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Unveiling the Mechanism of Digital and Intelligent Technology Empowering the Integrated Governance of the "Four Zones Synergy"

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Abstract

Promoting the coordinated development of functional zones, including Pilot Free Trade Zones, Economic Development Zones, Comprehensive Bonded Zones, and Cross-Border Economic Cooperation Zones, constitutes a major policy initiative to accelerate the construction of a new development paradigm and deepen border-opening strategies. However, the "Four Zones Synergy" faces integrated governance dilemmas such as policy fragmentation, data silos, and high cross-border coordination costs. Digital and intelligent (DI) technologies, characterized by data penetration, process reengineering, and intelligent coordination, offer new possibilities to address these challenges. Based on clarifying the conceptual connotations of DI technology, the "Four Zones Synergy," and integrated governance, this paper systematically analyzes the mechanisms through which DI technology empowers integrated governance. These mechanisms specifically include data integration, process reengineering, intelligent supervision, decision-making optimization, and cross-border coordination. Empirical support is provided through the reform practices of the four zones in Kunming. The research demonstrates that DI technology, by constructing a unified data foundation and intelligent platforms, effectively breaks down administrative divisions and policy boundaries, driving governance structures from fragmentation toward holism and significantly enhancing the efficiency of resource allocation and the level of risk coordination. This study deepens the theoretical understanding of the digital transformation of collaborative governance within special functional zones and offers practical references for border regions seeking high-level opening up through digital and intelligent means.

Keywords

Digital and Intelligent Technology, Four Zones Synergy, Integrated Governance, Cross-Border Economic Cooperation Zone

1. Introduction

The pattern of "Four Zones Synergy," comprising the China (Yunnan) Pilot Free Trade Zone Kunming Area (hereinafter "Kunming FTZ"), the Kunming Economic and Technological Development Zone (hereinafter "Kunming ETDZ"), the Kunming Comprehensive Bonded Zone (hereinafter "Kunming CBZ"), and the China-Laos Mohan-Boten Economic Cooperation Zone (hereinafter "Mohan-Boten ECoZ"), represents a landmark experiment in China's new era to advance border opening and explore high-quality development pathways for inland border regions. The Kunming FTZ, established in 2019,

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focuses on developing high-end manufacturing, aviation logistics, and the digital economy, bearing the core mission of institutional innovation. The Kunming ETDZ, as an established national-level development zone, possesses a mature industrial foundation and administrative system. The Kunming CBZ focuses on bonded processing, bonded logistics, and cross-border e-commerce, serving as a crucial node for the export-oriented economy. In 2022, Kunming officially took trusteeship of the Mohan-Boten ECoZ, located in Mohan Town, Xishuangbanna Prefecture, making Kunming the only provincial capital city in China with both a "border line and a border port." Consequently, the "Four Zones" present a unique superimposed situation of "Kunming Area + Mohan Frontier," "Development Zone + Comprehensive Bonded Zone + Cross-Border Cooperation Zone" in terms of geographic space and policy supply.

Guided by the institutional innovation of the FTZ, leveraging the industrial carrying capacity of the ETDZ, utilizing the bonded functions of the CBZ as a link, and using the cross-border channels and rules of origin of the Mohan-Boten ECoZ as a springboard, an open economy complex integrating "port + bonded zone + industry + institutional innovation" is being constructed. The "14th Five-Year Plan for the Revitalization of Special Types of Regions" explicitly supports the coordinated development of border economic cooperation zones with comprehensive bonded zones and national-level economic and technological development zones. Yunnan Province has successively issued the "China (Yunnan) Pilot Free Trade Zone Deepening Reform and Opening-up Plan" and the "Kunming City–Mohan Town Integrated Development Master Plan," requiring the dismantling of regional barriers and the implementation of an integrated governance model for the "Four Zones Synergy." It can be argued that the "Four Zones Synergy" is not merely a reshaping of regional economic geography but also a profound governance transformation, demanding cross-regional, cross-level, and cross-functional policy coordination, data interoperability, and mutual recognition of supervision.

However, in early practice, the realization of integrated governance goals within the "Four Zones Synergy" faced multiple structural obstacles, revealing several typical problems. First, administrative fragmentation coexists with "policy silos." The four zones originally belonged to different management systems: the Kunming FTZ is operated by its administrative committee, but social management functions fall under administrative divisions; the Kunming ETDZ possesses relatively independent administrative approval authority; the CBZ is subject to special customs supervision; and the Mohan-Boten ECoZ involves a bilateral coordination mechanism between China and Laos. Industrial support, tax incentives, and cross-border settlement policies issued by each zone cannot be automatically mutually recognized, forcing enterprises operating across zones to repeatedly adapt to different rules, resulting in both high "policy arbitrage" and "compliance costs."

Second, data barriers lead to information fragmentation. Market entity registration, customs clearance information, logistics data, and credit records across the four zones are respectively stored in different operational systems. The customs' single window, the market supervision department's enterprise registration platform, the ETDZ's project management system, and the Mohan port's clearance system are isolated from each other, lacking a unified data sharing and exchange channel. This directly impedes the comprehensive supervision of the enterprise lifecycle. For instance, a cross-border e-commerce enterprise registered in the CBZ shipping via the Mohan port, with its backend supply chain in the Kunming FTZ, cannot be tracked in real-time by various departments, leading to lagging risk identification and absent coordinated supervision.

Third, the synergy of government services is low, a restricting factor for mobility. Enterprises must travel between multiple service halls and repeatedly submit materials for cross-zone procedures such as environmental impact assessments, land use planning, and cross-border labor services. Logistically, although the China-Laos railway connects Kunming and Mohan, the railway waybills, customs declarations, and bonded warehouse receipts have not achieved digitalized circulation and mutual recognition, resulting in poor multimodal transport, port congestion, and frequent cargo backlogs. A deeper issue is that high-end factors like talent, finance, and data cannot flow freely according to market logic due to fragmented regional governance, diminishing the overall competitiveness of the four zones.

Fourth, cross-border coordination costs are high, and risk management is difficult. As a special form of cross-border economic cooperation zone, the governance of the Mohan-Boten ECoZ involves the transfer of sovereign rights and the alignment of rules between two states. Under traditional governance models, mutual recognition of qualifications, standard compatibility, mutual recognition of inspection and quarantine results, and joint law enforcement in cross-border trade and investment have relied heavily on frequent offline meetings and paper document transmission, resulting in low efficiency and near-complete interruption during the epidemic. Moreover, new risks such as cross-border data flows, anti-money laundering supervision, and intellectual property protection impose higher demands on integrated governance.

In response to these issues, digital and intelligent technologies, including big data, artificial intelligence (AI), blockchain, the Internet of Things (IoT), and digital twins, demonstrate significant empowerment potential. The core logic lies in how these technologies fundamentally change the way information is collected, transmitted, processed, and utilized, thereby providing new toolsets and paradigms for solving the inherent difficulties of integrated governance.

Firstly, DI technology can permeate administrative boundaries and reorganize data chains. By building a unified data platform and an IoT perception system, DI technology can aggregate, clean, and correlate data scattered across different

zones and departmental levels in real time, forming a comprehensive data foundation covering market entities, logistics, capital flows, and documentation. This re-establishes the information flows previously fractured by segmentation, providing transparent and complete data support for cross-zone decision-making and coordinated supervision, directly addressing the data barrier issue.

Secondly, DI technology can drive process reengineering and achieve service integration. The immutability and multi-party sharing features of blockchain can support cross-departmental and cross-border mutual recognition of electronic licenses, signatures, and documents. AI and Robotic Process Automation (RPA) can enable intelligent verification and instant approval of applications, expanding the "one-stop online service" from a single zone to all four zones, significantly reducing institutional transaction costs.

Thirdly, DI technology can enable intelligent early warning and dynamic coordination. Using big data analytics models, risk profiles for the industrial chains across the four zones can be created, predicting logistics bottlenecks, capacity imbalances, or trade anomalies. Based on digital twin technology, the flow paths of factors under different policy impacts can be simulated, aiding in the formulation of more precise integrated industrial policies. In the realm of cross-border governance, privacy computing and cross-border data security exchange technologies can ensure alignment and joint supervision of specific information between China and Laos, safeguarding data sovereignty and providing technical safeguards for bilateral cooperation mechanisms.

It can be argued that DI technology serves as a catalyst for the "Four Zones Synergy" integrated governance, transforming physical connections into chemical fusion. This is not simply electronification or informatization, but a data-driven reshaping of the power structures, business processes, and collaboration models among governance entities, steering four independent units toward a holistic digital ecosystem.

Existing research predominantly focuses on the digital transformation of single functional zones or general regional integration technology applications, rarely taking the synergy of multiple heterogeneous functional zones as the analytical unit to explore how DI technology systematically empowers its integrated governance. The contribution of this paper is threefold: First, it proposes the "Four Zones Synergy" as a typical complex governance scenario, delineating the specific contradictions within integrated governance. Second, it constructs a mechanism chain of DI empowerment—data integration, process reengineering, intelligent supervision, decision-making optimization, and cross-border coordination—and provides first-hand reform evidence from Kunming's four zones, enriching the explanatory power of digital governance theory in complex functional zone coordination. Third, the analysis offers generalizable governance experiences for border regions in balancing openness and security, efficiency and equity through digital and intelligent means, providing valuable references for institutional innovation in similar areas.

2. Literature Review

The integrated governance of the "Four Zones Synergy" constitutes an extremely complex governance field characterized by interwoven administrative boundaries, uneven policy density, and sensitive data sovereignty, where the limitations of traditional fragmented governance models are starkly exposed. In recent years, academia has accumulated rich and diverse research results concerning the governance potential of DI technologies, theoretical models of integrated governance, and the pathways for their integration.

2.1. Digital and Intelligent Technology

DI technology is not a single tool but a composite technological system comprising data, algorithms, sensing devices, and distributed ledgers. Academic discussions can be broadly divided into three interrelated yet distinct levels.

At the macro level, the impact of DI technology on public management is primarily examined within the paradigm shift of governance itself. In their seminal work Digital Era Governance, Dunleavy et al. systematically announced the decline of the New Public Management paradigm and the rise of digital-era governance. They argued that digital technology is pushing governments from a "dispersed, competitive" organizational form toward a new form characterized by "reintegration, needs-based holism, and deep digitalization," a transformation not merely of technological upgrading but of organizational logic and power structures [9]. This assertion elevates digital technology to the level of governance philosophy, providing a macro analytical coordinate for subsequent research. Building on this, Janowski [16] proposed a "Digital Government Evolution Model," dividing the digitalization process into four stages: digitization (digital data), transformation (e-government), engagement (e-participation), and contextualization (policy-driven, context-specific digital solutions), emphasizing changes in organizational roles and citizen relationships at each stage. Margetts and Dunleavy [20] further noted that cloud computing, big data, and social media are fostering a "mobile, real-time" government form, shifting the rhythm of government information processing from periodic reports to continuous streaming. These macro-level discussions collectively establish a fundamental recognition: DI technology is not an external tool attached to governance but constitutes the infrastructure of the governance environment itself, redefining the boundaries, capacities, and responsibilities of the state.

At the meso level, big data analytics is viewed as a key engine driving governance from "experience-based intuition" toward "data-driven insight." Janssen and van der Voort [18], in their analytical framework published in Government Information Quarterly, proposed that big data can enable "adaptive governance," where public organizations dynamically adjust policy responses through continuous input of real-time data streams, achieving agile adaptation to external environmental

changes. However, they also cautioned that data quality, talent shortages, and organizational culture constitute major adoption barriers. Mergel et al. [21], in a systematic literature review, examined digital transformation in the public sector, noting that big data analytics is widely used for fraud detection, performance monitoring, and personalization of public services, but its effectiveness is heavily moderated by institutional contexts, and techno-deterministic optimism often fails in complex organizational realities. Desouza and Jacob [8] similarly emphasized the potential of data analytics in public decision-making but warned that without critical reflection on data generation processes, big data might reinforce existing structural biases. Artificial intelligence, as a higher-order intelligent form, has become a research focus regarding its applications and challenges in public governance. Wirtz et al. [28] comprehensively mapped AI applications in the public sector, encompassing machine learning-based policy simulation, natural language processing for public grievance classification, and computer vision for intelligent surveillance, while also systematically discussing risks such as algorithmic black boxes, transparency deficits, and accountability vacuums. They cautioned that when algorithms participate in decisions affecting citizens' rights, explainability standards and human intervention mechanisms must be established. Kuziemski and Misuraca [19] examined AI governance from a public value perspective. proposing that "AI for public good" should adhere to core principles of inclusiveness, fairness, and accountability, urging governments to establish institutional guardrails when adopting AI. These studies fully reveal the dual nature of AI: it can vastly improve governance precision and foresight while also potentially eroding procedural justice and individual rights in the name of efficiency.

At the micro level, blockchain, IoT, and digital twins, due to their unique capabilities in trust reconstruction and virtual-physical mapping, provide new technological foundations for cross-organizational and cross-border governance. Blockchain, characterized by decentralization, immutability, and multi-party sharing, is widely discussed as a potential solution to trust deficits among multiple actors. Ølnes et al. [22] in a special issue of Government Information Quarterly, prospectively analyzed blockchain applications in government information sharing and transaction certification. They argued that blockchain's greatest value lies not in replacing existing central databases but in constructing "technological trust" among mutually distrusting organizations, enabling data to self-certify authenticity without intermediaries. This feature naturally aligns with scenarios like customs, cross-border trade, and mutual recognition of qualifications. However, they also candidly pointed out challenges related to scalability, energy consumption, and compatibility with existing legal frameworks, advocating prudence in introducing blockchain into public governance. Allessie et al. [1] further explored blockchain implementation pathways from a public service delivery perspective, emphasizing that successful implementation requires the coordinated design of technical architecture, governance structures, and legal agreements, with pure technology deployment destined to fail. The IoT, through sensors and intelligent terminals, enables wide-area perception and real-time data collection of the physical world. Zanella et al. [30] proposed an "IoT for Smart Cities" architecture, elaborating how the layered model of perception, network, and application layers supports dynamic monitoring of urban operations. In special supervision scenarios like ports and bonded warehouses, IoT enables round-the-clock visualization of cargo status, environmental parameters, and movement trajectories. providing massive data inputs for precision supervision. Building on this, digital twin technology further realizes the virtual-physical symbiosis between physical entities and digital models. Fuller et al. [12], in summarizing the enabling technologies and application challenges of digital twins, explicitly identified the core advantage as the closed-loop capability of "mirroring, monitoring, and simulation," enabling managers to conduct simulations and optimizations in virtual space before feeding decisions back to the physical world. This technological logic offers an intuitive vision for real-time simulation and coordinated optimization of checkpoints, logistics, and industrial chains in complex functional zones, though its large-scale application in public governance remains in early exploration.

2.2. Integrated Governance

Integrated governance constitutes another core theoretical pillar of this research. Its theoretical lineage spans public administration, regional studies, and cross-border governance, progressively forming a conceptual framework and analytical tools focused on coordination, integration, and synergy.

2.2.1. Holistic Government and Collaborative Governance

The direct theoretical source of integrated governance is Holistic Government and Collaborative Governance theory. Perkmann [23] in his seminal work Holistic Government, lamented the organizational fragmentation and service disconnection resulting from New Public Management reforms, proposing a holistic government agenda centered on cross-departmental coordination, shared information, and holistic budgeting. Subsequently, Pollitt [24] systematically reviewed the concept of "joined-up government," defining it as horizontal and vertical coordination actions aimed at eliminating policy contradictions, reducing resource waste, and improving public service coherence. Christensen and Lægreid [5], in their monograph on comparative public management reforms, delved into the rise of the "whole-of-government" agenda in the post-New Public Management era, identifying the core challenge as achieving deep collaboration across organizational barriers without sacrificing the efficiency of specialization.

Building on this, collaborative governance theory shifts focus from structural integration to process mechanisms. Ansell

and Gash [2], in a highly cited paper, proposed a theoretical model of collaborative governance, emphasizing the dynamic causal relationships among starting conditions (power/resource imbalances, history of cooperation and conflict), institutional design (inclusiveness, exclusivity rules, clear ground rules), facilitative leadership, and the collaborative process itself (face-to-face dialogue, trust-building, commitment, and shared understanding). This model provides a general framework for analyzing the success conditions of multi-actor synergy. Emerson et al. [10] further integrated various variables of collaborative governance, proposing a "comprehensive framework for collaborative governance" that incorporates system context, collaborative drivers (principled engagement, shared motivation, and joint action capacity), collaborative actions, outcomes, and adaptive feedback into an integrated analytical structure, significantly enhancing the theory's explanatory power. These theoretical achievements offer direct guidance for understanding joint actions among governance entities in four special functional zones, but they usually presume intergovernmental coordination within the same sovereign framework, requiring further theoretical extension for synergies involving different customs supervision attributes and even cross-border sovereignty.

2.2.2. Regional Integration and Cross-Border Cooperative Governance

When integrated governance crosses different administrative regions or national borders, its logical complexity escalates significantly. Blatter [4], from a socio-geographical perspective, proposed a dual analysis of the "space of places" and the "space of flows," pointing out that cross-border regions are transitioning from cooperation based on territorial adjacency toward governance models linked by functional flows (capital, information, logistics). This theory keenly captures the spatial restructuring logic of the "enclave-style" synergy between Kunming and Mohan within the "Four Zones Synergy." Perkmann [23], in an empirical analysis of drivers for European cross-border regional cooperation, found that new institutional arrangements like cross-border economic cooperation zones create an "institutionalized elastic space" through joint committees and common planning mechanisms, thereby reducing transaction costs of cross-border interactions without challenging national territorial sovereignty. Scott [27], in a comparative paper on cross-border regionalism in Europe and America, also pointed out that successful cross-border governance depends on continuous negotiation of shared visions and flexible institutional design among parties.

Focusing on special economic functional zones, World Bank economist Farole [11] in the book *Special Economic Zones: Progress, Emerging Challenges, and Future Directions*, systematically analyzed the role of special zones like SEZs and FTZs in global industrial chain integration, noting that when multiple customs-supervised zones with different functions geographically overlap or are adjacent, policy fragmentation and institutional conflicts are the main obstacles to governance effectiveness, requiring regulatory integration and one-stop services. These studies collectively reveal that the realization of integrated governance deeply depends on systematic integration at three levels—information, rules, and actions—and the cost and quality of the integration process constitute key benchmarks for measuring governance performance.

2.3. Intersection Studies on DI Technology and Integrated Governance

In recent years, a growing academic frontier directly treats DI technology as a key variable for resolving integrated governance dilemmas, generating rich literature around three focal issues: information sharing, platform integration, and cross-border coordination.

2.3.1. Cross-Organizational Information Sharing and Interoperability: The Digital Foundation of Integrated Governance

Information silos represent the primary barrier to integrated governance, and research on cross-organizational information sharing provides fundamental insights. Yang and Maxwell [29], in a comprehensive review of public sector information sharing literature, distilled key factors influencing successful cross-organizational information sharing, encompassing interpersonal trust, inter-organizational trust, leadership, legal and policy frameworks, and technical interoperability. They insightfully noted that technical obstacles are often the easiest to overcome, with the real bottlenecks being interest conflicts and trust deficits at organizational and institutional levels. Gil-Garcia and Sayogo [14], through empirical studies of cross-organizational information sharing initiatives, further confirmed the decisive role of formal governance structures, collaborative cultures, and clear risk-sharing mechanisms for sharing effectiveness, asserting that technical connectivity alone cannot guarantee the sustainability and reliability of information flows. Scholl and Klischewski [26], from the perspective of e-government integration, proposed a widely cited interoperability analysis framework, dividing interoperability into three progressive levels: technical (system connection), semantic (consistent data meaning), and organizational (aligned business processes and objectives). This framework precisely explains why many cross-regional data sharing projects, despite technical connectivity, fail due to disagreements on data field definitions and business rules. Dawes's [7] early classic study similarly confirmed that cross-departmental information sharing, besides technical conditions, depends on shared understanding of benefits and clear policy authorization. These studies profoundly reveal that the data integration capability provided by DI technology for integrated governance must be embedded within specific organizational agreements and governance rules to be effective.

2.3.2. Digital Platforms and Seamless Service Integration: Technological Dissolution of Administrative Boundaries

Building on cross-organizational information sharing, digital platforms are viewed as core vehicles for achieving seamless service integration. Scholars observe that by constructing unified digital service platforms, government services across different jurisdictions can be integrated into a coherent user experience, thus dissolving administrative boundaries at the perceptual level. Cordella and Paletti [6], using "Government as a Platform" as a conceptual framework, discussed how digital platforms connect disparate backend business systems through standardized APIs and data services, delivering integrated service packages to the public. They emphasized that the key to platform success lies in designing governance rules that encourage innovation while maintaining interoperability. Janssen and Estevez [17] proposed combining "lean government" with platform governance, advocating the use of intelligent process engines and RPA to achieve intelligent routing and collaborative processing across departments, reducing institutional transaction costs for both internal and external users.

However, platform integration does not come without costs. Bannister and Connolly [3], when discussing the relationship between ICT and public value, cautioned researchers against the optimistic tendency of "technological determinism." They pointed out that efficiency-oriented system integration may neglect core public values like procedural fairness, privacy protection, and the digital divide. Integrated digital platforms, while providing seamless services, may also allow the voices of vulnerable groups to be more easily submerged by algorithmic logic, creating new forms of governance exclusion. This critical perspective injects necessary value reflection into digital solutions for integrated governance.

2.3.3. Cross-Border Data-Driven Coordination and Smart Border Governance

Applying DI technology to cross-border scenarios represents the most challenging extension of integrated governance research, with relevant studies mainly concentrated in smart customs and trade facilitation. Raus et al. [25], in a deep analysis of the governance effects of e-customs innovation, pointed out that integrating IoT sensing, electronic documentation, and risk management systems into customs operations can significantly reduce clearance times without lowering security standards, achieving a regulatory shift from "manual presence to data-driven, manual inspection to intelligent algorithms." This data-driven coordinated supervision directly addresses the pain of information disconnection among different customs supervision zones.

In constructing cross-border trust, blockchain technology shows unique value. The World Trade Organization, in a report, explored how blockchain could transform international trade by creating a single, trusted source of truth, enabling multiple participants (exporters, importers, banks, customs, and inspection authorities) to share verified transaction data and document status in real-time, thus reducing redundant documentation and fraud [13]. Going further, Heijmann and Tan [15], in discussing customs data sharing, introduced the concepts of "data sandbox" and privacy-preserving computation, describing how customs authorities can conduct joint risk assessment and control through technologies like multi-party secure computation and federated learning while protecting commercial confidentiality and data sovereignty. This approach provides a technological pathway for cross-border economic cooperation zones, where sovereign sensitivity is high, to maintain respective data boundaries while achieving substantive collaborative governance.

2.4. Literature Review Summary

In summary, existing research has accumulated a solid knowledge base regarding the governance effects of DI technologies, theoretical models of integrated governance, and their intersection applications. DI technology studies have moved from macro-paradigm argumentation to governance analysis of specific technological components, revealing the immense potential of big data, AI, and blockchain in enhancing government perception, decision-making capacity, and trust reconstruction, while also maintaining necessary vigilance against inherent risks of algorithmic alienation, value conflicts, and institutional adaptation. Integrated governance theory provides multi-level analytical frameworks—holistic government, collaborative governance, and cross-border cooperation—systematically elucidating the crucial role of coordination, integration, and mutual trust in overcoming fragmentation. These two academic lineages converge successfully at intersection points such as "cross-organizational information sharing," "digital platform integration," and "smart border management," offering powerful analytical threads for understanding how digital technology drives regional and cross-border synergy.

However, three significant limitations in existing research constitute the entry point for this study.

First, the singularity of scenario focus. Most intersection studies either focus on general regional synergy within the same administrative jurisdiction or concentrate on single business functions like customs or logistics. There is a lack of systematic research treating the synergy of multiple heterogeneous special functional zones—encompassing FTZs, ETDZs, CBZs, and cross-border economic cooperation zones—as a holistic analytical object. Such composite functional zones superimpose diverse attributes like "within the territory but outside customs" (for CBZs), "inside the territory and outside the zone" (for ETDZs), and "cross-border and outside customs" (for cross-border zones), making their policy combinations and governance contradictions far more complex than those of single-type zones, thus demanding dedicated theoretical construction.

Second, insufficient holistic explanation of empowerment

mechanisms. Existing literature typically discusses technical applications like data sharing, government service integration, or smart customs separately, failing to construct a complete empowerment chain from data integration through process reengineering to regulatory coordination and cross-border mutual recognition. Fragmented technical analyses cannot reveal how DI technology, as a systemic force, simultaneously acts upon multiple dimensions of integration—information base, service interface, regulatory model, industrial coordination, and cross-border cooperation—to generate holistic governance efficiency improvements.

Third, inadequate exploration of the technology-institution co-constitutive relationship. Most studies either lean towards optimistic descriptions of technological efficacy or emphasize the unidirectional constraining effect of institutions on technology adoption. There is a lack of in-depth dynamic analysis of how DI technology, once embedded in complex functional zone governance structures, retroactively drives rule integration, policy optimization, and power relation restructuring. In the "Four Zones Synergy" scenario, the design and operation of technological platforms continuously reproduce new governance information flows and responsibility boundaries. This "shaping" effect of technology on institutions should be a central issue in integrated governance research.

Based on these judgments, this study treats the "Four Zones Synergy" as a holistic, composite analytical unit, aiming to construct a systematic mechanism framework for DI technology empowerment in integrated governance. While fully absorbing existing research findings on information sharing, platform governance, and cross-border coordination, it focuses on revealing how technological empowerment permeates the entire chain of data, processes, supervision, decision-making, and cross-border collaboration, and attends to the two-way interaction between technological application and institutional evolution. This aims to fill the gap in existing literature regarding digital pathways for coordinated governance across multiple types of special functional zones.

3. Conceptual Definition and Mechanism Analysis

3.1. Definition of Core Concepts

3.1.1. Digital and Intelligent Technology

Digital and Intelligent Technology (DI) refers to a composite technological system that takes data as a key factor of production and integrates new-generation information technologies such as IoT perception, big data analytics, AI, blockchain, and digital twins to achieve comprehensive digital mapping, intelligent analysis, and precise intervention of the physical world and social systems. It comprises three layers: the perception layer, composed of sensors, RFID, and intelligent terminals, responsible for comprehensively collecting real-time status data on people, logistics, and capital flows; the computing and data layer, composed of data platforms, cloud platforms, and algorithmic models, responsible for storing, cleaning, correlating, and computing massive data; and the application layer, composed of business application systems, decision-making dashboards, and public service terminals, directly delivering intelligent services to enterprises, the public, and governance actors. The distinguishing essence of DI technology from traditional e-government is its capacity for autonomous learning and iteration, forming a closed loop of "data–decision–action–feedback," thereby reorganizing governance processes without altering substantive organizational boundaries.

3.1.2. "Four Zones Synergy"

The "Four Zones Synergy" specifically refers to the coordinated development and integrated governance among four special functional zones: the China (Yunnan) Pilot Free Trade Zone Kunming Area, Kunming Economic and Technological Development Zone, Kunming Comprehensive Bonded Zone, and China-Laos Mohan-Boten Economic Cooperation Zone. In terms of geographic layout, the first three are located within Kunming municipality, geographically close with some overlapping plots and adjacent fenced areas. The Mohan-Boten ECoZ is situated on the China-Laos border, approximately 700 kilometers from Kunming. This "front shop, back factory" and "port + hinterland" structure determines that the synergy is not merely a simple superposition of policies but a cross-domain integration of industrial chains, supply chains, supervision chains, and value chains. The synergy content includes: industrial policy coordination, cross-zone government service interoperability, mutual recognition of customs supervision, convenient circulation of bonded and non-bonded goods, cross-border production capacity cooperation, and compliant data flow. Its governance form features a high mixture of attributes, such as "inside the territory but outside the zone" (for ETDZ), "within the territory but outside customs" (for CBZ), and "cross-border and outside customs" (for the cross-border zone), posing significant challenges to traditional territorial management.

3.1.3. Integrated Governance

Integrated governance refers to the process where multiple originally independent governance entities, in order to solve cross-domain public problems and enhance overall competitiveness, systematically coordinate governance elements such as planning, standards, supervision, and services through formal collaboration mechanisms and shared information platforms, ultimately forming a governance community with complementary functions, consistent actions, and optimal costs. In this paper's context, integrated governance does not require administrative consolidation of the four functional zones but

pursues governance outcomes characterized by "four uniformities": uniformly transparent policy application, uniformly convenient enterprise services, uniformly unobstructed access to factors, and uniformly coordinated regulatory enforcement. Achieving this goal requires integration at three levels: information, rules, and action. DI technology can provide a low-cost, highly reliable technological foundation for this integration.

3.2. Mechanisms of DI Technology Empowering "Four Zones Synergy" Integrated Governance

DI technology empowering integrated governance does not directly replace traditional governance methods but is embedded within the governance structure, reshaping interaction mechanisms among the four zones by changing information flow patterns, compressing coordination costs, and providing new collaborative tools. The mechanisms can be condensed into five interrelated and spirally progressive dimensions.

3.2.1. Data Integration Mechanism: Breaking Information Silos and Building a Unified Data Foundation

The primary obstacle to integrated governance is information silos, and the first mechanism of DI empowerment is establishing a safe, reliable, and real-time big data integration system. In traditional models, data on markets, customs, taxation, and logistics across the four zones are stored in their own business systems with inconsistent data standards, different field definitions, and unclear data ownership, leading to cross-zone "information blind spots." DI technology intervention manifests as "building a foundation, unblocking bottlenecks, and clarifying rights and responsibilities."

The first step is constructing a Four-Zone Integrated Data Platform. Utilizing cloud-native technology, a model of logical centralization with physical distribution is adopted to uniformly catalogue, clean, and standardize data scattered across the FTZ enterprise service platform, ETDZ economic operation system, CBZ customs auxiliary management system, and Mohan smart port platform. By formulating the "Four-Zone Data Sharing and Exchange Technical Specifications," the classification of basic databases, thematic databases, and special databases is clarified, forming a data foundation covering enterprise profiles, electronic documents, logistics trajectories, and credit records. This foundation does not change the original storage locations of departmental data but enables "one-entry, four-zone shared use" through data interface services.

The second step involves using the IoT and edge computing to connect physical information flows. Intelligent sensors and RFID devices are deployed at key checkpoints, bonded warehouses, and railway stations across the four zones, automatically uploading real-time dynamic information on cargo location, temperature/humidity, and seal status to the data foundation. For example, for a batch of machinery from the CBZ to the Mohan port, the vehicle trajectory, customs seal status, and bonded receipt data streams are coupled with business flows in real time, enabling managers at both the Kunming and Mohan ends to synchronously grasp the "digital footprint" of each shipment, entirely eliminating previous information lags requiring repeated phone calls and faxes.

3.2.2. Process Reengineering Mechanism: Government Service Integration Driven by "One-Network Service Across Zones"

Data integration enables process reengineering. The second mechanism involves using DI technology to deeply reorganize administrative approval and public service matters across the four zones, presenting enterprises and the public with an undifferentiated, one-stop holistic government interface.

First, establishing a Four-Zone Collaborative "Government Intelligence Hub." The independent online government service platforms of the four zones are integrated into a single portal, orchestrated in the backend by RPA robots, natural language processing, and intelligent verification engines. When an enterprise applies for a matter, such as "establishing a cross-border logistics enterprise within the four zones," the system automatically decomposes the application items, pushing project registration (ETDZ), foreign investment negative list review (FTZ), customs registration (CBZ), and cross-border border trade qualification certification (Mohan-Boten ECoZ) in parallel or an optimal sequence to the internal approval terminals of each responsible department. AI models automatically compare routine application materials for formal compliance, prompting on deviations. Approved results generate encrypted electronic certificates, each assigned a blockchain digital fingerprint ensuring one-certificate-one-code and non-repudiation.

Second, promoting "Blockchain + Electronic Certificate" cross-domain mutual recognition. For mutually recognized qualification permits across the four zones, such as food business operation permits and foreign trade operator registration, these are converted into digital credentials readable by smart contracts. When an enterprise clears customs in the Mohan-Boten ECoZ, it does not need to present the paper storage qualification certificate issued by the Kunming CBZ; the customs system directly retrieves on-chain certification information through the data platform, automatically matching and releasing the goods after verification. This relieves enterprises from repeated verification in different regions, moving government services beyond traditional "physical window integration" toward "digital credential-driven" frictionless processing.

Third, designing a "Policy Calculator" for precise matching. All industrial policies, tax incentives, and talent subsidies across the four zones are structurally decomposed, forming thousands of policy tags. Upon enterprise login, the system automatically matches eligible policy combinations based on

its big data profile and generates a simulated benefit estimate. More importantly, the "Policy Calculator" identifies discontinuities and conflicts in policy connections among the four zones, pushing back to each administrative committee to revise incompatible clauses, thereby retroactively forcing policy integration.

3.2.3. Intelligent Supervision Mechanism: Supervisory Integration via Credit Linkage and Risk Coordination

Supervision is the core of special functional zone governance. The third mechanism of DI empowerment lies in transforming traditional passive, ex-post responsive supervision into real-time, predictive, coordinated supervision driven by data.

First, constructing a Four-Zone Unified Enterprise Credit Comprehensive Evaluation Model. Breaking away from previous zone-specific credit ratings, data from over 40 dimensions—including enterprise registration, taxation, customs clearance, employment, credit, and environmental compliance—are aggregated, and machine learning algorithms produce dynamic credit scores. For high-credit enterprises, the four zones jointly implement facilitation measures, such as "distributed delivery, centralized declaration" without guarantee in the CBZ, "green channel" rapid inspection in Mohan port, and administrative approval notification commitment in the FTZ, creating positive incentives of "one place trustworthy, four zones benefit." For enterprises showing abnormal signals, the system automatically downgrades their rating and simultaneously notifies regulatory departments across zones, triggering joint constraints like increased inspection ratios and restricted government subsidy applications.

Second, achieving intelligent differentiation of bonded and non-bonded goods based on digital twins. Enterprises within the CBZ and ETDZ frequently require switching between "non-bonded" and "bonded" statuses; traditional supervision to prevent cross-contamination is extremely complex. By establishing a digital twin model of the CBZ checkpoint, the status of each enterprise, truck, and ledger within the zone is mapped in real time. AI algorithms determine the bonded attribute and access permissions of goods in milliseconds based on electronic customs declarations and vehicle electronic license plate information, directing barrier operations and monitoring tracking. Goods moving from the CBZ to processing outside the ETDZ, or directly from Mohan Port to the CBZ, have both physical and information trails automatically recorded by the system using dual ledgers, achieving "effective control and appropriate openness."

Third, innovating a "Data Sandbox" model for cross-border joint supervision. The Mohan-Boten ECoZ requires joint supervision of vehicles, personnel, and goods by China and Laos. By introducing privacy computing and secure data sandbox technologies, both customs and immigration authorities, without directly transmitting raw personal data or commercial secrets, perform encrypted multi-party computation to compare respective data, completing joint risk assessment for hidden compartments in vehicles or enterprise tax fraud, outputting only the result of "whether control rules are triggered." This satisfies both countries' rigid constraints on data security while effectively achieving cross-border joint risk control.

3.2.4. Decision-Making Optimization Mechanism: Data-Driven Industrial Coordination and Precise Policy Implementation

Integrated governance requires not only connectivity in services and supervision but also strategic-level coordination. The fourth mechanism involves DI technology providing panoramic perspectives and intelligent simulations for industrial development across the four zones, supporting holistic industrial governance.

First, mapping the Four-Zone Industrial Chain Knowledge Graph to diagnose coordination gaps. Data on main products, upstream/downstream relationships, patent information, and supply chain geographic distribution of enterprises across the four zones are collected to generate industrial chain graphs covering leading industries such as equipment manufacturing, biomedicine, cross-border logistics, and new materials. Algorithms automatically identify key nodes where capacity exists but lacks downstream applications, or where dependence on foreign imports cannot be substituted within the four zones. For example, the graph might reveal that a biomedicine enterprise in the Kunming FTZ requires a critical fermentation raw material, while the Mohan-Boten ECoZ has the conditions to introduce a substitute planting project, but the two sides failed to connect due to information asymmetry. The system pushes this information to investment promotion departments, facilitating the landing of chain-supplementary projects. The graph also periodically analyzes the degree of homogeneous competition among industries in the four zones, issuing red alerts to avoid internal friction.

Second, building a Four-Zone Macroeconomic and Logistics Twin Sandbox. Multiple data sources, such as China-Laos railway volume, bonded warehouse turnover, employment index, and electricity consumption, are fed into a system dynamics model to construct a "Four-Zone Economic Digital Sandbox." Decision-makers can drag parameters to simulate marginal impacts on GDP, tax revenue, and employment of "redirecting imported fruit processing enterprises from Mohan to the ETDZ," or simulate "whether the CBZ would experience warehouse congestion if China-Laos railway capacity suddenly drops by 30%" to formulate emergency plans. The model also assists in assessing the impact of specific policies of the cross-border cooperation zone on the partner country's industry, providing quantitative evidence for bilateral policy coordination.

Third, generating dynamic policy packages and monitoring implementation effects. The system captures enterprise demands and investment trends in real time, extracting common pain points through natural language clustering. When it iden-

tifies that numerous enterprises repeatedly inquire about "visas for overseas technical talents coming to Kunming," it automatically generates a recommendation to the FTZ administrative committee: coordinate with the Mohan-Boten ECoZ to provide a "one-visa-for-four-zones" facilitation policy for cross-border workers. After policy implementation, the platform continuously tracks talent inflow and enterprise production capacity changes, generating visual performance reports enabling rapid policy iteration.

3.2.5. Cross-Border Coordination Mechanism: Smart Ports and Factor Flow Facilitation

As a special node for cross-border mutual benefit, the integrated governance of the Mohan-Boten Economic Cooperation Zone necessarily extends across the border. The fifth mechanism focuses on using DI technology to build a cross-border yet highly coordinated digital bridge, giving the Four Zones Synergy genuine international dimensions.

First, building a Smart Port Integrated Platform for "Single Window" cross-border extension. China and Laos collaborate to adapt China's international trade "Single Window" modules to Lao regulations, deploying corresponding digital customs declaration and digital quarantine modules on the Boten side. Through bilaterally recognized electronic signatures and blockchain certification, enterprises can file a single declaration from their Kunming FTZ office, with information automatically translated and distributed to both countries' customs and inspection/quarantine systems, both receiving standardized electronic declaration data and feedback results almost simultaneously. This prototype "bilateral single window" significantly reduces redundant data entry and manual translation costs.

Second, promoting the "China-Laos Railway Single Waybill" and digital bills of lading. Traditional cross-border rail transport involves multiple carriers, and the paper waybill's ambiguous property rights hinder its use for trade finance. DI technology enables the issuance of digital bills of lading. When a freight forwarder consolidates cargo in the CBZ, a blockchain-based digital bill of lading is generated. This bill is continuously updated along the China-Laos railway journey by IoT events at each node (departure from Kunming, exit at Mohan, entry at Boten, arrival in Vientiane), synchronized with banks, insurers, and consignees. The consignee uses a key to retrieve the digital bill of lading for delivery, while banks provide pledge financing for SMEs based on the trusted full-process logistics records. This essentially extends the logistics integration of the Four Zones Synergy to supply chain finance integration.

Third, establishing facilitation channels for cross-border talent and data. For overseas technical talents and laborers needed by enterprises in the four zones, a "Digital Identity Code" integration scheme is introduced. Foreign nationals from neighboring countries like Myanmar, Laos, and Vietnam entering China through the Mohan port to work within the four zones can pre-submit qualification reviews online, receiving an encrypted QR code containing biometric information. Within the four zones, whether checking into apartments, applying for bank cards, or entering factory premises, this code is uniformly scanned to verify identity and permit validity, completely eliminating repeated procedures for temporary residence permits. For commercial data flows such as R&D data and design blueprints, a "Cross-Border Data Green Channel" is established, employing a "whitelist + ex-post supervision" model, replacing item-by-item manual review with data traffic monitoring for pre-assessed low-risk data flows.

In summary, the five mechanisms are logically rigorous and progressively hierarchical: data integration is the foundation, reshaping the information conditions of governance; process reengineering and intelligent supervision are efficiency revolutions targeting the two major governmental functions of service and regulation; decision-making optimization equips strategic-level coordination with scientific tools; and cross-border coordination radiates internal integration achievements outward, forming a complete empowerment closed loop.

4. Conclusion

This paper focuses on the "Four Zones Synergy" as a highly representative scenario for collaborative governance of composite functional zones, systematically studying the mechanisms through which DI technology empowers integrated governance. The main conclusions are as follows:

First, DI technology provides a viable pathway to resolve the paradox of integrated governance in special functional zones. The fundamental contradiction faced by the "Four Zones Synergy" lies in the conflict between the free flow of factors required for development and the rigidity of territorial management and policy differentiation. DI technology, by constructing a unified data foundation and a digital identity system, creates a logically unified digital governance space without fundamentally altering administrative divisions, enabling seamless cross-zone operations.

Second, DI empowerment of integrated governance forms a five-in-one mechanism system: "data integration – process reengineering – intelligent supervision – decision-making optimization – cross-border coordination." These five mechanisms function respectively at the levels of information connection, service provision, risk control, strategic planning, and international cooperation, mutually supporting each other, with none dispensable. Notably, the data integration mechanism plays a foundational role, with subsequent mechanisms all depending on high-quality, real-time, full-domain data supply.

Third, practical evidence indicates that the above mechanisms significantly enhance governance efficiency. Relevant pilots in Kunming's four zones show notable improvements in key indicators such as cross-zone processing time, customs clearance time, regulatory anomaly detection rate, and industrial policy precision. This demonstrates that DI technology is

not merely a decorative tool but a factor of production generating tangible governance dividends.

Fourth, the DI empowerment process is also a process of institutional reshaping. Cases like the "Policy Calculator" forcing policy integration, data sharing forcing clarification of rights and responsibility lists, and intelligent supervision forcing uniformity of enforcement standards highlight the feature of two-way co-constitution between technology and institutions. Successful DI-empowered integrated governance inevitably involves the simultaneous advancement of technical solutions and organizational transformation.

5. Discussion and Limitations

5.1. Research Contributions and Social Value

The social value of this paper is mainly reflected in three dimensions. In terms of theoretical value, it breaks through the traditional research paradigm focused on digital transformation of single functional zones, taking the synergy of multiple heterogeneous functional zones as a holistic analytical object, constructing a systematic empowerment mechanism framework, and enriching the intersection of regional collaborative governance and digital government research. In particular, it offers cautious exploration of DI applications in the sensitive field of cross-border cooperation zones involving sovereign concessions, providing an analytical benchmark for subsequent research.

In terms of practical value, Kunming's "Four Zones Synergy" is the only national testing ground integrating an FTZ, ETDZ, CBZ, and cross-border economic cooperation zone. This paper deeply portrays its integrated governance pain points and offers practically tested digital solutions, possessing significant demonstration and replication value for other regions in China with multiple policy overlaps but struggling with integration challenges, such as border areas like Pingxiang in Guangxi and Horgos in Xinjiang. Specific practices proposed, such as "one-network service across four zones," "digital bills of lading," and "cross-border data sandbox," can be directly transformed into reform checklists.

In terms of strategic value, this paper actively responds to national requirements for border opening and building a radiation center for South and Southeast Asia. Efficient Four Zones Synergy empowered by DI can not only stabilize industrial chains and smooth major corridors but also help skillfully handle cooperation and friction in economic governance among sovereign states through technical means, exploring a new path for deepening China-ASEAN cooperation in the digital era.

5.2. Limitations

Due to space constraints and data availability, this research has the following limitations. First, case singularity and early-stage limitations. The research is mainly based on the practice of Kunming's four zones; despite its typicality, different regional endowments and institutional environments vary widely, so the external validity of the conclusions requires verification through broader cross-case comparisons. Moreover, many digitalization projects of the "Four Zones Synergy" are still under construction or in early application stages; long-term performance and potential risks (such as large-scale technical system failures or data leaks in extreme scenarios) have not yet been fully exposed. Current evidence mostly consists of short-term efficiency improvement data, lacking long-term structural effect evaluations.

Second, insufficient exploration of the deep tensions in technology-institution co-constitution. Although this paper observes technology forcing institutional optimization, it does not deeply analyze potential risks of digital governance, such as excessive power concentration, the digital Leviathan risk, or the ethical concerns and resistance behaviors of frontline staff under algorithmic surveillance. Nor does it finely dissect the interest struggles and compromise processes among the four zone management departments when facing data interface unification. This may lead to an overly optimistic and smooth description of the empowerment picture.

Third, quantitative evidence and causal identification need strengthening. Constrained by commercial confidentiality and government data secrecy, the governance effect evidence used in this paper mostly comprises macro-statistics from management data or typical case lists. It has not yet applied quasi-experimental methods like difference-in-differences to precisely isolate the "net effect of DI technology." Micro-level enterprise experiences and sense of gain (e.g., whether SMEs genuinely benefit from digital financial dividends) also need to be supplemented through large-scale questionnaires and in-depth interviews to enrich the argument with more grounded evidence.

Fourth, the depth of the cross-border governance section is limited. The deep governance of the Mohan-Boten ECoZ involves the laws, political will, and technical capacity of Laos. This paper mainly deduces and describes from the perspective of China's reforms, with less detailed treatment of the difficulties in system alignment with Laos and the resolution of digital sovereignty sensitivities due to data access constraints. This reduces the dimensionality of the cross-border coordination mechanism analysis within the framework.

Future research could focus on the above limitations, conduct ongoing follow-up investigations, and introduce theories such as socio-technical systems theory and actor-network theory for deeper, thick-description qualitative studies of the entire digital transformation process of the Four Zones Synergy. Simultaneously, it could attempt to construct more rigorous evaluation models to further refine the theoretical system of DI-empowered integrated governance of complex functional zones.

Abbreviations

DI	Digital and Intelligent

FTZ	Free Trade Zone
ETDZ	Economic and Technological Development Zone
CBZ	Comprehensive Bonded Zone
Mohan-Boten ECoZ	China-Laos Mohan-Boten Economic Cooperation Zone

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The data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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