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A study on the driving effects of digital trade development on total factor productivity growth and potential economic growth rate

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Abstract: This study investigates the driving effects of cross-border digital trade development on Total Factor Productivity (TFP) growth and potential economic growth rates, addressing the macroeconomic puzzle of rapid digital expansion coexisting with sluggish productivity growth—the contemporary "Solow Paradox." The study constructs a theoretical framework integrating digital trade into the production function, employing comprehensive analysis of macro- and micro-level evidence from panel data across multiple economies. The research utilizes econometric methods including fixed-effects models and threshold effect analysis to examine transmission mechanisms. Digitalization exhibits a non-linear, U-shaped impact on productivity. Most firms remain below a critical digitalization threshold (approximately 0.1373), where adjustment costs outweigh efficiency gains. Infrastructure gaps, skill shortages, institutional rigidities, and fragmented cross-border data governance limit spillovers and concentrate benefits among frontier firms. The Solow Paradox reflects a sub-threshold trap rather than technological failure. Productivity gains from digital trade are conditional on complementary investments in infrastructure, human capital, institutional reform, and coherent data governance. Policymakers should prioritize digital infrastructure development, implement sequenced reform strategies, and address institutional frictions. Elevating the TFP of the bottom 90% of firms could potentially drive an 18% GDP increase over 6-8 years.

Keywords: *Cross-border data governance, Digital infrastructure, Digital trade, Digital transformation, Green productivity, Total factor productivity.*

1. Introduction

The global economy is currently navigating a profound structural shift, transitioning from a paradigm dominated by the cross-border exchange of physical goods to one increasingly driven by intangible flows. The rapid proliferation of information and communication technologies (ICT) has given rise to "cross-border digital trade", defined not only as cross-border e-commerce but also as the transmission of digital services, data flows, and intellectual property. According to recent estimates, trade in digital services has grown substantially faster than trade in goods over the past decade, acting as a crucial buffer against global economic volatility.

Table 1 illustrates the comparative global evolution of digital trade and physical trade from 2010 to 2024, clearly revealing their divergent growth trajectories and changing scales.

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Table 1.
Global Trends in Digital vs. Physical Trade (2010–2024).

Category	2005 (million USD)	CAGR 2005-2010	CAGR 2010-2015	CAGR 2015-2020	CAGR 2020-2024
Total Merchandise Exports	10,459,495	7.64%	1.63%	1.32%	8.49%
High-skill and Technology-intensive Manufacturing Exports	2,972,190	7.09%	2.52%	2.92%	6.38%
Total Services Exports	2,698,440	8.16%	4.88%	0.96%	13.55%
Telecommunications, Computer, and Information Services Exports	186,097	12.48%	7.36%	10.39%	12.47%
Total Merchandise Imports	10,729,739	7.32%	1.57%	1.38%	8.51%
High-skill and Technology-intensive Manufacturing Imports	3,166,689	6.93%	2.50%	2.98%	6.41%
Total Services Imports	2,635,639	8.15%	4.99%	0.34%	12.43%
Telecommunications, Computer, and Information Services Imports	129,974	9.35%	10.29%	7.28%	9.87%

Note: The table combined 2 datasets — "Merchandise: Intra-trade and extra-trade of country groups by product, annual (analytical)" updated 16 Oct. 2025, and "Services (BPM6): Exports and imports by service category, trading partner world, annual" updated 25 Jul. 2025.
Source: UNCTADstat Data centre.

Despite the accelerated expansion of the digital economy, a puzzling macroeconomic phenomenon persists: the global slowdown in productivity growth. Since the 2008 financial crisis, Total Factor Productivity (TFP) growth in both developed and emerging economies has remained sluggish, contradicting the Solow paradox expectation that "you can see the computer age everywhere but in the productivity statistics" [1]. This divergence raises a critical question: Is the digitalization of trade failing to translate into economy-wide efficiency gains, or are the transmission mechanisms more complex than traditional trade theories suggest?

Understanding this relationship is vital because TFP is the primary driver of potential economic growth the maximum level of output an economy can sustain without generating inflation. While capital accumulation and labor supply have natural limits, efficiency gains driven by digital technology represent the only sustainable path for long-term economic expansion [2, 3].

Current literature has extensively documented the impact of digital transformation at the firm level, noting how enterprise digitalization improves innovation performance and operational efficiency [4, 5]. However, a gap remains in aggregating these micro-level effects to the macroeconomic level. Specifically, the link between Digital Trade (an external variable) and Potential Economic Growth (an internal structural capacity) lacks sufficient empirical evidence.

Ideally, digital trade should generate stronger knowledge spillovers and competitive pressures than domestic digitalization alone, as it involves the importation of advanced global technologies and the exportation of services. However, the mechanism by which these cross-border flows translate into capital deepening and technical efficiency requires a rigorous analytical framework. Consequently, this study seeks to address three specific research questions: (1) Does digital trade significantly enhance potential economic growth? (2) Through what transmission channels, specifically TFP growth versus capital accumulation, does this impact occur? and (3) Are these effects heterogeneous across economies with different levels of digital infrastructure? This study also posits a transmission mechanism: Cross-border digital trade serves as the external catalyst that accelerates corporate digital transformation. In turn, corporate digital transformation acts as the micro-level vehicle through which these global digital flows are internalized, ultimately driving improvements in Total Factor Productivity (TFP).

The primary purpose of this study is to bridge the gap between micro-level digitalization benefits and macro-level growth stagnation. By constructing a theoretical framework that integrates digital trade into the production function, this research empirically tests the causal relationship between digital trade openness and potential economic growth.

Theoretically, this study aims to extend the literature on the Solow paradox by distinguishing between domestic ICT adoption and cross-border digital trade, clarifying why productivity statistics may lag behind technological adoption. Practically, the findings should provide policymakers with evidence-based strategies for sustaining long-term growth. Rather than relying solely on monetary stimulus or traditional capital investment, the results suggest that integrating into the global digital trade network is a critical lever for unlocking new sources of potential output and reversing the trend of productivity stagnation.

Table 2 provides an overview of the pathways through which digital trade generates economic and social effects.

Table 2.
Channels and Mechanisms of Digital Trade Impact.

Channel	Mechanism	Impact
Innovation/Technology Diffusion	Import of ICT Services: Importing digitally deliverable intermediate services provides firms with access to technologies and knowledge-intensive inputs. Knowledge Spillover: ICT service exports accelerate productivity growth [6]. Enhanced R&D Efficiency: Digital trade facilitates the acquisition of advanced digital tools and data, lowers R&D risks, and fosters green technology innovation [7, 8].	Increases the TFP residual by promoting technological progress and improving production efficiency. This shifts the production frontier outward, raising the economy's potential output level.
Resource Allocation & Structural Change	Supply chains optimization: Digitalization reduces transaction, coordination, and search costs. It smooths supply chain management and lowers costs [3, 9]. Industry integration: Digital trade facilitates digitization, intelligent manufacturing, and cross-sector convergence [8]. Creative destruction: Firm-level digital transformation studies suggest it reallocates capital and labor to more productive users.	Improves efficiency across firms and sectors. By reducing market distortions and friction, resources flow to more productive uses, enhancing TFP and the potential growth rate.
Scale/GVC Integration	Market Expansion: Digital trade enables firms to reach global customers easily, strengthening integration into Global Value Chains (GVCs) and inducing growth in non-ICT service exports [6, 9]. Economies of Scale: Larger market access allows firms to achieve economies of scale in purchasing, production, and sales, reducing unit costs and enabling larger-scale R&D investments [10].	Enables sustainable scale expansion without proportional cost increases. This capitalizes on increasing returns, contributing to long-run GDP growth and raising the economy's capacity.
Human Capital & Ecosystem	Skill development in ICT services requires workforce upskilling, fostering a broader digital ecosystem [6]. Compensation for demographic challenges: the digital economy promotes human capital accumulation, helping offset the negative TFP effects of population aging [11].	Enhances the quality of labor input. This channel sustains or increases the potential growth rate over the long term.
Competition & Quality Upgrading	Heightened market contestability: participation in global digital markets exposes domestic firms to international competition, compelling them to improve product/service quality and operational efficiency.	Forces efficiency and quality among firms, lifting the productivity level and thus its output.

2. Literature Review

2.1. Core Concept Definition and Variable Standardization

The recent literature converges on a distinction between digital trade, digital transformation, and productivity, emphasizing their interdependence as engines of economic efficiency. Unlike the broad concept of the "digital economy," which includes domestic e-commerce and internal administrative digitization, this study explicitly defines the research subject as "cross-border digital trade." The boundary is drawn at the national border, concerning the international exchange of digitally deliverable services and data rather than purely domestic technological adoption.

In line with recent work on digital economics and trade policy [6, 8, 9], "digital trade" is defined as the trade of goods and services ordered and/or delivered digitally. To ensure empirical consistency, this study standardizes the macro-level proxy variable for digital trade as "ICT service imports/exports as a percentage of total digital service trade" [6, 8, 9]. This represents an evolution from earlier work that relied on broad internet penetration, moving toward a sharper focus on actual cross-border digital service flows.

By contrast, "digital transformation" is defined as a micro-level concept. Verhoef et al. [12] describe it as the process by which enterprises leverage digital technologies (e.g., big data, cloud computing) to reconfigure business processes and organizational structures. Firm-level studies increasingly measure this using text analysis of corporate reports to construct digitalization indices [5, 13, 14]. Alternatively, measures like the share of ICT capital are used but are often viewed as downward-biased proxies [5, 7, 14]. Finally, Total Factor Productivity (TFP) and Green Total Factor Productivity (GTFP) serve as the principal outcome measures, capturing technological progress and efficiency gains, with GTFP extending this to account for environmental sustainability [8, 14, 15].

Table 3 summarizes the conceptual distinctions, establishing cross-border digital trade as the external catalyst and corporate digital transformation as the internal micro-level vehicle.

Table 3.
Conceptual Distinctions between Digital Trade and Digital Transformation.

Concept	**Cross-border Digital Trade**	**Digital Transformation**
Primary Scope	Macro / Cross-Border	Micro / Firm-Level
Definition	Trade in goods and services ordered and/or delivered digitally; encompasses cross-border data flows and ICT-enabled services; acts as a catalyst for market access and non-ICT service exports.[1, 6, 8-10].	Process by which firms integrate digital technologies such as big data, cloud, and AI into core operations, business models, and organizational structures.[12].
Proxies	ICT service imports/exports as a percentage of total digital service trade [6, 8, 9].	Text-based digitalization indices from corporate reports, ICT capital investment share, and survey-based adoption measures.[4, 5, 7, 13, 14, 16].
Mechanism	Knowledge spillovers, technology transfer, market expansion, scale economies, and GVC integration [1, 6, 8-10, 17].	Internal information processing and knowledge sharing, operational cost reduction, management efficiency, innovation, and resource reallocation. [4, 5, 7, 13, 14, 16].

Summary: The consensus in the literature highlights the necessity of separating macro-digital trade from micro-digital transformation. However, a point of historical disagreement and inconsistency remains: the fragmented use of proxy variables (e.g., equating domestic internet use with digital trade), which complicates cross-study comparisons. Furthermore, an unresolved issue is that few studies explicitly unite these concepts into a single framework where the macro-variable (trade) acts as the direct catalyst for the micro-variable (corporate transformation).

2.2. Effects of Digitalization on TFP

Empirical work verifying the effects of digitalization is broadly organized into macro-level analyses of trade outcomes and micro-level studies of firm performance. At the macro level, cross-country panel evidence indicates that digital services trade, particularly ICT services exports, exerts a significant positive long-term effect on per-capita GDP and aggregate TFP [6, 9, 18]. Using P-VAR models, Mulenga and Mayondi [9] show that shocks to digital services exports have persistent effects on economic growth. Similarly, country-specific macro studies verify that ICT adoption upgrades human capital and offsets negative demographic drags on TFP [11] while increasing the technical efficiency of peripheral economies [3]. At the firm level, a substantial body of micro-evidence confirms that digital transformation significantly enhances enterprise TFP and GTFP. Ren et al. [7] report that for Chinese enterprises, a one-unit increase in a digital transformation index raises TFP by approximately 0.0212 percentage points. Similar positive effects on TFP and GTFP are validated in heavily polluting enterprises [13, 14, 16]. Furthermore, digital transformation improves financial outcomes (ROA/ROE) and reduces stock price crash risk by enhancing corporate governance [19, 20]. Despite this broad verification of positive impacts, theoretical tension persists around the macroeconomic "Solow Paradox" of visible digital investment but muted aggregate productivity gains. As Cheng et al. [5] identify, large sunk investments and organizational inertia initially depress productivity before a firm can successfully realize TFP gains, suggesting digitalization's benefits are neither automatic nor immediate.

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Summary: There is robust empirical consensus that digital tools positively impact productivity at both the macro (national GDP) and micro (firm efficiency) levels. However, a major disagreement, framed as the Solow Paradox, persists regarding why massive global digital trade volumes coexist with sluggish aggregate productivity growth. The unresolved issue is that the literature largely verifies macro-effects and micro-effects in isolation, lacking a rigorous aggregation mapping from firm-level disruption to economy-wide gains.

2.3. Transmission Mechanism

To bridge the gap between trade and productivity, the literature identifies specific transmission channels through which corporate digital transformation acts as the micro-level vehicle to internalize the benefits of cross-border digital trade. First, regarding innovation and technology diffusion, digital trade facilitates access to advanced ICT inputs, which firms subsequently use to drive internal technological and green innovation [4, 7, 14]. Recent studies confirm that AI in cross-border digital services generates significant global knowledge spillovers [17]. Second, regarding Resource Allocation, digital transformation reduces information asymmetries and external transaction costs [7, 13]. Digital platforms lower search and matching costs, enabling efficient factor allocation and reducing operational cost stickiness [5, 7, 11]. Third, regarding Scale and GVC Integration, digital trade allows firms to access broader markets, supporting economies of scale and deeper integration into global value chains [6, 8, 9].

Finally, a rapidly expanding strand of literature highlights the sustainability mechanism. Digital transformation drives green TFP primarily by shifting the green technological frontier (GTC) rather than solely increasing green efficiency (GEC) [13, 14]. Digital trade lowers the cost of accessing foreign green technologies, enabling firms to reorganize production toward low-carbon models [8, 10].

Table 4 summarizes representative macro- and micro-level studies and highlights the mechanisms and methodological approaches they use.

Table 4.
Summary of Key Empirical Findings for Mechanism and Bottleneck Analysis.

Macro & Cross-Country				
Mulenga and Mayondi [9]	Global	Macro	Digital trade boosts growth by reducing transaction costs and facilitating technology diffusion.	P-VAR
Houngbonon and Mothobi [6]	Global	Macro	ICT exports raise TFP, but the impact depends on domestic digital connectivity (infrastructure bottleneck).	Fixed Effects, IV
Mazorodze [3]	S. Africa	Macro	ICT adoption increases absorptive capacity, allowing firms to realize efficiency gains from trade.	SFA, IV
Meng and Wen [11]	China	Macro	Digitalization offsets the negative TFP impact of population aging by upgrading human capital.	Moderating Effect
Andrews, et al. [2]	OECD	Macro	Tech diffusion is stalled by structural bottlenecks: weak managerial skills and rigid labor markets.	Industry Regression
Firm-Level (Micro)				
Ren, et al. [7]	China	Micro	Raises TFP via operational efficiency, cost reduction, and innovation capabilities.	Panel Data, IV
Wang, et al. [14]	China	Micro	Drives Green TFP (GTFP) primarily through technological progress rather than just efficiency.	EBM-GML, DID
Han, et al. [13]	China	Micro	Boosts GTFP by lowering external transaction costs (asset specificity) and enhancing management.	Text Analysis, Panel
Zhai, et al. [20]	China	Micro	Improves performance (ROA) through cost control; emphasizes long-term accumulation of benefits.	Panel Data, IV
Cheng, et al. [5]	China	Micro	Solow Paradox: Identifies a U-shaped TFP impact. Most firms are currently below the threshold required for gains.	Nonlinear Panel
Peng and Tao [19]	China	Micro	Validates positive impact on financial performance (ROA/ROE) after correcting for endogeneity.	Panel Data, IV
Chen and Kim [4]	China	Micro	Enhances innovation quantity and quality, specifically benefiting non-state-owned enterprises.	Panel Regression

Summary: The literature generally agrees that innovation, cost reduction, and scale economies are the primary mediating mechanisms connecting digitalization to productivity. However, disagreements persist regarding the environmental channel, specifically whether the "scale effect" of massive digital trade suppresses Green TFP (via energy consumption) or if the "technological effect" overrides it. The unresolved issue remains that most micro-studies treat digital transformation as a spontaneous firm choice, failing to model it as a reactive vehicle triggered by the external catalyst of global digital trade.

2.4. Heterogeneity and Threshold Effect

Heterogeneity and non-linearities are critical themes cutting across the evidence. The "productivity paradox" is increasingly interpreted through the lens of threshold effects. Cheng et al. [5] demonstrate a U-shaped pattern: in the initial "installation stage," learning costs depress productivity; TFP only rises sharply once a critical digitalization threshold (approx. 0.1373) is exceeded. Similarly, Zhang [8] and Zhang [15] find that the structural and environmental benefits of ICT-based digital trade exhibit threshold effects regarding human capital and R&D; strong carbon-reducing effects emerge only when complementary factors surpass critical levels.

Furthermore, several studies document that productivity gains vary by ownership, region, and baseline capabilities. Digital transformation tends to have stronger effects on TFP in non-state-owned enterprises and in sectors starting from lower digital baselines (e.g., traditional manufacturing) [7, 13]. Regionally, positive impacts are heavily concentrated in areas with superior infrastructure and talent pools [7, 11, 14]. At the international level, while digital trade benefits all countries, developing economies capture smaller aggregate gains due to massive infrastructure gaps and capability constraints [2, 6, 9].

Summary: There is widespread consensus that digitalization yields highly asymmetric dividends, creating regional and sectoral "islands of efficiency." However, scholars differ on whether these threshold barriers are primarily technological (e.g., broadband speeds) or institutional (e.g., data governance and rigid labor markets). Consequently, an unresolved issue is the lack of a sequenced implementation pathway in the literature that provides policymakers with actionable steps to push the "long tail" of sub-threshold firms past the critical tipping point.

2.5. Summary and Research Gaps

To evaluate the diverse impacts of digitalization discussed above, empirical studies have developed a robust set of econometric and quantitative methods. These approaches reflect efforts to address endogeneity, dynamic feedback, and measurement complexity across both macro and micro contexts.

Table 5 provides a concise overview of the most common methodological approaches utilized in the current literature.

Table 5.
Common Econometric Approaches in Digitalization Research.

Methodology	Primary Use Case / Purpose	Studies
Fixed Effects (FE)	Controls for unobserved, time-invariant heterogeneity (e.g., firm culture, national institutions) in panel data.	Chen and Kim [4]; Han, et al. [13]; Meng and Wen [11]; Ren, et al. [7]; Wang, et al. [14]
Instrumental Variables (IV)	Addresses endogeneity and reverse causality. Instruments include historical data (e.g., 1950s birth rate), peer averages, or geographic dummies.	Han, et al. [13]; Meng and Wen [11]; Ren, et al. [7]; Su, et al. [16]; Wang, et al. [14]
Textual Analysis	Converts qualitative data (corporate reports) into quantitative indices of "Digital Transformation" via keyword frequency.	Chen and Kim [4]; Su, et al. [16]; Wang, et al. [14]
Difference-in-Differences (DID)	Estimates the causal impact of specific policy shocks or the staggered adoption of digital strategies.	Wang, et al. [14]
P-VAR / VECM	Models dynamic feedback loops and interdependencies between macro variables (e.g., trade & GDP) across countries.	Mulenga and Mayondi [9]
Mediation & Moderation	Identifies how (transmission channels) or under what conditions (boundary effects like aging) digitalization impacts performance.	Chen and Kim [4]; Meng and Wen [11]
Propensity Score Matching (PSM)	Reduces selection bias by creating a statistically comparable control group for treated firms.	Su, et al. [16]
Simultaneous Equations	Accounts for mutual causality between interdependent macro variables (e.g., ICT supply vs. demand).	Knobel, et al. [18]

Despite these methodological advances, including the standard use of fixed-effects panels, instrumental variables (IV), and text-analysis indices, three critical shortcomings remain in the existing literature.

First, a micro-macro disconnect remains unresolved. While macro-level studies robustly demonstrate that digital trade boosts national GDP and aggregate productivity, and micro-level analyses confirm that digital transformation enhances firm-level TFP, the literature lacks a unified framework that explicitly links these two strands. The specific mechanism through which micro-level gains aggregate to drive macro-level growth essentially functions as a "black box."

Furthermore, inconsistent variable boundaries continue to pose a challenge, as the frequent conflation of broad domestic internet penetration with actual cross-border digital services trade has led to significant measurement issues and conceptual blurring.

Finally, explanations for the enduring "Solow Paradox" remain incomplete. Although contemporary research acknowledges important nonlinearities and threshold effects, it has not sufficiently leveraged these insights to fully explain why massive expansions in global digital trade volumes fail to translate into commensurate aggregate TFP growth, nor has it provided a clear, sequenced policy pathway to help economies overcome the specific frictions that create this disparity.

To address these gaps, this study makes three distinct contributions. Theoretically, it establishes a seamless logical chain from the macro to the micro level by explicitly modeling cross-border digital trade as the external catalyst and corporate digital transformation as the internal micro-level vehicle through which global trade flows ultimately influences Total Factor Productivity. Conceptually, the study introduces rigor by unifying and standardizing the core variables, employing "ICT service imports/exports as a percentage of total digital service trade" to strictly define digital trade, thereby eliminating the boundary ambiguities prevalent in earlier studies that relied on broader proxies like internet penetration. Practically, it moves beyond merely diagnosing the frictions behind the Solow Paradox by integrating the "sub-threshold trap" into the analysis; this enables the study to map a sequenced, complement-first implementation pathway, thereby providing policymakers with targeted strategies to overcome the specific capability and institutional bottlenecks that currently stifle aggregate productivity growth.

3. Analysis

3.1. The Divergence Between Digital Expansion and Productivity

The global economy is currently witnessing a massive volumetric expansion in cross-border digital trade. Between 2005 and 2023, global ICT service exports grew at an average annual rate of 11.2%, far outpacing the growth of non-digitally delivered services [6]. Across major economies, the digital economy now accounts for nearly half of the combined GDP, driving deep capital accumulation and restructuring trade flows [9, 11].

However, despite this massive digital capital deepening, a pronounced macroeconomic divergence persists: the "Solow Paradox." While computer age investments are highly visible in trade and infrastructure statistics, post-2008 Total Factor Productivity (TFP) growth in many advanced and emerging economies has remained subdued [1, 2]. This analysis posits that the essence of the Solow paradox is a sub-threshold trap. While cross-border digital trade acts as a powerful external catalyst, the internal micro-level vehicle, corporate digital transformation, requires overcoming significant initial adjustment costs. The average level of corporate digital transformation remains far below the critical threshold required to trigger positive returns [5]. Consequently, the vast majority of economic actors are currently stuck in the downward-sloping portion of a U-shaped productivity curve, where digital investment temporarily inhibits rather than drives TFP growth.

3.2. The "As-Should-Be" Pathways of Digital Trade

To understand the mechanics of this trap, it is necessary to first delineate the "as-should-be" transmission pathways. In an optimal scenario, cross-border digital trade alters firms' access to frontier technologies and global markets. These external shocks catalyze corporate digital transformation, which subsequently reorganizes production to drive TFP through several interlinked channels.

First, cross-border digital trade possesses the unique advantage of facilitating international knowledge spillovers and innovation diffusion. Unlike domestic digitalization, importing ICT-intensive inputs acts as a direct conduit for foreign technology transfer, significantly lowering R&D risks for domestic firms [7, 9]. Furthermore, AI-intensive digital services exponentially increase cross-border user acquisition and knowledge sharing [17].

Figure 1 illustrates the U-shaped impact of digital transformation on total factor productivity (TFP) identified in existing research [5], revealing the nonlinear relationship between digitalization and productivity growth.

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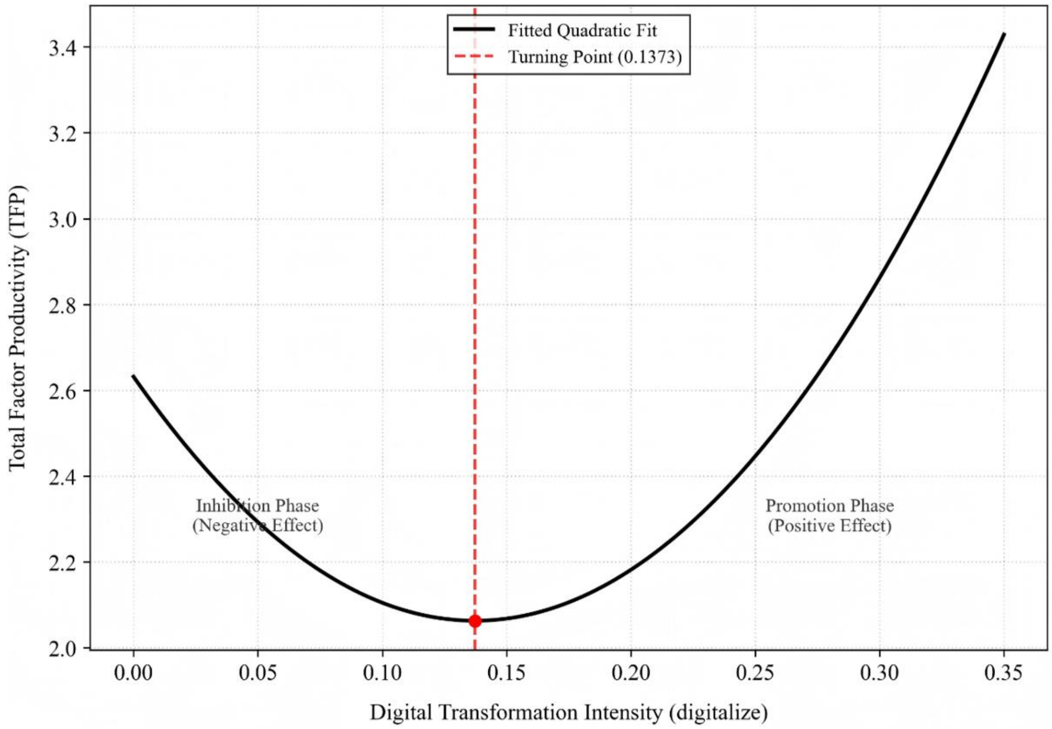

Figure 1.
The U-Shaped Impact of Digital Transformation on TFP.
Note: The figure plots the fitted values from the empirical model TFP=α_0+α_1·digitalize+α_2·〖digitalize〗^2. The coefficients (α_1=-8.2859***,α_2=30.1787***) confirm a U-shaped relationship where TFP initially declines due to adjustment costs before rising. The calculated turning point is 0.1373. Given the sample mean is only 0.0090, the figure illustrates the "Subthreshold Trap" described in Section 3.1, indicating that the majority of firms have not yet crossed the efficiency threshold.
Source: Adapted from Cheng et al. [5].

Second, digital trade fundamentally reshapes resource allocation and scale economies. By lowering search and matching costs on global platforms, digital transformation reduces asset specificity and external transaction costs [3, 13]. This reduction in friction theoretically allows capital and labor to flow toward their highest-value uses. Concurrently, digital trade lowers access barriers to foreign markets, enabling firms to achieve unprecedented economies of scale without proportional increases in physical footprint [9, 21].

Figure 2 quantifies the magnitude of efficiency shortfalls and the corresponding output improvements achievable through digital transformation, illustrating the economic potential embedded in narrowing efficiency deficits.

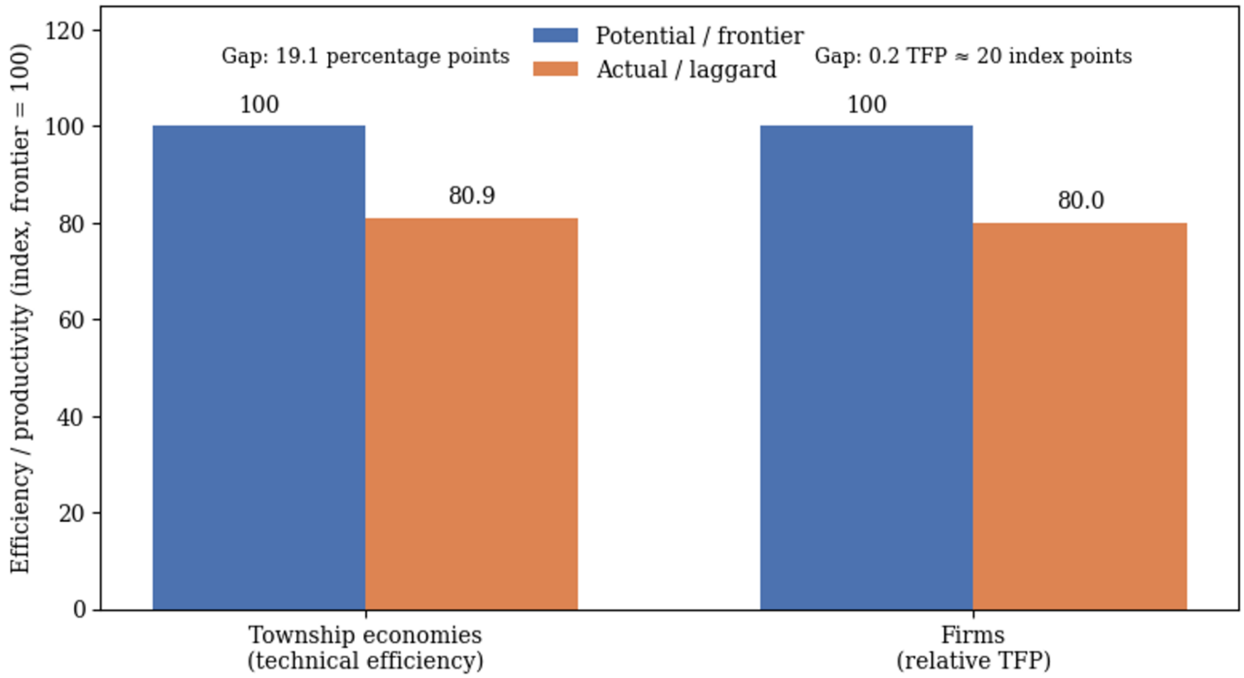

Figure 2.
Quantifying Structural Efficiency Gaps and the Macroeconomic "Reallocation Dividend."
Note: This figure illustrates the unrealized economic potential trapped by structural frictions, comparing the actual productivity of lagging segments against the maximum efficiency frontier (set at 100%). Empirical estimates indicate that peripheral (township) economies operate roughly 19% below their full potential due to barriers in ICT adoption [3]. Similarly, a TFP gap of approximately 0.2 exists between the top 2% of frontier firms and the lagging firms. Closing this gap through corporate digital transformation is critical; macro-simulations project that elevating the TFP of the bottom 90% of firms to the frontier level could unlock a "reallocation dividend," potentially driving an 18% increase in GDP over a 6-to-8-year horizon [18].
Source: Data adapted from macroeconomic simulations in Knobel et al. [18] and technical efficiency estimates in Mazorodze [3].

Third, these technological and structural shifts require the active functioning of human capital and contestability channels. The influx of global digital services necessitates workforce upskilling, which theoretically compensates for demographic headwinds such as population aging [11]. Simultaneously, exposure to global digital markets heightens contestability, compelling incumbent firms to enhance corporate governance and operational efficiency to survive [19, 22].

Figure 3 reveals the varying degrees to which the digital economy alleviates the pressures of population aging among different regions in mainland China.

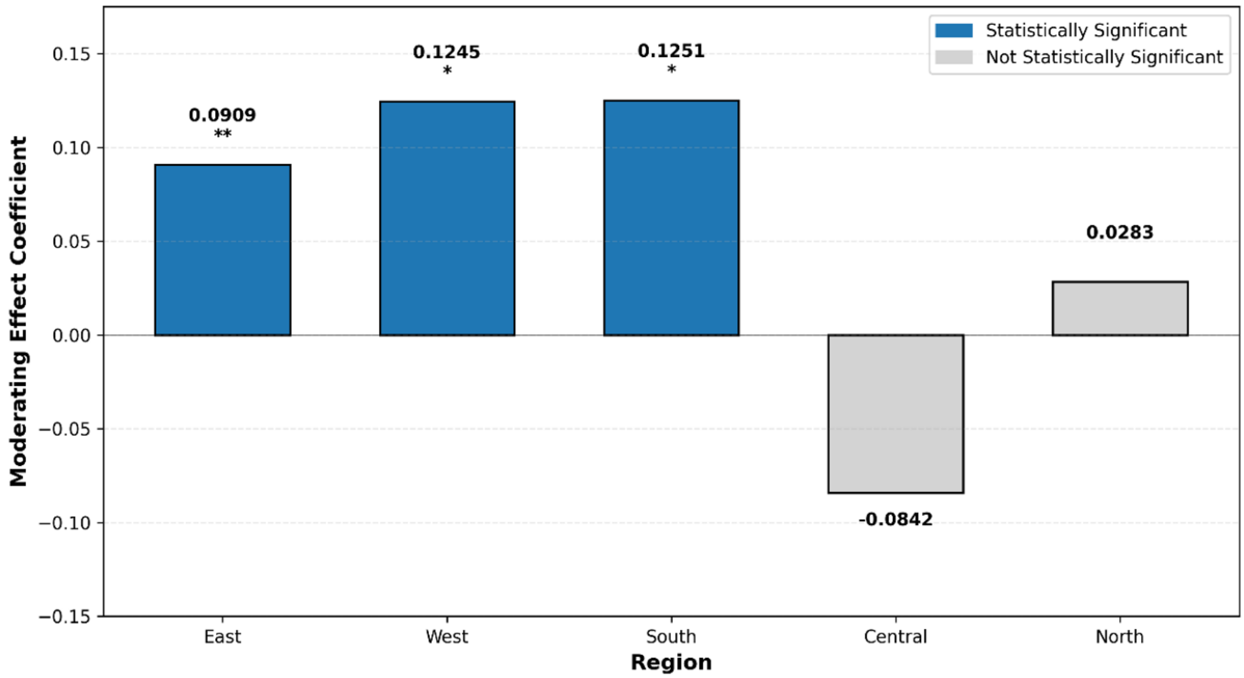

Figure 3.
Regional Heterogeneity in the Digital Economy's Capacity to Offset Demographic Headwinds (China).
Note: This figure visualizes the moderating effect of the digital economy on the relationship between the aging population and TFP. The bars represent the regression coefficients of the interaction term (old × digital). A positive, significant coefficient indicates that digitalization successfully acts as a compensatory mechanism, mitigating the negative TFP drag caused by an aging workforce. The compensatory effect is significant in the Southern (0.1251), Western (0.1245), and infrastructure-rich Eastern (0.0909) regions. In contrast, the effect is insignificant in the Central (-0.0842) and Northern (0.0283) regions. This divergence illustrates the "structural constraints" bottleneck: in regions burdened by lagging reforms, reliance on heavy industry, and capability gaps, the human capital transmission channel breaks down, preventing digitalization from yielding aggregate productivity gains.
Source: Data extracted from regional heterogeneity tests in [11].

Crucially, these transmission channels do not operate in isolation; they exhibit strong linkage effects. The realization of the scale effect is entirely dependent on the efficiency of the resource allocation channel; if rigid labor markets prevent workforce reallocation, scaling cannot occur. Similarly, the innovation diffusion channel relies heavily on the human capital channel; without sufficient absorptive capacity and managerial skills, imported ICT services cannot be translated into domestic TFP gains [2].

3.3. The Dual Impact on Green Total Factor Productivity (GTFP)

A critical, yet often fragmented, dimension of digital trade is its impact on sustainability. The analysis of Green TFP (GTFP) reveals that digital trade exerts a unique, dual impact on environmental outcomes, creating a complex trade-off between technological advancement and physical scale.

On the positive side, digital transformation acts as a powerful driver for shifting the green technological frontier (GTC). Access to cross-border digital tools enables real-time monitoring of energy use, optimizes resource allocation, and lowers the cost of acquiring foreign green technologies [10, 14]. By reducing external transaction costs, firms can reorganize production networks to integrate into greener global value chains [13].

However, this technological dividend is counterbalanced by a negative scale effect. The sheer volumetric expansion of ICT-based digital trade and the associated infrastructure (e.g., data centers, hardware production) inherently increases aggregate energy consumption and carbon emissions [8, 15]. Therefore, digital trade does not automatically result in green growth; its net impact on GTFP depends entirely on whether the efficiency gains from the technological effect can successfully outpace the energy demands of the scale effect.

Figure 4 presents the key mediating pathways through which digitalization drives the improvement of green total factor productivity (GTFP).

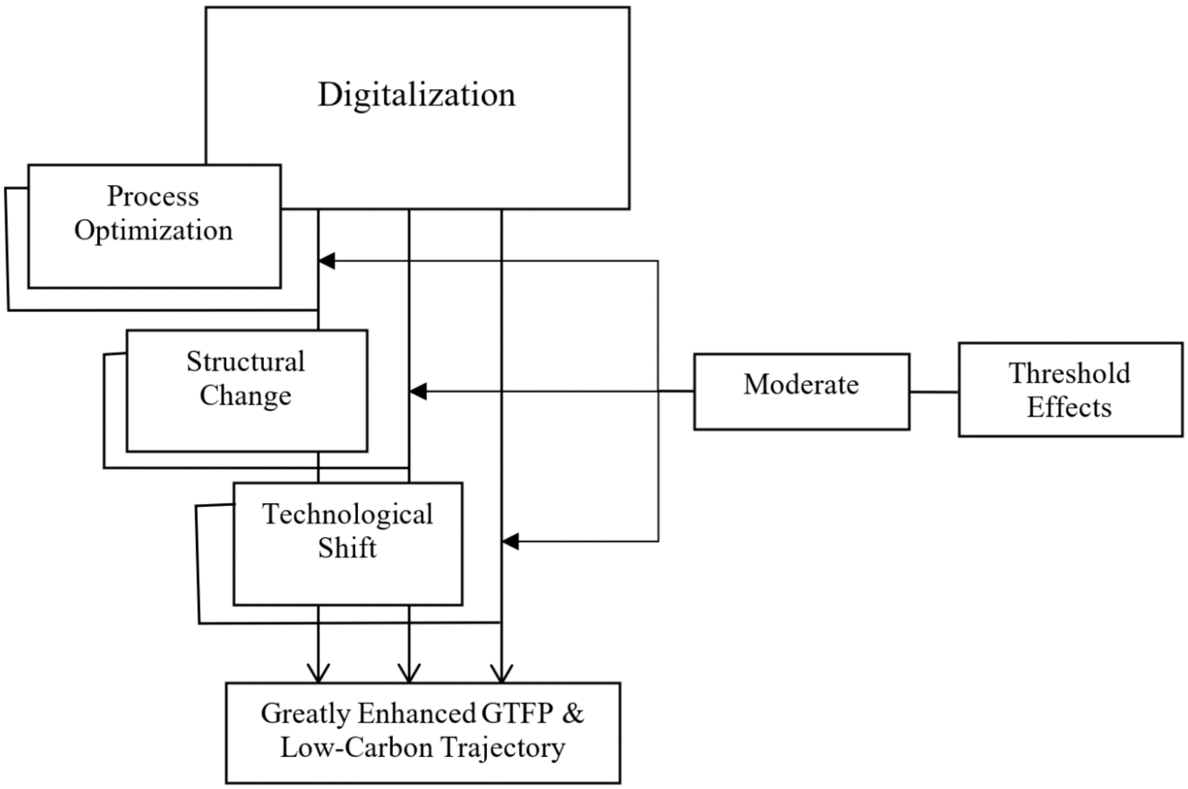

Figure 4.
Transmission Channels from Digitalization to Green Total Factor Productivity (GTFP).
Note: The diagram illustrates the three primary mechanisms, Process Optimization, Structural Change, and Technological Shift, through which digitalization drives the transition to a low-carbon economy. Crucially, the "Moderating" arrow highlights that these gains are not automatic; as discussed in Section 3.3, Threshold Effects (such as infrastructure maturity and R&D intensity) determine whether the structural efficiency gains outweigh the energy-intensive scale effects, thereby unlocking the "Greatly Enhanced GTFP."
Source: Authors' elaboration based on the theoretical frameworks in [8, 10, 14, 15].

3.4. The "As-Is" vs. "As-Should-Be" Divergence

The theoretical synergy of the channels described above rarely materializes fully due to severe structural constraints, creating divergence between digital expansion and aggregate productivity.

First, infrastructure and capability gaps act as a binary filter, severely bottlenecking innovation and human capital channels. High-speed broadband access and baseline ICT skills are prerequisites for digital adoption [2]. Because these capabilities are unevenly distributed, the benefits of digital trade accrue disproportionately to a small tier of frontier firms, leaving laggards unable to absorb cross-border knowledge spillovers.

Second, institutional and market frictions sever the linkage between innovation and resource allocation. Rigid labor markets and credit constraints heavily bias digital dividends toward well-capitalized or state-owned enterprises [7, 20]. Because capital and labor cannot fluidly exit obsolete sectors and enter digitally intensive ones, the "reallocation dividend", which macro-simulations suggest could raise GDP by up to 18% [18], remains largely unrealized at the aggregate level.

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Third, regulatory fragmentation restricts the scale of channels. Cross-border data flow restrictions and divergent digital trade rules act as artificial borders in the digital space. These frictions specifically attenuate the international impact of AI and data-intensive services, increasing compliance costs and neutralizing the global scale economies that digital trade is supposed to provide [17, 23].

3.5. Formation Mechanisms of the Sub-Threshold Trap

When the idealized transmission mechanisms collide with these structural constraints, the macro-level result is the formation of the sub-threshold trap. The trap forms through a compounding sequence of frictions.

When a firm is exposed to the external catalyst of digital trade, it must initiate internal digital transformation. However, due to the aforementioned capability gaps (lack of managerial talent) and institutional frictions (credit constraints), the firm faces massive upfront adjustment costs, sunk investments, and organizational inertia. Because the inter-channel linkages are broken, for instance, the firm imports ICT tech but lacks the flexible labor market to utilize it, the firm falls into the "productivity dip" of the U-shaped curve [5].

Without adequate complementary conditions (e.g., cross-border data regulatory harmony, high-speed infrastructure, and deep human capital), the firm lacks the momentum to push past the critical digitalization threshold. The firm remains in a state of perpetual, inefficient disruption. Multiplied across millions of enterprises, this micro-level stagnation aggregates into the macro-level Solow Paradox. Therefore, the failure of digital trade to lift economy-wide potential growth is not a failure of the technology itself but a systemic failure to clear the structural and capability thresholds required to operationalize the digital vehicle.

Table 6 provides a structured overview of the core motivations and corresponding analytical modes examined in this section, illustrating how internal demands and external pressures influence pathways out of this trap.

Table 6.
Summary of Motivation and Mode Analysis.

Dimension	**Content**	**Characteristics**	**Logic**
Internal Motivation	Enterprise efficiency improvement, technological innovation demand, cost reduction, and competitive advantage enhancement.	Active-driven, enterprise-oriented, closely linked to development goals	Internal motivation determines the initiative and depth of digital transformation
External Motivation	Policy guidance, market competition pressure, technological iteration, and cross-border digital spillover.	Passive-induced, environment-dependent, with strong pertinence	External motivation provides the impetus and external conditions for transformation.
Independent R&D Mode	Enterprises independently develop digital technologies and build transformation systems.	High autonomy, high R&D investment, strong adaptability to enterprise needs	Suitable for enterprises with strong internal motivation and sufficient technical strength
Cooperation Empowerment Mode	Enterprises cooperate with digital platforms and tech firms to obtain technical and resource support.	Low investment risk, fast implementation, complementary advantages	Matches the external motivation of technological iteration and resource sharing
Platform-Driven Mode	Relying on industrial digital platforms to realize the integrated transformation of the industrial chain.	Industrial linkage, scale effect, standardized transformation path	Driven by both internal efficiency demand and external industrial coordination needs

4. Analysis of Implementation Path and Strategy

4.1. Digital Trade Requires Complements

The empirical results in Section 3 show that expanding digital trade volumes is a necessary but not sufficient condition for raising economy-wide productivity. Digital services exports and ICT-intensive trade contribute positively to per-capita income, yet aggregate TFP growth remains weak and highly uneven. Most firms operate below the digitalization threshold at which TFP effects turn positive, and large gaps persist between frontier and laggard regions and firms. These findings indicate that digital trade raises potential growth only when it is accompanied by complements, which include reliable digital infrastructure, firm-level capabilities, supportive institutions, and productivity-compatible data and environmental governance.

Therefore, an implementation path must be complement-first rather than volume-first. Policies that seek to maximize digital exports without countering domestic bottlenecks will reinforce "islands of efficiency" and entrench divergence. The following subsections will translate this principle into strategies at the levels of infrastructure, capabilities, allocation mechanisms, and regulatory frameworks.

4.2. Infrastructure Supports Adoption

To address the infrastructure frictions and the “binary filter” effect identified in Section 3.4, policies must prioritize overcoming the specific connectivity thresholds that currently segment the economy. The empirical finding that digital adoption rates double only when broadband speeds exceed 30 Mbit/s implies that substandard connectivity is a binding constraint rather than a marginal friction [2]. Consequently, infrastructure investment must be targeted rather than diffuse, aiming to expand the “islands of efficiency” by ensuring that lagging industrial zones and rural areas meet this technical prerequisite. By lifting the long tail of firms above this connectivity floor, such investments activate the “reallocation dividend”, potentially raising GDP by significant margins as simulated in recent literature [18], and allow the extensive margin of digital trade to function effectively.

Furthermore, infrastructure strategy must go beyond physical connections to address the high fixed costs of digital entry. Integrating network expansion with access to cloud services and basic cybersecurity support directly mitigates the barriers that prevent SMEs from connecting to Global Value Chains (GVCs). This approach facilitates the resource reallocation described in Section 3.3.2 by allowing smaller entities to leverage the same digital backbone as frontier firms. At the international level, cross-border infrastructure cooperation is essential to operationalize the scale and GVC-integration channels (Section 3.3.3). Establishing regional data corridors and harmonizing digital standards can lower latency and improve the quality of cross-border digital services, ensuring that the theoretical market expansion effects translate into tangible domestic productivity gains rather than remaining concentrated in a few digital hubs.

Table 7 summarizes the key relationships identified between digital transformation and total factor productivity (TFP).

Table 7.
The Connections between Digital Transformation and TFP.

Aspect	Findings	Studies
Overall impact	The digital economy has a significant positive effect on the growth rate of total factor productivity (TFP). At the firm level, digital transformation in the real economy, new energy, and heavily polluting enterprises generally increases TFP.	Meng and Wen [11]; Cheng, et al. [5]; Ren, et al. [7]; Su, et al. [16]
Non-linear relationship	For real-economy enterprises, the impact of digital transformation on TFP follows a non-linear U-shaped pattern: TFP is initially dampened in the early stages of transformation but rises significantly once a critical level of digitalization is reached.	Cheng, et al. [5]
Compensatory / moderating effects	The digital economy mitigates the negative impact of population aging on TFP. The interaction term between aging and the digital economy is significantly positive, indicating a compensatory (moderating) effect.	Meng and Wen [11]
Mediating mechanisms	Capital and financing: Improves capital efficiency, such as higher working capital turnover, and alleviates financing constraints. Human capital: Optimizes the human capital structure by upgrading workforce skills. Innovation and technology: Strengthens innovation capacity, increasing patent output and green technology innovation. Operational efficiency and costs: Raises asset turnover, reduces operating costs and cost stickiness, and enhances corporate social responsibility (CSR). Information and knowledge flows: Strengthens information exchange and human capital accumulation, promoting technological progress through a coupling effect between the digital economy and aging.	Cheng, et al. [5]; Ren, et al. [7]; Su, et al. [16]; Han, et al. [13]; Meng and Wen [11]
Heterogeneity	Ownership: The positive impact of digital transformation on (green) TFP is often more pronounced in state-owned enterprises (SOEs) than in non-SOEs. Region: Effects are stronger in eastern China, where digital infrastructure and market conditions are more advanced. Industry / type: Larger gains are observed for non-high-tech, non-manufacturing, heavily polluting, and new energy enterprises. Firm size: Digital transformation tends to have a stronger effect on TFP in large-scale enterprises.	Ren, et al. [7]; Su, et al. [16]; Han, et al. [13]; Chen and Kim [4]
Trade and macro context	At the macro level, digital services trade and ICT-based digital trade foster economic growth and productivity, supporting higher TFP in developing, emerging, and developed economies.	Mulenga and Mayondi [9]; Houngbonon and Mothobi [6]

4.3. Capabilities Push Firms Beyond Thresholds

This subsection targets the “sub-threshold trap” and the associated “adjustment costs” analyzed in Section 3.1. The empirical confirmation of a U-shaped relationship between digital transformation and TFP indicates that policy must accelerate firms’ transition through the initial productivity dip where digital investment currently inhibits growth. Given that the average firm’s digitalization level of 0.0090 sits far below the critical threshold of 0.1373 required for positive returns [5], incremental support is insufficient. Policies must instead incentivize deep, transformative investments that push firms past this inflection point, ensuring that the innovation channel (Section 3.3.1) can deliver its deferred benefits.

To achieve this, strengthening "absorptive capacity" is decisive. As highlighted in Section 3.4, low managerial quality and persistent skills mismatches are primary barriers that prevent effective adoption even when infrastructure is present. Therefore, capability-building programs must prioritize managerial training in process redesign and data-driven decision-making, ensuring that digital tools are integrated into core business functions rather than remaining superficial add-ons. This focus on managerial quality is essential to convert the "quantity" of digital investment into the "quality" of innovation output [4, 19].

Finally, these interventions must address the demographic and financial contexts outlined in the analysis. To mitigate the demographic drag on TFP, as documented in Section 3.3.4, upskilling initiatives must be designed to complement the aging workforce, thereby allowing the digital economy to act in its compensatory role [11]. At the same time, because the largest productivity gains arise from overcoming non-linear thresholds, financial instruments such as risk-sharing guarantees or time-bound tax incentives are justified. These should be structured to lower the downside risks of lumpy, transformative investments, encouraging firms in lagging sectors to undertake the comprehensive changes necessary to escape the sub-threshold regime and contribute to growth.

4.4. Institutions Improve Allocation

This strategy would address the market and institutional frictions identified in Section 3.4, which currently prevent resources from moving toward high-productivity digital activities. As noted in Section 3.3.2, while digitalization improves within-firm efficiency, structural rigidities limit the "reallocation dividend." The empirical simulation suggests that lifting the TFP of the bottom 90% of firms, the long tail of laggards, could increase GDP by approximately 18% [18]. However, the current landscape is defined by "islands of efficiency," where gains accrue disproportionately to large, state-owned, or well-capitalized firms [5, 7]. To unlock this latent potential, institutional reforms must focus on dismantling the barriers that trap factors of production in low-efficiency uses.

First, financial institutions must adapt to correct the misallocation of credit described in Section 3.3.2. Since credit constraints currently bias digital gains toward firms with better initial conditions [20], policy should target the extensive margin, facilitating the entry and growth of potentially productive SMEs. Financial instruments, such as performance-based lending or digital-asset collateralization, should be designed to identify and assist laggard firms capable of crossing the efficiency threshold. By shifting capital allocation criteria from traditional asset ownership to digital potential, policymakers can help the "long tail" of firms overcome the financing constraints that currently stifle their TFP growth.

Second, labor-market institutions must address the "skills mismatch" and mobility frictions highlighted in Section 3.4. The transition to a digital economy requires that labor move freely from declining sectors to those expanding through digital trade. To facilitate this, policies such as portable social benefits and recognition of prior learning are essential to lower the friction of movement. This directly supports the reallocation channel, ensuring that the labor savings generated by digital efficiency [16] are absorbed by new high-value activities rather than resulting in structural unemployment or stagnation.

Finally, competition policy must be calibrated to manage the "winner-take-most" risks identified in Section 3.3.5. While evidence shows that digitalization improves performance most effectively in competitive sectors [19, 20], network effects can entrench incumbents and dampen the pressure to pass efficiency gains to the wider economy [1]. Regulatory frameworks must therefore enforce interoperability and data portability to maintain contestability. This ensures that the digital economy drives broad-based structural change rather than simply reinforcing the dominance of existing frontier firms.

Figure 5 compares the evolving trends of total factor productivity (TFP) between firms in ICT-intensive and non-ICT-intensive industries, showing how ICT intensity shapes the dynamic productivity performance of enterprises.

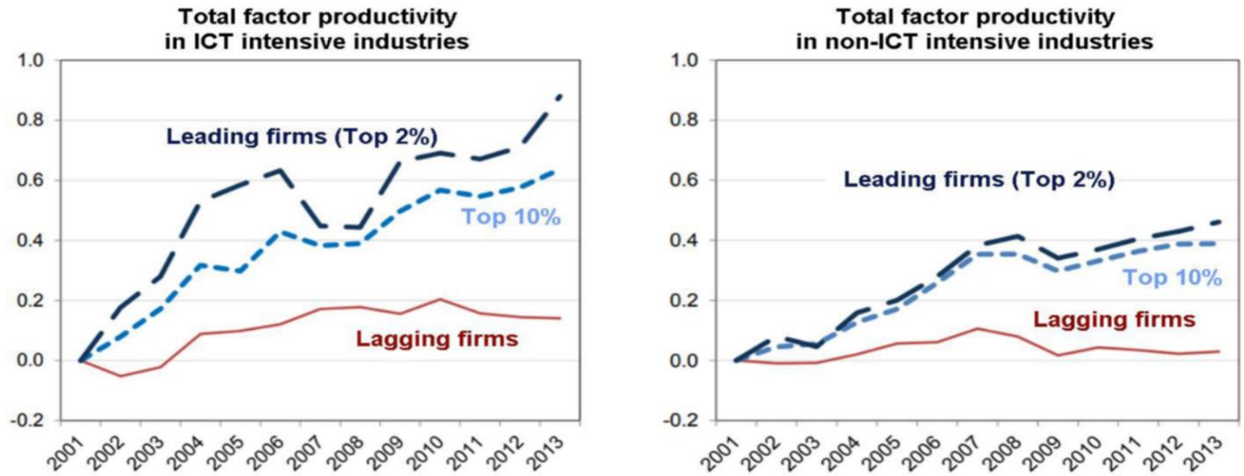

Figure 5.
Comparison of TFP dynamics of firms in ICT-intensive and non-ICT-intensive industries.
Note: The graph plots the TFP evolution of leading vs. lagging firms. The parallel trends illustrate the "structural misallocation" discussed in Section 3.3.2, where the efficiency gap remains constant over time despite general economic growth.
Source: Reproduced from Knobel et al. [18], Figure 4.

4.5. Governance Shapes Cross-Border Spillovers

This section aims to respond to the regulatory frictions and cross-border constraints analyzed in Sections 3.3.1 and 3.4. The empirical analysis demonstrates that while digital services trade acts as a conduit for technology diffusion, this effect is "substantially attenuated" in jurisdictions with restrictive data-flow regimes [17]. Specifically, the finding that AI applications significantly boost foreign user acquisition only in open regulatory environments indicates that data governance is a binding constraint on the innovation channel. Consequently, the design of data regimes is not merely a compliance issue but a determinant of whether the economy can capture the long-run growth benefits of digital trade.

To reconcile the trade-off between security and diffusion, national governance should adopt a risk-based approach rather than blanket restrictions. As Section 3.3.1 highlights, cross-border knowledge diffusion is highly sensitive to data governance; therefore, differentiating data flows based on sensitivity allows for the continued transmission of commercial and technological knowledge while protecting critical interests. This approach preserves the "conduit" function of digital services exports [6, 9], ensuring that the domestic digital economy continues to benefit from talent mobility and knowledge spillovers that define the global frontier.

At the international level, reducing regulatory fragmentation is critical to activating the scale and GVC-integration channels (Section 3.3.3). The concentration of digital trade benefits in a small set of leading countries [6] is partly driven by the high fixed costs of navigating divergent regulatory regimes. Harmonizing digital trade rules and establishing mutual recognition of data standards would lower these barriers, allowing a broader set of countries and firms to participate in the digital economy. By mitigating the regulatory frictions that currently fragment the global market, such cooperation ensures that the scale benefits of digital trade are not neutralized by compliance costs, thereby sustaining the positive link between digital export expansion and GDP growth [9].

4.6. Policies Coordinate Digitalization and Sustainability

This strategy responds to the environmental and demographic trade-offs analyzed in Sections 3.3.6 and 3.3.4, respectively. The empirical evidence reveals a complex dynamic: while digital transformation raises Green Total Factor Productivity (GTFP) by shifting the "green technological frontier" (GTC), the sheer scale effect of ICT-based trade can simultaneously increase energy consumption and inhibit GTFP [8, 10]. Furthermore, while digitalization offers a "compensatory effect" against the negative

TFP impact of population aging [11], this mechanism is conditional on the workforce's ability to adapt. Therefore, implementation must actively manage these opposing forces to ensure that digital growth remains both sustainable and comprehensive.

To resolve the tension between scale and sustainability, policies must decouple digital trade expansion from carbon intensity. Since the analysis above confirms that, once certain thresholds are exceeded, renewable energy and digitalization only deliver strong carbon-reducing effects [15], support for digital infrastructure, such as data centers and 5G networks, should be conditioned on the integration of low-carbon energy sources. Policy must incentivize innovations that purposely shift the green technological frontier, which ensures that the "efficiency gains" from digitalization outweigh the "scale effects" of increased data usage. By aligning digital industrial policy with environmental performance criteria, governments can ensure that the digital economy drives GTFP growth rather than merely expanding the volume of emissions-intensive trade.

Concerning demographics, the strategy must operationalize the "compensatory effect" identified in the growth accounting framework. Since the interaction between the digital economy and aging is statistically positive but limited by human capital quality [11], the implementation path must prioritize the "absorptive capacity" of the older workforce. Lifelong learning and reskilling programs should focus on upgrading digital competencies for mid-career workers, thereby reducing the "skills mismatch" that currently drags on TFP [6]. Additionally, promoting inclusive design in digital interfaces can lower the adjustment costs for older cohorts, ensuring that demographic headwinds are mitigated by labor-augmenting technologies rather than exacerbated by structural displacement.

5. Implementation Path Sequencing and Reform Priorities

The implementation path outlined above must be sequenced to reflect the structural heterogeneity and non-linearities summarized in Section 3.5. Recognizing that the binding constraints differ by development stage, governments should prioritize reforms based on their economy's position relative to the critical efficiency thresholds identified in the analysis.

For economies and sectors still operating in the "sub-threshold" regime, where digital investment generates adjustment costs rather than TFP gains [5], the immediate priority is to overcome the fundamental barriers to adoption. Policies must focus on closing the "binary filter" of infrastructure access (Section 3.4) and building the basic managerial and ICT capabilities required to move firms up the initial slope of the U-shaped productivity curve. In this phase, public investment in connectivity and broad-based digital literacy is a prerequisite to escaping the low-productivity trap.

Conversely, for economies that have already achieved critical mass in infrastructure and adoption, the policy focus must shift toward unlocking the "reallocation dividend" and enhancing diffusion. Here, the priority is to dismantle the institutional and regulatory frictions that confine benefits to "islands of efficiency" (Section 3.3.1). Reforms should target competition policy, labor mobility, and cross-border data governance to ensure that efficiency gains spill over from frontier firms to the wider economy. By sequencing reforms in this manner, governments can ensure that the "complementary conditions" required for growth are built cumulatively, allowing the channels of innovation, allocation, and scale to operate at full strength and deliver the sustained improvements in potential growth projected in macro-level studies [9].

Table 8 systematically summarizes the practical implementation routes and corresponding strategic measures identified in this study.

Table 7.
Summary of Implementation Paths and Strategies.

Focus	Measures	Objective	Logic
Infrastructure Support	Meet the broadband threshold, build cloud services, and establish cross-border data corridors	Break the digital adoption threshold and reduce regional/enterprise heterogeneity	Infrastructure is the foundation for digital adoption and cross-border cooperation.
Capability Building	Enhance enterprise management, ICT skills and digital organizational adaptation	Help firms escape the sub-threshold trap and improve digital absorption capacity.	Enterprise capability determines the effect of digital technology adoption.
Institution Improvement	Reform financial, labor and competition systems to reduce allocation frictions	Optimize digital resource allocation and promote TFP growth.	Sound institutions can release the potential of digital resource reallocation
Cross-Border Governance	Adopt risk-classified data governance and coordinate global digital trade rules.	Boost cross-border digital spillovers and reduce compliance costs.	Reasonable cross-border governance balances security and efficiency
Policy Coordination	Decouple digital expansion from carbon intensity, promote human capital upgrading.	Balance digitalization and sustainability, offset aging impacts	Policy synergy avoids drawbacks of single-dimensional development.
Reform Prioritization	Differentiate reform sequences by digital development stages	Promote efficient and orderly digital transformation with targeted policies	Differentiated prioritization ensures reform efficiency and pertinence

6. Conclusion

First, the "Solow Paradox" reflects a sub-threshold trap rather than a failure of technology. The divergent pattern between rapid digital trade expansion and subdued productivity growth arises because the majority of firms remain in the "installation phase" of the digital transition. Empirical evidence confirms a U-shaped relationship where high adjustment costs and organizational inertia suppress TFP until digitalization exceeds a critical threshold of 0.1373, a level the average firm has yet to reach.

On the second dimension, structural divergence has confined productivity gains to isolated "islands of efficiency." While frontier firms and digitally connected regions capture significant returns, a "binary filter" in infrastructure blocks the diffusion of benefits to the broader economy. Adoption rates double only after broadband speeds surpass 30 Mbit/s, leaving the "long tail" of laggard firms disconnected from the innovation and knowledge spillovers generated by digital trade.

Third, unlocking the "reallocation dividend" requires dismantling institutional market frictions. The potential for digital trade to raise aggregate TFP hinges on the ability of resources to move from low- to high-productivity activities. Currently, credit constraints and labor market rigidities stifle this creative destruction, preventing the economy from realizing the estimated 18% GDP gain available from lifting the efficiency of the bottom 90% of firms.

The fourth point is that regulatory fragmentation substantially attenuates the scale and spillover effects of digital trade. The capacity for digital services, particularly AI-intensive ones—to act as conduits for technology transfer is heavily conditional on data governance. Restrictive cross-border data regimes raise fixed costs and fracture the global market, thereby neutralizing the scale economies that are the primary engine of digital trade's contribution to growth.

Ultimately, and prospectively, digitalization offers a conditional remedy for demographic headwinds and environmental transition. While the digital economy acts as a compensatory force against the negative TFP impact of population aging, this effect depends on the continuous upskilling of the workforce. Similarly, realizing "Green TFP" requires policy to actively decouple data growth from emissions, ensuring that the structural efficiency gains of digitalization outweigh the energy-intensive scale effects of expanded infrastructure.

Transparency:
The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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