneity concern arises from reverse causality. While GVC upgrading may promote trade in environmental goods, increased EG exports can also drive structural upgrading through technology spillovers and stricter environmental standards. Firms may adopt cleaner production practices in response to trade pressures, making the direction of causality between GVC positioning and green trade inherently bidirectional.

To address the potential endogeneity, this study employs the first lag of GVC position and forward GVC participation (FGVCP) as instrumental variables. Li et al. (2023) argue that the FGVCP captures exogenous variation in a country's upstream positioning in GVCs, while the first lag of the GVC status index serves to mitigate potential reverse causality between current GVC positioning and environmental performance. The combination of these instruments strengthens the identification strategy by addressing endogeneity concerns associated with contemporaneous GVC embedding.

Table 0-4 presents results for endogeneity check by re-estimating the model using Instrumental Variable (IV) Two-Stages Least-Squares (2SLS). Results show that the validity of the instrumental variables is confirmed. Diagnostic tests results in Table 0-4, including the Kleibergen-Paap LM statistic and the Cragg-Donald Wald F-statistic, confirm the strength of the instruments, while the Hansen J statistic supports the validity of the instruments. These results are consistent with those presented above and indicate that the core analysis is not affected by potential endogeneity issues.

Table 0-4: Endogeneity Check

	(1)
	2SLS
	EG_{ijst}
$GVCPosition_{ijst}$	0.611***
	(0.0406)
$GVCPosition_{ijst}^2$	0.105***
	(0.0154)
$Constant$	8.168***
	(0.133)
N	10212373
R^2	0.040
Country-pair FE	Yes
Country-time FE	Yes
Sectoral FE	Yes
Kleibergen-Paap rk LM statistic	1248.989
F-test of excluded instruments	1.1e+04
Hensen J test	1.322

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.3.3 Extended Analysis by Incorporating Mediating Variables

Existing literature underscores the significant influence of GVC positioning and GVC participation on trade. However, the combined effects of these two factors remain underexplored. This section seeks to bridge this gap by introducing interaction terms to examine the heterogeneous effects of GVC participation on EGs trade across different stages of GVC integration. Furthermore, the analysis extends to explore the interplay between GVC positioning and digitalization, offering insights into how digital advancements shape the trade dynamics of EGs within the GVC framework.

For further details, column (1) of Table 0-5 presents the results estimated using equation (2), which examines the combined impact of GVC positioning and GVC participation on EG trade. The analysis includes GVC Position, its quadratic term (i.e., $GVCPosition_{ijst}^2$), and GVC participation as control variables. Compared to the results in the baseline analysis, the interactive terms (i.e., $GVCParticipation_{ijst} * GVCPosition_{ijst}$) reflect the mediating effects on GVC position and trade in EGs. Column (2) presents the results estimated using equation (3), which examines the joint effects of digitalization and GVC positioning on EG trade through the inclusion of interaction terms (i.e., $Digitalization_{ijst} * GVCPosition_{ijst}$). The analysis also incorporates digitalization, GVC Position, and its quadratic term (i.e., $GVCPosition_{ijst}^2$) as control variables.

Table 0-5 Mediating Effects Analysis by Incorporating Interactive Terms

	(1)	(2)
	EG_{ijst}	EG_{ijst}
$GVCPosition_{ijst}$	0.025	0.140***
	(0.014)	(0.011)
$Digitalization_{ijst}$		-0.098***
		(0.015)
$Digitalization_{ijst} * GVCPosition_{ijst}$		0.029***
		(0.006)
$GVCPosition_{ijst}^2$	0.019***	0.021***
	(0.004)	(0.004)
$GVCParticipation_{ijst}$	-0.364***	
	(0.065)	
$GVCParticipation_{ijst} * GVCPosition_{ijst}$	-0.579***	
	(0.038)	
$Constant$	10.40***	10.56***
	(0.027)	(0.003)
N	10208163	10206966
R^2	0.368	0.367
Country-Pair FE	Yes	Yes
Country-Time FE	Yes	Yes
Sector FE	Yes	Yes
UTEST	PASS	PASS
U-shaped Curve	U-Shaped	U-Shaped
Turning point	-0.677	-3.270

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

In column (1), the estimated coefficients for the interaction terms are negative and statistically significant. This indicates that GVC participation plays a critical role in shaping the effect of GVC positioning on EG trade. Specifically, the negative coefficient suggests that the impact of GVC positioning on EG trade is significantly amplified for countries with downstream specialization. This amplification can be attributed to backward GVC participation, which facilitates access to advanced green technologies, fosters local innovation, and enhances the trade of environmental products. The resulting technology transfer extends beyond production processes to higher levels of integration and innovation, thereby strengthening the positive effects of GVC positioning on EG trade. By enabling the adoption of green technologies, backward GVC participation supports the production of goods that meet international environmental standards, boosting regions' competitiveness in global markets (Colozza et al., 2024). This dual advantage—combining backward participation with strategic GVC positioning—enhances these regions' capacity to produce and export environmental products more effectively, solidifying their competitive standing in the global marketplace.

Furthermore, column (2) of Table 0-5 offers the combined effects of GVC position and digitalization on trade in EGs. Specifically, the coefficient of linear interaction ($Digitalization_{ijst} * GVCPosition_{ijst}$) is positive and statistically significant (i.e., 0.0635), indicating that a higher level of digitalization strengthens the overall effect of GVC position on trade in EGs. This could because that digitalization contributes to the modernization of industrial structures and the adoption of green technologies, enabling firms in higher GVC positions to more effectively produce products that meet green standards, thereby further promoting the trade of environmental products. As the level of digitalization increases, this facilitating effect becomes more pronounced (Ma et al., 2023).

Furthermore, the introduction of moderating variables, such as GVC participation and digitalization, can uncover U-shaped or inverted U-shaped relationships between the independent and dependent variables. These moderators can influence the direction or magnitude of the primary effect (i.e., the impact of GVC positioning on EG trade), thereby introducing nonlinear dynamics. Specifically, moderating variables may cause the marginal effects of the independent variable on the dependent variable to shift from negative to positive, or vice versa, under different moderating conditions (Lind and Mehlum, 2010).

Additionally, with the presence of nonlinear relationship, it is essential to assess the robustness of U-shaped or inverted U-shaped relationships. A statistically significant coefficient for the quadratic term does not necessarily confirm the existence of a U-shaped relationship. This is because many empirical studies include a nonlinear (typically quadratic) term in standard linear regression models to test for such relationships. A genuine U-shaped or inverted U-shaped relationship is confirmed only if the quadratic term is statistically significant and the estimated turning point lies within the observed data range.

However, Lind and Mehlum (2010) argue that this criterion is insufficiently robust, as model estimation can erroneously produce an extreme point and suggest a U-shaped or inverted U-shaped relationship when the actual relationship is convex and monotonic. To address this limitation, this study employs the UTEST command developed by Lind and Mehlum (2010) to rigorously test whether the two variables exhibit a genuine U-shaped or inverted U-shaped relationship.

The UTEST for U-shaped or inverted U-shaped relationships is inherently complex, as the null hypothesis stipulates an increase on the left side of the interval and a decrease on the right side. UTEST offers a precise method to test whether a U-shaped relationship exists within a given interval. In this study, UTEST is applied to the estimation results in Table 0-5. The findings confirm that the calculated turning points fall within the range of observed data values and reject the null hypothesis at the 1% statistical significance level.

The moderating variables, specifically backward GVC participation and digitalization, reshape the marginal effect of GVC positioning on environmental product trade, transitioning it from a convex monotonic increase to a U-shaped relationship. This shift is marked by diminishing marginal effects before the turning point, followed by increasing marginal effects beyond it. The results also align with Hanns et al. (2016), demonstrating that moderating variables can alter the dynamic balance between potential benefit and cost functions, leading to the emergence of new nonlinear relationships or the disappearance of existing ones.

A country's position within the GVC is critical in determining its ability to leverage backward participation for technological upgrading. At lower GVC stages, technological lock-in effects can restrict opportunities for progress, hindering the adoption and adaptation of new technologies. Conversely, countries at higher GVC stages are better equipped to harness the innovation and productivity gains facilitated by backward participation, enhancing their roles within the value chain and realizing greater economic benefits (Colozza & Pietrobelli, 2023).

Digitalization influences GVC positioning by mediating productivity enhancements, with its effects varying significantly across different stages of the GVC (Zhang et al., 2023). The U-shaped relationship between digitalization and GVC positioning identified by Li et al. (2024) highlights this variation and aligns with this study's findings on the moderating role of digitalization in the relationship between GVC positioning and environmental product trade. At lower GVC stages, countries often encounter constraints such as limited technological adaptability, which hinder the growth of EG trade. In contrast, at higher GVC stages, digitalization acts as a transformative force, significantly boosting trade by enhancing productivity and optimizing value chain operations. This dynamic explains the observed shift in the relationship between GVC positioning and environmental product trade from a convex pattern to a positive U-shaped pattern under the influence of digitalization as a moderating factor.

4.3.4 Heterogeneity Analysis

This section presents a disaggregated analysis of various types of EGs. Using the OECD Combined List of Environmental Goods (CLEG) (Sauvage, 2014), all 255 EGs are classified into 11 categories, as outlined in Section 2.2.1. Tables (6) to (8) display the results of the disaggregated analysis based on equations

(1) through (3). Section 3.4.1 evaluates the impact of GVC positioning on the trade of specific EG categories, while Sections 3.4.2 and 3.4.3 examine the combined effects of GVC positioning with GVC participation and digitalization, respectively, on different types of EGs. Although the baseline regression results demonstrate that improved GVC positioning enhances overall trade in environmental products, they do not reveal the nuanced effects on specific EG categories. This heterogeneity analysis offers more detailed empirical insights into these dynamics.

4.3.4.1 Impacts of GVC position on Different Types of EGs

Columns (1) through (11) of Table 0-6 present the empirical results on the impacts of GVC positioning across various categories of EGs. Specifically, the columns correspond to the following categories: (1) Air Pollution Control, (2) Cleanup or Remediation of Soil and Water, (3) Cleaner or More Resource-Efficient Technologies and Products, (4) Environmental Monitoring, Analysis, and Assessment Equipment, (5) Environmentally Preferable Products Based on End-Use or Disposal Characteristics, (6) Heat and Energy Management Products, (7) Management of Solid and Hazardous Waste and Recycling Systems, (8) Natural Resource Protection, (9) Noise and Vibration Abatement, (10) Renewable Energy Plant, and (11) Wastewater Management and Potable Water Treatment.

Results suggest that improvements in GVC positioning have differentiated effects on the cross-border trade of various environmental product categories, exhibiting both linear and nonlinear influences. Compared to the baseline regression, only results in column (6) demonstrate a similar pattern, i.e., a convex relationship. As explained in Yang et al. (2022), as countries upgrade to higher position within GVCs, countries particularly tend to leverage the GVC integration to acquire advanced energy-saving technologies, steering technological progress toward energy efficient. Moreover, the results in column (5) indicate that a 1% improvement in GVC positioning corresponds to a 0.83% increase in trade of Environmentally preferable products based on end-use or disposal characteristics. This can be attributed to the fact that countries with higher GVC positioning often implement stricter environmental regulations, such as mandatory energy efficiency standards. These regulations incentivize local firms to invest in and innovate energy-saving technologies, equipment, and environmentally friendly products (Sauvage, 2014). The results emphasize the increasing environmental awareness and the transition toward green consumption in mid- and high-tier GVC countries, highlighting the growing and sustained market demand for energy-efficient and environmentally-preferable products in the context of global trade.

Table 0-6 Impacts of GVC position on Trade in Different Types of EGs

	(1) Air Pollution Control	(2) Clean up or remediation of soil and water	(3) Cleaner or more resource-efficient technologies and products	(4) Environmental monitoring, analysis, and assessment equipment	(5) Environmentally preferable products based on end-use or disposal characteristics	(6) Heat and energy management	(7) Management of solid and hazardous waste and recycling systems	(8) Natural resource protection	(9) Noise and vibration abatement	(10) Renewable energy plant	(11) Wastewater management and potable water treatment
$GVCPosition_{ijst}$	-0.039	-0.133**	-0.129***	-0.019	0.830***	0.244***	0.033	0.135*	0.030	0.024	0.307***
	(0.079)	(0.047)	(0.022)	(0.015)	(0.065)	(0.030)	(0.027)	(0.061)	(0.050)	(0.018)	(0.023)
$GVCPosition_{ijst}^2$	-0.067***	-0.002	0.003	0.014	0.041	0.023**	-0.040***	-0.161***	-0.001	-0.034***	-0.077***
	(0.016)	(0.017)	(0.009)	(0.008)	(0.021)	(0.008)	(0.007)	(0.032)	(0.023)	(0.005)	(0.007)
$Constant$	10.82***	10.21***	10.29***	10.31***	9.206***	10.25***	11.07***	9.515***	11.06***	10.75***	10.82***
	(0.007)	(0.017)	(0.008)	(0.018)	(0.020)	(0.008)	(0.007)	(0.032)	(0.023)	(0.005)	(0.007)
N	1756027	176440	1035859	1836096	130594	1015797	1106352	92460	199745	2278632	1756027
R^2	0.480	0.478	0.320	0.376	0.473	0.412	0.399	0.499	0.715	0.351	0.480
Country-Pair FE	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-Time FE	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE				Yes							
Time FE				Yes							
UTEST	PASS	NO PASS	NO PASS	NO PASS	NO PASS	NO PASS	PASS	PASS	NO PASS	PASS	PASS
U-shaped Curve	Inverse						Inverse	Inverse		Inverse	Inverse
Turning point	-0.297						0.411	0.419		0.350	1.979

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The results in columns (2) and (3) indicate a negative linear relationship between GVC positioning and the trade of specific environmental products. A 1% increase in GVC positioning corresponds to a 0.133% decline in trade for cleanup or remediation of soil and water products and a 0.129% decline for cleaner or more resource-efficient technologies and products. These products may often in higher demand in countries at lower GVC positions, as they are typically used in the early stages of pollution control. Conversely, demand could decrease in higher-positioned countries where pollution control efforts have largely been completed or have shifted towards investments in other types of environmentally friendly products. Moreover, low-cost production countries maintain a competitive advantage in these products, resulting in a decline in trade performance as GVC positioning improves. In contrast, the results in columns (4) and (9) show that changes in GVC positioning have no significant impact on the trade of environmental monitoring, analysis, and assessment equipment or noise and vibration abatement products.

Notably, for other environmental goods—specifically column (1): Air Pollution Control, column (7): Management of Solid and Hazardous Waste and Recycling Systems, column (8): Natural Resource Protection, column (10): Renewable Energy Plant, and column (11): Wastewater Management and Potable Water Treatment—the negative and statistically significant coefficients of the quadratic terms suggest an inverted U-shaped relationship. To ensure robustness, the study applies the UTEST, which confirms the presence of these inverted U-shaped relationships.

The inverted U-shaped relationship indicates that improvements in GVC positioning initially enhance the trade of these EGs, but this trend reverses as countries progress to advanced GVC stages. At higher GVC stages, demand shifts towards more sophisticated and efficient technologies, such as energy-efficient technologies and environmentally preferable products, reducing the demand for other types of EGs. Consequently, demand peaks at the mid-tier stage of GVC positioning, while remaining relatively lower at both the lower and higher ends of the GVC spectrum.

4.3.4.2 Impacts of GVC Positioning & GVC Participation on Different Types of EGs

This section examines the mediating effects of GVC participation on the trade of environmental products, categorized by product types as outlined in Section 7.2.2.1. The detailed results are presented in Table 0-7. A negative coefficient indicates that the trade-promoting effects of GVC positioning are stronger when combined with higher levels of backward GVC participation. Conversely, a positive coefficient suggests that forward participation has a more favorable influence on environmental product trade

Table 0-7 Impacts of GVC Positioning & GVC Participation on Different Types of EGs

	(1) Air Pollution Control	(2) Clean up or remediation of soil and water	(3) Cleaner or more resource-efficient technologies and products	(4) Environmental monitoring, analysis, and assessment equipment	(5) Environmentally preferable products based on end-use or disposal characteristics	(6) Heat and energy management	(7) Management of solid and hazardous waste and recycling systems	(8) Natural resource protection	(9) Noise and vibration abatement	(10) Renewable energy plant	(11) Wastewater management and potable water treatment
$GVCPosition_{ijst}$	-0.168	-0.287***	-0.169***	-0.061	0.714***	0.006	-0.093**	-0.221	-0.511***	-0.367***	0.215***
	(0.103)	(0.075)	(0.029)	(0.046)	(0.115)	(0.040)	(0.035)	(0.124)	(0.103)	(0.028)	(0.026)
$GVCParticipation_{ijst}$	-0.343	-1.232***	-0.207	-0.432***	-0.337	-0.127	1.599***	-1.352***	-0.322	1.819***	0.300
	(0.503)	(0.313)	(0.122)	(0.120)	(0.239)	(0.151)	(0.253)	(0.279)	(0.380)	(0.128)	(0.171)
$GVCParticipation_{ijst} * GVCPosition_{ijst}$	-0.848***	-0.525***	-0.146*	-0.011	-0.340	-1.235***	-0.589***	-1.238***	-1.273***	-1.631***	-0.776***
	(0.014)	(0.152)	(0.063)	(0.108)	(0.196)	(0.106)	(0.098)	(0.223)	(0.233)	(0.0877)	(0.088)
$GVCPosition^2_{ijst}$	0.0163	0.0197	0.015	0.010	0.092**	0.031***	-0.060***	0.0055	-0.060*	-0.072***	-0.0345***
	(0.026)	(0.018)	(0.009)	(0.012)	(0.032)	(0.009)	(0.011)	(0.037)	(0.027)	(0.006)	(0.009)
$Constant$	10.59***	9.585***	10.18***	10.13***	9.026***	10.25***	11.78***	8.498***	10.84***	11.40***	10.91***
	(0.241)	(0.153)	(0.059)	(0.053)	(0.136)	(0.045)	(0.116)	(0.183)	(0.191)	(0.049)	(0.067)
N	587119	176392	1034865	1835080	130592	1013303	1104827	92460	198917	2276484	1755518
R^2	0.488	0.479	0.320	0.376	0.473	0.413	0.399	0.502	0.716	0.352	0.481
Country-Pair FE	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-Time FE	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE				Yes							
Time FE				Yes							
UTEST	NO PASS	NO PASS	NO PASS	NO PASS	PASS	PASS	PASS	NO PASS	NO PASS	PASS	NO Pass
U-Shaped Curve					U-shaped	Inverse	Inverse			Inverse	
Turning point					-3.877	-0.100	-0.770			-2.567	

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

GVC participation exerts a heterogeneous moderating effect on the relationship between GVC positioning and the trade of different categories of environmental products. Among the eleven categories, nine [i.e., columns (1), (2), (6), (7), (8), (9), (10), and (11)] show that higher levels of backward GVC participation enhance the positive relationship between GVC positioning and EG trade, consistent with the findings in Table (5). Specifically, as the level of backward participation increases, the marginal effect of GVC positioning on trade becomes more pronounced, underscoring the reinforcing role of backward GVC participation.

The introduction of the interaction term between GVC participation and GVC positioning reveals substantial changes in the nonlinear relationship between GVC positioning and EG trade across different categories of environmental products. In columns (7) and (10), the inverted U-shaped relationship between GVC positioning and EG trade remains significant. However, incorporating GVC participation as a moderating factor causes notable shifts in the turning points: from 0.411 to -0.77 in column (7) and from 0.350 to -2.567 in column (10). This shift may occur because the moderating variable alters the marginal benefit or cost functions, leading to changes in the turning points (Lind & Mehlum, 2010).

Specifically, the findings indicate that the moderating effect of GVC participation accelerates the onset of diminishing marginal effects of GVC positioning on EG trade. At lower GVC stages, backward GVC participation significantly enhances trade's marginal effects through mechanisms such as technology transfer and resource optimization, resulting in trade peaks at earlier GVC stages. In contrast, at higher GVC stages, intensified market competition and resource saturation gradually diminish the marginal benefits of GVC participation (Antràs, 2020).

Moderating variables can alter the dynamic balance between potential benefits and costs, leading to the emergence of new nonlinear relationships or the attenuation of existing ones (Haans et al., 2016). In columns (1) and (8), the results indicate that the interaction between GVC participation and GVC positioning eliminates the previously significant inverted U-shaped relationship, thereby reducing nonlinearity. Backward GVC participation exerts a balancing effect that harmonizes the marginal impacts across different GVC stages, resulting in more linear effects. At lower levels of GVC positioning, backward participation enhances the positive trade effects, offsetting initial negative impacts. At higher levels, it mitigates the rate of marginal reductions in the trade-enhancing effects of GVC positioning, particularly for Air Pollution Control and Natural Resource Protection products.

Moreover, the moderating effect of GVC participation reveals differing nonlinear relationships between GVC positioning and EG trade. In column (5), a positive U-shaped relationship is observed for Environmentally Preferable Products Based on End-Use or Disposal Characteristics, while column (6) exhibits an inverted U-shaped relationship. In column (5), the initial impact of GVC positioning on trade is negative, likely due to high entry costs and the complexity of coordination at early stages. However, as GVC positioning improves, these barriers are gradually mitigated, resulting in enhanced technological capabilities and stronger market connectivity, which ultimately lead to a positive U-shaped relationship. Conversely, the results in column (6) indicate that GVC positioning initially exerts a strong positive effect on trade. Yet, as positioning advances to higher levels, diminishing marginal returns emerge, eventually producing an inverted U-shaped relationship.

4.3.4.3 Impacts of GVC Positioning & Digitalization on Different Types of EGs

This study investigates the moderating effect of digitalization on the relationship between GVC positioning and EGs trade. Specifically, a positive coefficient for the interaction term signifies a reinforcing (positive) effect, while a negative coefficient indicates a mitigating (negative) effect. The results in Table 0-8 reveal that digitalization negatively moderates the impact of GVC positioning on EG trade in columns (1), (6), (10), and (11), while positively moderating this relationship in columns (3), (5), (8), and (9).

Compared to the results in Table (6), the inverted U-shaped relationship between GVC positioning and environmental product trade remains consistent in columns (1), (7), (8), (10), and (11), though with notable shifts in the turning points due to the inclusion of the moderating variable. Specifically, the turning points shift to the right in columns (1), (7), and (11), moving from -0.297 to -0.170, from 0.411 to 0.835, and from 1.979 to 1.158, respectively, indicating that digitalization delays the diminishing marginal trade-enhancing effects of GVC positioning on EG trade. Conversely, the turning points in columns (8) and (10) shift to the left, from 0.490 to 0.282 and from 0.350 to 0.428, respectively, suggesting that digitalization accelerates the onset of diminishing effects, causing the trade peak to occur at earlier stages of GVC positioning.

Additionally, column (4) highlights the emergence of a new positive U-shaped relationship between GVC positioning and trade in environmental monitoring, analysis, and assessment equipment. Digitalization significantly modifies the marginal effects of GVC positioning on this category, reducing the trade effects at lower GVC stages while amplifying them at higher stages. These findings underscore the transformative role of digitalization in shaping the dynamics of EG trade across different GVC stages.

Table 0-8 Impacts of GVC Positioning & Digitalization on Different Types of EGs

	(1) Air Pollution Control	(2) Clean up or remediation of soil and water	(3) Cleaner or more resource-efficient technologies and products	(4) Environmental monitoring, analysis, and assessment equipment	(5) Environmentally preferable products based on end-use or disposal characteristics	(6) Heat and energy management	(7) Management of solid and hazardous waste and recycling systems	(8) Natural resource protection	(9) Noise and vibration abatement	(10) Renewable energy plant	(11) Wastewater management and potable water treatment
$GVCPosition_{ijst}$	-0.040	-0.125**	-0.141***	0.027	0.866***	0.238***	0.070*	0.091	-0.060	0.043*	0.296***
	(0.078)	(0.048)	(0.023)	(0.017)	(0.068)	(0.030)	(0.029)	(0.0634)	(0.056)	(0.019)	(0.024)
$Digitalization_{ijst}$	0.213***	0.072	-0.084***	0.071***	0.058	0.021	0.010***	0.053	0.062	0.049**	0.164***
	(0.044)	(0.039)	(0.020)	(0.011)	(0.064)	(0.029)	(0.021)	(0.063)	(0.063)	(0.018)	(0.019)
$Digitalization_{ijst} * GVCPosition_{ijst}$	-0.112***	0.014	0.037***	0.0194	0.065*	-0.061***	0.011	0.202***	0.082***	-0.029***	-0.101***
	(0.014)	(0.020)	(0.010)	(0.017)	(0.027)	(0.012)	(0.010)	(0.033)	(0.019)	(0.008)	(0.011)
$GVCPosition^2_{ijst}$	-0.120***	-0.001	0.011	0.028*	0.056**	-0.017	-0.042***	-0.160***	0.002	-0.050***	-0.128***
	(0.017)	(0.017)	(0.009)	(0.011)	(0.022)	(0.011)	(0.008)	(0.031)	(0.023)	(0.006)	(0.008)
$Constant$	10.89***	10.21***	10.29***	10.31***	9.204***	10.26***	11.07***	9.525***	11.09***	10.75***	10.83***
	(0.016)	(0.017)	(0.009)	(0.019)	(0.021)	(0.009)	(0.007)	(0.032)	(0.023)	(0.005)	(0.007)
N	587269	176440	1034878	1836096	130594	1011883	1104235	92460	196672	2277801	1756027
R^2	0.488	0.478	0.320	0.376	0.473	0.412	0.399	0.501	0.715	0.351	0.481
Country-Pair FE	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-Time FE	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE				Yes							
Time FE				Yes							
UTEST	PASS	NO PASS	NO PASS	PASS	NO PASS	NO PASS	PASS	PASS	NO PASS	PASS	PASS
U-Shaped Curve	Inverse			U-shaped			Inverse	Inverse		Inverse	Inverse
Turning point	-0.170			-0.487			0.835	0.282		0.428	1.158

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.4 Conclusion

This study provided an in-depth analysis of the relationship between GVC positioning and the trade of EGs, emphasizing the moderating roles of GVC participation and digitalization. Using a harmonized dataset from 1995 to 2020, the research integrates HS 6-digit product-level trade data, country-sectoral GVC indicators, and digitalization indices to deliver robust insights. The analysis applies structural PPML estimation to account for multilateral resistance and mitigates heteroskedasticity, with further checks for robustness and endogeneity.

The results confirm that advancements in GVC positioning significantly promote EG trade, exhibiting an accelerating positive impact (i.e., convex relationship). Countries with higher GVC positioning derive greater marginal trade benefits, underscoring the importance of moving up the value chain. The study also reveals that backward GVC participation and digitalization amplify the positive effects of GVC positioning on overall EG trade by enhancing access to advanced technologies, fostering innovation, and improving production efficiency. Moreover, the relationship between GVC positioning and EG trade varies across different categories of EGs, with evidence of both linear and nonlinear effects. The moderating roles of GVC participation and digitalization also differ across product categories, reflecting their nuanced influences on trade dynamics.

These results provide critical insights for policymakers and industry stakeholders aiming to promote sustainable trade. Targeted strategies to improve GVC positioning, combined with investments in digital infrastructure and policies supporting GVC participation, can optimize green trade outcomes. Future research should further explore the interactions between GVC dynamics, digitalization, and environmental policies to deepen understanding of their role in advancing global sustainability objectives.

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4.5 Appendix A

Concordance Between Different Data Sources

	Environmental Product Group	HS 6-digit Code	ISIC Rev.4 Sector	OECD Code	Trade Share by Environmental Product
1.	Air pollution control	840420,840490,840510,841410 841430,841440,841459,841480 841490,841960,842139	28 25	C28 C25	6.61%
2	Clean up or remediation of soil and water	842119,842191,851629,890790	27 28 30	C27 C28 C30	0.54%
3	Cleaner or more resource-efficient technologies and products	730210,730230,730240,730290 732111,732190,850680,850980 853010,853080,853090,860110 860120,860210,860290,860310, 860390,860400,860500,860610 860630,860691,860692,860699 860711,860712,860719,860721 860729,860730,860791,860799 860800,870290,870390,871200 871410,871411,871419,871420 871491,871492,871493,871494 871495,871496,871499,871639	24 27 29 30	C24 C27 C29 C30	10.17%
4	Environmental monitoring, analysis, and assessment equipment	900580,901530,901540,901580 901590,902511,902519,902610 902620,902680,902690,902710 902720,902730,902750,902780 902790,902810,902820,903010 903020,903031,903032,903033 903039,903083,903084,903089 903090,903120,903149,903180 903190,903210,903220,903281 903290,903300	26	C26	10.29%
5	Environmentally preferable products based on end-use or disposal characteristics	441830,441872,530310,530500 530590,560721,560790,630510	11 13 16	C10T12, C13T15, C16	0.22%
6	Heat and energy management	390940,392030,392111,392113 450410,450490,540500,680610 680690,680800,681011,681019 681091,700800,701931,701939, 841950,850220,853921,853931 853932,902830,902890,940510 940520,940540	16, 20, 22, 23, 26, 27,28	C16, C20, C22, C23,C26, C27,C28	5.92%
7	Management of solid and hazardous waste and recycling systems	392010,400259,761290,840219,8 40290,841780,841790,841940,84 2220,842290,842833,842940 846291,846596,846599,846694,8 47420,847982,847989,847990,85 0590,851410,851420,851430,851 490	20 22 25 27 28	C20 C22 C25 C27 C28	12.55%
8	Natural resource protection	560811 560890 950720	13 32	C13T15, C31T33	0.09%
9	Renewable energy plant	392510,700991,700992,730820,7 30890,732113,732119,732183,73 2189,761090,761100,830630,840 681,840682,840690,841011,8410 12,841013,841090,841181,84118 2,841199,841280,841290,841581, 841861,841869,841919,841990,8	22 23 25 26 27 28	C22 C23 C25 C26 C27 C28	32.01%

		48340,848360,850161,850162,850163,850164,850231,850239,850300,850421,850422,850423,850431,850432,850433,850434,850440,850490,850720,853710,853720,854140,900190,900290,901380,901390,903289			
10	Noise and vibration abatement	840991,840999,903110	26 29	C26 C29	4.91%
11	Wastewater management and potable water treatment	380210,560314,691010,730300,730431,730490,730630,730690,730900,731010,731029,732490,732510,732690,841320,841350,841360,841370,841381,841939,841989,842121,842129,842199,848110,848130,848140,848180,848190,854370,854389,854390	13 20 23 24 25 27 28	C13T15, C20, C23,C24, C25,C27, C28,	16.67%

Source: Author's own elaboration

4.6 Appendix B

Measurement of Digitalization Index

Following Zhang & Yu (2020), the digitalization index is constructed by containing both direct digital input and indirect digital input. Direct digital inputs refer to resources directly supplied by the four identified digital sectors and utilized by industries. Indirect digital inputs, on the other hand, represent digital components embedded within the broader supply chains of these sectors. By integrating both aspects, the digital intensity index provides a holistic view of digital technology diffusion, highlighting its multifaceted role in sectoral integration.

The digital index for the use of digital input j in sector g, b_{gj}, is:

$$b_{gj} = a_{gj} + \sum_{m=1}^{N} a_{gm}a_{mj} + \sum_{n=1}^{N}\sum_{m=1}^{N} a_{gn}a_{nm}a_{mj} + \cdots \qquad (1)$$

Where a_{gj} refers to the direct consumption of digital output by sector g, as defined above. $\sum_{m=1}^{N} a_{gm}a_{mj}$ is the indirect digital sector j's output consumed by the sector g via sector m. $\sum_{n=1}^{N}\sum_{m=1}^{N} a_{gn}a_{nm}a_{mj}$ represents the additional indirect consumption of sector g to digital sector j through sectors m and n (and so on) until it covers indirect digital inputs in all relevant sectors.

4.7 Appendix C

This paper follows Koopman et al. (2010) to construct GVC participation index at country-sectoral level. Koopman et al. (2010) decomposes the value-added components of a country's exports. Assuming G countries and N sectors, a multi-country, multi-sector analysis is conducted using the direct value-added coefficient diagonal matrix $\hat{V}$ and the export diagonal matrix $\hat{E}$. By multiplying the direct value-added coefficient matrix $\hat{V}$ with the Leontief inverse matrix B and the export matrix $\hat{E}$, the value-added decomposition of exports across countries can be achieved.

$$V\hat{B}E = \begin{bmatrix} V_1 \sum_r^G B_{1r}E_{r1} & V_1 \sum_r^G B_{1r}E_{r2} & \cdots & V_1 \sum_r^G B_{1r}E_{rG} \\ V_2 \sum_r^G B_{2r}E_{r1} & V_2 \sum_r^G B_{2r}E_{r2} & \cdots & V_2 \sum_r^G B_{2r}E_{rG} \\ \cdots & \cdots & \cdots & \cdots \\ V_G \sum_r^G B_{Gr}E_{r1} & V_G \sum_r^G B_{Gr}E_{r2} & \cdots & V_G \sum_r^G B_{Gr}E_{rG} \end{bmatrix}_{(GN*GN)} \quad (2)$$

Equation (2) shows the sum of the off-diagonal elements in the corresponding row of matrix $V\hat{B}E$ represents the indirect value-added exports of country *r*. The sum of the off-diagonal elements in the corresponding column of matrix $V\hat{B}E$ represents the foreign value-added $FV_r (FV_r = \sum_{s \neq r} V_s B_{sr} E_{r^*})$ to the exports of country r. This reflects the portion of country *r*'s exports that consists of value added by other countries in the GVCs. The diagonal elements of matrix $V\hat{B}E$ reflect the domestic value-added portion $DV_r (DV_r = V_r B_{rr} E_{r^*})$ in the exports of each country. Based on this decomposition in Koopman et al. (2010), this paper constructs the GVC participation index to measure a country's degree of involvement in GVCs. A higher value of the index indicates a greater degree of participation by the country in GVCs:

$$GVC\ Participation = \frac{IV_{ir}}{E_{ir}} + \frac{FV_{ir}}{E_{ir}} \quad (3)$$

In equation (3), IV_{ir} represents the indirect value-added exports of industry i in country r, capturing the value of intermediate goods exported to other countries and subsequently re-exported to a third country after processing. This measures the extent to which value-added from r's industry i is embedded in its intermediate exports. FV_{ir} denotes the foreign value-added embedded in the exports of final goods by industry i in country r, representing the value of imported intermediates contained in its final goods exports. Lastly, E_{ir} indicates the value-added exports of industry i in country *r*.

4.8 Appendix D

Construction of GVC Position Index

Following Koopman et al. (2010), the GVC position index is measured as follows:

$$GVC\_Position_{ir} = \ln\left(1 + \frac{IV_{ir}}{E_{ir}}\right) - \ln\left(1 + \frac{FV_{ir}}{E_{ir}}\right) \quad (4)$$

In equation (4), the $GVC\_Position_{ir}$ reflects the role of country r and industry i in the international division of labor within GVCs. IV_{ir}, FV_{ir}, and E_{ir} indicate the same content with those in the equation (4).

The positive value of GVC position means that the country is relatively located in upstreamness while the negative one denotes the position in downstreamness. According to Koopman et al. (2010), when a country operates in the 'upstream' segment of an industry's GVC (characterized by activities such as innovation, R&D, design, branding, and the production of components), it primarily contributes to GVC production by supplying intermediates to other countries. For such countries, the share of indirect value-added (IV_{ir}) in total exports (E_{ir}) tends to exceed the share of foreign value-added (FV_{ir}) in total exports. Conversely, countries engaged in the downstream segment of a GVC, such as final product assembly, rely heavily on imported intermediates to produce final goods. In these cases, IV_{ir} is typically lower than FV_{ir}. Therefore, the higher the $GVC\_Position_{ir}$ value, the higher the country's industry position in the GVC's international division of labor. Conversely, a lower $GVC\_Position_{ir}$ indicates a lower position within the GVC.

4.9 Appendix E

Table R1: Interaction-Based Robustness Checks

	(1)Country-characteristics interactions	**(2)Industry-proxy interactions (centered)**
GVC position	14.598***	1.034***
	(0.605)	(0.062)
GVC position^2	19.992***	0.049
	(1.547)	(0.136)
Digitalization	-0.285***	-1.092***
	(0.085)	(0.188)
Digitalization*GVC position	4.958***	5.009***

	(0.305)	(0.311)
Digitalization *GVC position^2	12.904***	12.850***
	(0.823)	(0.827)
LnGDP *GVC position	-0.736***	
	(0.041)	
LnGDP * GVC position^2	-1.547***	
	(0.105)	
LnPOP * GVC position	0.020	
	(0.041)	
LnPOP *GVC position^2	1.031***	
	(0.113)	
Digitalization*Sector-mean Digitalization		3.412***
		(0.523)
Constant	3.893***	3.925***
	(0.013)	(0.008)
Observations	8,662,948	10,217,877
R-squared	0.367	0.384
Exporter×Year FE	Yes	Yes
Importer×Year FE	Yes	Yes
Pair FE	Yes	Yes
Sector FE	Yes	Yes
SE clustered by pair	Yes	Yes
Number of clusters	4,783	5,504

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10. Column (2) uses mean-centered GVC positioning and digitalization to facilitate interpretation when multiple interactions are included.

To address the concern that the baseline estimates may be driven by other country or industry characteristics correlated with GVC positioning and digitalization, the study implements interaction-based robustness checks while preserving the original fixed-effects structure (exporter×year, importer×year, country-pair, and sector). First, the study allows the effects of GVC positioning (including its quadratic term) to vary with bilateral country characteristics already contained in our dataset by interacting GVC positioning with pair-average log GDP and log population (Table R1, col. 1). The core nonlinear GVC-positioning terms remain positive and highly significant, and the digitalization–GVC interactions remain strongly positive, indicating that the main results are not driven by general country size/development factors. Second, to mitigate the possibility that the digitalization interaction proxies for underlying industry attributes, the study interacts digitalization with a sector-level proxy (sector-average digital intensity) constructed internally from the same panel (Table R1, col. 2). The estimated Digitalization×GVC and Digitalization×GVC^2 interactions remain virtually unchanged in magnitude and significance. Overall, these checks support the robustness of our conclusions regarding digitalization's moderating role in strengthening the (nonlinear) trade gains from GVC upgrading.

Chapter 5 Conclusion

This thesis investigates the impacts of digitalization on different dimensions of GVCs and their joint impacts on green trade patterns. Through a combination of econometric techniques and CGE modelling, the thesis offers new insights into the evolving role of technology, trade policy, and production integration in the global economy. The first paper in the thesis focused on the impacts of digitalization, with and without the presence of RTAs, on manufacturing GVC trade. The second paper in the thesis explored the impacts of digitalization on manufacturing GVC participation across regions. The third paper analyzed impacts of GVC positioning on green trade. Each of the three papers makes an original empirical contribution to existing literature, to the best of my knowledge.

There has been wide discussion about the role of digitalization on the development of manufacturing GVCs (Dollar et al., 2019; Antràs, 2020; among others), especially in the presence of RTAs (Blanchard et al., 2016; Mitchell & Mishra, 2020; among others). The first paper in the thesis aimed to present novel empirical evidence on how sectoral digitalization affects GVC trade, with and without in the presence of RTAs. I used the ADB MRIO to capture countries' digital intensity and RTA variable to evaluate whether countries are a member of a trade agreement. In addition, manufacturing sectors were categorized into groups based on their sectoral digital intensity. This should inform policy makers on the need to design policies that facilitate the combined effects of digitalization and RTAs on the development of GVCs, considering the heterogeneity across sectors.

One of the key findings from the first paper is that while digitalization facilitates the development of GVCs, the existing RTAs have not fully unlocked its potential. The effectiveness of digitalization in promoting GVC participation varies significantly across countries, depending on income levels and sectoral digital intensity. This outcome could be explained by the growing trend of digital protectionism, as countries increasingly assert digital sovereignty by embedding restrictive digital provisions in RTAs, a phenomenon also highlighted by Mitchell and Mishra (2020). These developments reflect the complex interplay between digital transformation and trade policy in the evolving global trade landscape.

In 2011, Germany first introduced the concept of Industry 4.0 at the Hannover Fair. The concept of Industry 4.0 has equivalent terms such as 'manufacturing industry' in South Korea, the 'Industrial Internet' in North America (Ghobakhloo & Fathi, 2019), 'Smart Industry' in the Netherlands, or 'Digitization' in the Norwegian government (Mogos et al., 2019). Beyond its technological scope, Industry 4.0 has profound implications for the reconfiguration of value-added distribution and the division of labor within GVCs. The second paper of this thesis investigates the broader economic implications of Industry 4.0, with a particular focus on its effects on regional manufacturing GVC participation. This involved the use of a CGE model, integrated with an MRIO framework and GVC accounting methodology, not attempted earlier in the literature. This study categorizes manufacturing sectors based on their digital intensity and contributes significantly to the literature by introducing sector-specific digital input shocks to capture heterogeneous digital adoption. It models manufacturing digitalization as a core driver of Industry 4.0 and assesses its impact on regional GVC participation patterns.

The results suggest that digitalization brings substantial economic gains, including improved welfare, increased trade, and deeper GVC participation, particularly through enhanced backward linkages. However, the impacts are heterogeneous, depending on regional development levels, digital readiness, and their role within GVCs. Digitalization tends to shorten GVCs and encourage regionalization, leading to the relative decline of complex GVCs and reinforcing simpler, more regionalized production structures.

While green trade has emerged as a critical pathway for achieving sustainable development (World Trade Report, 2022), GVCs serve as a key mechanism through which countries engage in and benefit from green trade. Understanding the role of GVC positioning in shaping cross-border trade in environmental goods is therefore essential for identifying how structural upgrading within GVCs supports green trade integration. The third paper in this thesis examines the effects of countries' positions within GVCs, as well as the joint impacts of GVC positioning with digitalization and GVC participation, on bilateral trade in environmental goods. To the best of my knowledge, this is the first study to harmonize and match product-level green trade flows with sector-level GVC indicators and digitalization measures in a unified empirical framework.

The findings demonstrate that improvements in GVC positioning significantly enhance trade in environmental goods, following a convex pattern in which the marginal gains increase with higher value chain positions. This underscores the strategic importance of moving up the GVC ladder to promote green trade. Additionally, both GVC participation—especially through backward linkages—and digitalization are found to strengthen the trade-enhancing effects of GVC upgrading. The analysis further reveals substantial heterogeneity across different types of environmental goods, with both linear and nonlinear effects observed. The moderating roles of GVC participation and digitalization also vary by product category, highlighting their context-specific influence on green trade dynamics.

Overall, the three papers in this thesis contribute to the literature by offering a multi-dimensional understanding of the complex interrelationships between digitalization, GVCs, and green trade outcomes. Future research could explore how digitalization affects services-driven GVCs and different dimensions of digitalization in shaping digital trade gains. Moreover, studies at the firm-level, should further investigate how specific digital trade policies, such as cross-border data rules, interact with digitalization therefore reshaping GVCs. Finally, as digital transitions continue to co-evolve, further research is needed to understand how digitalization can amplify the benefits of GVC integration.

Chapter 6 References

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