TRANSFORMING TRANSFER OF DEVELOPMENT RIGHTS (TDR) INTO DIGITAL ASSETS: BLOCKCHAIN, SMART CONTRACTS, PROPERTY TITLES, AND THE REIMAGINED DIGITAL LAND BANK (DLB)

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Christodoulou Dimitrios
Ph.D candidate, Department of Planning and Regional Development, School of Engineering, Universityof Thessaly, Greece
dimischris@gmail.com

Abstract
Transfer of Development Rights (TDR) is a complex institutional mechanism relying on trust and transparency to generate demand for building coefficients. Within this framework, the Digital Land Bank (DLB) emerges as a mechanism for recording and managing development rights, functioning as a specialized cadastre for TDR titles and related property rights. This research explores the transformation of TDR titles into digital, tradeable assets through blockchain technology and Smart Contracts. The central research question investigates whether blockchain can act as a property institution comparable to legal mechanisms. Through a systematic review of literature and international practices, we propose a lifecycle model for TDR titles encompassing creation, transfer, and utilization within a blockchain-based DLB.

Key words: *Transfer of Development Rights (TDR), Blockchain, Smart Contracts, Digital Land Bank (DLB), Tokenization, Property Rights, Urban Development*

1. INTRODUCTION

Property titles represent the essential institutional foundation for individual wealth and national economic growth. According to (De Soto, 2000), formalizing property rights turns land ownership from “dead capital” into productive leverage for credit, investment, and entrepreneurship. However, urban planning plays a contradictory role in this process. While it unquestionably increases land value through zoning and organized infrastructure (Brueckner, 2011), it also imposes regulatory restrictions—such as environmental protection—that limit development potential (Fischel, 2001). This conflict creates a regulatory paradox where planning acts simultaneously as a value-enhancer and a value-restrictor (Webster & Lai, 2003).

To reconcile these competing interests, the Transfer of Development Rights (TDR) has emerged as a robust market-oriented policy instrument. By permitting owners of restricted parcels to sell unused building capacity to developers in designated “receiving areas,” TDR compensates the former while facilitating managed density (Pruetz & Standridge, 2009). Theoretically, TDR unbundles the right to develop from the right to own, creating a floating entitlement that circulates independently of the soil (Machemer & Kaplowitz, 2002; Renard, 2007). Yet, efficacy depends on institutional rigor. Successful implementation demands transparent legal frameworks and the administrative capacity to validate transactions (Kaplowitz et al., 2008). Without such clarity, TDR markets often underperform or stall (Linkous, 2016).

In Greece, this mechanism is institutionalized as the Transfer of Building Coefficient (Metafora Syntelesti Domisis, MSD). Law 4759/2020 introduced the Digital Land Bank (DLB), an electronic platform designed to register and trade these floating coefficients. Functioning as a specialized digital cadastre for development rights, the DLB creates a financing channel for urban regeneration. For the first time, MSD transactions are executed electronically, signaling a paradigmatic shift toward digital spatial governance (Christodoulou, 2023).

Despite this modernization, the DLB’s success relies on trust and verification. Distributed Ledger Technologies (DLT), specifically blockchain and Smart Contracts, offer a technical architecture capable of reinforcing these attributes through immutability. Recent scholarship explores blockchain’s utility in geospatial data (Chafiq et al., 2024), participatory planning (Melissas, 2022), and land registration (De Filippi, 2018; Öğüdücü et al., 2021). Unlike centralized cloud registries, which remain vulnerable to manipulation, blockchain offers systemic resilience. A preliminary review of the Scopus database confirms this trajectory: research on “blockchain and land registration” significantly outpaces inquiries into “cloud and land registration,” underscoring its recognition as a transformative technology.

This research operates on the premise that a TDR title functions as a property title. As argued in prior work (Christodoulou, 2023), the TDR certificate is a quasi-property right—a transferable, enforceable entitlement analogous to fee-simple ownership. However, a significant gap persists regarding the management of derivative rights. While blockchain frameworks have been modeled for traditional land titling, detached TDRs have received minimal attention. Existing studies are either purely theoretical (Patil, 2024; Allam & Jones, 2019) or lack empirical validation (Dwivedi et al., 2023). This oversight is critical: TDRs require tailored mechanisms to ensure transparency and enforceability—requirements that blockchain is theoretically optimized to meet.

This study synthesizes the evidence into a techno-institutional framework to operationalize the TDR lifecycle within a Digital Land Bank. The Central Research Question (CRQ) asks: "Can blockchain technology function as a property institution equivalent to traditional legal mechanisms, and how can it operationalize the complete lifecycle of TDR titles within a DLB framework?"

Since property rights are dynamic institutional formations created and extinguished through regulated processes, demonstrating equivalence requires evidence that a decentralized system can perform the full suite of constitutive acts: registration, transfer, subdivision, and enforcement. The study consequently evaluates blockchain’s capacity to govern the TDR lifecycle, assessing both technical feasibility and institutional adequacy.

Situating the DLB within debates on computational institutions (Pagallo, 2017) and decentralized governance (Ishmaev, 2017; De Filippi & Wright, 2018), this research examines whether blockchain-based systems can satisfy essential property conditions—recognition, enforcement, and transferability—without a central authority. This positions blockchain as an institutional architecture capable of embedding normative rules directly into code. The analysis shifts from isolated technical efficiencies to whether decentralized systems can reproduce functions traditionally monopolized by legal regimes.

The objective is to formalize structural components of a computational architecture that resolves challenges of institutional completeness and transparency. These components support a blockchain-based DLB capable of efficiently financing urban development. Key elements include deploying Smart Contracts to automate processes like title transfers (Mik, 2017; Rizzo, 2020), and tokenizing TDR titles to transform them into tradable digital assets (Hassan & De Filippi, 2021; Paech, 2020).

To operationalize this inquiry, the research focuses on the DLB as a blockchain-native platform for end-to-end TDR lifecycle management. This encompasses every phase: from tokenized issuance to verification, transfer, and retirement. The DLB integrates technical subsystems—including tokenization standards (e.g., ERC-721 / ERC-1155) and decentralized storage (IPFS)—to define the digital existence of the TDR title. Methodologically, the study utilizes a systematic literature review guided by the PICOS framework, synthesizing contributions from the Scopus database to construct a lifecycle model against which blockchain's institutional affordances are evaluated.

The paper structure follows: Section 2 establishes TDR legal equivalence; Section 3 reviews blockchain as an institutional technology; Section 4 details the SLR protocol; Sections 5–7 synthesize the architectural model; and Section 8 concludes with implications.

2. THEORETICAL AND INSTITUTIONAL FRAMEWORK: PROPERTY RIGHTS AND TDR EQUIVALENCE

2.1. Conceptual Foundations of Property Rights

Property rights constitute a cornerstone of market economies. From an institutional perspective, well-defined rights enable individuals to internalize investment benefits and support credit systems (De Soto, 2000). Legally, real rights are enforceable against third parties, granting exclusive power to use or transfer ownership objects. The distinction between absolute ownership and derivative real rights underpins property law, balancing private autonomy with collective objectives (Fischel, 2001).

In urban planning, these intersect with public regulation: zoning and conservation shape permissible uses while preserving public goods (Brueckner, 2011). Such interventions modify underlying real rights. Property rights are contextually contingent, reflecting negotiations between individual entitlements and societal priorities (Webster & Lai, 2003). Within this space, TDRs redistribute development potential while preserving ownership integrity.

2.2. The Legal and Institutional Nature of TDR Titles

Transferable Development Rights (TDR) function as a radical institutional severance, effectively unbundling the "right to develop" from the "right to own" the underlying soil. As (Hou, Chan, and Li, 2018) argue, TDRs are not merely administrative permits but distinct, tradeable entitlements—quasi-property rights that can be inherited, exchanged, and collateralized. While they convey no physical possession, they establish legally enforceable interests. This separation provides planning authorities with a fiscal escape valve: they can pursue regulatory objectives—such as heritage preservation—and compensate affected owners through market mechanisms rather than direct public expenditure (Renard, 2007).

In the Greek regulatory landscape, this mechanism is codified as the Transfer of Building Coefficient (Metafora Syntelesti Domisis – MSD). This instrument allows owners of constrained properties to mobilize unexploited building density, transferring it to parcels located within designated receiving zones. (Makris, 1998) posits that the right embedded in an MSD certificate constitutes a genuine real right (Greek: 'empragmatiko dikaioma'), i.e., a right enforceable erga omnes and registrable in the relevant public records. This distinction is vital. It situates TDR squarely within the domain of property law rather than administrative discretion, endowing the certificate with the substantive attributes of ownership: exclusivity, transferability, durability, and enforceability.

2.3. Trust and Institutional Credibility

Trust acts as a necessary precondition for market functionality. As demonstrated in (Christodoulou, 2023), the historical trajectory of TDR schemes in Greece reveals that failure often stems less from defective legal formulation than from a deficit in the credibility of administering institutions. Viewed through the lens of institutional economics, trust serves primarily to reduce transaction costs by eliminating the need for constant, costly verification (North, 1990; Micelli, 2002).

When property transactions occur within transparent, auditable architectures, risk perception drops; liquidity rises. Conversely, opacity and administrative friction generate institutional uncertainty, which directly erodes the value of the TDR certificate. International empirics corroborate this dynamic: TDR markets sustain volume only where regulatory clarity and administrative capacity are unimpeachable (Pruetz & Standridge, 2009; Linkous, 2016). Consequently, enhancing institutional trustworthiness is not an optional upgrade—it is a structural prerequisite for transforming a dormant regulatory instrument into a functional market.

2.4. The DLB: Transitioning from Analog to Digital

Yet, despite introducing digital efficiency, the DLB remains a "Web 2.0" solution tethered to centralized data management. Centralized databases contain inherent vulnerabilities—single points of failure, susceptibility to bureaucratic opacity, and the potential for data manipulation. The current DLB thus represents a transitional institutional form. To fully operationalize TDRs as liquid assets, the underlying infrastructure must evolve: shifting from reliance on administrative promises of trust to systems guaranteeing technological certainty.

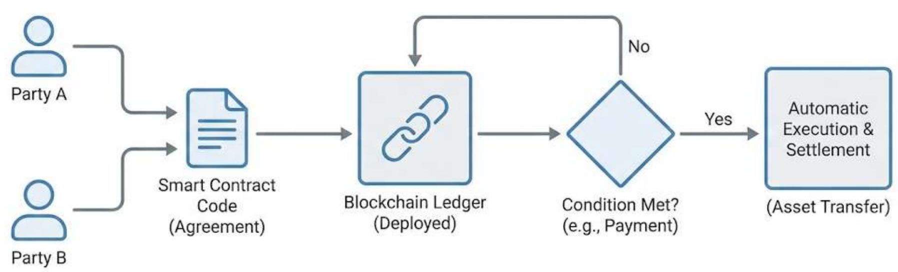
3. TECHNOLOGICAL FRAMEWORK: BLOCKCHAIN AND DECENTRALIZED GOVERNANCE

3.1. Blockchain Technology and Smart Contracts

Blockchain-based ledgers can reallocate trust from centralized record-keepers to cryptographic verification and distributed consensus mechanisms, subject to governance and oracle design choices. As a subset of DLT, blockchain operates as a decentralized, immutable registry where transactions are not filed centrally but "mined" into blocks, cryptographically chained to their predecessors (Nakamoto, 2008). This architecture ensures that data, once entered, remains resistant to retroactive alteration without network consensus. Consequently, it creates a "trustless" environment where confidence is vested in cryptographic proofs rather than fallible human intermediaries (De Filippi & Wright, 2018).

The operational capacity of this infrastructure expands significantly with the "Smart Contract"—self-executing scripts deployed on platforms like Ethereum. These protocols automatically enforce agreement terms once pre-conditions are satisfied (Szabo, 1997), as illustrated in Figure 1.

Figure 1: Conceptual workflow of a Smart Contract executed on a Blockchain ledger (Source: Author).



In the specific domain of property rights, smart contracts can govern the entire asset lifecycle—minting titles, executing transfers upon payment receipt, and extinguishing rights upon utilization—bypassing the manual verification steps traditionally performed by notaries or legal clerks (Mik, 2017).

3.2. Applications in Land Administration and Case Studies

Transitioning from theoretical abstraction to administrative praxis, blockchain pilots in land registries have proliferated, driven by the imperative to eliminate fraud, reduce transaction friction, and enhance transparency.

- **Sweden:** The Swedish mapping authority, Lantmäteriet, pioneered a multi-phase pilot (2016-2019) focused on transactional velocity. Leveraging a private blockchain, the project demonstrated a reduction in the contract-to-registration interval from months to mere hours. It successfully modeled a digital workflow where signatures trigger irrevocable ledger updates across banks, buyers, sellers, and the land registry (Kempe, 2016; Lantmäteriet, 2018).
- **Republic of Georgia:** In contrast, Georgia adopted a hybrid verification model in 2016. The National Agency of Public Registry partnered with Bitfury to anchor the cryptographic "hash" of every land title to the public Bitcoin blockchain while retaining a centralized primary registry. This architecture allows citizens to independently verify title authenticity, reinforcing public trust in the security of property rights (Shang & Price, 2019).
- **Ghana:** In contexts characterized by weak formal institutions, initiatives like Bitland have utilized blockchain to formalize extra-legal settlements. Here, immutable ledgers record GPS coordinates and land claims to substantiate ownership where state cadastres are either absent or compromised (Kritikos, 2018).

Collectively, these cases suggest that the primary bottleneck is no longer technical feasibility but legal integration—specifically, the statutory recognition of digital signatures and smart contracts as valid instruments for the transfer of in rem rights (Bennett et al., 2019).

3.3. Blockchain as a Property Institution

Framing blockchain as a property institution rather than a mere database represents a substantive shift in analytical framing. Historically, property institutions have derived their legitimacy exclusively from centralized state authorities (Deininger & Feder, 2009). Blockchain challenges this monopoly. It provides a decentralized infrastructure that satisfies three constitutive functions of a property system: rights representation (tokenization), ownership verification (consensus), and entitlement transfer (smart contracts).

(Ishmaev, 2017) argues that by providing universally accessible, tamper-resistant records, blockchain satisfies the formal criteria of a property institution. (De Filippi, 2018) characterizes this emergence as "computational property systems," architectures capable of automating the creation and division of rights. When applied to TDRs, the technology does more than record an asset; it instantiates the right as a digital token—unique, tradeable, and resistant to double-spending—thereby creating functional equivalence between the legal certificate and the digital token.

4. RESEARCH METHODOLOGY: ANALYTICAL FRAMEWORK AND PROTOCOL

To interrogate the intersection of blockchain technology and land administration, this study employs a Systematic Literature Review (SLR) methodology, adhering to the guidelines established by (Kitchenham et al., 2009). The review process began with the precise formulation of research questions to strictly delimit the scope of inquiry. A structured search strategy was subsequently executed, primarily leveraging Scopus due to its extensive multidisciplinary coverage—encompassing both the technical and legal-institutional dimensions of land administration. Complementary searches and snowballing techniques were employed to capture relevant grey literature and seminal works outside the primary index.

Following initial retrieval, duplicate entries were purged. Predefined inclusion and exclusion criteria were then applied sequentially to titles, abstracts, and finally, full texts to ensure relevance. Backward and forward snowballing further refined the corpus. This systematic filtering resulted in a final selection of 40 primary studies, distilled from an initial pool of 134 papers. To mitigate the selection bias inherent in single-author research, the selection process was conducted by the author through strict, iterative adherence to the established protocol.

4.1. Research Scope and Definition (PICOS Framework)

To ensure systematic, unbiased literature selection relevant to operationalizing Transferable Development Rights (TDRs) within a DLB, this study employs the PICOS framework, delineating search boundaries and eligibility criteria.

- **Population (P):** Land Administration Systems, Property Rights regimes, and TDR markets, specifically fragmented or paper-based registries managing heterogeneous property rights.
- **Intervention (I):** Blockchain Technology (DLT), Smart Contracts, Tokenization (ERC standards), and Decentralized Identity (DID) applied to land governance and the DLB concept.
- **Comparison (C):** Traditional Land Registries, conventional cadastre systems, and paper-based legal mechanisms for transferring development rights.
- **Outcome (O):** Institutional Equivalence (security, legitimacy), Lifecycle Operationalization (minting to transfer), Market Liquidity, Interoperability, and Technical Scalability.
- **Context (S):** Global Context, focusing on architectural frameworks, pilot implementations (e.g., Ghana, Sweden, Dubai), and theoretical models of crypto-spatial governance.

4.2. Hierarchical Research Questions

The study is guided by the CRQ, addressing both institutional legitimacy and technical execution of blockchain in land administration, deconstructed into four subservient questions.

SRQ 1 (Asset Definition): How can blockchain technology and smart contracts transform heterogeneous property rights, such as TDRs and air rights, into fungible digital assets, enabling unified lifecycle management within modern land administration frameworks?

SRQ 2 (System Architecture): What is the conceptual and architectural framework for a blockchain-based DLB managing the entire lifecycle of TDR titles as tokenized real property assets, ensuring interoperability with traditional cadastre or land registry?

SRQ 3 (Barriers & Transition): What are the primary institutional, legal, and technical challenges and opportunities in transitioning from traditional, fragmented land registries to unified blockchain-based systems managing both conventional property titles and specialized development rights like TDRs?

SRQ 4 (Market Impact): To what extent does tokenization of building rights and TDRs on blockchain platforms enhance market liquidity, transparency, and security compared to conventional, paper-based mechanisms?

4.3. Data Extraction and Synthesis: The 10 Critical Analytical Axes

To operationalize lifecycle analysis and bridge the gap between abstract literature and Research Questions, ten critical analytical axes were identified through iterative scanning of contemporary blockchain–land administration literature. Each axis corresponds to a core institutional function of property systems, serving as targeted search directions during screening and technical indicators during synthesis.

Phase I: Creation and Identity (Addressing RQ1 & RQ3)

1. **Initial Registration (Genesis/On-chain Minting):** Examines mechanisms for first registration of rights, including oracles, off-chain document anchoring, survey verification, and IPFS hashing, directly informing RQ1 (standardizing heterogeneous rights) and RQ2 (creating authoritative lifecycle entries).
2. **Identity Management (DID, SSI, Verifiable Credentials):** Decentralized identity infrastructure essential for replacing or complementing state verification. Evidence here is crucial for RQ3, revealing if systems can support legitimate, non-repudiable actors.
3. **Token Standards and Metadata Structures:** Token architecture (ERC-721, ERC-1155, dynamic NFTs, metadata schemas) reveals digital representation of property rights, strongly supporting RQ1 and RQ4, as fungibility, composability, and updatability directly affect TDR liquidity and functional behavior.

Phase II: Transaction and Management (Addressing RQ2 & RQ4)

4. **Smart-Contract Transfer Logic:** Identifies models for escrow-less transfers, atomic swaps, timelocks, and verifiable off-chain data, constituting direct evidence for RQ2 and RQ4, determining whether blockchain transfers increase transparency, efficiency, and automation.
5. **Management of Encumbrances:** Examines how blockchains encode burdens, fractional shares, or liens through token binding or nested smart contracts, central to RQ3, assessing if blockchain can replicate complex legal structures beyond simple ownership.
6. **Error Correction and Governance Models:** Analyzes proxies, multi-sig governance, DAO-based validation, and court-ordered oracles, testing whether blockchain can support institutional functions of adjudication and dispute resolution, addressing the Central RQ's core.

Phase III: Systemic Integration and Feasibility (Addressing RQ2 & RQ3)

7. **Interoperability and Legal Integration:** Studies cross-chain messaging, mirrored registries, and legal wrappers for recognizing on-chain titles, directly relevant to RQ2 (cadastre interoperability) and RQ3 (legal constraints).
8. **Cost, Scalability, and Technical Sustainability:** Informs whether blockchain-based land systems can operate at national scale through literature on Layer-2 solutions, gas optimization, and state channels, answering RQ3 (technical constraints) and RQ4 (market efficiency).

Phase IV: Synthesis (Addressing Central RQ)

9. **Case Studies and Implemented Pilots:** Empirical evidence is integrated throughout the thematic analysis (Section 5) to validate theoretical frameworks against real-world implementations in jurisdictions such as Georgia, Sweden, and Ghana.
10. **Gap Analysis Across Studies:** This axis drives the Synthesis (Section 6) and Discussion (Section 7), identifying missing institutional functions to determine whether the current literature supports a complete DLB lifecycle.

4.4. Search Strategy and Protocol

This systematic literature review was conducted following PRISMA guidelines. The protocol minimized selection bias and ensured comprehensive retrieval of studies pertaining to the DLB lifecycle.

4.4.1. Database Selection and Search Strategy

Scopus was selected as the primary source due to extensive interdisciplinary coverage at the intersection of computer science, urban planning, and law. A stratified, two-tiered search strategy was employed: **Tier 1** focused on technological convergence of DLT and TDRs, addressing RQ1; **Tier 2** expanded to broader Land Administration literature, addressing RQ2 and RQ3.

4.4.2. Search String Formulation

An iterative keyword identification process optimized retrieval. The final search string utilized Boolean operators intersecting three core conceptual clusters: (1) Property/Development Rights, (2) DLT/Blockchain Technologies, and (3) Land Administration Domains, executed within "Title, Abstract, and Keywords" fields.

The search was executed within the "Title, Abstract, and Keywords" (TITLE-ABS-KEY) fields using the following syntax:

Search String:("property right*" OR "land right*" OR "real property" OR "property title*" OR "transferable development right*" OR "TDR" OR "air right*" OR "transfer of building coefficient*" OR "building right*" OR "floor area ratio" OR "FAR" OR "floor-to-area ratio") AND ("blockchain" OR "smart contract*" OR "tokenization" OR "DLT") AND ("land administration" OR "land registry" OR "cadastre" OR "land management" OR "real estate")

4.4.3. Eligibility Criteria

To ensure the methodological rigor and relevance of the review, a set of Inclusion Criteria (IC) and Exclusion Criteria (EC) was defined.

The temporal scope was restricted to 2015–2025. The start year of 2015 was selected to coincide with the emergence of second-generation blockchains (e.g., Ethereum), which introduced the smart contract capabilities essential for managing complex rights such as TDRs.

Table 1: Inclusion and Exclusion Criteria

Criterion Type	Description
Inclusion Criteria (IC)	• **Topic:** Studies explicitly examining blockchain/DLT applications in land administration, cadastral systems, or property rights management. • **Timeline:** Published between January 1, 2015, and September, 2025. • **Language:** Full text available in English. • **Source:** Peer-reviewed journal articles and conference proceedings.
Exclusion Criteria (EC)	• Type: Secondary studies (SLRs, meta-analyses), book chapters, and grey literature (tutorials, workshops, keynotes, panels, corrigenda). • Relevance: Studies addressing blockchain in supply chains or finance without a direct link to land/property rights. • Availability: Studies where the full text was inaccessible. • Redundancy: Duplicate records.

4.4.4. Selection Process

The selection process followed a multi-stage workflow:

1. **Identification:** Records were retrieved from Scopus using the defined search string.
2. **Deduplication:** Duplicate entries were identified and removed.

3. **Screening:** Titles and abstracts were screened against the exclusion criteria. Articles clearly falling outside the scope (e.g., cryptocurrency speculation) were rejected.
4. **Eligibility:** The remaining articles underwent a full-text review to verify compliance with the inclusion criteria, specifically regarding technical relevance to the DLB framework.

4.4.5. Methodological Limitations

While the search string underwent iterative refinement, the study remains subject to specific methodological constraints. First, the exclusive reliance on Scopus as the primary bibliographic reservoir inevitably creates a blind spot for relevant scholarship indexed solely in alternative repositories. Similarly, the specific taxonomy of selected keywords imposes lexical boundaries; studies employing adjacent nomenclatures—such as "urban land finance" or "development entitlements" rather than strict TDR terminology—may have evaded retrieval. A risk of semantic filtering bias also persists. By mandating the intersection of legal constructs and technical descriptors, the protocol may have inadvertently filtered out interdisciplinary contributions that emphasize one dimension while leaving the other implicit.

A structural caveat also warrants mention: as a single-author inquiry, this study lacks the inter-rater reliability checks standard in multi-researcher teams. To counterbalance potential selection bias, the research protocol was not merely applied but executed iteratively—incorporating a secondary re-evaluation of selected studies to ensure rigorous consistency. Finally, the deliberate prioritization of land administration domains may have limited the identification of hybrid models that bridge physical land governance with nascent digital property paradigms—experimental architectures that, while peripheral here, could inform the future trajectory of blockchain-based property systems.

5. THEMATIC ANALYSIS OF ARCHITECTURAL FRAMEWORKS

The following analysis is structured according to the first eight analytical axes defined in the methodology, mapping the TDR lifecycle from registration to scalability. Axis 9 (Case Studies) is woven into these sections to provide empirical context, while Axis 10 (Gap Analysis) forms the basis of the subsequent Synthesis and Discussion sections.

The table below summarizes the studies retained in the final stage of the systematic literature review.

Table 2 : studies selected in the final stage

Citation	Thematic Cluster	Research Methodology	Key Contribution	Technology Used
Mohanty et al., 2025	Technical Frameworks	Prototype Implementation / Comparative Analysis	Proposes a new transaction governance framework with a 13% improved block generation time.	Blockchain, pBFT, Smart Contracts
Ullah & Al-Turjman, 2023	Land Administration & Cadastre	Systematic Literature Review & Conceptual Framework	Proposes a 6-layer conceptual framework for adopting smart contracts in smart cities.	Ethereum (EVM)
Kshetri, 2022	Land Administration & Cadastre	Case Study (Andhra Pradesh, India)	Analyzes how blockchain enhances property rights protection in the Global South.	Blockchain (Land Registry)
Singh et al., 2024	Technical Frameworks	Conceptual Framework / Architecture Design	Proposes a 3-tier architecture (Government, Citizens, Banks) for the Indian land registry.	Ethereum, IPFS
Abualhamayl et al., 2024	Technical Frameworks	Prototype Implementation (GREP)	Presents the hybrid "Global Real Estate Platform" for data authenticity and access management.	Hybrid Blockchain
Kasprzak, 2021	Real Estate Tokenization	Conceptual Framework	Examines the role of retail banks as "Oracles" in the real estate tokenization process.	Blockchain, Stablecoins

Khadanga & Jain, 2021	Land Administration & Cadastre	Conceptual Framework / Blueprint	Proposes a blueprint for land registry management in India to resolve disputes.	Hyperledger
Mihna et al., 2025	Metaverse & Virtual Land	Quantitative Analysis (Machine Learning)	Uses ML algorithms (Random Forest) to classify digital contracts (Ownership vs. Lease).	NFTs, Decentraland, Sandbox
Avantaggiato & Gallo, 2019	Technical Frameworks	Prototype Implementation (REchain)	Proposes the REchain platform for direct real estate transactions without intermediaries.	MultiChain
Konashevych, 2020	Legal & Regulatory	Qualitative / Legal & Policy Analysis	Analyzes the technical and legal constraints of DLTs for public registries.	DLT (Permissioned vs Public)
Jebril et al., 2024	Land Administration & Cadastre	Theoretical Analysis	Investigates the impact of blockchain on risk management and sustainability in estate governance.	Blockchain
Konashevych, 2021	Land Administration & Cadastre	Case Study (Afghanistan)	Critical analysis of the LTO Network implementation in Afghanistan's land registry.	LTO Network
Bennett et al., 2021	Land Administration & Cadastre	Comparative Analysis (Case Studies)	Proposes a hybrid approach combining smart contracts with existing land registry roles.	Blockchain, ChromaWay
Tahar et al., 2023	Technical Frameworks	Prototype Implementation	Implements a multisignature system for transparency in land transfer transactions.	Hyperledger Iroha
Podshivalov, 2022	Legal & Regulatory	Legal Modeling & Economic Analysis	Proposes legal measures and the use of Virtual Reality (VR) for real estate registration.	Blockchain, VR/AR
Verma et al., 2024	Land Administration & Cadastre	Review / Conceptual	Assesses blockchain for security and transparency in land transactions.	Ethereum, Smart Contracts
Akhmetbek & Špaček, 2021	Land Administration & Cadastre	Case Study (Kazakhstan)	Identifies legislative gaps and technical complexity as barriers to real estate registration.	Blockchain
Paavo et al., 2025	Land Administration & Cadastre	Design Science / Prototype	Presents a roadmap and system prototype for land registration in Sub-Saharan Africa (Namibia).	MetaMask (Ethereum-based)
Habib et al., 2025	Land Administration & Cadastre	Conceptual Framework	Proposes a framework for cadastral systems in conflict-impacted communities.	Blockchain
Shahaab et al., 2023	Land Administration & Cadastre	Action Design Science / Proof of Concept	Develops a POC for Companies House (UK) to check beneficial owners of overseas entities.	Blockchain
Mottaghi et al., 2024	Real Estate Tokenization	Literature Review & Qualitative Analysis	Analyzes the current state and future of tokenization and fractional ownership.	Blockchain, IoT, AI
Ferreira, 2021	Legal & Regulatory	Legal Analysis	Argues that smart contracts require legal evolution rather than revolution.	Smart Contracts
Subbarayudu & Hemalatha, 2024	Technical Frameworks	Conceptual / Algorithm Proposal	Proposes the "Modified Proof of Authorization" (M-PoA) consensus mechanism for security.	Blockchain, PoA
Siriphen et al., 2024	Real Estate Tokenization	Sentiment Analysis (Social Media)	Analyzes public sentiment regarding digital real estate token investments post-pandemic.	Digital Tokens
Arora & Sarkar, 2023	Land Administration & Cadastre	Auto-ethnography / Critical Analysis	Critiques the "tech hype" surrounding land management in India.	Blockchain (as hype)
Garcia-Teruel & Simón-Moreno, 2021	Legal & Regulatory	Comparative Legal Analysis	Proposes a tokenization model for usufruct rights, comparing 6 jurisdictions.	Asset-backed tokens
Manahov & Li, 2025	Real Estate Tokenization	Quantitative (Volatility Spillover Test)	Examines the effect of hacker attacks on real estate token volatility (e.g., Propy).	Ethereum, Real Estate Tokens
van Erp & Zimmermann, 2022	Legal & Regulatory	Legal / Conceptual Analysis	Examines the digitalization of the EU Succession Certificate via blockchain and e-wallets.	Blockchain, E-wallets
Allam & Jones, 2019	Land Administration & Cadastre	Conceptual Model	Proposes a model for trading "air rights" to curb urban sprawl.	Smart Contracts

Zhang et al., 2024	Technical Frameworks	Prototype / System Design	Time-stamping and registration system for authenticating informal real estate transactions.	Ethereum
Zhang et al., 2025	Real Estate Tokenization	System Design / Conceptual	Tokenized investment platform designed to lower market entry barriers.	Ethereum, Smart Contracts
Daniel & Ifejika Speranza, 2020	Land Administration & Cadastre	Conceptual / Case Discussion	Discusses blockchain for documenting land use rights in the informal rental market.	Blockchain
Baum, 2021	Real Estate Tokenization	Qualitative Analysis / Market Review	Examines mechanisms for creating secondary markets in tokenized assets.	Blockchain
Zhitomirskiy et al., 2023	Technical Frameworks	Prototype / Design Science	Proposes a new token design (ERC-20) for dividend distribution based on holding time.	Ethereum (ERC-20)
Creta & Tenca, 2021	Real Estate Tokenization	Qualitative (Multiple Case Studies)	Exploratory analysis of 12 crowdfunding platforms adopting tokenization.	Blockchain, Tokens
Abualhamayl et al., 2023	Real Estate Tokenization	Prototype Implementation (JOINFT)	Proposes the JOINFT system using fractional NFTs (F-NFTs) for joint ownership.	Fractional NFTs
Veuger, 2018	Land Administration & Cadastre	Interviews / Qualitative Analysis	Investigates the role of trust and disruption in the Dutch real estate market.	Blockchain
Mashatan et al., 2021	Technical Frameworks	Agent-based Modelling / Prototype	Solution to prevent double-ending fraud by real estate agents.	Hyperledger Fabric
Narowski et al., 2025	Metaverse & Virtual Land	Quantitative Analysis	Analyzes 207 Decentraland transactions to test conventional valuation methods.	Decentraland (MANA), NFTs
Leonhard et al., 2025	Metaverse & Virtual Land	Quantitative (Wavelet Coherence Analysis)	Examines the dynamic correlation of returns between virtual land and physical real estate.	Metaverse, Digital Assets

The systematic review of the selected 40 studies reveals seven critical dimensions—or axes—that constitute the architectural framework of a DLB. This analysis moves beyond a simple enumeration of technologies to examine how distinct technical choices address specific institutional and legal challenges.

5.1. Registration Mechanisms: The "First Mile" Problem

In an application such as the DLB, two fundamental challenges arise. The first concerns the certification and validation of the initial set of property titles introduced into the system. The second relates to the controlled admission of newly created titles, ensuring that any additional digital representations correspond to legally valid and verifiable real-world property rights.

The analysis of registration mechanisms therefore addresses the critical problem of reliable tokenization, namely the process of converting a physical or legal asset into its digital counterpart. This challenge is commonly referred to as the “First Mile Problem”, which highlights the difficulty of establishing a trustworthy linkage between off-chain legal reality and on-chain digital records. Given the immutability of distributed ledger technologies, the registration of inaccurate, incomplete, or unauthorized data leads to persistent and irreparable inconsistencies within the system, encapsulated in the dictum that erroneous input data invariably compromises system integrity (“garbage in, garbage out”). Consequently, the design of robust institutional and technical safeguards at the point of initial registration is essential for preserving the integrity and credibility of the DLB as a property governance infrastructure.

The review identifies five distinct approaches to mitigating this risk:

- **The State-Led Approach (Trusted Oracle):** Dominant in the literature, this model posits that blockchain cannot replace legal oversight. A central authority (government agency, notary, or certified inspector) acts as an "oracle" to validate physical ownership before minting the digital record (Mohanty et al., 2025; Abualhamayl et al., 2024; Tahar et al., 2023; Subbarayudu & Hemalatha, 2024; Mashatan et al., 2021; Zhang et al., 2025). The consensus is that technology supplements, rather than supplants, state validation.

- **The Corporate Wrapper Approach (SPV):** Primarily observed in investment contexts, this method utilizes Special Purpose Vehicles (SPVs). The blockchain records shares in the SPV rather than the property title itself, thereby bypassing the need to alter property laws (Baum, 2021; Zhitomirskiy et al., 2023).
- **The Hybrid Digitization Approach:** This strategy bridges legacy systems with DLT. Existing databases remain the primary repository, while cryptographic hashes of documents are stored on-chain to ensure integrity (Konashevych, 2021; Bennett et al., 2019; Zhang et al., 2024; Veuger, 2018).
- **The Virtual-Only Approach (Metaverse):** In virtual environments (e.g., Decentraland), the asset is native to the code. Registration is automatic upon deployment, eliminating the need for physical verification (Mihna et al., 2025; Narowski et al., 2025; Leonhard et al., 2025).
- **Innovative Technical Approaches:** Outlier studies propose novel mechanisms such as DNA encryption for maximum security (Verma et al., 2024) or bottom-up crowdsourcing tools (e.g., STDM) for documenting informal settlements (Daniel & Ifejika Speranza, 2020).

Conclusion: A significant portion of the literature remains theoretical, failing to define the "genesis block" mechanism. However, the prevailing evidence suggests that for physical real estate, no fully decentralized registration process is currently viable; a trusted third party remains essential.

5.2. Identity Management and Verification

Identity management in blockchain real estate systems presents a fundamental paradox: reconciling the native pseudonymity of DLT addresses with the strict identification requirements of land registries.

Five primary strategies were identified:

1. **Integration with National Identity Systems:** Studies from the EU and India advocate leveraging existing infrastructure. Examples include linking wallets to Aadhaar biometrics (Kshetri, 2022; Singh et al., 2024; Khadanga & Jain, 2021) or complying with eIDAS standards (Ferreira, 2021; van Erp & Zimmermann, 2022).
2. **Banking Sector Gatekeeping:** This approach offloads identity verification to financial institutions via KYC/AML protocols. Banks serve as "whitelisting" agents, approving wallet addresses for participation (Kasprzak, 2021; Mottaghi et al., 2024).
3. **On-Chain Identity (Soulbound Tokens):** A technically sophisticated solution involves issuing non-transferable NFTs (Soulbound Tokens) or "Identity Certificates" to a user's wallet. Smart contracts verify the presence of this token before permitting transactions (Verma et al., 2024; Zhitomirskiy et al., 2023).
4. **Web3 Native Anonymity:** Restricted largely to the Metaverse, this model treats the wallet key as the sole identity, disregarding physical legal personhood (Paavo et al., 2025; Narowski et al., 2025; Leonhard et al., 2025).
5. **Role-Based Access Control (RBAC):** Common in permissioned government blockchains, this method utilizes a central administrator to assign specific roles (e.g., Notary, Citizen) to network participants (Abualhamayl et al., 2024; Mashatan et al., 2021).

Implication: A trade-off exists between legal certainty and decentralization. While "whitelisting" preserves some privacy, integration with national ID systems appears inevitable for official land registries.

5.3. Token Architecture and Taxonomy

The choice of token standard is not arbitrary but is determined by the system's functional objective: Title Security versus Liquidity.

Table 3: Comparative Analysis of Token Architectures

Token Type	Standard	Primary Use Case	Representative Studies
Unique Title	NFT (ERC-721)	Property Transfer, Metaverse	(Mihna et al., 2025; Garcia-Teruel & Simón-Moreno, 2021; Narowski et al., 2025; Leonhard et al., 2025)
Investment Share	Fungible (ERC-20)	Crowdfunding, SPVs, Dividends	(Mottaghi et al., 2024; Zhang et al., 2025; Zhitomirskiy et al., 2023)
Hybrid	Fractional NFT (ERC-1155)	Co-ownership of specific assets	(Abualhamayl et al., 2023)
Proof Record	Hash / Struct	Public Administration, Record Integrity	(Khadanga & Jain, 2021; Konashevych, 2021; Paavo et al., 2025; Zhang et al., 2024)
Exotic	Time-Sensitive	TDRs, Air Rights	(Allam & Jones, 2019)

For urban planning, the distinction is vital: government registries prioritize record integrity (hashes), while financial platforms prioritize fractionalization (fungible tokens). Notably, "Time-Sensitive Tokens" (Allam & Jones, 2019) offer specific utility for Transferable Development Rights (TDRs), allowing rights to expire if not exercised, thus preventing speculation.

5.4. Transfer Logic and Automation

Transfer logic defines how smart contracts replace bureaucratic procedures. The literature demonstrates a progression from simple value transfers to complex process orchestration.

- **Atomic Exchange:** The simultaneous swap of title and funds within a single transaction block, eliminating counterparty risk ($msg.value == price \rightarrow transfer$) (Mohanty et al., 2025; Subbarayudu & Hemalatha, 2024; Zhang et al., 2024; Zhang et al., 2025).
- **Conditional Transfer:** The smart contract acts as a compliance gatekeeper, executing transfers only if specific criteria (e.g., whitelist status, no liens) are met (Paavo et al., 2025; Zhitomirskiy et al., 2023).
- **Workflows and Multi-Signature:** Reflecting the reality of multi-party consent, these systems require a quorum of digital signatures (e.g., buyer, seller, bank) to finalize a state change (Avantaggiato & Gallo, 2019; Bennett et al., 2021; Tahar et al., 2023).
- **Transparent Bidding:** Utilizing public ledgers to record bids prevents "double-ending fraud" by agents (Mashatan et al., 2021).
- **Inheritance Mechanisms:**"Dead Man's Switch" contracts automatically transfer titles to heirs upon prolonged inactivity or receipt of a digital death certificate (van Erp & Zimmermann, 2022).

Relevance to TDR: Conditional transfer logic is particularly applicable to TDRs. Smart contracts can verify development feasibility or hold funds in escrow until zoning approval is confirmed, automating the complex compliance checks required by municipal authorities.

5.5. Management of Liens and Encumbrances

A land registry unable to manage mortgages is economically obsolete. The review identifies four levels of maturity in handling encumbrances:

1. **Dynamic Indicator (Status Flag):** A passive metadata field (e.g., isMortgaged: True) that prevents transfer. This mimics traditional paper registries (Kshetri, 2022; Zhang et al., 2024; Zhang et al., 2025).
2. **Smart Pledge (Active Enforcement):** The asset is locked in a smart contract escrow. The system manages permissions and can technically facilitate liquidation or automatic discharge upon loan repayment (Bennett et al., 2021; Akhmetbek & Špaček, 2021; Subbarayudu & Hemalatha, 2024).
3. **Unbundling of Rights:** Tokenization allows for the separation of use rights, ownership rights, and air rights. This allows, for example, a farmer to collateralize a lease without owning the land (Allam & Jones, 2019; Daniel & Ifejika Speranza, 2020).
4. **Fractionalization as Financing:** Instead of traditional debt, owners sell equity tokens to investors, effectively replacing mortgages with crowd-financing (Mottaghi et al., 2024; Baum, 2021; Zhitomirskiy et al., 2023).

Conclusion: For national registries, a combination of Status Flags (for legal certainty) and Smart Pledge workflows (for automation) is the most viable path.

5.6. Governance and Legal Interoperability

The literature indicates a shift away from the "Code is Law" ethos toward "Regulatory Isomorphism"—adapting blockchain to fit existing legal frameworks.

Five strategies bridge the digital-legal divide:

1. **The Legal Wrapper:** Utilizing SPVs to lend legal substance to digital tokens (Baum, 2021; Zhitomirskiy et al., 2023).
2. **Standardization (ISO/LADM):** Aligning data models with ISO 19152 (Land Administration Domain Model) to ensure compatibility with state systems (Habib et al., 2025; van Erp & Zimmermann, 2022).
3. **The Archival Bond (GDPR Compliance):** Storing PII (Personally Identifiable Information) off-chain while keeping only hashes on-chain to satisfy the "Right to be Forgotten" (Shahaab et al., 2023; Mashatan et al., 2021).
4. **The Mirror Registry:** Establishing the state registry as the superior "source of truth," with the blockchain serving merely as a transparent secondary layer (Mohanty et al., 2025; Bennett et al., 2021).
5. **New Legislative Frameworks:** The emergence of specific laws, such as the Swiss DLT Act, that legally recognize ledger-based securities (Ferreira, 2021; Zhitomirskiy et al., 2023).

5.7. Cost, Scalability, and Technical Sustainability

The feasibility of national-scale deployment is ultimately predicated on a delicate balance: technical scalability versus economic viability. Public blockchains, such as the Ethereum Mainnet, often fail this test; they are plagued by volatile transaction fees ("gas fees") and network congestion, rendering routine administrative acts economically lethargic. As (Zhitomirskiy et al., 2023) observe, the unpredictability of operational costs on public chains erects a formidable barrier to entry for both citizens and municipalities. Consequently, to ensure long-term institutional sustainability, a DLB requires a cost structure that is not only low but predictable—decoupled from the wild fluctuations of the cryptocurrency market.

In response to these structural constraints, the scholarly discourse converges on four distinct optimization strategies:

- **Permissioned Blockchains:** Frameworks like Hyperledger Fabric or Corda are favored for their high throughput and the elimination of user-facing transaction fees. In this model, the operational cost burden is shifted from the citizen to the consortium members (e.g., the Municipality). This ensures zero-cost access for the public while maintaining a predictable IT budget (Mohanty et al., 2025; Tahar et al., 2023; Subbarayudu & Hemalatha, 2024; Mashatan et al., 2021).
- **Hybrid Models:** This architecture balances security and cost by utilizing private networks for high-volume data processing, interacting with public networks only to anchor final proofs. This significantly reduces the frequency of expensive on-chain transactions (Konashevych, 2021; Shahaab et al., 2023).
- **Off-Chain Storage (IPFS):** To mitigate the prohibitive cost of on-chain storage, heavy documents—such as deeds and topographical maps—are stored on distributed file systems like IPFS. Only the cryptographic hash, which is lightweight and cheap to store, is recorded on the blockchain (Singh et al., 2024; Verma et al., 2024; Zhang et al., 2024).
- **Layer 2 Solutions:** These protocols (e.g., Polygon, Arbitrum) scale efficiency by bundling thousands of transactions into a single batch, thereby reducing the effective cost per transaction on public networks to negligible levels (Zhitomirskiy et al., 2023; Leonhard et al., 2025).

6. SYNTHESIS OF ARCHITECTURAL ARCHETYPES

The multi-axis analysis crystallizes four distinct "holistic archetypes," each offering a specialized framework tailored to specific use cases:

- **The Commercial Investment Model:** (Zhitomirskiy et al., 2023) provides a robust blueprint for asset tokenization, featuring on-chain KYC, SPV integration, and complex dividend distribution logic.
- **The Government Registry Model:** (Mashatan et al., 2021) presents the most viable template for state adoption, emphasizing permissioned networks, fraud prevention, and strict GDPR compliance via "Archival Bonds."
- **The Transaction Cycle Model:** (Subbarayudu & Hemalatha, 2024) uniquely integrates the banking sector as a core validator, effectively resolving the "Lien" gap found in other models.
- **The Workflow Management Model:** (Bennett et al., 2019) excels in defining complex administrative workflows, such as mortgage discharge, through hybrid database-blockchain architectures.

Implications for TDR Systems: For urban planning authorities, the evidence suggests that permissioned, hybrid architectures are the only viable solution. Public blockchain fees render small-scale TDR transfers uneconomical, while total decentralization fails to meet administrative requirements. The architectural model proposed by (Mashatan et al., 2021)—utilizing a "Guardian" role for the municipality—offers the most robust template for a DLB focused on development rights.

7. DISCUSSION

This inquiry sought to determine whether blockchain technology could operate not merely as a database, but as a property institution equivalent to traditional legal mechanisms—specifically within the context of Transferable Development Rights (TDRs). Through a systematic analysis of 40 primary studies and the identification of seven critical architectural axes, several key interpretations emerge regarding the transition from analog to digital land governance.

7.1. Institutional Equivalence and the "Oracle Paradox" (Addressing the CRQ)

The Central Research Question interrogated whether blockchain could mimic the legitimacy of traditional institutions. The synthesis suggests that while blockchain possesses functional equivalence, it lacks originating legitimacy. The technology offers superior mechanisms for Exclusivity (via non-fungible tokens) and Transferability (via atomic swaps), yet it cannot independently satisfy the condition of Recognizability without an external source of truth.

This limitation highlights what may be termed the "Oracle Paradox," prevalent in the analyzed studies (e.g., Mohanty et al., 2025; Mashatan et al., 2021). Unlike native cryptocurrencies where the asset is the code, a TDR is a derivative right—it is tethered to physical land. Consequently, the blockchain cannot "know" the state of the physical world (e.g., if a building is historically listed) without a trusted data feed. Thus, the blockchain does not replace the State; rather, it reconfigures the State's role from a manager of records to a certifier of oracles. The institutional validity of the DLB depends, therefore, not on the decentralization of the ledger, but on the integrity of the "Minting" authority.

7.2. Operationalizing the TDR Lifecycle (Addressing SRQ 1 & 2)

The literature review reveals a sharp architectural divergence between general real estate tokenization and the specific requirements of Transferable Development Rights (TDRs). While standard real estate models prioritize fractional investment strategies (typically utilizing ERC-20 standards), TDRs demand a unique "Lifecycle Architecture" that most current frameworks overlook.

Drawing on findings regarding "Time-Sensitive Tokens" (Allam & Jones, 2019) and "Conditional Transfers" (Paavo et al., 2025), a functional TDR model must implement a strict, linear state-change process consisting of three phases:

1. **Genesis (Minting):** The creation of the asset is triggered exclusively by a planning authority's administrative decree.
2. **Circulation (Trading):** The movement of the asset is governed by smart contracts that strictly enforce zoning compatibility between Sending and Receiving zones.
3. **Extinguishment (Burning):** Unlike standard fee-simple property which is held in perpetuity, a TDR is consumed upon utilization.

To enforce this trajectory, a simple NFT standard (ERC-721) proves insufficient unless paired with a hard-coded "Burn Function." This mechanism ensures the irrevocable destruction of the token upon the issuance of a building permit, effectively preventing the double-spending of density rights—a critical failure point in traditional paper-based systems.

7.3. The Necessity of Hybrid Governance (Addressing SRQ 3)

In addressing transition barriers, the analysis strongly refutes the viability of fully public, permissionless blockchains (e.g., Bitcoin, Ethereum Mainnet) for land administration. The dominant constraints identified—GDPR compliance (Shahaab et al., 2023), gas fee volatility (Zhitomirskiy et al., 2023), and the need for identity reversion (Singh et al., 2024)—point inevitably toward Permissioned or Hybrid Architectures.

A DLB must essentially operate as a Consortium Blockchain. In this model, the public may hold read-access (transparency), but write-access (validation) is restricted to a quorum of trusted nodes (e.g., the Municipality, the Land Registry, the Notariat). This hybrid approach resolves the tension found in Section 5.2 between "Web3 Anonymity" and "State Identification," allowing for the immutable recording of rights while permitting the rectification of errors through multi-signature governance—effectively creating a "digital safety valve" for judicial intervention.

7.4. Market Liquidity vs. Regulatory Control (Addressing SRQ 4)

The review confirms that tokenization significantly enhances market liquidity by reducing transaction friction. However, for TDRs, liquidity is a double-edged sword. Unregulated velocity can lead to speculative bubbles in development rights, making housing unaffordable.

Here, the "Smart Contract as Regulator" concept (Ferreira, 2021) becomes paramount. The discussion suggests that the DLB should not merely facilitate trade but actively regulate it. Smart contracts can be programmed with "Circuit Breakers"—code that limits price volatility or restricts transfers to valid developers only. This finding represents a paradigm shift: the DLB becomes an active policy instrument that enforces urban planning rules ex-ante (before the transaction), rather than relying on ex-post bureaucratic enforcement.

8. CONCLUSIONS

8.1. Summary of Contributions

This study employed a Systematic Literature Review to construct an analytical framework for the implementation of a blockchain-based DLB. By dissecting 40 primary studies through the PICOS framework, this research identified seven critical "architectural axes" necessary for the system's viability. The primary contribution of this work is the conceptual decoupling of Land Title Management (static, perpetual) from Development Rights Management (dynamic, consumable), establishing that TDRs require a distinct tokenomic model characterized by "Mint-and-Burn" mechanics and conditional logic.

8.2. Theoretical Implications

Theoretically, this research challenges the "Code is Law" narrative often associated with blockchain. Instead, it supports a theory of "Regulatory Isomorphism," where blockchain structures must morph to fit existing legal containers to achieve legitimacy. It is concluded that blockchain acts as a techno-institutional layer that does not supplant property rights but "hardens" them—transforming administrative promises (paper certificates) into cryptographic guarantees (digital assets).

8.3. Policy and Practical Recommendations

For policymakers implementing the DLB (e.g., under Greek Law 4759/2020), the following recommendations are drawn from the empirical evidence:

- **Adopt a Permissioned Infrastructure**: Utilize frameworks like Hyperledger Fabric rather than public chains to ensure GDPR compliance and zero-cost transaction fees for citizens.
- **Standardize the "Oracle":** Legislation must explicitly define the digital entry point (the specific administrative act) that triggers the minting of a TDR token to prevent fraudulent creation.
- **Implement "Smart" Zoning:** Encode receiving zone restrictions directly into the TDR token metadata, ensuring that a right can only be transferred to a parcel that legally accepts it.

8.4. Limitations and Future Research

While this study maps the architectural requirements, it is limited by the lack of longitudinal data on TDR-specific blockchain pilots, as most case studies focus on standard land titling. Future research should focus on interoperability standards—specifically bridging the DLB with the National Cadastre—and governance longevity, exploring how immutable ledgers can accommodate changes in urban planning laws over decades.

More broadly, the proposed architecture aligns with ongoing discussions on rule-encoding and automation in planning governance, while raising questions about long-term legal adaptability and accountability.

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