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Digital Transformation and Digital Trade Performance: A Comparative Empirical Study with a Systems Thinking Perspective on Capability and Institutional Factors (2015–2024)

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ABSTRACT

Digital transformation has become a critical driver of economic competitiveness and global trade integration. However, the mechanisms through which domestic digital adoption translates into digital trade performance remain insufficiently understood, particularly in emerging and transitional economies. This study investigates the relationship between business-level digital adoption and digital trade dynamics through a comparative longitudinal analysis of four economies—China, India, South Korea, and Iran—over the period 2015–2024. To capture these dynamics, the study constructs two composite indices: Business Digital Adoption and Integration (BDAI), reflecting the extent to which firms adopt and integrate digital technologies into economic activities, and Digital Trade Momentum (DTM), representing the growth and intensity of digitally enabled trade participation. The indices are built using internationally comparable indicators from sources including the World Bank, International Telecommunication Union (ITU) ,United Nations Conference on Trade and Development (UNCTAD),Organisation for Economic Co-operation and Development(OECD), and International Monetary Fund(IMF), and are normalised using a min–max scaling procedure .The findings reveal significant cross-country divergence in both digital capability formation and digital trade performance. South Korea demonstrates consistently high levels of digital adoption and stable digital trade competitiveness, while China exhibits rapid growth driven by large-scale digital ecosystem expansion. India shows gradual improvement in digital adoption but more moderate progress in digital trade diversification. In contrast, Iran remains structurally constrained, with comparatively limited digital adoption and weak integration into global digital trade networks. Interpreting the results through a system dynamics perspective suggests that digital transformation operates through reinforcing feedback mechanisms linking infrastructure development, firm-level digital capabilities, innovation capacity, and global trade participation. Economies that successfully align these dimensions experience cumulative advantages, whereas structural constraints may reinforce persistent digital gaps. The study contributes to the digital economy literature by linking micro-level digital capability formation with macro-level trade outcomes and by highlighting the systemic conditions required for translating digital adoption into sustainable digital trade competitiveness.

Keywords

Digital Transformation, Digital Trade, Business Digital Adoption, Digital Economy, Absorptive Capacity, Dynamic Capabilities

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1. Introduction

Over the past decade, the digital economy has evolved from a peripheral technological phenomenon into a central organising principle of contemporary economic systems. Beyond the digitisation of existing processes, digital transformation has fundamentally reconfigured patterns of value creation, organisational learning, and institutional coordination through data-intensive production, platform-based intermediation, and algorithmic decision-making, reshaping competitive dynamics across sectors and regions (Kremen et al., 2019; Verhoef et al., 2021; Kraus et al., 2022). In this emerging environment, digital technologies function not merely as operational tools but as generative infrastructures capable of enabling continuous recombination, innovation, and distributed value creation across interconnected ecosystems (Nambisan et al., 2019; Vial, 2021).

The concept of generativity is particularly important for understanding the developmental implications of digital transformation. Unlike conventional industrial technologies, digital systems are modular, reprogrammable, and scalable, allowing firms and institutions to continuously create new applications, services, and organisational configurations (Leonardi, 2011; Markus and Silver, 2008). Recent research emphasises that such generative digital infrastructures facilitate new forms of platform ecosystems, data-driven innovation, and digitally mediated coordination mechanisms across organisational boundaries (Gawer, 2022; Nambisan et al., 2019). As digital infrastructures expand, competitive advantage increasingly depends on the ability of economic actors to exploit these generative capabilities through adaptive learning, organisational flexibility, and strategic coordination. Consequently, digital transformation has become deeply intertwined with broader processes of capability accumulation, institutional adaptation, and economic restructuring (Warner and Wäger, 2019).

At the global level, digitalisation has significantly altered the organisation of production, trade, and innovation networks. Advances in information and communication technologies have reduced coordination costs, facilitated cross-border data flows, and accelerated the international fragmentation of value chains (Baldwin, 2016; Goldfarb and Tucker, 2019). Digital trade ecosystems increasingly enable firms to participate in international markets through platform-based intermediation, cloud infrastructures, and digitally mediated services, thereby reshaping patterns of global competitiveness (Ferracane et al., 2021). However, the benefits of digital integration remain unevenly distributed across countries. While advanced economies

have largely consolidated their positions within digitally intensive sectors, many developing and late-industrialising economies continue to experience fragmented and uneven digital development trajectories (Galindo-Martín et al., 2021).

Access to digital infrastructure and connectivity alone has not been sufficient to generate sustained productivity growth, innovation capacity, or international digital competitiveness. Existing evidence suggests that the developmental outcomes of digital transformation are strongly conditioned by organisational learning processes, absorptive capacity, and institutional quality (Cohen and Levinthal, 1990; Zahra and George, 2002). Firms and economies differ substantially in their ability to identify, assimilate, transform, and exploit digital knowledge for productive and innovative purposes. In this respect, digital transformation is not simply a technological transition but a capability-intensive process requiring continuous adaptation and strategic reconfiguration (Teece et al., 1997; Warner and Wäger, 2019).

At the same time, institutional environments play a decisive role in shaping digital transformation trajectories. Institutional theory emphasises that economic behaviour is embedded within regulative, normative, and cognitive structures that influence incentives, coordination mechanisms, and long-term developmental outcomes (North, 1990; Scott, 2008). Contemporary research further highlights that digital transformation processes are strongly mediated by institutional quality, regulatory adaptability, and governance capacity, particularly in emerging economies undergoing structural transformation (Katz and Callorda, 2018; Vu et al., 2020). Differences in governance quality, policy consistency, regulatory flexibility, and public–private coordination contribute significantly to cross-country variation in digital transformation performance.

This divergence raises a critical analytical question: why do countries with relatively similar access to digital technologies exhibit markedly different patterns of digital economic development? Existing research has largely addressed this issue through cross-sectional benchmarking, descriptive policy inventories, or sector-specific analyses. Although these approaches provide important insights, they often underestimate the dynamic and feedback-driven nature of digital transformation processes. In reality, digital transformation unfolds through cumulative interactions among technological infrastructures, institutional adaptation, organisational capabilities, and market responses over extended time horizons (Verhoef et al., 2021; Kraus et al., 2022).

From a systems perspective, digital transformation constitutes a complex adaptive process characterised by nonlinear interactions, feedback loops, and path-dependent development

trajectories (Sterman, 2000; Meadows, 2008). Recent studies applying systems thinking to socio-technical transitions emphasise that reinforcing innovation cycles and institutional feedback mechanisms play a crucial role in shaping long-term technological trajectories (Perez, 2010; Groesser and Schaffernicht, 2012). Early investments in digital infrastructure, institutional coordination, and capability formation may generate reinforcing feedback mechanisms that accelerate innovation diffusion and economic upgrading. Conversely, institutional rigidities, fragmented governance structures, and weak absorptive capacities may produce balancing feedback dynamics that constrain learning processes and limit long-term transformation outcomes.

Against this background, the present study investigates the digital transformation trajectories of four major Asian economies—China, India, South Korea, and Iran—over the period 2015–2024. Combining harmonised panel data from international databases with composite indicators of Business Digital Adoption and Integration (BDAI) and Digital Trade Momentum (DTM), the study adopts a system-dynamics-informed comparative approach to examine how digital capabilities evolve under different institutional and developmental conditions. Rather than conceptualising digital development as a static outcome, the study interprets it as an evolving configuration of interdependent capabilities, governance arrangements, and market structures.

The contribution of this paper is threefold. First, it develops transparent and replicable composite indices for evaluating business digital adoption and digital trade dynamics in data-constrained environments. Second, it identifies divergence patterns, critical transitions, and asymmetric trajectories across selected Asian economies. Third, it advances a mechanism-oriented interpretation grounded in system dynamics to explain how reinforcing and balancing feedback structures shape long-term digital transformation outcomes.

In doing so, the study contributes to the growing literature on digital transformation by integrating perspectives from generativity theory, absorptive capacity, institutional analysis, and systems thinking into a unified comparative framework capable of informing both theory and policy design.

2. Theoretical Framework and Literature Review

2.1. Digital Economy Foundations and Generativity

The emergence of the digital economy has fundamentally transformed the mechanisms through which value is created, exchanged, and appropriated across contemporary economic systems.

Unlike traditional industrial models centred on physical production and linear value chains, digital economies are increasingly characterised by data-intensive interactions, platform-mediated coordination, and knowledge-driven innovation processes (Kremen et al., 2019; Verhoef et al., 2021; Kraus et al., 2022). Accordingly, digital technologies operate not merely as operational instruments but as enabling infrastructures that reshape organisational architectures, institutional arrangements, and patterns of global economic integration (Vial, 2021).

A defining characteristic of digital technologies is their generativity, referring to the capacity of digital systems to facilitate continuous and distributed innovation through recombination and decentralised experimentation (Nambisan et al., 2019). Digital technologies are inherently modular, editable, reprogrammable, and scalable, allowing firms and users to develop new applications, products, and organisational configurations beyond their original design purposes (Yoo et al., 2010). These generative infrastructures increasingly support platform ecosystems, data-driven innovation, and distributed entrepreneurial experimentation across organisational and geographic boundaries (Nambisan et al., 2019; Gawer, 2022). Consequently, digital transformation differs from earlier technological modernisation processes because innovation increasingly emerges through interactions among firms, users, platforms, and data ecosystems rather than through isolated organisational activities.

The affordance perspective further explains how digital technologies create new possibilities for organisational action while simultaneously shaping outcomes according to institutional and organisational contexts (Leonardi, 2011; Markus and Silver, 2008). Digital affordances do not generate uniform developmental outcomes because the ability to exploit technological possibilities depends on user competencies, governance structures, and institutional arrangements (Warner and Wäger, 2019). Therefore, similar digital investments may produce substantially different transformation trajectories across countries and industries.

Digitalisation has also reshaped the structure of global production and trade. Advances in information and communication technologies have reduced coordination costs, facilitated cross-border data flows, and enabled the international fragmentation of production networks (Baldwin, 2016; Goldfarb and Tucker, 2019). Platform-based ecosystems and digitally mediated services increasingly allow firms to participate in global value chains with lower transaction costs and greater operational flexibility (Ferracane et al., 2021). However, these benefits remain unevenly distributed, particularly across developing and late-industrialising

economies where institutional constraints, infrastructure gaps, and capability asymmetries continue to limit digital upgrading and innovation performance (Galindo-Martín et al., 2021).

Accordingly, digital transformation should be understood not as a purely technological transition but as a systemic process involving the co-evolution of technological infrastructures, organisational learning, institutional adaptation, and market coordination mechanisms. The developmental consequences of digitalisation therefore depend on the extent to which firms and economies can integrate digital infrastructures into broader systems of knowledge creation, innovation, and governance.

2.2. Absorptive Capacity, Dynamic Capabilities, and Institutional Embeddedness

While digital technologies create extensive opportunities for innovation and productivity enhancement, their economic effects are mediated by organisational capabilities and institutional conditions. Digital transformation therefore depends not only on technological adoption but also on the ability of firms and economies to identify, assimilate, transform, and exploit external knowledge to generate sustained value creation. This perspective aligns with the concept of absorptive capacity, which defines organisational learning as the capability to recognise the value of new information, assimilate it, and apply it to commercial and innovative activities (Cohen and Levinthal, 1990). Subsequent research further developed this framework by distinguishing acquisition, assimilation, transformation, and exploitation as interconnected dimensions of knowledge utilisation (Zahra and George, 2002).

In digitally intensive environments, absorptive capacity becomes increasingly critical because technological change is rapid, cumulative, and dependent on continuous learning processes (Kraus et al., 2022). Firms and economies capable of effectively integrating external digital knowledge are more likely to achieve productivity gains, technological upgrading, and innovation resilience. Conversely, limited absorptive capacity may prevent organisations from translating digital investments into meaningful developmental outcomes, particularly in contexts characterised by fragmented governance structures and institutional instability.

The capability-based perspective on digital transformation is further reinforced by dynamic capabilities theory. Dynamic capabilities refer to the organisational capacity to integrate, build, and reconfigure internal and external competencies in response to rapidly changing environments (Teece et al., 1997). Within digital transformation contexts, these capabilities enable firms and institutions to adapt organisational routines, redesign business models, and reallocate resources in response to technological disruption and evolving competitive

conditions (Warner and Wäger, 2019). Recent empirical research further demonstrates that the interaction between digital capabilities and strategic flexibility plays a critical role in shaping firm performance and innovation outcomes in digital environments (Li et al., 2024).

However, organisational capabilities alone cannot fully explain cross-country differences in digital transformation trajectories. Institutional theory suggests that economic behaviour is embedded within regulative, normative, and cognitive structures that shape incentives, coordination mechanisms, and patterns of organisational adaptation (North, 1990; Scott, 2008). Contemporary research further highlights that digital transformation processes are strongly mediated by institutional quality, regulatory adaptability, and governance capacity, particularly in emerging economies undergoing structural transformation (Katz and Callorda, 2018; Vu et al., 2020).

Institutional embeddedness is particularly significant for emerging and late-industrialising economies, where digital transformation often unfolds under conditions of uneven infrastructure development, limited technological capabilities, and fragmented policy implementation. In such contexts, institutional bottlenecks may constrain digital upgrading even when technological infrastructures are available. Conversely, coherent institutional frameworks supporting experimentation, knowledge diffusion, and public–private coordination can facilitate cumulative learning and long-term digital resilience.

Recent empirical research further demonstrates that digital transformation outcomes are shaped by the interaction between technological capability accumulation and institutional support systems (Tay and Loh, 2022; Karimi et al., 2015). Countries capable of aligning digital policy frameworks with organisational learning processes are therefore more likely to convert digitalisation into sustained structural transformation.

2.3. Digital Transformation, Resilience, and Nonlinear Dynamics

Digital transformation is increasingly associated not only with innovation and productivity enhancement but also with the resilience of economic and organisational systems under conditions of uncertainty and disruption. In contemporary digital economies, resilience refers to the capacity of firms, industries, and national systems to absorb shocks, adapt to changing conditions, and maintain functional continuity through learning and reconfiguration processes.

The relationship between digitalisation and resilience is inherently nonlinear and context dependent. Although digital technologies can improve coordination efficiency, information processing, and adaptive flexibility, their benefits depend on complementary institutional

capacities and organisational readiness (Ji and Huang, 2024). Threshold effects may emerge because the positive impacts of digital transformation often become substantial only after sufficient levels of technological infrastructure, human capital development, and governance coordination have been achieved.

Digital resilience should therefore be understood as an emergent property of interconnected socio-technical systems rather than as a static organisational attribute. Adaptive resilience depends on distributed learning, institutional flexibility, and the ability to continuously reconfigure technological and organisational arrangements in response to environmental disruptions (Groesser and Schaffernicht, 2012). Li et al. (2025) further argue that digital transformation can strengthen resilience by accelerating information flows, improving decision-making processes, and enabling more flexible resource allocation mechanisms.

At the same time, excessive dependence on concentrated digital infrastructures may increase systemic vulnerabilities related to cybersecurity risks, platform dependency, and technological concentration. These trade-offs illustrate the complex and context-dependent nature of digital resilience in rapidly evolving technological environments.

2.4. Path Dependence, Feedback Loops, and System Dynamics

Understanding digital transformation requires analytical frameworks capable of capturing dynamic interactions, cumulative adaptation processes, and long-term structural change. System dynamics provides such a perspective by emphasising the role of reinforcing and balancing feedback loops in shaping behavioural patterns over time (Sterman, 2000). Rather than conceptualising transformation as a linear process, system dynamics interprets development as an evolving interaction among technological change, institutional adaptation, organisational learning, and policy responses.

A central insight of systems thinking is that complex systems generate outcomes through recursive relationships among interconnected components (Meadows, 2008). In digital economies, these interactions frequently produce cumulative and path-dependent effects in which early technological investments, institutional arrangements, and governance choices influence future trajectories of innovation and competitiveness (Arthur, 1994). Path dependence is therefore particularly important for explaining divergence among countries undergoing digital transformation.

System dynamics also highlights the importance of delayed effects and unintended consequences in digital policy implementation. Policies designed to accelerate digital adoption

may generate uneven outcomes when complementary institutional and organisational capacities are insufficient. Similarly, rapid platform expansion may simultaneously improve efficiency and increase systemic vulnerability through technological dependency and market concentration. Effective digital governance therefore requires adaptive and forward-looking policy frameworks capable of balancing innovation promotion with resilience, inclusiveness, and long-term institutional sustainability.

This perspective aligns closely with foresight-oriented approaches emphasising uncertainty, scenario analysis, and strategic adaptability in complex environments (Wilkinson and Kupers, 2013; Ködding et al., 2023). By integrating systems thinking with institutional and capability-based perspectives, digital transformation can be understood not as a discrete technological event but as a continuous evolutionary process shaped by feedback dynamics, strategic adaptation, and multi-level governance interactions.

The proposed conceptual framework, illustrated in Figure 1, delineates the structural relationships among Digital Infrastructure (DI), Absorptive Capacity (AC), Dynamic Capabilities (DC), and Institutional Embeddedness (IE) as the primary antecedents of BDAI. Furthermore, the model proposes that BDAI positively influences DTM. Hypotheses H1 through H5 articulate the direct relationships among these constructs, while the integrated feedback loop reflects the system dynamics perspective underlying this study.

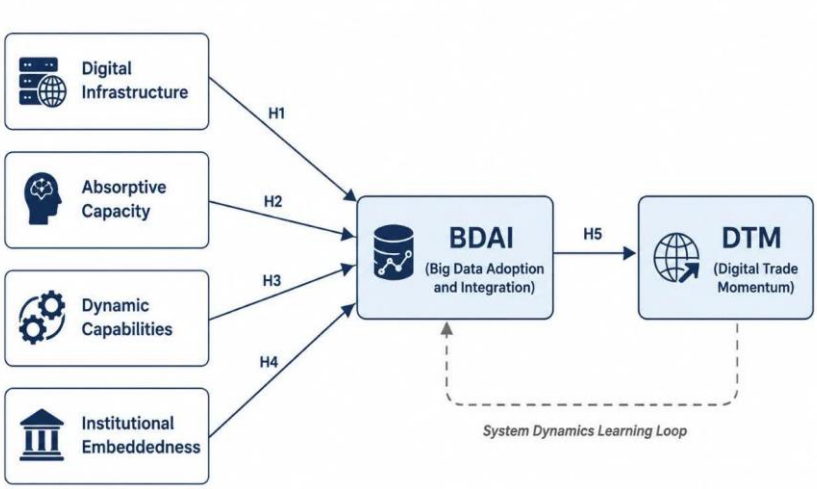

Figure 1. The Hypothesised Conceptual Framework.

3.Methodology

3.1. Research Design

This study adopts a comparative longitudinal research design to examine the evolution of digital transformation and digital trade dynamics across four Asian economies—China, India, South

Korea, and Iran—over the period 2015–2024. The research is informed by an integrative conceptual framework combining insights from digital economy theory, absorptive capacity, dynamic capabilities, institutional theory, and system dynamics. Within this perspective, digital transformation is treated as a cumulative, path-dependent, and institutionally embedded process rather than a static technological outcome.

Given the multidimensional and evolving nature of digital transformation, the study relies on a composite-index-based analytical strategy. This design is particularly appropriate for capturing complex structural phenomena that cannot be directly observed through a single indicator. The methodological objective is to compare how national digital capabilities and trade-related digital performance develop over time and to identify structural asymmetries in digital advancement across the selected countries.

3.2. Case Selection and Analytical Scope

The four selected economies represent distinct digital development trajectories and offer meaningful comparative variation in terms of institutional capacity, technological sophistication, and integration into global digital systems.

China is included due to its large-scale digital ecosystem, strong platform economy, and extensive state-supported digital industrialisation.

South Korea represents a highly advanced digital economy characterised by strong infrastructure, innovation capacity, and coordinated policy support.

India reflects a rapidly expanding but uneven digital economy, combining significant digital growth with persistent structural and regional disparities.

Iran provides a contrasting case of constrained digital transformation, shaped by sanctions, institutional fragmentation, uneven infrastructure, and limited global digital integration.

The study focuses on the period 2015–2024, a decade marked by accelerated digitalisation, post-pandemic restructuring, platform expansion, and the increasing strategic importance of digital trade in national development agendas.

3.3. Data Sources and Data Preparation

The empirical analysis relies on secondary data derived from internationally recognised, publicly accessible databases, specifically the World Bank Open Data, (ITU), UNCTAD, OECD Digital Economy Database, and the IMF Data Portal. Where necessary, supplementary

information from national statistical and policy reports was incorporated to facilitate consistency checks and enhance data robustness.

Indicators were meticulously selected based on three primary criteria: theoretical relevance to the core dimensions of digital transformation and digital trade; cross-country comparability across the sampled economies; and temporal consistency throughout the 2015–2024 study period. Prior to the formal analysis, the dataset underwent a rigorous harmonisation process, including unit standardisation, comprehensive consistency checks, the treatment of missing observations, and the alignment of indicator definitions across diverse sources. This systematic approach helps ensure that the resulting indices accurately reflect substantive variations in digital development, thereby mitigating potential biases arising from inconsistencies in measurement or reporting standards.

3.4. Variable Construction

To operationalise digital transformation in a multidimensional manner, the study constructs two composite indices: BDAI and DTM. These indices are designed to capture the domestic and external dimensions of digital transformation, respectively.

Table 1 provides a comprehensive summary of the operationalisation of the primary indices, detailing their constituent indicators and respective data sources. To ensure comparability, all indicators were normalised using the min–max scaling technique across the pooled sample (2015–2024) and subsequently aggregated with equal weights to construct the composite BDAI and DTM indices. In this scoring system, higher values denote superior performance. The empirical data were primarily sourced from the World Bank, (ITU), UNCTAD, OECD, and the IMF.

Table 1. Conceptualisation and Operationalisation of Digital Transformation Indices.

Variable/ Index	Definition	Indicators	Data Sources	Expected Relevance and Theoretical link

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BDAI	A composite measure representing the depth and breadth of digital technology integration within the national business ecosystem.	Fixed broadband subscriptions per 100 inhabitants Percentage of enterprises with internet access Business e-commerce participation rate Adoption rate of cloud computing and data analytics by firms Digital payment penetration in business transactions.	ITU, World Bank (WDI), UNCTAD, OECD	Serves as a proxy for Digital Absorptive Capacity. It reflects the readiness of firms to embed technologies into operations, facilitating dynamic capabilities (Teece, 1997)
DTM	A composite measure capturing the dynamics, scale, and competitiveness of a country's participation in global digitally-enabled trade flows.	ICT services exports (% of total service exports) Digitally deliverable services exports (current US$) High-technology exports (% of manufactured exports) Cross-border digital transaction volume or growth rate Degree of participation in global digital value chains.	UNCTAD, WTO, IMF, World Bank	Indicates the External Competitiveness and trade-related trajectory of the digital economy. It aligns with Digital Trade Theory and global value chain integration.
Institutional and Contextual Control Variables	Macroeconomic and institutional factors that influence the environment in which digital transformation occurs.	GDP per capita (PPP, constant international $) Human Capital Index (HCI) Regulatory Quality Index (World Governance Indicators) Research and Development (R&D) expenditure (% of GDP)	World Bank (WGI), UNDP, IMF	Used to contextualise the Digital Divide and explain asymmetries in adoption patterns between advanced and emerging economies.

3.4.1 BDAI

The BDAI index serves as a proxy for the internal dimension of digital transformation, assessing the degree to which firms incorporate digital technologies into their core production, communication, transactional, and organisational processes. This index evaluates the extent to which businesses are embedded within a digitally enabled ecosystem. To capture this multidimensional construct, the index incorporates variables related to internet connectivity and broadband infrastructure, cloud computing readiness, the adoption of digital payment systems, e-commerce participation, and the utilisation of business-oriented digital services. Collectively, these indicators provide a comprehensive measure of both digital accessibility and the functional integration of advanced technologies into daily business operations.

3.4.2. DTM

The DTM index captures the outward-facing dimension of digital transformation by quantifying the dynamism and expansion of digitally enabled trade. This index reflects an economy's integration into global digital trade flows and its capacity for technology-driven international exchange. The DTM is constructed using metrics such as ICT service exports, the volume of digitally deliverable services, high-technology merchandise exports, cross-border digital

transaction proxies, and various measures of trade-related digital participation. Consequently, the DTM serves as a robust indicator of a nation's external digital competitiveness and its overall performance in the global digital marketplace.

3.5. Index Construction Procedure

Because the selected indicators are expressed in different units and scales, all variables were normalised using the Min–Max normalisation technique:

$$X_{it}^{*} = \frac{(X_{it} - X_{min})}{(X_{max} - x_{min})} \quad (1)$$

where X_{it}^{*} denotes the normalised value of indicator X for country i in year t, and X_{min} and X_{max} represent the minimum and maximum observed values of that indicator across the full panel.

Following normalisation, the indicators were aggregated using an equal-weighting scheme. Equal weighting was adopted for two methodological reasons. First, there is no sufficiently robust theoretical basis for assigning differential weights to the selected indicators across heterogeneous country contexts. Second, equal weighting enhances transparency, simplicity, and replicability in cross-country comparative research.

The composite indices were calculated as follows:

$$BDAI_{it} = \left(\frac{1}{n}\right) \times \Sigma_{k=1}^{n} Z_{kit} \quad (2)$$

$$DTM_{it} = \left(\frac{1}{m}\right) \times \Sigma_{j=1}^{m} Z_{jit} \quad (3)$$

where (Z) represents normalised indicator values, (n) is the number of indicators included in the BDAI,and (m) is the number of indicators included in the DTM.

3.6. Missing Data Treatment

Given the uneven reporting of some digital-economy indicators across countries and years, limited missing observations were expected. To preserve the continuity of the panel while minimising information loss, missing values representing less than 10% of total observations were treated using linear interpolation between adjacent years.

This method was considered appropriate because macro-level digital development indicators generally evolve gradually rather than abruptly. Indicators with excessive missingness,

inconsistent reporting, or definitional discontinuities were excluded from the final index construction process.

To assess the impact of interpolation on the results, sensitivity checks were performed by comparing the index trajectories generated with and without interpolated observations. The comparison indicated that interpolation did not materially alter the relative position of countries or the main trend patterns.

3.7. Reliability and Robustness Assessment

To ensure methodological rigour, several reliability and robustness procedures were implemented.

First, alternative normalisation checks were conducted to verify that country rankings and temporal patterns were not merely artefacts of the selected scaling method. Second, internal consistency analysis was performed using Cronbach's alpha, where appropriate, to evaluate whether the grouped indicators captured coherent underlying dimensions. Third, indicator sensitivity analysis was undertaken through sequential exclusion of individual indicators to determine whether the results were overly dependent on any single component.

These tests confirmed that the composite indices were sufficiently stable and that the main comparative findings remained consistent across alternative specifications.

3.8 Analytical Strategy

The empirical analysis is structured in three distinct, sequential stages. First, the study employs a longitudinal descriptive approach to map the annual trajectories of BDAI and DTM across the four selected economies from 2015 to 2024, identifying key patterns of acceleration, stagnation, divergence, and convergence. Second, the study conducts a comparative cross-country assessment to evaluate structural asymmetries in digital adoption, capability accumulation, and the expansion of digital trade. This stage clarifies how varying institutional and infrastructural conditions drive heterogeneous development outcomes. Finally, these empirical findings are synthesised through a system-oriented analytical lens. Moving beyond the conceptualisation of digital transformation as a linear progression, this study examines how reinforcing and balancing mechanisms—ranging from infrastructure investment and organisational capability building to institutional adaptation and trade integration—induce either cumulative advantages or persistent developmental constraints. This interpretive framework provides a nuanced

understanding of digital transformation as a fundamentally nonlinear and path-dependent phenomenon.

3.9. Methodological Justification

The selected methodology is appropriate for the objectives of this study for three main reasons. First, digital transformation is a multidimensional phenomenon that cannot be adequately represented by a single observable variable. Second, the selected countries differ significantly in terms of institutional capacity, technological readiness, and digital trade integration, making comparative analysis analytically necessary. Third, the purpose of the study is not limited to estimating isolated statistical associations, but rather to understand how digital transformation trajectories emerge, diverge, and become embedded in broader national development structures.

4. Findings

4.1. Dynamics of DTM

The DTM index provides further insight into how domestic digital capabilities translate into participation in global digital trade networks. Compared with BDAI, DTM reveals even sharper divergence patterns among the selected economies.

China demonstrates the most dynamic growth in digital trade performance. The expansion of ICT services exports, high-technology manufacturing exports, and digitally enabled cross-border platforms contributes to a steep upward trajectory. These developments indicate deepening integration into global digital value chains and highlight the role of platform-based trade ecosystems in amplifying export capacity.

South Korea maintains consistently high DTM values, reflecting the maturity of its technology-intensive export structure. The country's strong semiconductor industry, advanced electronics sector, and highly digitalised logistics systems contribute to stable digital trade performance. The trajectory suggests structural resilience rather than rapid expansion.

India shows moderate but positive growth in DTM. Much of this growth is driven by the expansion of digitally deliverable services, particularly in the IT and business process outsourcing sectors. However, the structure of digital trade remains relatively concentrated, limiting the extent to which broader sectors of the economy participate in digitally enabled global trade.

Iran's DTM performance remains comparatively limited throughout the observation period. Although some incremental improvements are visible, structural constraints—including limited

global integration, trade restrictions, and institutional barriers—appear to hinder the expansion of digitally enabled export activities.

These findings suggest that participation in digital trade ecosystems depends not only on domestic digital adoption but also on institutional openness, global connectivity, and the ability to integrate into international digital value chains. As shown in Figure 2, countries exhibit distinct trajectories in DTM, reflecting differences in digital ecosystem development and trade integration.

Figure 2 illustrates the comparative trajectories of DTM across the selected countries over the study period. The trajectories highlight differences in digital trade expansion, stability, and structural momentum across national digital ecosystems.

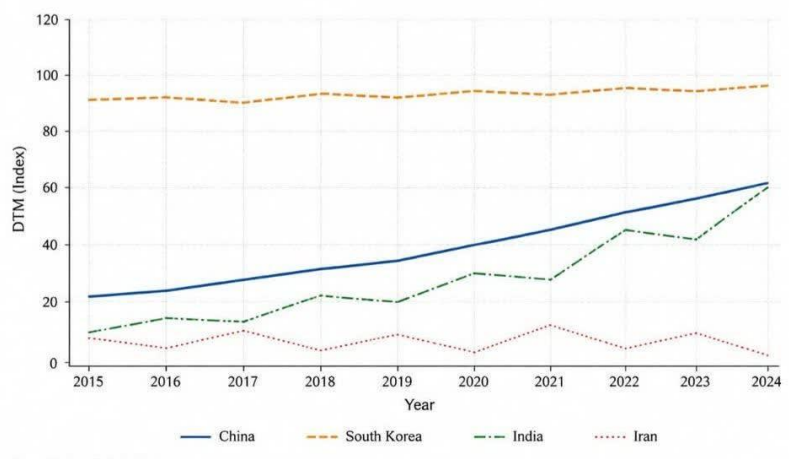

Figure 2. Comparative Trajectories DTM, (2015-2024).

4.2 Evolution of BDAI

The longitudinal assessment of the BDAI index over 2015–2024 indicates persistent cross-country heterogeneity in the accumulation of business-sector digital capabilities. Such divergence is consistent with differences in technological infrastructure, organisational learning capacity, and institutional contexts that shape national pathways of digital transformation.

South Korea consistently records the highest BDAI levels throughout the observation period. The relative stability of its trajectory points to a mature digital ecosystem marked by strong absorptive capacity, robust innovation systems, and advanced firm-level integration of digital technologies. Rather than exhibiting a catch-up pattern, South Korea reflects a phase of capability consolidation in which digital tools are deeply embedded in production processes, supply chains, and service platforms.

China displays the steepest upward trajectory in BDAI. The marked acceleration—particularly from the mid-2010s onward—aligns with large-scale investments in digital

infrastructure, the rapid expansion of platform-based ecosystems, and industrial digitalisation initiatives. From a dynamic capabilities perspective, this pattern suggests a strong alignment of sensing, seizing, and transforming capabilities, enabling firms to integrate digital technologies into operational and commercial processes at scale.

India shows a gradual yet increasingly accelerated improvement in BDAI. Although its initial levels remain below those of China and South Korea, expanded broadband access, improved digital financial infrastructure, and the growth of digital entrepreneurship have supported steady gains in firm-level adoption. Nonetheless, the trajectory suggests uneven diffusion, indicating that digital capabilities remain heterogeneously distributed across sectors and regions.

Iran registers the lowest BDAI values over the study period. While modest improvements are observable, the overall pattern remains relatively flat, implying that structural constraints—related to infrastructure development, institutional quality, and limited integration into global digital ecosystems—continue to impede the accumulation of business digital capabilities.

Overall, the findings underscore enduring asymmetries in digital capability formation, suggesting that business digital adoption is conditioned not only by technological endowments but also by broader institutional arrangements and national innovation system characteristics.

Figure 3 depicts the comparative trajectories of BDAI across the four countries. Divergence in the curves reflects cross-country differences in enterprise-level digital technology uptake and in the maturity and enabling quality of national digital infrastructures.

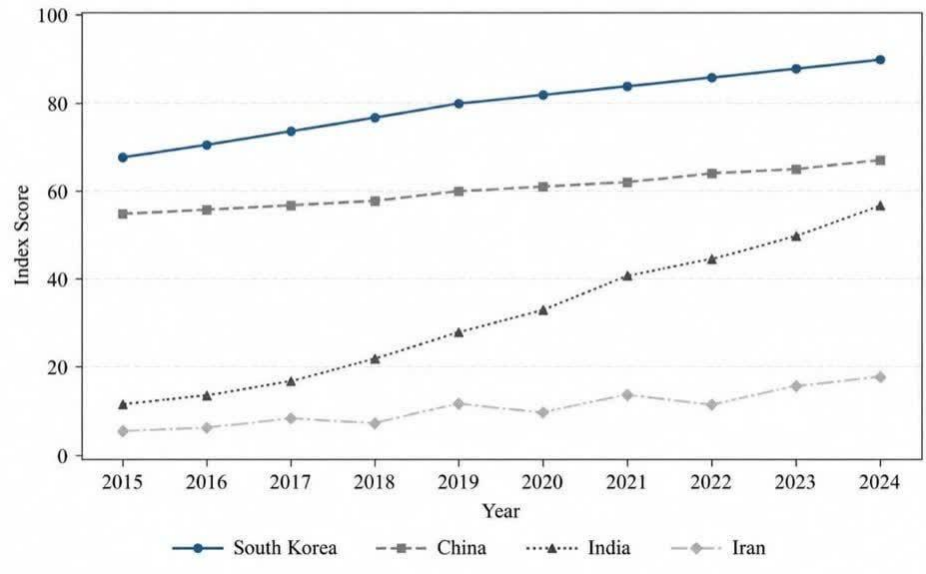

Figure 3. BDAI Trajectories, (2015-2024).

4.3. Capability–Trade Alignment and Structural Asymmetries

A comparative examination of BDAI and DTM reveals distinct patterns in the alignment

between domestic digital capabilities and external trade performance.

South Korea represents a case of high capability–trade alignment. Strong firm-level digital integration is accompanied by high digital trade performance, indicating systemic coherence between internal capability formation and external competitiveness.

China represents a case of accelerated capability accumulation accompanied by rapid expansion in digital trade. The simultaneous growth of BDAI and expansion of DTM suggest the presence of reinforcing feedback mechanisms between domestic digitalisation and global market participation.

India represents an intermediate configuration. While digital adoption among firms has expanded considerably, the translation of these capabilities into diversified digital trade remains partial. This suggests that complementary institutional and structural factors continue to mediate the transformation of digital capability into trade competitiveness.

Iran represents a structurally constrained configuration in which both domestic digital adoption and digital trade remain limited. In such contexts, weak infrastructure development and institutional barriers may reinforce a low-capability equilibrium.

These comparative patterns underscore that digital transformation is not merely a technological process but a systemic phenomenon shaped by institutional arrangements, innovation capacity, and global economic integration.

4.4. Divergence and Conditional Convergence

The longitudinal evidence suggests limited convergence among the four economies during the study period. South Korea and China maintain structural leadership positions in both digital capability formation and digital trade integration. India shows signs of conditional convergence in digital adoption but slower convergence in digital trade performance. Iran remains persistently separated from the higher-performing group.

This divergence pattern suggests that digital transformation processes may generate cumulative advantages for early digital leaders, reinforcing structural gaps between advanced and constrained digital economies.

4.5. Robustness Assessment

Robustness checks were conducted to evaluate the stability of the composite indices. Alternative normalisation procedures produced similar country rankings and trend patterns. Sequential exclusion of individual indicators did not significantly alter the relative positioning

of countries. In addition, the limited use of interpolation for missing observations did not materially affect longitudinal trajectories.

These results increase confidence that the observed patterns reflect structural differences rather than artefacts of measurement construction.

4.6. System Dynamics Interpretation

Interpreting the findings through a system dynamics perspective reveals the presence of reinforcing feedback loops shaping digital transformation trajectories.

In digitally advanced economies such as China and South Korea, investments in digital infrastructure stimulate firm-level technology adoption, which enhances innovation capacity and export competitiveness. Increased participation in digital trade subsequently generates additional resources and incentives for further digital investment, reinforcing the transformation cycle.

In more constrained environments, weaker infrastructure and institutional limitations reduce incentives for firm-level digital integration. This restricts participation in digital trade networks, limiting the economic returns that could otherwise support further technological upgrading.

India appears to occupy an intermediate position within this system, where expanding digital adoption is gradually creating conditions for stronger integration into global digital trade networks, although structural constraints remain.

Overall, the results indicate that digital transformation operates as a cumulative and path-dependent process in which technological capability formation, institutional conditions, and global trade integration interact dynamically over time.

5. Discussion

The findings of this study provide important insights into the systemic nature of digital transformation and its implications for global trade dynamics. By examining the interaction between BDAI and DTM across four major emerging and technologically significant economies—China, India, South Korea, and Iran—this research contributes to a deeper understanding of how digital capabilities translate into economic competitiveness in the digital era.

5.1. Digital Capability Formation and Economic Outcomes

One of the central insights emerging from the analysis is the strong but non-linear relationship

between domestic digital capability formation and digital trade performance. The results demonstrate that economies with higher levels of BDAI tend to exhibit stronger DTM trajectories; however, this relationship is mediated by institutional structures, innovation systems, and global integration mechanisms.

South Korea represents a case where advanced digital capabilities are effectively translated into sustained digital trade competitiveness. This alignment reflects the maturity of its innovation ecosystem, strong absorptive capacity, and the integration of digital technologies across manufacturing and service sectors. The findings reinforce arguments in the dynamic capabilities literature suggesting that firms and economies able to continuously integrate, build, and reconfigure digital resources are better positioned to maintain competitive advantage in rapidly evolving technological environments.

China illustrates a different but equally important pathway: rapid capability accumulation combined with large-scale digital platform development. The strong co-evolution of BDAI and DTM in China suggests the presence of mutually reinforcing mechanisms between domestic digitalisation and global trade expansion. Platform-based ecosystems, digital infrastructure investment, and strong state-supported digital strategies appear to accelerate the translation of digital capabilities into trade competitiveness.

India presents an intermediate configuration in which substantial progress in domestic digital adoption is not yet fully matched by equivalent expansion in digital trade diversification. Although the growth of digitally deliverable services has strengthened India's global position in IT-enabled services, broader integration into digital value chains remains uneven. This pattern highlights the importance of complementary factors such as innovation diffusion, industrial diversification, and regulatory coordination in transforming digital capabilities into global market outcomes.

Iran, by contrast, reflects the challenges faced by economies where institutional constraints, limited global connectivity, and structural barriers restrict the development of digital ecosystems. Even where incremental improvements in digital adoption are observed, the absence of strong institutional and international integration mechanisms appears to limit the economic returns from digital transformation.

5.2. The Role of Institutional Embeddedness

The comparative patterns observed across the four countries underscore the importance of

institutional embeddedness in shaping digital transformation outcomes. Digital infrastructure alone is insufficient to generate sustained digital trade growth. Instead, the broader institutional environment—including regulatory quality, openness to international markets, innovation policies, and governance effectiveness—plays a critical role in enabling digital capabilities to translate into economic performance.

Countries with more coherent institutional frameworks tend to exhibit stronger alignment between digital adoption and trade outcomes. In contrast, fragmented institutional environments may slow the diffusion of digital technologies and reduce the ability of firms to leverage digital capabilities for international competitiveness.

This finding supports institutional perspectives within digital economy research, which emphasise that digital transformation processes are embedded within broader socio-economic and regulatory structures.

5.3. Digital Transformation as a Systemic and Path-Dependent Process

The results also highlight the cumulative and path-dependent nature of digital transformation. Economies that achieve early advances in digital infrastructure and capability formation appear more likely to generate reinforcing feedback loops that sustain long-term growth in digital trade.

From a system dynamics perspective, digital transformation operates through reinforcing cycles: investments in digital infrastructure facilitate firm-level adoption; increased adoption stimulates innovation and productivity gains; enhanced competitiveness supports expansion into global digital trade networks; and the resulting economic returns create incentives for further technological investment.

Conversely, economies that face persistent structural constraints may experience reinforcing negative cycles, where limited digital adoption restricts trade participation, thereby reducing incentives and resources for further digital upgrading.

This systemic interpretation suggests that digital transformation is not merely a technological transition but a complex socio-economic process shaped by interactions among technological, institutional, and market forces. Figure 4 depicts the causal loop structure underlying the dynamics of digital transformation and trade momentum.

5.3. Implications for Digital Development Trajectories

Taken together, the findings indicate that successful digital transformation requires more than technological infrastructure expansion. Instead, it involves the coordinated development of

digital capabilities, innovation systems, institutional frameworks, and international connectivity.

Countries that effectively align these dimensions are more likely to achieve sustained digital trade growth and stronger integration into global digital value chains. Conversely, partial or fragmented digital development strategies may limit the economic benefits of digitalisation.

These results therefore highlight the importance of integrated digital development strategies that simultaneously strengthen infrastructure, human capital, institutional quality, and global digital connectivity.

Figure 4 illustrates the systemic relationships between digital infrastructure, absorptive capacity, institutional coordination, and digital trade integration. The model includes reinforcing feedback loops (R1–R3) and balancing mechanisms (B1–B3) shaping the dynamics of national digital transformation.

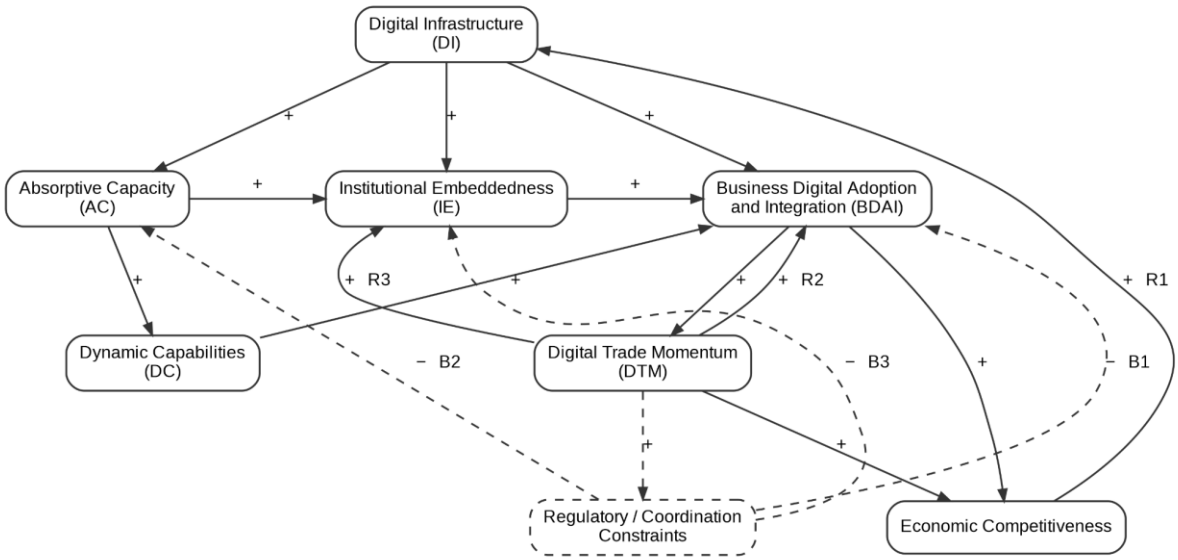

Figure 4. Causal Loop Diagram of Digital Transformation Dynamics.

Table 2 provides a systematic overview of the reinforcing and balancing mechanisms that govern the dynamics of the digital transformation system. Following standard notation, “R” denotes reinforcing feedback loops, while “B” denotes balancing feedback loops.
Conceptually, these reinforcing loops act as drivers of system change, facilitating cumulative growth and acceleration. Conversely, balancing loops function as structural constraints that exert stabilising pressure on the system, thereby tempering unchecked expansion. Together, these feedback mechanisms characterise the nonlinear evolution of the relationship between

digital transformation and trade momentum, highlighting the complex, self-regulating nature of the digital economy.

Table 2. Reinforcing and Balancing Feedback Mechanisms in the Digital Transformation System

Loop	Type	Core Mechanism	Description	Expected effect
R1	Reinforcing	Capability accumulation loop	Improved digital infrastructure enhances absorptive capacity, which strengthens dynamic capabilities and supports broader BDAI, leading to higher DTM.	Positive growth acceleration
R2	Reinforcing	Adoption- Integration loop	Greater BDAI improves organisational learning, process efficiency, and digital coordination, which further increase DTM and reinforce adoption behaviour.	Self-reinforcing expansion
R3	Reinforcing	Institutional Learning loop	Stronger institutional embeddedness improves policy coordination, reduces transaction frictions, and facilitates digital ecosystem development, thereby further supporting digital adoption and trade growth.	Structural amplification
B1	Balancing	Regulatory fragmentation constraint	Rapid digital growth increases regulatory complexity and compliance burdens, which slow down adoption and moderate further expansion in DTM.	Growth moderation
B2	Balancing	Absorptive constraint loop	Even with strong infrastructure, insufficient absorptive capacity limits knowledge transfer and technology assimilation, reducing the effectiveness of adoption and integration.	Constraint on conversion
B3	Balancing	Coordination balance loop	As digital interactions expand, coordination requirements rise; when coordination capacity lags, system efficiency declines and growth slows.	Stabilising constraint

Figure 5 illustrates the baseline dynamic behaviour of BDAI and DTM within the established feedback structure. This trajectory demonstrates the long-term evolution of digital adoption and its subsequent impact on trade momentum, capturing the resultant interplay between the system's reinforcing drivers and balancing constraints. The observed pattern underscores the nonlinear nature of these interactions, reflecting how the model balances accelerated growth against structural limitations over the study period.

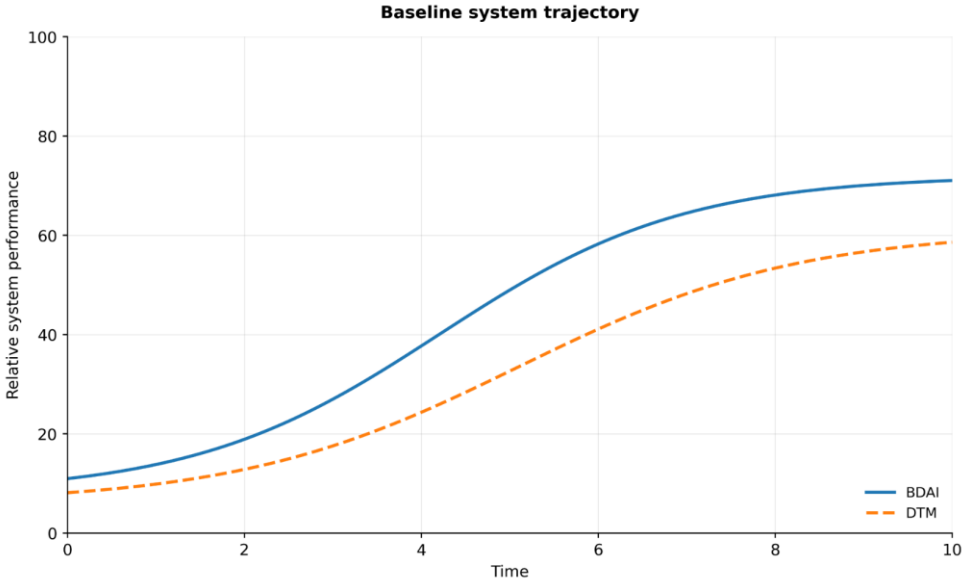

Figure 5. Baseline System Trajectory for BDAI and DTM.

Figure 6 presents the simulated system behaviour under a scenario where reinforcing feedback mechanisms are intensified. As these mechanisms dominate the system dynamics, the accelerated accumulation of digital capabilities and the subsequent surge in adoption rates generate a compounding effect on DTM. The resulting trajectory illustrates how the system transitions into a state of rapid, sustained growth, underscoring the critical role of reinforcing loops in driving long-term digital expansion.

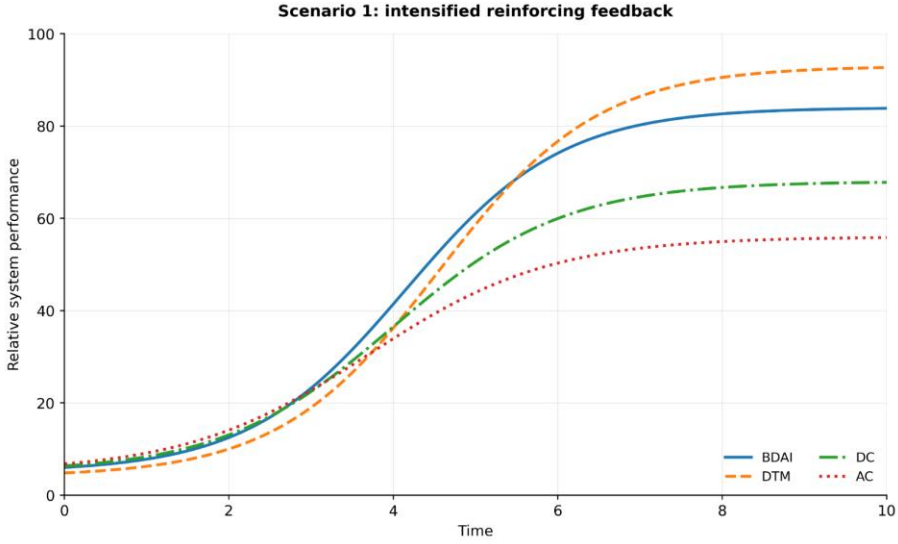

Figure 6. System Trajectory under Intensified Reinforcing Feedback Mechanisms.

Figure 7 illustrates the system behaviour under a scenario of intensified balancing constraints. As regulatory fragmentation, absorptive capacity limitations, and coordination bottlenecks

become more pronounced, the system's growth trajectory is significantly moderated, leading to a stabilised development path. This simulation highlights the critical role of institutional frameworks and coordination mechanisms in curbing unchecked expansion, thereby ensuring that digital transformation remains within sustainable, albeit constrained, operational limits.

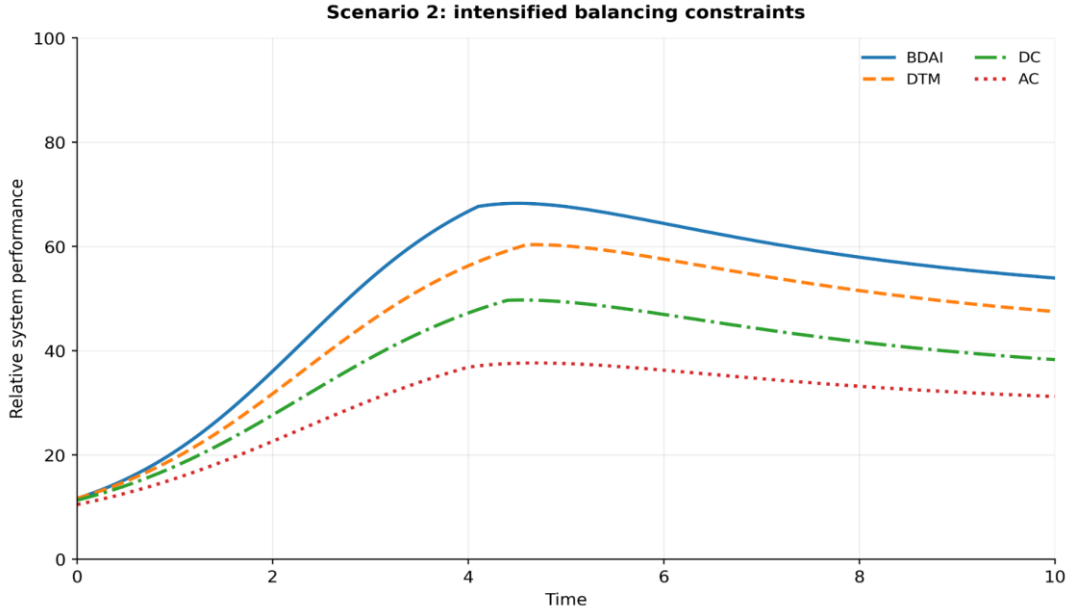

Figure 7. System Trajectory under Intensified Balancing Constraints.

6. Theoretical Contributions

This study makes several distinct theoretical contributions to the digital economy and international business literature:

Integrating Digital Adoption and Trade Theories: By operationalising BDAI and DTM, this research provides a conceptual bridge between micro-level theories of digital adoption (e.g., absorptive capacity, dynamic capabilities) and macro-level economic outcomes DTM. It shifts the focus from static digital readiness metrics to dynamic, outcome-oriented performance indicators.

Extending System Dynamics to Macro-Digitalisation: The study demonstrates that digital transformation is not a linear progression but a system-driven process characterised by reinforcing feedback loops. This provides a theoretical framework for analysing why digital divides persist even in the face of significant infrastructure investment.

Contextualising Institutional Embeddedness: The findings show that institutional quality acts as a "multiplier" for digital capabilities. This contributes to institutional theory by

demonstrating that the efficacy of dynamic capabilities (e.g., in Chinese or South Korean firms) is fundamentally conditional upon the institutional environment that facilitates or hinders global trade integration.

7. Managerial and Policy Implications

Beyond Infrastructure: Policy efforts must transition from mere infrastructure expansion to fostering "Institutional Openness." Investment in broadband is ineffective without corresponding regulatory quality that allows firms to integrate into global digital value chains.

Sequential Policy Prioritisation: Developing economies should prioritise absorptive capacity (human capital and R&D) alongside digital connectivity to ensure that domestic digital adoption translates into export competitiveness.

Capability Calibration: Firms must recognise that adopting digital tools BDAI is not an end state but a precursor to "digital export readiness." Managers should align internal digital integration with the demands of the global digital markets (e.g., cross-border e-commerce, cloud-based services) to ensure they are not just "using" technology but "competing" with it.

8. Limitations and Future Research

Macro-Level Scope: While this study provides essential insights at the country level, future research should utilise firm-level longitudinal data to investigate the micro-foundations of the observed BDAI-DTM feedback loops.

Scope of Technology: Future studies could disaggregate the BDAI index to specifically capture the impact of emerging frontier technologies, such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT), which may exhibit different trajectories than traditional ICT services.

Regional Diversity: Expanding the sample size to include a more diverse set of economies (e.g., Latin American or African nations) would help generalise the findings regarding the "divergence" versus "convergence" patterns identified in this comparative longitudinal analysis.

Disclosure statement

The lead author was previously employed as Planning Manager in the case organisation but has no current affiliation or financial relationship with the company. The authors declare no competing interests—financial or non-financial—related to the content of this manuscript.

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