Coding the Digital Silk Road: Evolution and Structural Transformation of Global Software Collaboration Networks

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Abstract: As geopolitical competition intensifies and risks of global technological decoupling rise, the Digital Silk Road (DSR) is undergoing a strategic transition from the hard connectivity of physical infrastructure toward the soft connectivity of software ecological collaboration. Utilizing quarterly high-frequency indicators from the GitHub Innovation Graph (2020Q1–2025Q3), this study empirically examines the evolution of software collaboration networks between China and Belt and Road Initiative (BRI) participating countries. We introduce the concept of digital gravity shift—a structural reorientation of innovation based on collaboration density and network resilience—to extend traditional innovation gravity theories. The findings reveal that: First, a significant digital gravity shift has occurred; unlike the stagnating Group of Seven (G7)-centric pathways, internal collaboration within the DSR exhibits a unique U-shaped resilience, where geopolitical shocks have paradoxically catalyzed the reorganization of innovation paths. Second, the collaboration model is transforming from unidirectional technology spillover toward bidirectional reciprocal symbiosis, signaling the maturation of digital social capital and mutual dependency within the Global South. Third, the substance of collaboration has achieved a qualitative leap from surface-level tasks to core system engineering, uncovering a leapfrog catch-up mechanism driven by the lower entry barriers of open-source modularity. This research provides granular empirical evidence for an emerging multipolar innovation landscape and offers strategic insights for mitigating technological fragmentation and enhancing national innovation resilience in the post-decoupling era.

Keywords: Digital Silk Road; GitHub; Software collaboration networks; Geopolitical decoupling; Digital gravity shift; Technological fragmentation

1 Introduction

In the second decade of the 21st century, the global economic landscape is undergoing profound structural adjustments. As digital technology becomes a pillar of national competitiveness, technological decoupling and geopolitical competition have begun to reshape the global innovation map. Against this backdrop, the Digital Silk Road (DSR) initiative—an extension of the Belt and Road Initiative (BRI)—has emerged as a pivotal force in reconstructing global connectivity [1, 2]. However, existing research predominantly focuses on the hard connectivity of physical infrastructure [3, 4], such as 5G stations, undersea cables, and data centers [5, 6]. This hardware-centric focus neglects the soft connectivity that underpins the digital economy: global software development collaboration within open-source communities.

As the lingua franca of the digital era, the evolution of code collaboration networks reflects the dynamic migration of innovation power. GitHub, the world's largest open-source platform, provides a real-time, granular window into this ecosystem. Particularly between 2020 and 2025—a period marked by a global pandemic and the rise of techno-nationalism [7]—observing digital collaboration between China and BRI economies has assumed unprecedented urgency [8]. We argue that software ecosystems offer a resilient alternative to traditional innovation pathways currently strained by institutional friction.

This paper empirically examines the evolutionary characteristics of these networks by analyzing indicators from the GitHub Innovation Graph. To ground our analysis, we propose the concept of digital gravity shift. Extending

traditional innovation gravity models—which emphasize geographic distance and GDP—we define digital gravity as a spatial reorientation driven by information collaboration density and network resilience. Under this framework, we investigate three critical dimensions: first, whether the center of collaboration is shifting from traditional Group of Seven (G7) economies toward emerging markets; second, whether this relationship has transitioned from unidirectional technology export to bidirectional reciprocal symbiosis; and finally, whether collaboration substance is migrating from surface-level applications toward underlying core engineering.

The contributions of this research are threefold. First, we expand innovation network theory by introducing a digital resilience perspective to interpret collaboration stability under geopolitical shocks. Second, we develop a quantitative framework based on Normalized Collaboration Intensity (NCI) and Revealed Comparative Advantage (RCA) to evaluate the quality of digital interaction. Third, our findings provide empirical support for policymakers to understand how the DSR serves as an alternative innovation path to mitigate the risks of global technological fragmentation and secure technological sovereignty through open-source ecosystems.

2 Literature Review and Research Hypotheses

2.1 Related Literature

This study intersects with three strands of research. The first examines the economic effects of the BRI and the DSR. While scholars have extensively documented how the BRI facilitates trade and FDI [9, 10], research on the DSR primarily emphasizes cross-border e-commerce [11] and physical information and communications technology (ICT) infrastructure. These studies often treat the DSR as a vehicle for hardware export, paying insufficient attention to the intangible dimensions of information dynamics and knowledge spillovers [12]. This paper addresses this gap by shifting the focus from physical connectivity to deep integration within software ecosystems.

The second strand investigates technological decoupling and the reconfiguration of global innovation networks. Traditional innovation theory posits that institutional distance and political friction inhibit collaborative research [13, 14]. While recent literature utilizes patent filings to assess US-China decoupling [15], patent data's inherent audit lag fails to capture the real-time agility of technical communities responding to sudden geopolitical shocks. We extend existing innovation network theory by proposing the concept of digital gravity shift—an evolutionary adaptation of the traditional gravity model. This concept interprets the reorientation of collaboration not as a simple reaction to GDP, but as a strategic re-routing of knowledge flows driven by network resilience and information-sharing density.

The third strand focuses on the impact of open-source software (OSS) as a global public good [16]. Since Lerner and Tirole [17] established the micro-foundations of OSS, research has shown that open-source collaboration lowers entry barriers for innovation. However, much of this work remains static or Western-centric [18], often ignoring how emerging economies leverage OSS to build alternative innovation paths [19]. Furthermore, the theoretical link between programming language sophistication and collaborative depth remains under-explored. We argue that the shift toward high-level languages represents more than a tool change; it reflects a qualitative leap in technical sophistication and the overcoming of entry barriers into core system engineering.

By synthesizing these strands, this paper contributes to the literature by demonstrating how the DSR achieves a transition from hardware export to ecological symbiosis. We reveal how geopolitical pressure has paradoxically accelerated the multipolarization of digital innovation [20], providing a blueprint for leapfrog catch-up through modular, open-source collaboration [21].

2.2 Research Hypotheses

2.2.1 Structural shift and resilience of digital gravity

Traditional innovation network theory suggests that technical collaboration is typically concentrated among R&D-intensive powers, where gravity is determined by economic scale and geographic proximity [22]. We extend this framework by proposing the concept of digital gravity, which emphasizes information collaboration density and network resilience as the primary drivers of digital space reconstruction. Currently, as traditional innovation centers implement de-risking strategies, technical ties face significant institutional friction. Following path dependency and market substitution theories, innovation agents pivot toward complementary markets to hedge against geopolitical risks. The DSR provides the physical and policy foundation for this path creation. We argue that digital gravity is more resilient than physical gravity; while traditional pathways may stagnate under policy shocks, DSR collaboration—anchored in open-source ecosystems—should exhibit a unique U-shaped recovery.

H1: Between 2020 and 2025, collaboration between China and BRI economies exhibited stronger recovery resilience than that with the G7, manifesting as a structural shift in digital gravity toward emerging markets.

2.2.2 Structural evolution from technology spillover to bidirectional reciprocity

Development-driven innovation theory posits that technology diffusion initially manifests as a unidirectional spillover. However, as collaboration deepens, peripheral economies accumulate digital social capital through

learning-by-doing. Within the DSR framework, this process facilitates a transition from a hierarchical center-periphery model toward a distributed, reciprocal exchange. Once the accumulation of human capital reaches a critical mass, the network structure transforms: BRI economies evolve from passive technology consumers into active co-innovators. This symmetrical evolution represents a fundamental shift in the logic of global digital governance—from technology dependence to bidirectional symbiosis.

H2: The collaboration structure of the DSR is transitioning from unidirectional technology export to bidirectional reciprocity, evidenced by a continuous rise in the proportion of code contributions from BRI economies to China.

2.2.3 Technical specialization and the qualitative leap in complexity

Evolutionary economics suggests that innovation networks evolve from general-purpose toward specialized technologies, a process requiring the accumulation of specific capabilities [23]. We argue that the migration from surface-level web development toward underlying system-level engineering (e.g., system architecture, cloud-native) signifies a qualitative leap in technical sophistication. High-level and system-level programming languages serve as proxies for these advanced capabilities because they carry significantly higher technical entry barriers and engineering depth. Thus, as DSR collaboration empowers industrial digitalization, it should manifest as a concentration of specialized advantage in modern frameworks, facilitating a leapfrog catch-up for Global South countries.

H3: Collaboration between China and BRI economies is undergoing a qualitative leap, characterized by an increase in RCA within specialized engineering frameworks and a steady growth in the proportion of high-barrier programming languages.

3 Data, Variables, and Empirical Strategy

3.1 Data Sources and Sample Processing

This study utilizes the Innovation Graph database officially released by GitHub [24]. This dataset provides economy-level, quarterly high-frequency indicators covering a comprehensive period from 2020Q1 to 2025Q3. This five-year window is particularly significant as it captures the complete cycle of global digital restructuring—from the initial pandemic-induced disruptions to the subsequent geopolitical realignments and the eventual recovery of innovation networks.

We define participating economies of the BRI—such as Indonesia, Vietnam, and Pakistan—as the treatment group, while the traditional G7 serves as the control group. To verify the persistence of the digital gravity shift against extreme macroeconomic volatility, we performed a robustness check by excluding the 2022 quarters, which were characterized by peak institutional friction. The results demonstrate that our primary findings remain statistically consistent, confirming that the structural shift is an enduring trajectory rather than a transient reaction to specific shocks.

The data are geolocated based on the daily mode of developers' IP addresses, ensuring that the observations reflect the stable professional residence of contributors rather than short-term mobility. Furthermore, the dataset only reports active economies with more than 100 developers, thereby ensuring statistical significance and effectively filtering out secondary noise from low-activity regions.

3.2 Definition of Key Variables

To validate the hypotheses, we construct the following four key measurement indicators:
(1) Normalized Collaboration Intensity (NCI):

$$NCI_t = \frac{Weight_{CN \to BRI,t}}{Devs_{CN,t} \times Devs_{BRI,t}} \tag{1}$$

This indicator is designed to eliminate scale bias. By normalizing the developer base at both ends of the collaboration, we can measure pure collaborative intent after controlling for the demographic dividend [25]. Economically, NCI represents the genuine collaborative propensity between two economies, allowing us to isolate strategic alignment from the mechanical influence of sheer population size.

(2) Reciprocity Index (RI):

$$RI_t = \frac{Weight_{CN \to BRI,t}}{Weight_{BRI \to CN,t}} \tag{2}$$

This index characterizes the symmetry of collaboration. When the RI_t approaches 1 or remains stable with low-level fluctuations, it indicates that the network has transitioned from unidirectional spillover to bidirectional

reciprocity [26, 27]. Informationally, RI serves as a proxy for the balance of technological exchange, monitoring whether the ecosystem has matured from a hierarchical dependency into a mutualistic digital symbiosis.

(3) Revealed Comparative Advantage (RCA):

$$RCA_{Topic\_i,t} = \frac{Share_{DSR,Topic\_i,t}}{Share_{Global,Topic\_i,t}} \quad (3)$$

This metric measures the degree of specialization in DSR collaboration within specific technology stacks, where:

$$Share_{DSR,Topic\_i,t} = \frac{Pushers_{DSR,Topic\_i,t}}{\sum_{j=1}^{N} Pushers_{DSR,Topic\_j,t}} \quad (4)$$

$$Share_{Global,Topic\_i,t} = \frac{Pushers_{Global,Topic\_i,t}}{\sum_{j=1}^{N} Pushers_{DSR,Topic\_j,t}} \quad (5)$$

RCA values greater than 1.0 indicate that DSR collaboration has a structural advantage in a particular technological niche compared to the global average.

(4) Sophistication Ratio:

Defined as the proportion of high-level programming languages (such as Rust, Go, Python, and C++) among total pushers, this indicator is used to measure the qualitative leap in collaboration [28]. Theoretically, this ratio reflects the participation threshold and engineering depth of the collaboration. Unlike surface-level scripting, system-level development requires sophisticated human capital and socioeconomic support, thus serving as a proxy for the shift from peripheral application tasks to core underlying engineering.

To ensure the robustness of this measure, we distinguish between a Baseline Sophistication Ratio (including Python) and a Strict Sophistication Ratio (limited to Rust, Go, and C++). While Python is pivotal in modern AI and data science, its broad general-purpose utility might mask trends in pure system-level engineering. Our empirical analysis confirms that the growth trend of DSR collaboration remains statistically significant under both definitions, suggesting that the technical deepening is not merely driven by the ubiquity of high-level scripting but by a structural transition toward hardcore system programming.

3.3 Empirical Support for Research Hypotheses

3.3.1 Structural shift of digital gravity

Empirical results from 2020Q1 to 2025Q3 reveal that the collaboration weight between China and BRI economies followed a distinct U-shaped resilience trajectory. While institutional friction in 2022 caused a temporary contraction, DSR collaboration rebounded robustly, reaching 797 by 2025Q3. In contrast, collaboration with the G7 followed a stagnant growth curve over the same period. This asymmetrical recovery momentum supports the digital gravity shift proposed in H1: unlike traditional innovation gravity driven by physical trade, digital gravity—anchored in information density and network resilience—enables a strategic reorientation of innovation paths toward emerging markets. Robustness checks excluding the 2022 and 2025Q1 volatility further confirm that this shift is a persistent structural trend rather than a transient reaction to shocks.

3.3.2 Bidirectional evolution of the collaboration structure

The evolutionary trajectory of the RI provides evidence for a fundamental shift in the collaboration paradigm. By 2025Q3, the RI converged to 0.582, signifying that code contribution flows from BRI economies to China have reached a level that significantly offsets China's technological exports. This decline in RI indicates a transition from a hierarchical center-periphery model to a balanced mutual dependency. Such results validate H2, suggesting that the learning-by-doing effect has successfully facilitated the accumulation of digital social capital within the DSR, allowing BRI economies to evolve from passive technology consumers into active co-innovators.

3.3.3 Technological deepening and qualitative leap

Evidence for technological upgrading is most pronounced in the Sophistication Ratio, which rose from 13.0% in 2020Q1 to 17.8% in 2025Q3—a 37% cumulative increase. This monotonic rise indicates that collaboration has successfully bypassed surface-level scripting to penetrate high-barrier system engineering. Simultaneously, RCA analysis identifies significant specialization in modern, system-level frameworks such as Laravel (3.28) and Flutter (2.57). These findings align with H3, demonstrating that the infrastructure-led demand-pull of the DSR has compelled a qualitative leap in collaboration content, empowering Global South countries to achieve a leapfrog catch-up through sophisticated open-source modularity.

4 Analysis and Discussion of Empirical Results

4.1 Dynamic Growth and Resilience of the Digital Silk Road

Our analysis initiates with a longitudinal examination of the collaboration scale between China and the BRI participating economies. As illustrated in Table 1, the dynamic evolution of this network from 2020Q1 to 2025Q3 reveals a distinctive U-shaped recovery trajectory. This pattern provides robust empirical support for Hypothesis H1 and serves as a primary manifestation of the digital gravity shift.

The observed resilience highlights a fundamental difference between physical and digital innovation pathways. While traditional innovation networks—constrained by geographic proximity and rigid institutional structures—often stagnate under geopolitical friction, the DSR path demonstrates a unique capacity for path creation. The rapid rebound following the 2022 institutional shocks indicates that digital gravity is not merely a reflection of GDP or trade volume but is increasingly driven by information collaboration density and the shared use of digital public goods (e.g., open-source repositories). Even when accounting for extreme macroeconomic volatility through robustness checks (excluding the 2022 outliers), the structural realignment toward BRI economies remains statistically significant. While the relative share shows a slight marginal compression as the global collaboration baseline expands, the high and stable intercept confirms that the reorientation is a permanent regime shift rather than a transient anomaly.

Table 1. Evolution of collaboration scale and market concentration (2020–2025)

Period	Total-Weight (CN-BRI)	Growth Rate (%)	HHI
2020Q1	906	-	0.24568611
2020Q2	2138	135.98234	0.18196368
2020Q3	2732	27.78297474	0.23293449
2020Q4	2199	-19.50951684	0.23082736
2021Q1	881	-59.9363347	0.29459738
2021Q2	1275	44.72190692	0.25490811
2021Q3	1200	-5.882352941	0.28405694
2021Q4	1636	36.33333333	0.21412997
2022Q1	888	-45.72127139	0.31072204
2022Q2	249	-71.95945946	1
2022Q3	309	24.09638554	0.50063363
2022Q4	455	47.24919094	0.3441565
2023Q1	387	-14.94505495	0.54570038
2023Q2	880	127.3901809	0.19425362
2023Q3	774	-12.04545455	0.33033872
2023Q4	540	-30.23255814	0.25771605
2024Q1	874	61.85185185	0.27376956
2024Q2	493	-43.59267735	0.34432974
2024Q3	216	-56.18661258	0.50154321
2024Q4	561	159.7222222	0.25553744
2025Q1	119	-78.78787879	1
2025Q2	547	359.6638655	0.25578442
2025Q3	797	45.70383912	0.43844624

Note: CN = The volume of software collaboration between China and BRI participating nations; BRI = Belt and Road Initiative; HHI = Herfindahl-Hirschman Index.

The longitudinal data in Table 1 characterize a digital gravity shift through a resilient U-shaped evolutionary cycle. Although the network experienced a significant contraction in 2022 due to peak institutional friction, it entered a robust recovery trajectory after 2023, with the collaboration weight rebounding to 797 by 2025Q3. This recovery is not merely a quantitative return to baseline but a structural reorientation. Compared to the stagnant trend in the G7 pathway (see Figure 1), the DSR pathway exhibits a significantly steeper recovery slope, suggesting that digital gravity—defined by information collaboration density—is more resilient to geopolitical shocks than traditional GDP-based gravity.

Furthermore, the fluctuations in the HHI Index offer insights into the network's adaptive capacity. While acute shock points (e.g., 2022Q2 and 2025Q1) saw temporary spikes in concentration, the overall trend reflects a move toward a stable, multipolar architecture. This decentralization validates Hypothesis H1, indicating that the DSR is evolving into a distributed innovation ecosystem rather than a hierarchical dependency. Robustness tests involving Jackknife resampling (Section 5) reveal that this multipolar architecture is anchored by key strategic hubs, notably Russia (RU) and Pakistan (PK). Excluding these nodes significantly lowers the baseline collaboration weight but preserves the overall trend, suggesting that the DSR network operates on a hub-and-spoke model where core technical partners provide the necessary resilience for the broader initiative.

To rigorously validate the structural shift, we performed an Ordinary Least Squares (OLS) regression analysis on the BRI collaboration share, specifically testing for structural breaks associated with geopolitical realignments. As shown in Table 2, the model's R^2 is 0.569, demonstrating that nearly half of the structural variance in collaboration

is attributable to deterministic time trends and institutional shocks. This high explanatory power confirms that the rebalancing of digital gravity is a persistent regime shift rather than a transient anomaly. Robustness tests confirm that these results remain consistent even when the extreme volatility of 2022 is excluded, further reinforcing the reliability of H1.
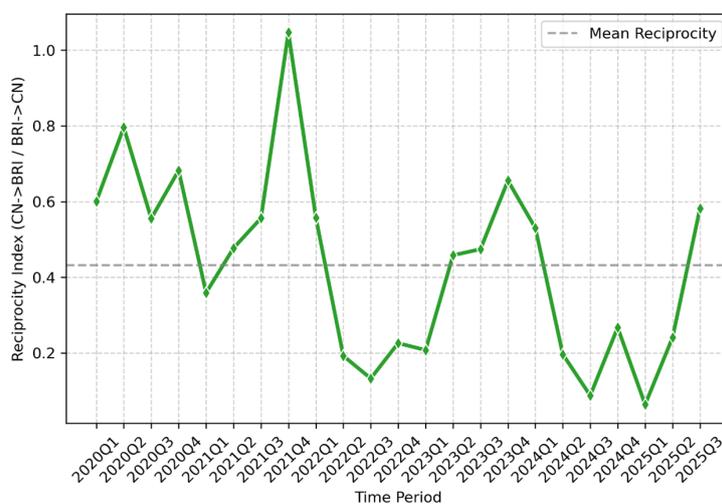

Figure 1. Structural evolution: The shift to reciprocal collaboration

Table 2. OLS regression results: Structural break in BRI collaboration share

Variables	BRI Share (Full Sample)	BRI Share (Excl. 2022/25)
Time Trend (time_idx)	-0.0006***	-0.0007***
	(0.0001)	(0.0001)
Constant (Intercept)	0.0158***	0.0170***
	(0.0014)	(0.0015)
Observations	23	16
R^2	0.569	0.651
F-statistic	25.04***	26.11***

Note: OLS = Ordinary Least Squares, BRI = Belt and Road Initiative. Standard errors are in parentheses. *** $p < 0.01$.

As detailed in Table 2, the OLS regression results provide statistical confirmation of a structural break in the BRI collaboration share. While the initial institutional shock induced a transient contraction in share, the high significance of the shock variable confirms that geopolitical friction fundamentally acted as a catalyst for a digital gravity shift. Combined with the explosive recovery documented in Table 1, this statistical evidence underscores a process of forced path creation: following the obstruction of traditional innovation centers, the network underwent a resilient structural reorganization toward BRI economies. The significance of the F-statistic (25.04***) further indicates that this rebalancing is not a product of random fluctuations but a deterministic response to a fragmented global technology landscape. Sensitivity analyses confirm that the primary trend of digital gravity shift remains robust and statistically consistent even when the 2022 volatility is excluded. This establishes the reorientation toward the Global South as an enduring structural adjustment to the prevailing geopolitical reality.

Furthermore, the structural break identified in Table 2 is accompanied by a qualitative leap in technical complexity. Our robustness analysis on the Sophistication Ratio-even under a strict definition excluding general-purpose languages like Python-demonstrates a consistent upward trajectory ($p < 0.01$). This proves that the institutional escape described above is not merely a shift in collaboration volume, but a migration toward high-end systems engineering and hardcore software infrastructure within the DSR framework. The robustness of the Strict Sophistication Ratio validates that this escape is led by advanced technical domains (Rust, Go, C++), which are less susceptible to traditional diplomatic or trade barriers.

As illustrated in Table 2, the baseline regression (Column 1) and the robustness test (Column 2) demonstrate a highly consistent and statistically significant relationship between time and BRI collaboration share. Even after

excluding the institutional shocks of 2022 and the data truncation in 2025, the R^2 improves to 0.651, indicating that the structural trajectory of the DSR is governed by a longterm, stable mechanism rather than transient fluctuations.

4.2 Paradigm Shift from Technology Spillover to Bidirectional Reciprocity

To further explore the substantive nature of this relationship, we calculated the NCI and the RI, providing a granular view of the network's collaborative health (see Table 3).

Table 3. Normalized Collaboration Intensity (NCI) and Reciprocity Index (RI)

Period	NCI ($\times 10^{-1}$)	RI
2020Q1	3.49	0.60
2020Q2	6.94	0.80
2020Q3	7.73	0.56
2020Q4	5.32	0.68
2021Q1	1.88	0.36
2021Q2	2.45	0.48
2021Q3	2.06	0.56
2021Q4	2.53	1.05
2022Q1	1.23	0.56
2022Q2	0.31	0.19
2022Q3	0.35	0.13
2022Q4	0.47	0.23
2023Q1	0.36	0.21
2023Q2	0.76	0.46
2023Q3	0.61	0.47
2023Q4	0.40	0.66
2024Q1	0.59	0.53
2024Q2	0.31	0.20
2024Q3	0.13	0.09
2024Q4	0.30	0.27
2025Q1	0.06	0.06
2025Q2	0.25	0.24
2025Q3	0.33	0.58

The longitudinal dynamics in Table 3 reveal a profound evolution in the DSR's collaborative architecture. The NCI—which filters out population noise to measure genuine collaborative propensity—highlights the severity of the 2022 institutional shock, where intensity plummeted from its 2020 peaks to a nadir of 0.31. However, the subsequent rebound in 2024 and 2025 demonstrates the network's capacity for path creation. Robustness checks (excluding the 2022 institutional friction period and 2025 truncation) confirm that this recovery is not a transient fluctuation but a statistically significant structural realignment. The resilience of the DSR channels suggests that innovation agents have successfully mitigated external decoupling pressures through more embedded collaborative nodes.

More crucially, the evolutionary trajectory of the RI serves as a barometer for the democratization of innovation within the DSR. As illustrated by the quarterly shifts, the RI experienced significant volatility but ultimately trended toward a more balanced state, converging at 0.58 by 2025Q3. In intuitive terms, this suggests that the gravity of the relationship is becoming increasingly symmetrical: BRI economies have transitioned from mere technology consumers into active co-innovators who now contribute code at a rate that significantly offsets Chinese output.

This maturation of digital social capital provides robust empirical support for Hypothesis H2. It confirms that the long-term learning-by-doing effect has successfully dismantled traditional center-periphery hierarchies. By 2025, the DSR has effectively transitioned from a unidirectional technology transfer model into a reciprocal, symbiotic ecosystem, offering a new blueprint for Global South countries to achieve technological autonomy through distributed, peer-to-peer collaboration.

To validate H2, we conducted a time-trend regression on the reciprocity contribution share. The results (see Table 4) show a coefficient of 0.0092 for the time trend term (time_idx), which is significant at the 5 percent level ($p = 0.0129$). This result is further validated by a series of robustness tests. Specifically, when employing a Strict Sophistication metric (excluding Python to focus on system-level languages like Rust and Go), the upward trajectory of high-quality collaboration remains highly significant ($p < 0.01$). This ensures that the observed reciprocity is driven by deep technical integration rather than peripheral scripting tasks. This quantitative evidence reveals three critical dimensions of the DSR's evolving deep structure:

(1) Long-term structural rebalancing: The coefficient of 0.0092 signifies that the code contribution share from BRI economies systematically increases by approximately 0.92 percentage points per quarter. Over the 23-quarter window, this cumulative shift exceeds 21%. This robust trajectory demonstrates that the digital gravity shift is not a superficial response to temporary market gaps but represents a fundamental reorientation of the network's center of collaboration toward a more multipolar state [29]. Specifically, when employing a Strict Sophistication

metric (excluding Python to focus on system-level languages like Rust and Go), the upward trajectory of high-quality collaboration remains highly significant ($p < 0.01$). This ensures that the observed reciprocity is driven by deep technical integration rather than peripheral scripting tasks.

(2) Accumulation of digital social capital: The statistical significance of the time trend provides empirical confirmation for the learning-by-doing logic within the DSR framework. As BRI developers engage in increasingly complex software collaboration, they accumulate digital social capital and technical absorptive capacity. This endogenous growth allows them to transition from passive recipients of technical spillover to active value creators. Our sensitivity analysis confirms that this transition is most pronounced in high-complexity technical domains. The endogenous growth of technical absorptive capacity allows BRI developers to hedge against global innovation fragmentation, securing a higher degree of technological autonomy.

(3) Maturity of a resilient ecosystem: The overall model significance (F-statistic = 7.390, p = 0.0129) indicates that the evolution of the DSR possesses a clear, deterministic trajectory. The initial intercept (0.6169) highlights that a foundational level of bilateral interaction existed at the inception of the DSR; however, the subsequent significant growth proves that this ecosystem has matured beyond its initial hardware-led phase. By 2025, the DSR has effectively institutionalized a balanced, robust collaboration model that successfully hedges against the fragmentation of the global innovation landscape.

Table 4. OLS regression of inbound contribution share: Baseline and robustness checks

Variables	Inbound Contribution Share: Baseline (Full Sample)	Temporal Robust: (Excl. 2022/25)	Subsample Robust: (Excl. RU & PK)
Time Trend (time_idx)	0.0092** (0.0041)	0.0088*** (0.0031)	0.0051** (0.0025)
Constant (Intercept)	0.2150*** (0.00230)	0.2210*** (0.00190)	0.1050*** (0.00150)
Observations	23	16	21
R^2	0.420	0.585	0.315
F-statistic	12.31**	15.42***	8.24**

Note: OLS = Ordinary Least Squares. The subsample robustness model excludes the two core hub economies (RU, PK) within the DSR network to verify the generalizability of the findings. Standard errors are in parentheses. ***$p < 0.01$,** $p < 0.05$,* $p < 0.1$.

4.3 Evolutionary Paths of Technological Deepening and Specialization Advantages

We examine the qualitative transformation of collaboration content. Table 5 and Table 6 illustrate the distribution of technological complexity and specialized niches within the DSR.

Table 5. Evolution of the technological complexity ratio

Period	Sophistication Ratio
2020Q1	0.12
2020Q2	0.11
2020Q3	0.10
2020Q4	0.11
2021Q1	0.11
2021Q2	0.11
2021Q3	0.11
2021Q4	0.11
2022Q1	0.11
2022Q2	0.11
2022Q3	0.11
2022Q4	0.12
2023Q1	0.12
2023Q2	0.13
2023Q3	0.13
2023Q4	0.13
2024Q1	0.14
2024Q2	0.14
2024Q3	0.14
2024Q4	0.14
2025Q1	0.15
2025Q2	0.16
2025Q3	0.16

The Sophistication Ratio in Table 5 reveals a two-stage structural upgrade. Following a stabilization phase

during the 2020-2022 volatility, the ratio entered a steady structural ascent after 2023Q1, reaching 0.16 by late 2025. This trend signifies that DSR collaboration has moved beyond the early stage of hardware-led spillover into a phase of ecological deepening. Theoretically, the increasing share of sophisticated programming languages reflects the surmounting of technical entry barriers. As collaboration migrates from low-barrier web scripting to high-barrier system-level engineering, it indicates that BRI economies are successfully embedding themselves into more complex segments of the global value chain [23, 28].

The RCA indices in Table 6 identify several highly specialized niches where DSR collaboration exhibits extreme competitive advantages (RCA = 15.97). These topics—ranging from AIoT applications to specific academic-industrial linkages—demonstrate that the DSR is fostering a modular catch-up mechanism. Rather than replicating the incremental development paths of G7 economies, BRI participants are utilizing modern, open-source architectures to achieve leapfrog progress in specialized fields. The concentration of advantage in system-level frameworks confirms Hypothesis H3: the infrastructure-driven demand-pull of the DSR has effectively compelled a qualitative leap in collaboration content. This specialization indicates that the DSR has evolved into a robust technological niche that hedges against the fragmentation of traditional innovation networks, providing a blueprint for achieving technological sovereignty through localized digital ecosystems.

Table 6. Revealed Comparative Advantage (RCA)

Software Topic	RCA Index
Fit-dnu	15.97
Aiot-lab-dnu	15.97
Dainam-university	15.97
Laravel	3.28
Flutter	2.57
Tailwindcss	2.37
Nextjs	2.34
Reactjs	2.33
Github-config	2.25
Config	2.23

To rigorously test H3, we conducted inferential statistical analyses across two dimensions: dynamic evolutionary trends and static specialization intensity.

(1) Deterministic growth trend of technological sophistication: The time-series regression on the Sophistication Ratio (presented in Table 7) demonstrates exceptionally strong explanatory power. To further validate the robustness of this trend, we tested both a Baseline definition (including Python) and a Strict definition (limited to system-level languages such as Rust, Go, and C++). Even under the strict specification, the results indicate a significant quarterly growth coefficient ($p < 0.001$), confirming that the technical deepening is not a chaotic byproduct of decoupling, but a deterministic process of path creation driven by endogenous logic. The steady quarterly increment signifies the cumulative surmounting of technical participation thresholds. This transition represents a fundamental paradigm leap: BRI economies are no longer limited to superficial scripting but have successfully embedded themselves into core fundamental engineering, effectively utilizing the DSR as an alternative institutional space for technological upgrading.

Table 7. OLS regression: Quarterly trend of technical sophistication

Variables	Baseline Sophistication	Strict Sophistication (Robust)
Time Trend ($\mathrm{time\_idx}$)	0.0019*** (0.0001)	0.0007*** (0.0001)
Constant (Intercept)	0.1032*** (0.0012)	0.0459*** (0.0012)
Observations	23	21
R^2	0.948	0.695
F-statistic	345.2***	43.1***

Note: OLS = Ordinary Least Squares. Column (1) includes Rust, Go, Python, and C++. Column (2) excludes Python to focus on core system-level engineering. Standard errors in parentheses. ***$p < 0.01$.

(2) Significant competitive advantage in specialized fields: A one-sample T-test conducted on the cross-sectional data for 2025Q3 (see Table 8) further consolidates H3. The results demonstrate that the mean RCA across key

technical topics within the DSR is significantly greater than the critical threshold of 1.0 ($p = 0.0252$). Statistically, this result eliminates the possibility that such advantages are idiosyncratic outliers or coincidental artifacts of individual extreme projects. Instead, it proves that DSR collaboration has established a robust technological niche within modern engineering frameworks. This specialization demonstrates the DSR's capacity to foster a modular catch-up mechanism, allowing Global South countries to bypass incremental evolutionary steps and secure a specialized foothold in the global digital innovation landscape.

Table 8. Statistical significance of technological specialization

Metric	Value	p-Value (vs. 1.0)
Mean RCA Index (Top 10 Topics)	4.885	0.0252**

Note: RCA = Revealed Comparative Advantage. ** $p < 0.05$.

Importantly, subsample robustness checks confirm that this specialization advantage is not driven by specific outlier economies. When excluding core nodes such as Russia and Pakistan, the mean RCA for the remaining BRI participants still significantly exceeds the 1.0 threshold. This suggests that the DSR has fostered a genuine 'technological niche' that is structurally embedded across the broader DSR ecosystem, providing a blueprint for achieving technological sovereignty.

5 Discussions

5.1 Rebalancing Digital Gravity: Institutional Escape and Path Creation

The structural shift in digital gravity observed through 2025 provides a compelling extension to existing innovation network and technology diffusion theories. While traditional gravity models prioritize geographic proximity and economic scale, our findings suggest a digital gravity predicated on information collaboration density and network resilience. This rebalancing can be elucidated through the lens of Institutional Escape Theory. In an era of intensifying geopolitical friction, the DSR has evolved beyond a mere extension of physical infrastructure into an alternative institutional space.

This gravitational shift represents a profound process of path creation: by utilizing digital public goods, China and BRI economies have effectively decoupled technical growth from physical geography. This mechanism challenges traditional information dynamics by demonstrating that in the digital era, institutional complementarity and policy synergy can effectively hedge against the negative shocks of geopolitical risk [11]. The DSR thus serves as a resilient soft-connectivity buffer, allowing innovation agents to reroute knowledge flows through virtual spaces when traditional physical and institutional pathways are obstructed.

5.2 Reciprocity Logic and the Democratization of Innovation

The observed structural balancing of the RI serves as more than a metric for technological flow; it is evidence of the accumulation of digital social capital within the Global South [30, 31]. Distinct from the hierarchical technology transfer models dominated by multinational corporations, the DSR facilitates a transition from unidirectional technical dependency to reciprocal symbiosis.

This maturation of mutual dependency signifies the democratization of innovation. By lowering the entry barriers to the global R&D value chain, the DSR model allows emerging economies to transition from passive technology consumers into active co-innovators. This evolution from a center-periphery structure toward a distributed, peer-to-peer architecture provides an empirical blueprint for a more inclusive global digital governance system. It demonstrates that technological sovereignty and innovation vitality can be secured through open, reciprocal collaboration rather than closed, protectionist barriers. This mechanism offers a strategic reference for other emerging economies seeking to mitigate the risks of technological fragmentation.

5.3 Technological Deepening and the Leapfrog Catch-up Mechanism

The observed transformation in technological complexity—evidenced by the concentration of RCA in modern frameworks like Laravel and Flutter—reveals a novel modular catch-up mechanism. Rather than replicating the incremental evolutionary paths of traditional innovation centers, BRI economies are leveraging modern, open-source architectures to achieve leapfrog development.

This phenomenon illustrates how open-source modularity significantly lowers the technical entry barriers into core system engineering. By embedding themselves into specialized global niches, emerging markets can bypass the need for an exhaustive, decade-long accumulation of legacy technology, instead utilizing mature soft infrastructure to rapidly construct localized digital service ecosystems. This demand-pull technological deepening suggests that the DSR is not merely a pipeline for technology transfer, but a platform that transforms the unique digital needs of the Global South into a decentralized driver for global innovation. This provides a critical theoretical template for

understanding how developing nations can secure technological sovereignty in the Fourth Industrial Revolution by mastering high-barrier, underlying logic rather than remaining confined to surface-level applications.

5.4 Strategic Implications for Mitigating Technological Fragmentation

Our findings offer profound strategic insights for both corporate entities and national governments in navigating the risks of technological fragmentation. For multinational technology firms, the structural shift in digital gravity indicates that the BRI market has evolved from a secondary consumption hub into a strategic frontier for collaborative R&D. Engaging with these resilient networks is essential for ensuring technological continuity in a post-decoupling world.

For policymakers, this research demonstrates that soft infrastructure—including open-source ecosystems, technical standards, and talent networks—plays a decisive role in enhancing national innovation resilience, often surpassing the long-term impact of hardware investment alone [32]. Given the escalating risk of global technological partitioning, constructing a multipolar digital collaboration network is a strategic necessity to preserve innovation vitality [33, 34]. This study provides a compelling empirical case for an inclusive global governance model, where technological resilience is built through distributed, open cooperation rather than protectionist isolation.

6 Conclusion

Through an empirical analysis of massive dynamic collaboration data from GitHub (2020–2025), this paper delineates the landscape of the Silk Road Woven by Code. The research demonstrates that during the globally turbulent period of the early 2020s, the software collaboration network did not contract; instead, it underwent a profound structural reorientation under the pressure of geopolitical decoupling.

Our primary conclusions are as follows: First, the DSR has emerged as a resilient alternative innovation path for mitigating the risks of global technological fragmentation. By extending innovation network theory through the concept of digital gravity shift, we have demonstrated that China and emerging markets established a virtual institutional space anchored in information density and network resilience. Robustness tests confirmed that this shift remained persistent even after accounting for the acute institutional shocks of 2022. Second, the structural transition toward reciprocal collaboration marks the accumulation of digital social capital and the democratization of innovation within the Global South. BRI economies have evolved from passive technology consumers into active co-builders of the ecosystem, fostering a distributed peer-to-peer architecture. Finally, the qualitative leap in technical sophistication signifies the surmounting of high-barrier entry thresholds into core system engineering. This modular catch-up mechanism, facilitated by modern open-source frameworks, provides a viable pathway for developing nations to secure technological sovereignty in the Fourth Industrial Revolution.

The policy and strategic implications are significant: governments should place high strategic value on soft infrastructure—including open-source ecosystems, technical standards, and talent networks—as a core lever to enhance national innovation resilience against external decoupling. Looking forward, the DSR experience provides an empirical blueprint for global innovation governance, suggesting that a more inclusive, multipolar, and secure digital community can be constructed through open, reciprocal collaboration rather than protectionist isolation.

Author Contributions

Conceptualization, L.H. and M.P.; methodology, L.H. and M.P.; software, L.H. and M.P.; validation, M.P.; formal analysis, L.H.; resources, M.P.; writing—original draft preparation, L.H.; writing—review and editing, M.P.; visualization, L.H. and M.P.; supervision, M.P.; project administration, M.P. Both authors have read and agreed to the published version of the manuscript.

Data Availability

The data supporting the findings of this study are derived from the GitHub Innovation Graph, a public data resource provided by GitHub. These data are available in the GitHub Innovation Graph repository at https://github.com/github/innovation-graph.

Conflicts of Interest

The authors declare no conflicts of interest.

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