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Research Article

Advances in Real-Time Reconciliation and Data Integrity Assurance for Institutional Digital Asset Portfolios

Emmanuel Chukwuma Okeke[1], Ifeanyichukwu Okwesa[2], Precious Nnamdi Ibe[3], Ifeoma E. Okoli[4*], Funmilayo Ashore[5], Nnaemeka Egbuhuzor[6], Kofi Okyere Mensah[7]

[1]Arcesium, New York, NY, USA
[2]Barclays, USA
[3]University of Port Harcourt, Port Harcourt, Nigeria
[4]Maersk Logistics, Canada
[5]University of Georgia, Terry College of Business, Athens, GA, USA
[6]Columbia Business School, New York, NY, USA
[7]CIBC Bank USA, USA
* Corresponding author: Ifeoma E. Okoli, Ifeomaokoli47@gmail.com

Abstract

Purpose. Recent developments moved digital assets into the regulated operating model of asset managers, custodians and banks. Spot bitcoin exchange-traded products were approved in the United States, large managers issued tokenized fund shares on public blockchains, the European Union's Markets in Crypto-Assets Regulation (MiCA) entered into application, and the Basel Committee finalized its cryptoasset disclosure framework. These changes exposed a weakness in reconciliation and data integrity practices inherited from traditional finance, which assume batch processing, a single authoritative ledger and end-of-day finality. This paper examines how these developments changed reconciliation requirements and what advances emerged to meet them.

Design and methodology. The study is a structured narrative review combining 34 regulatory, standard-setter, market infrastructure and industry sources with 218 related and semi-related academic studies, all published to date. The academic corpus was screened from a consolidated list of 1,056 records and coded into ten themes, and the findings were synthesized into a conceptual model.

Findings. Four groups of advances stand out: authoritative reference data published on-chain by accountable providers; tokenized fund structures that require three-way and four-way agreement across chains, registers and custodians; cryptographic attestation such as zero-knowledge proof of reserves; and AI-assisted structuring of unstructured data validated through model consensus. Together they shift integrity assurance upstream, toward the point of data creation, and outward, toward third-party verifiability.

Contribution. The paper proposes a six-layer reconciliation architecture linked to five integrity properties (accuracy, completeness, timeliness, provenance and verifiability), states five propositions for testing, and sets out implications for practitioners and regulators, the study's limitations and an agenda for future research. The central argument is that these developments shifted the reconciliation question from "do our records agree at the close?" to "can we prove, continuously and to a third party, that our records agree with the chain?"

Keywords: digital asset operations; real-time reconciliation; data integrity; tokenized funds; proof of reserves; oracles; continuous assurance; MiCA; ASU 2023-08; Basel cryptoasset standard; custody

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1. Introduction

Reconciliation is the control that confirms an institution's internal records of positions, cash and transactions agree with an independent external source. In securities operations, that external source is typically a custodian statement, a

central securities depository or a fund administrator report, delivered in batch at the end of a business day. Breaks are investigated the next morning and resolved over days. This rhythm is tolerable because the underlying settlement systems themselves operate in cycles, and because the external source is, by design, authoritative.

Digital assets disrupt each of these assumptions. Public blockchains settle continuously, every day of the year. A single position may be represented across several networks at once, through native issuance, bridged representations or wrapped tokens. The authoritative record is not a statement prepared by a trusted intermediary but the state of a distributed ledger, which must itself be read, interpreted and sometimes reorganized. Unsolicited inbound transfers, staking rewards, airdrops and protocol-level events can change a wallet balance without any instruction from the holder. Practitioners in 2024 described the operational result: internal ledgers that are often unstructured, missing reference data needed to link a customer transaction across liquidity provider, order management and blockchain records, and omnibus arrangements that complicate auditability (Rundlet, 2024). These properties have also prompted an academic literature on distributed ledger payment infrastructure, which examines interoperability, scalable gateway architecture, high-throughput platform engineering and peer-to-peer settlement models (Adesuyi, Akomolafe, et al., 2023; Akomolafe et al., 2024a; Osuji et al., 2021; Shittu et al., 2021).

Until 2024 these challenges were largely confined to crypto-native funds, exchanges and a small number of specialist custodians. Three developments changed the scale and the stakes in 2024. First, regulated mainstream investment products holding digital assets directly came to market. Second, large traditional asset managers began issuing fund shares as tokens on public blockchains. Third, binding prudential, conduct and accounting requirements specific to digital assets were finalized or began to apply. Each development pushed reconciliation and data integrity out of the back office and into the domain of regulatory reporting, audit and fiduciary duty. The broader context is a sustained digital transformation of banking, transaction services and financial inclusion (Agboada et al., 2020; Agboada et al., 2022; Ezeako et al., 2019; Okafor et al., 2021; Okafor, Osuji, et al., 2024; Ukadike, 2022; Uzondu et al., 2020), accompanied by increasingly data-driven approaches to risk evaluation, underwriting, business continuity and client analytics in financial services (Akomolafe & Agu, 2019b; Fadero et al., 2020; Oluwo et al., 2022; Oluwo et al., 2024; Ukadike & Ibeh, 2023).

Despite this, there is no integrated account of how reconciliation and data integrity practice changed in response. Regulatory texts, market pilots and vendor material each describe one part of the picture, while the academic literature on audit, payments, cybersecurity and data governance addresses adjacent problems without focusing on institutional digital asset portfolios. This paper addresses that gap by asking three research questions:

RQ1. What changed in 2024 that made real-time reconciliation an institutional requirement for digital asset portfolios?

RQ2. What market infrastructure and technology advances emerged during 2024 to meet that requirement, and how do they relate to the wider literature on control and assurance?

RQ3. What architecture and control model best captures those advances for an institution building or assessing its capability?

The paper makes three contributions. It provides a structured synthesis of 2024 developments across regulation, accounting and market infrastructure. It connects those developments to ten themes in the related academic literature.

And it proposes a conceptual model, comprising a six-layer architecture, five integrity properties and five testable propositions. Section 2 describes the research method. Section 3 presents the results and discussion, comprising the literature synthesis, the conceptual model, the discussion of findings and their implications. Section 4 concludes and states the limitations of the study and directions for future research.

2. Research Method

2.1 Review design

The study adopts a structured narrative review design. A narrative approach was chosen over a formal systematic review because the phenomenon is recent, much of the relevant evidence sits in regulatory publications and industry pilot reports rather than peer-reviewed journals, and the aim is to build a conceptual model rather than to estimate an effect size. To reduce the subjectivity typical of narrative reviews, the study used explicit inclusion criteria, a documented screening process and a thematic coding scheme, described below.

2.2 Sources

Two bodies of evidence were assembled. The first is a set of regulatory, standard-setter, market infrastructure and industry sources identified through targeted searches of regulator and standard-setter websites (including the Basel Committee, the Monetary Authority of Singapore, the UK Financial Conduct Authority and EU national authorities), market infrastructure and technology provider publications (including DTCC and Chainlink), securities filings, law firm briefings and specialist financial news. The second is a corpus of academic studies drawn from a consolidated reference list of 1,056 records spanning 68 subject areas, compiled from several author publication lists and citation lists and deduplicated before screening.

2.3 Inclusion and exclusion criteria

Sources were included if they were published to date and addressed at least one of the following: digital asset custody, settlement or tokenization; reconciliation, internal control or audit; financial reporting or financial analytics; fraud, anti-money laundering or financial crime; regulatory compliance; cybersecurity; data governance, provenance or privacy; AI governance; or enterprise data and system architecture. Records were excluded if they were published after 2024 or undated, if their bibliographic details were incomplete, or if their subject lay outside these areas (for example clinical care, agriculture, education practice or mechanical engineering). Industry sources were limited to those published to date whose publication date could be established; a small number of 2022 and 2023 sources were retained for background on proof of reserves and accounting standards.

2.4 Screening and selection

Of the 1,056 academic records, 322 published after 2024 and one undated record were excluded, leaving 733. These were screened in two stages. First, titles were scored for topical relevance against a keyword list derived from the inclusion criteria, with negative weights for clearly unrelated domains. Second, the highest-ranked records and borderline cases were reviewed manually, and records were retained where they were directly related or semi-related to the research questions. Records flagged in the source list as incomplete were excluded. This process yielded 218 academic studies published between 2018 and 2024, of which 55 were published in 2024. Combined with 34 industry and regulatory sources, the final evidence base comprises 252 sources.

2.5 Coding and synthesis

The academic studies were coded inductively into ten themes, shown in Table 1. Industry sources were coded by the 2024 development they describe (exchange-traded products, MiCA, Basel disclosure, accounting, tokenization frameworks, on-chain reference data, tokenized funds, messaging interoperability, cryptographic attestation, AI-assisted data structuring and matching platforms). Synthesis proceeded in three steps: describing the reconciliation problem and its 2024 drivers (RQ1); mapping 2024 advances and relating each to the relevant academic themes (RQ2); and abstracting recurring design patterns into layers, properties and propositions (RQ3).

Table 1: Thematic composition of the academic corpus (n = 218, published 2018 to 2024)

Theme	*Studies*	*Years*
Distributed ledger payments and tokenization	14	2018 to 2024
Banking transformation and financial risk	21	2018 to 2024
Audit, internal control and continuous assurance	19	2018 to 2024
Financial reporting and financial analytics	28	2018 to 2024
Fraud, AML and financial crime analytics	14	2021 to 2024
Regulatory compliance and technology law	23	2019 to 2024
Cybersecurity and security operations	41	2018 to 2024
Data governance, provenance and privacy	17	2018 to 2024
AI governance and model validation	14	2022 to 2024
Enterprise architecture and real-time pipelines	27	2018 to 2024
Total	218	2018 to 2024

3. Results and Discussion

This section presents the results of the review and discusses them. Sections 3.1 to 3.3 synthesize the evidence on the nature of the reconciliation problem for digital assets, the regulatory and accounting drivers that crystallized in 2024, and the market infrastructure and technology advances of the year. Section 3.4 summarizes what the academic literature contributes and where it falls short. Section 3.5 presents the conceptual model derived from the synthesis, Section 3.6 discusses the findings against the research questions, and Section 3.7 sets out the implications.

3.1 The reconciliation problem for digital assets

3.1.1 From batch agreement to continuous agreement

Traditional reconciliation compares two snapshots taken at the same cut-off time. For digital assets, choosing the cut-off is itself non-trivial. A blockchain does not have a business day; the relevant reference point is a block height, and different networks produce blocks at different cadences. A portfolio spread across several chains therefore requires an institution to define, for every reporting event, which block on each chain constitutes the official snapshot, and to retain evidence of that choice. Finality adds a further complication: on some networks a block that has been observed may later be reorganized, so a balance read too early can differ from the eventual settled state. The shift this demands mirrors a wider movement in governance research away from periodic assurance and toward real-time compliance pipelines, real-time KPI tracking,

operational data streams and business-intelligence-driven early warning (Akhigbe et al., 2023; Ebisi et al., 2024; Sakyi et al., 2024b; Tonoyan et al., 2024b; Uchechi et al., 2022).

3.1.2 Multiplicity of records

An institutional digital asset position typically appears in at least four places: the on-chain state of one or more addresses; the custodian's internal ledger, which may pool client assets in omnibus wallets; the investment manager's order and portfolio management systems; and the fund administrator's or transfer agent's books. In the spot bitcoin exchange-traded products launched in 2024, these roles were often split across unrelated firms. A Grayscale executive explained in a 2024 panel that because banks had difficulty holding crypto, the fund used Coinbase as custodian while its transfer agent was a separate bank, a departure from the usual practice of housing these functions at one institution (U.S. Securities and Exchange Commission, 2024). Every additional party adds a reconciliation boundary. Studies of reconciliation control and financial workflow redesign, automated multinational consolidation, tiered treasury architecture, integrated data management and standardized reporting workflows show that each additional system boundary raises the risk of timing and mapping breaks (Agu et al., 2023b; Alieme et al., 2022; Bola-Sadipe et al., 2023; Dada et al., 2021a; Dogbatsey et al., 2019). Research on cross-border payments operations, blockchain-based cross-border data exchange, multinational audit liaison and cross-border SOX compliance similarly finds that end-to-end monitoring across institutions is a precondition for reducing counterparty and control-ownership risk (Agu et al., 2023a; Ebhojie et al., 2023a; Kumuyi et al., 2023; Okafor, Farounbi, et al., 2024).

3.1.3 Unsolicited and protocol-driven events

Public addresses can receive assets from anyone. Shortly after its 2024 launch, BlackRock's tokenized liquidity fund wallet received unsolicited tokens from third parties, an episode commentators noted could raise sanctions-screening questions for the fund (Bits of Blocks, 2024). Public on-chain records also showed small test deposits into the fund before launch, illustrating how every on-chain movement becomes part of the observable record (Kitco News, 2024). Staking rewards, rebasing tokens, airdrops and fee mechanics similarly change balances without an internal instruction. A reconciliation process that only matches expected transactions against observed ones will flag these as breaks every time; a mature process must classify them, screen them and decide their accounting treatment. Literature on predictive AML detection in commercial banking, integrated cybersecurity and AML governance, comparative AML regimes and machine learning fraud detection in banking offers models for embedding such screening directly into the reconciliation workflow (Atakpa & Abetoh, 2022; Atakpa, 2021; Fadayomi et al., 2021; Ominyi & Anichukwueze, 2021).

3.1.4 The cost of failure

Reconciliation is also a detective security control. Blockchain analytics firm Chainalysis reported that funds stolen from crypto platforms rose about 21 percent in 2024 to roughly $2.2 billion across 303 incidents, with private key compromise the single largest vector at 43.8 percent of stolen value (Nairametrics, 2024). The largest incidents of the year, at DMM Bitcoin in May and WazirX in July, involved centralized services (Nairametrics, 2024), and attacks shifted from decentralized protocols toward centralized services in the second and third quarters (Benzinga, 2024b). For an institution, a near-real-time comparison between expected and actual wallet state is one of the few controls

able to detect an unauthorized outflow within minutes rather than at the next daily close.

A substantial body of research supports this detective role. Work on adaptive real-time fraud risk scoring, AI-assisted anomaly detection in high-volume transactions and anomaly detection in financial time series addresses the detection problem directly (Atakpa & Fobellah, 2023; Fadayomi et al., 2024; Ominyi et al., 2024a), while studies of fraud detection in public systems, synthetic identity fraud and forensic analytics for regulatory monitoring supply candidate techniques (Adelanwa et al., 2023b; Elebe et al., 2023; Mbonu et al., 2021). Related work on investment risk assessment, portfolio fraud exposure and financial forensics shows that fraud frequently surfaces first as unexplained data discrepancies (Atakpa et al., 2024; Eboh & Aliliele, 2023; Eboh & Aliliele, 2024; Ekechi et al., 2022). Cybersecurity risk management, maturity assessment and cyber risk quantification frameworks place these controls within enterprise risk governance (Bello et al., 2024; Dosunmu & Ogundele, 2024b; Fadayomi et al., 2019; Fadero et al., 2021).

3.2 Regulatory and accounting drivers in 2024

The technical advances reviewed in Section 3.3 were pulled forward by requirements that crystallized during 2024, summarized in Table 2. The broader compliance literature notes both the burden that layered financial regulation can impose and the value of integrated governance, enterprise risk management and compliance-risk modeling in absorbing it, particularly in cross-border and multi-jurisdictional settings (Akomolafe & Agu, 2019c; Akomolafe et al., 2023b; Falemi et al., 2024; Jones & Ominyi, 2023; Jones & Ominyi, 2024a; Jones & Ominyi, 2024b; Ominyi & Anichukwueze, 2020; Ominyi et al., 2021; Ominyi, 2020).

Table 2: Key 2024 regulatory and accounting developments affecting reconciliation and data integrity

Development	*Date*	*Relevance to reconciliation and integrity*
US spot bitcoin exchange-traded products approved (11 products)	10 Jan 2024	Daily NAV, creations and redemptions require auditable agreement between custodian, administrator and transfer agent across separate firms.
US spot ether exchange-traded products begin trading	Jul 2024	Extends the multi-party custody model to a second network with different finality and account semantics.
MiCA Titles III and IV (asset-referenced and e-money tokens) apply	30 Jun 2024	Reserve, redemption and safeguarding obligations for stablecoin issuers.
MiCA applies in full, including CASP authorization regime	30 Dec 2024	Custody and safeguarding obligations for crypto-asset service providers; national transitional periods of up to 18 months.
Basel Committee final cryptoasset disclosure framework (DIS55) and targeted amendments	17 Jul 2024	Standardized public tables on exposures, accounting classification and liquidity; implementation date set for 1 Jan 2026.
FASB ASU 2023-08 (fair value for in-scope crypto assets) approaches effective date	FY beginning after 15 Dec 2024	Per-asset disclosure of units, cost basis and fair value each period; 2024 was the preparation and early-adoption year.
Presidential veto of congressional resolution disapproving SEC SAB 121	31 May 2024	Kept on-balance-sheet treatment for safeguarded crypto in place through 2024.

Development	*Date*	*Relevance to reconciliation and integrity*
MAS publishes Guardian Funds Framework and Guardian Fixed Income Framework	4 Nov 2024	Industry frameworks for tokenized fund and bond lifecycles, including data and interoperability expectations.

3.2.1 Exchange-traded products and multi-party custody

On 10 January 2024 the US Securities and Exchange Commission approved eleven spot bitcoin exchange-traded products, and Coinbase was named custodian for eight of them (The Block, 2024). The products brought digital assets into an operating model in which daily net asset value calculation, authorized participant creations and redemptions, and investor reporting all depend on agreement between an independent crypto custodian and traditional fund service providers. Banks remained involved as administrators and in other roles even where they did not hold the bitcoin (Ripple, 2024). This arrangement made cross-firm reconciliation a daily, regulator-visible process for the first time at scale.

3.2.2 MiCA and safeguarding

MiCA was rolled out in stages, with provisions for asset-referenced and e-money tokens applying from June 2024 and the remaining provisions, covering crypto-asset service providers such as exchanges, trading platforms and custody firms, applying from 30 December 2024 (GreySpark Partners, 2024). Firms already providing services under national law could benefit from transitional periods, which in the Netherlands, for example, ran for up to 18 months (AKD, 2024). National authorities also allowed existing investment firms and fund managers to extend their licences to crypto-asset services by notification (Malta Financial Services Authority, 2024). The combined effect was that custodial reconciliation moved from an internal policy choice to a matter examined at authorization: a firm seeking a MiCA licence must show how client entitlements are segregated and evidenced, and reconciliation frequency is the most direct measure of that capability. Research on regulatory adaptation of payment products, risk scoring of cross-border payments, regulatory scenario analysis and the standardization of compliance controls across distributed networks is directly relevant to firms redesigning safeguarding processes for MiCA (Adesuyi et al., 2024; Akinola et al., 2020; Olaogun et al., 2023; Uchechi et al., 2023).

3.2.3 Basel disclosure framework

On 17 July 2024 the Basel Committee published its final disclosure framework for banks' cryptoasset exposures together with targeted amendments to its prudential standard, both to be implemented by 1 January 2026 (Basel Committee on Banking Supervision, 2024). The disclosure standard introduces a qualitative table and quantitative templates covering exposures and capital requirements, accounting classification, and liquidity requirements (Regulation Tomorrow, 2024). For banks, cryptoasset positions must therefore be reconciled not only for operational accuracy but to a level of granularity and classification that will be publicly disclosed and comparable across institutions. This aligns with work on capital adequacy and risk-weighted asset optimization, risk-based internal control models for banking and insurance, and risk-based auditing (Akomolafe & Agu, 2019a; Akomolafe et al., 2023a; Mensah et al., 2019).

3.2.4 Accounting: ASU 2023-08 and SAB 121

FASB's ASU 2023-08 requires in-scope crypto assets to be measured at fair value with changes recognized in net income, and applies to fiscal years beginning after 15 December 2024, meaning 2025 for calendar-year reporters (Texas Society of CPAs, 2024). Its disclosures require, for each significant holding, the name, cost basis, fair value and number of units (Weaver, 2023). During 2024, preparers had to build the data lineage to support these disclosures: unit counts reconciled to the chain, cost basis tracked through lots across transfers between wallets and custodians, and fair values sourced from a defensible principal market. Unit-level reconciliation thus became a financial statement assertion rather than an operational metric. The demand for granular, traceable disclosure echoes research on data-driven financial reporting in banking, comprehensive reporting models, accounting systems for transparency and data integration methods that improve reporting accuracy (Azeez & Badmus, 2024a; Bola-Sadipe et al., 2019; Bola-Sadipe et al., 2022; Lamidi, 2023; Medon & Oduleye, 2022).

SEC Staff Accounting Bulletin 121, issued in 2022, required firms safeguarding customers' digital assets to bring those assets onto their own balance sheets with related disclosures. Congress passed a resolution, H.J. Res. 109, to overturn it, which the President vetoed on 31 May 2024 (CryptoSlate, 2024). Throughout 2024, therefore, US public companies that safeguarded crypto assets continued to carry them on balance sheet, which raised the stakes of custodial reconciliation for those firms' audited financial statements. Studies of tax governance analytics, compliance workflow design and statutory reporting show how regime changes of this kind propagate into close processes and audit readiness (Dogbatsey & Ebhojie, 2018; Eyetsemitan et al., 2021; Lawal & Oduleye, 2018b).

3.2.5 Tokenization frameworks

In November 2024 the Monetary Authority of Singapore announced measures to commercialize asset tokenization, noting that Project Guardian had convened more than 40 stakeholders across seven jurisdictions for trials in six currencies (Rajah & Tann Asia, 2024). Alongside this, two industry frameworks were published: the Guardian Fixed Income Framework and the Guardian Funds Framework (Rahmat Lim & Partners, 2024). The UK Financial Conduct Authority, a Guardian policymaker group member, described the funds framework as setting out a phased vision for distributed ledger technology in asset management and discussing the standards needed to scale tokenization (Financial Conduct Authority, 2024). These frameworks matter for reconciliation because they begin to standardize the data that tokenized instruments carry and the roles that maintain it. Academic work on smart contract payment automation and dispute resolution, blockchain-driven compliance reporting, blockchain-based audit trails and secure blockchain data exchange offers complementary evidence on how tokenized records can support lifecycle controls (Abioye et al., 2023; Akomolafe et al., 2022; Akomolafe et al., 2024b; Ekwunife et al., 2024; Oshoba et al., 2020; Shittu et al., 2022).

3.3 Market infrastructure and technology advances

3.3.1 Authoritative reference data on-chain

A recurring integrity problem in digital asset operations is that on-chain applications rely on reference data, such as prices or fund NAVs, whose provenance is unclear. In May 2024 DTCC published results of its Smart NAV pilot with Chainlink, which explored a digital extension of DTCC's Mutual

Fund Profile Service I, the industry standard for transmitting price and rate data (DTCC, 2024). Ten large financial institutions participated, including BNY Mellon, Franklin Templeton and J.P. Morgan (Finadium, 2024). In the pilot DTCC acted as both the source of the data and the governor of the on-chain solution storing it, while Chainlink's Cross-Chain Interoperability Protocol (CCIP) acted as the interoperability layer (DTCC, 2024).

The pilot found that publishing structured data on-chain with standard roles and processes allowed foundational data to feed many on-chain use cases, including tokenized funds and contracts holding data for multiple funds (DTCC, 2024). It also established a pattern in which the entity that is authoritative off-chain remains accountable for the on-chain copy, giving reconciliation teams a single provenance chain to verify. In July 2024 Fidelity International and Sygnum announced a collaboration with Chainlink to bring the NAV of Fidelity's $6.9 billion Institutional Liquidity Fund on-chain, making it accessible in real time rather than after each trading day (Cointelegraph, 2024). This pattern parallels research on tamper-proof regulatory recordkeeping and on traceability and chain-of-custody integrity in other regulated industries, where data integrity failures have repeatedly been traced to unclear provenance (Aneke & Adesemoye, 2019; Aneke et al., 2023; Anichukwueze et al., 2021; Nnabueze et al., 2021; Peteranaba et al., 2022).

3.3.2 Tokenized funds and the transfer agent of record

In March 2024 BlackRock launched its first tokenized fund on a public blockchain, the USD Institutional Digital Liquidity Fund (BUIDL), with Securitize acting as transfer agent and tokenization platform responsible for managing the tokenized shares and reporting subscriptions, redemptions and distributions (BlackRock, 2024). The fund targets a stable $1 per token value and pays daily accrued dividends to investor wallets as new tokens each month, with BNY Mellon enabling interoperability between digital and traditional markets (The Full FX, 2024). BNY was named fund administrator and custodian, and in November 2024 the fund expanded to Aptos, Arbitrum, Avalanche, Optimism and Polygon in addition to Ethereum (Crowdfund Insider, 2024).

This structure illustrates a distinctive reconciliation pattern. The token ledger on each chain is a public, real-time record of beneficial ownership, but the legal register is maintained by the transfer agent, and the underlying cash and securities are held by a traditional custodian. Integrity therefore requires agreement across all three: total tokens outstanding across all supported chains must equal the shares on the register, which must in turn be supported by assets at the custodian. Multi-chain issuance makes the first leg harder, because supply on each chain must be summed at a consistent point in time and any cross-chain transfer must be counted exactly once. Corporate finance and treasury research on cross-border strategic finance, predictive cash and working capital management, demand and revenue forecasting and trade finance design offers useful analogues for summing positions across venues at a consistent point in time (Agboada et al., 2018; Isiekwu et al., 2021; Medon & Oduleye, 2024; Oduleye & Medon, 2023a; Tonoyan et al., 2021a; Tonoyan et al., 2021b).

3.3.3 Interoperability with existing messaging

A practical barrier to real-time reconciliation is that institutional back offices run on established messaging standards rather than blockchain APIs. In 2024, as part of Project Guardian, Swift, UBS Asset Management and Chainlink settled tokenized fund subscriptions and redemptions using the Swift network, an exercise Swift described as bridging digital assets with established systems (Chainlink, 2024c). This allows on-chain events to arrive in the same channels,

and in the same formats, that existing matching engines already consume. Research on API governance in financial institutions, risk-based business intelligence architecture for fintech platforms, secure enterprise messaging architectures and AI-supported liquidity management in payment systems reinforces the value of reusing established integration channels (Ahmed & Odejobi, 2018a; Akomolafe et al., 2023; Aliliele et al., 2023b; Mbonu et al., 2021a).

3.3.4 Cryptographic attestation of reserves and liabilities

Following the failures of 2022, centralized platforms adopted proof of reserves programs based on Merkle trees, in which each user's balance is a leaf and the root commits to the total of all balances. In a 2022 proposal, Ethereum co-founder Vitalik Buterin argued that zero-knowledge proofs would make such schemes more confidential, so that the branch given to one user as evidence reveals nothing about other clients' balances (ForkLog, 2022). Binance subsequently combined zk-SNARKs with its Merkle tree so that it can show all leaf balances contribute to the claimed total while proving the tree contains no negative net balances (Coin Bureau, 2023), initially covering 13 assets (The Block, 2023). By 2024 such reports had become routine: Bybit, for example, published monthly proof of reserves reports in 2024 covering 32 cryptocurrencies with reserve ratios above 100 percent (Bybit, 2024).

For institutions, these techniques offer a way to verify inclusion of their own balances without relying solely on an auditor's opinion, and a model for continuous, privacy-preserving attestation to clients and supervisors. Their key limitation is that a proof is built from a snapshot of the platform's wallets (ForkLog, 2022), so a platform could in principle borrow assets temporarily before the snapshot. Proofs of reserves therefore complement, rather than replace, continuous reconciliation and liability-side controls. Wider research on privacy-preserving data governance using blockchain and cryptographic strategies, attribute-based encryption, privacy-preserving analytics architectures and cross-jurisdictional data protection indicates that the toolkit for such attestations is broadening (Afrihyia, Ojukwu, et al., 2024; Atakpa & Abolaji, 2022; Mbonu, Aliliele, et al., 2019; Shittu & Nabil, 2023).

3.3.5 AI-assisted data structuring with consensus validation

Corporate actions are a persistent source of reconciliation breaks because the underlying information arrives as unstructured issuer disclosures, and there are more than seventy types of corporate action, each with its own data requirements (Chainlink, 2024b). At Sibos in October 2024, Chainlink, Euroclear, Swift and six financial institutions presented an initiative that combined large language models with oracle infrastructure to distribute corporate actions data in near real time across three blockchain networks (Chainlink, 2024a). The approach used multiple models to interpret disclosures and aimed to create a shared, real-time golden record accessible to all participants (Benzinga, 2024a). The design principle is the important advance: no single model's output is trusted; multiple independent extractions are compared and only agreed values are published, with the resulting record cryptographically attested. This is reconciliation applied at the point of data creation.

The approach is consistent with research on LLM-based evaluation and release gating, AI with predictive analytics and AI-supported decision systems (Nwakamma et al., 2024a; Rukh et al., 2024), and with frameworks for responsible automated decision systems, algorithmic accountability and model risk management, readiness for the EU AI Act and governance of AI-driven management (Afrihyia, Akinse, et al., 2024; Annan, 2024; Ominyi &

Anichukwueze, 2023; Ominyi & Anichukwueze, 2024; Ominyi et al., 2024b). Human-in-the-loop and data curation studies, together with work on structuring problems for AI, efficient model adaptation, technology adoption and securing agentic AI workflows, caution that model consensus should be paired with human oversight and hardened tool access (Alieme et al., 2024; Ladapo, Dosunmu, et al., 2022; Ladapo, Jooda, et al., 2024; Nwakamma et al., 2024b; Oteri & Chibwaye, 2022; Oyesiji et al., 2023; Oyesiji et al., 2024).

3.3.6 Multi-source matching platforms

Underlying these advances is an operational shift from manual, spreadsheet-based reconciliation to automated matching across many sources. Vendors described platforms in 2024 that connect dozens of blockchains with exchanges, liquidity providers and custodians, match records on criteria such as time, transaction hash and category with configurable tolerances for timing and volume differences, and produce exception reports, with reconciliation run daily or in hourly batches to support licensing requirements including MiCA (Rundlet, 2024). The remaining step, from hourly batches to continuous event-driven matching, is largely an engineering question of data pipelines. Research on predictive early-warning analytics, capacity forecasting, AI-predictive maintenance, cloud resource scaling and rightsizing informs the design of these pipelines (Ahmed et al., 2020; Mayo et al., 2021; Okwesa et al., 2024; Olagunju et al., 2022; Upreti & Oteri, 2023), while research on continuous performance monitoring, multi-tenant and multi-cloud performance, IT service management, cloud migration, change and incident governance and support operations addresses how to keep them dependable (Anyanwu, 2019; Edivri & Oteri, 2024; Ladapo, Dosunmu, et al., 2023b; Ladapo, Jooda, et al., 2022; Ladapo, Jooda, et al., 2023a; Odejobi & Ahmed, 2018b; Ogbole, Okoruwa, Babatope, et al., 2021; Olagunju et al., 2023; Olagunju et al., 2024; Ukadike, 2024; Wikiri, 2021).

3.4 Literature synthesis: contributions and gaps

Across the ten themes in Table 1, the academic literature contributes three things to this problem. First, it supplies mature models for continuous monitoring, automated controls and audit readiness that transfer directly to digital asset reconciliation. Second, it supplies detection techniques, from anomaly detection to AML analytics, that can operate on reconciliation exceptions. Third, it supplies governance frameworks for security, data and AI that define how such controls should be owned, measured and evidenced.

The corpus also has clear gaps. Most studies are conceptual frameworks or reviews rather than empirical evaluations, and few address digital asset portfolios specifically; the distributed ledger studies concentrate on payments rather than custody and fund administration. None examines block-height snapshot conventions, multi-chain supply counting or omnibus custody attestation, which are the problems most specific to institutional digital asset reconciliation. The conceptual model in Section 3.5 is designed to bridge this gap by connecting the 2024 industry developments to the controls the wider literature already describes.

3.5 Conceptual model

Synthesizing the evidence, this section proposes a conceptual model of real-time reconciliation and data integrity assurance for institutional digital asset portfolios (Figure 1). The model has three parts: the 2024 drivers that shape requirements; a six-layer reconciliation architecture; and five integrity properties that the architecture is intended to assure. It is technology-neutral and draws on enterprise architecture research covering infrastructure-as-code and cloud misconfiguration monitoring, identity and access management

across hybrid and federated environments, secure analytics architectures, ERP data migration and cloud database optimization (Ahmed et al., 2019; Aliliele et al., 2023a; Aliliele et al., 2024b; Chibwaye & Oteri, 2023; Ladapo, Jooda, et al., 2023b; Mbonu et al., 2020; Mbonu et al., 2020a; Mbonu et al., 2020b; Mbonu et al., 2022b; Odejobi et al., 2019; Oshoba et al., 2019).

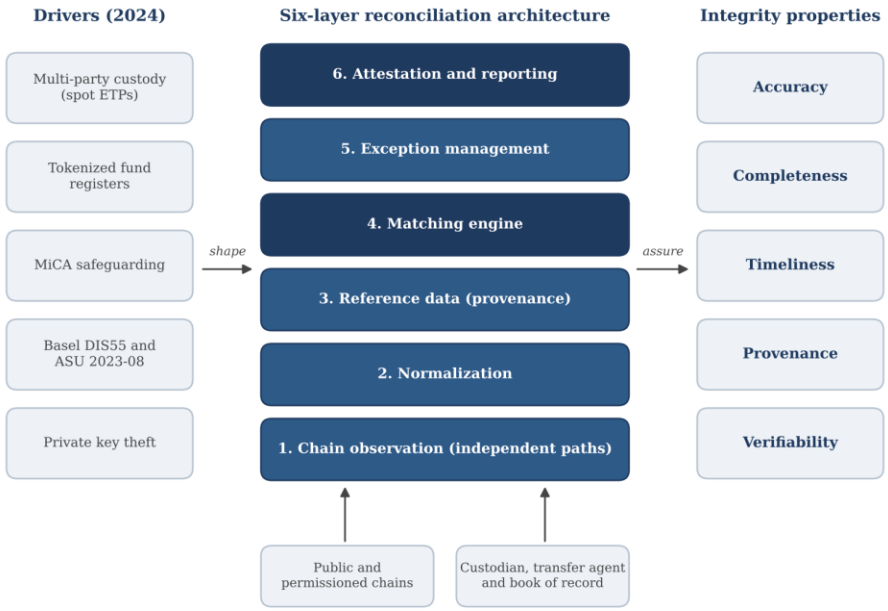


Figure 1: Conceptual model: 2024 drivers shape a six-layer reconciliation architecture that assures five integrity properties

3.5.1 Reconciliation architecture

Table 3 describes the six layers. Each layer has a distinct function and a set of design choices, and each is illustrated by a 2024 exemplar from the synthesis.

Table 3: Six-layer reconciliation architecture

Layer	*Function*	*Key design choices*	*2024 exemplar*
1. Chain observation	Read blocks, transactions, logs and balances from each network	Multiple independent nodes per chain; finality thresholds per network; reorg handling	Multi-chain data aggregation (Rundlet, 2024)
2. Normalization	Convert raw chain data into a canonical event model (transfer, mint, burn, reward, fee)	Asset identifiers that link native, bridged and wrapped forms; consistent timestamps and block references	Multi-chain fund share classes (Crowdfund Insider, 2024)
3. Reference data	Prices, NAVs, corporate actions, entity and wallet ownership	Single accountable provider per data item; on-chain publication with provenance	Smart NAV (DTCC, 2024); corporate actions golden record (Benzinga, 2024a)
4. Matching engine	Compare chain state, custodian ledger, books of record and register	Continuous plus formal snapshots at defined block heights; tolerance rules by asset	Hash and time matching with tolerances (Rundlet, 2024)
5. Exception management	Classify, route, investigate and resolve breaks	Taxonomy covering unsolicited inbound, rewards, timing and true breaks; sanctions screening hooks	Unsolicited token receipts (Bits of Blocks, 2024)

Layer	*Function*	*Key design choices*	*2024 exemplar*
6. Attestation and reporting	Evidence agreement to auditors, supervisors and clients	Immutable logs of snapshots and decisions; cryptographic proofs where feasible	zk proof of reserves (Coin Bureau, 2023); Basel DIS55 (Regulation Tomorrow, 2024)

Three design principles cut across the layers. **Snapshots and the continuous record.** Continuous monitoring compares each new on-chain event against expected activity and raises alerts within seconds or minutes; its purpose is detection. Formal snapshots are taken at defined block heights corresponding to accounting and regulatory cut-offs and are retained with full evidence; their purpose is assertion. A snapshot should be reproducible from the continuous record, which in turn should be reproducible from the chain.

Three-way and four-way agreement. For a directly held position, the core agreement is three-way: on-chain balance, custodian ledger and investment book of record. For a tokenized fund, a fourth leg is added: the transfer agent's register, which must agree with token supply summed across all chains. Where a custodian uses omnibus wallets, the on-chain balance supports only the total across clients, so client-level integrity depends on custodian attestation, ideally supported by inclusion proofs of the kind used in proof of reserves.

Independence of observation. The observation layer is a single point of failure if an institution relies on one node provider, or on the custodian's own reporting of on-chain state. The model therefore requires at least two independent observation paths for material positions, one operated or contracted by the institution itself, and treats disagreement between paths as an exception. Security operations research on threat actor analysis, threat intelligence integration, log analytics with automated incident response and integrated network and security operation centers supports treating such disagreement as a monitored signal (Dosunmu & Ogundele, 2022; Dosunmu & Ogundele, 2023; Ladapo, Dosunmu, et al., 2024; Mbonu, Iwuanyanwu, et al., 2019).

3.5.2 Integrity properties and controls

The architecture is assessed against five integrity properties (Table 4). Accuracy, completeness and timeliness reflect the needs practitioners described in 2024, namely a complete and accurate view of holdings reconciled at least daily (Rundlet, 2024); provenance and verifiability are added to reflect the 2024 advances in on-chain reference data and cryptographic attestation. The control set builds on research into AI-enabled IT general controls and SOX automation, technology-enabled internal audit, security audit, data-driven auditing for financial statement validation and audit analytics (Abetoh & Atakpa, 2024; Akomolafe & Agu, 2018; Dosunmu & Ogundele, 2019; Mbonu et al., 2022; Okoli et al., 2022).

Table 4: Integrity properties and supporting controls

Property	*Definition*	*Representative controls*
Accuracy	Recorded units and values match the authoritative source	Unit-level chain-to-book matching; independent price sources with tolerance checks; dual observation nodes
Completeness	All addresses, chains and events are captured	Wallet inventory reconciled to custody agreements; supply totals across all chains; capture of rewards, fees and unsolicited receipts
Timeliness	Discrepancies are detected within a	Streaming alerts on unexpected outflows; maximum

Property	*Definition*	*Representative controls*
	defined window	detection latency targets by risk tier; finality-aware confirmation rules
Provenance	The origin and custody chain of each data item is known	Accountable provider for each reference data item; signed or on-chain published NAVs and corporate actions; lineage from snapshot to disclosure
Verifiability	A third party can independently confirm the record	Retained snapshot evidence at block heights; Merkle inclusion and zero-knowledge proofs; reproducible reconciliation runs

The properties connect reconciliation to three adjacent control domains. **Security.** Because private key compromise was the dominant theft vector in 2024 (Nairametrics, 2024), any outflow that does not correspond to an approved instruction should trigger escalation regardless of amount, which requires the matching engine to see instruction data at approval, not only after settlement. Zero trust and IT and OT security architecture research, including work on adversarial machine learning, SIEM and network detection, vulnerability governance and ransomware defense, provides patterns for restricting and verifying that instruction path (Adebayo et al., 2022; Adebayo, Adegbite, et al., 2023; Adegbite et al., 2020; Adegbite et al., 2022; Adegbite et al., 2023; Adegbite et al., 2024a; Adegbite et al., 2024b; Ahmed et al., 2021; Ogbole, Okoruwa, Fadayomi, et al., 2021; Ojukwu et al., 2023; Shittu et al., 2024), while incident response, intrusion detection, insider threat modeling, directory attack analysis, breach-and-attack simulation, malware classification, DDoS mitigation and secure software testing studies offer methods for testing whether alerts fire as intended (Akeju et al., 2018; Borah et al., 2022; Dosunmu & Ogundele, 2020; Dosunmu & Ogundele, 2021; Dosunmu & Ogundele, 2024a; Dosunmu & Ogundele, 2024c; Dosunmu & Ogundele, 2024d; Idika et al., 2021; Jimoh & Ahmed, 2024; Ladapo et al., 2018; Ladapo, Dosunmu, et al., 2023a; Mbonu et al., 2021b).

Financial reporting. Under fair value accounting, the formal snapshot for a reporting date should be the same snapshot used for disclosure of units, cost basis and fair value (Weaver, 2023), with lineage an auditor can trace back to specific block heights and transactions. Financial analytics research on capital allocation, data-driven executive decision systems, behavioral analytics, cost management, transfer pricing risk and predictive budgeting underlines why traceable lineage matters for decision quality as well as compliance (Adesuyi et al., 2022; Lawal & Oduleye, 2018a; Lawal & Oduleye, 2019a; Lawal & Oduleye, 2019b; Lawal & Oduleye, 2021a; Lawal & Oduleye, 2021b; Lawal & Oduleye, 2023b; Oduleye & Medon, 2021). **Prudential disclosure.** For banks, reconciliation outputs should carry the classification attributes required by the Basel templates (Regulation Tomorrow, 2024) from the normalization layer onward, so that disclosure is produced from reconciled data. Models for data sensitivity classification and regulatory traceability, data protection impact assessment in multi-cloud financial infrastructure, harmonized privacy compliance, privacy-focused digital identity and data governance architectures offer templates for carrying such attributes end to end (Aliliele et al., 2024a; Annan, 2022; Ilodigwe & Adesemoye, 2021; Kumuyi et al., 2024b; Mbonu et al., 2018; Mbonu et al., 2022a; Ominyi & Anichukwueze, 2022a; Peteranaba et al., 2023a).

3.5.3 Propositions

The model implies five propositions that future empirical work can test:

P1. Institutions that reconcile at block-height snapshots aligned to NAV and reporting cut-offs will experience fewer unexplained breaks at period end than institutions that reconcile to custodian statements alone.

P2. Independent observation of on-chain state, separate from the custodian, will shorten the time to detect unauthorized outflows.

P3. Reference data published on-chain by the accountable off-chain provider will reduce reference-data breaks relative to data sourced from third-party aggregators.

P4. Cryptographic inclusion proofs will increase client and auditor confidence in omnibus custody only when combined with continuous reconciliation and liability-side evidence.

P5. Multi-model consensus in AI-assisted data extraction will reduce downstream exceptions, with the effect strongest where human review is retained for low-agreement cases.

3.6 Discussion

Returning to the research questions, the synthesis shows first (RQ1) that 2024 converted reconciliation for digital assets from an operational practice into an institutional obligation. Exchange-traded products split custody and fund servicing across separate firms (U.S. Securities and Exchange Commission, 2024), tokenized funds made the blockchain a live register of beneficial ownership (BlackRock, 2024), and MiCA, the Basel disclosure framework and the approaching fair value standard turned reconciliation outputs into supervisory and financial statement inputs. At the same time, the scale of private key theft in 2024 (Nairametrics, 2024) showed that reconciliation is also a security control.

Second (RQ2), the advances of 2024 share a common direction. They move integrity assurance upstream, toward the point where data is created, as when DTCC remained accountable for NAV data it published on-chain (DTCC, 2024) or when AI extractions of corporate actions were reconciled before publication (Benzinga, 2024a). And they move it outward, toward third parties, as proof of reserves let clients verify inclusion without relying only on the record keeper (Coin Bureau, 2023). Read against the academic literature, these are applications of familiar ideas, namely continuous control monitoring, data provenance and independent verification, in a setting where the authoritative record is a public ledger.

Third (RQ3), the conceptual model suggests that the hardest problems are not computational. Reading a blockchain and matching records are well understood. The difficult questions are conventions and accountability: which block is the official snapshot, how cross-chain supply is counted, who attests to omnibus allocations, and what evidence an auditor should accept. These are matters of agreement between institutions, service providers and supervisors, which explains why the most productive 2024 initiatives were multi-party collaborations such as Smart NAV and Project Guardian.

Two tensions deserve attention. The first is between frequency and cost. Continuous reconciliation is technically feasible, but the 2024 vendor evidence describes daily and hourly batches (Rundlet, 2024), indicating that most institutions had not yet moved to event-driven matching. The second is between transparency and confidentiality. Public chains make positions observable, which aids verification but exposes institutional activity, and zero-knowledge techniques only partly resolve this. Research on data governance, privacy and cybersecurity governance (Adebayo, Adepoju, et al., 2023; Amayo et al., 2024a; Jimoh et al., 2023; Okoruwa et al., 2024; Ozowara et al., 2022)

suggests these trade-offs should be made explicitly at governance level rather than left to system design.

3.7 Implications

3.7.1 Theoretical implications

For research on audit and internal control, the study extends the concept of continuous assurance to an environment in which the external record is public and continuously updated, which removes the traditional distinction between the reconciliation source and the audit evidence. For research on data governance, it adds provenance and verifiability as first-class integrity properties alongside the conventional accuracy, completeness and timeliness. For information systems research, it frames reconciliation as a multi-party coordination problem, consistent with studies of cross-border data sharing and compliance harmonization.

3.7.2 Practical implications

For asset managers and asset owners, the model implies four actions:

1. Define official snapshot conventions (block height selection rules per chain) for every NAV, reporting and audit cut-off, and document them in the valuation policy.
2. Operate or contract at least one chain observation path independent of the custodian for all material positions.
3. Treat any unexplained outflow as a security incident, with detection latency targets measured in minutes for hot and warm wallets.
4. Require custodians to provide client-level inclusion proofs or equivalent attestation where assets are held in omnibus structures.

For custodians, transfer agents and administrators, it implies three:

1. Publish reference data, such as NAVs and supply figures, through channels that carry clear provenance and, where practical, on-chain attestation.
2. Reconcile token supply across all supported chains to the register at each NAV strike, and disclose the method used for in-flight cross-chain transfers.
3. Deliver on-chain events to clients through existing messaging standards so they can be consumed by current matching engines.

For all institutions, the literature on human factors in security, including awareness, authentication behavior, device practices and records confidentiality, is a reminder that controls fail through people as well as systems (Okoruwa et al., 2020; Onche & Ogbonna, 2022; Onche et al., 2020; Onche et al., 2023; Onche et al., 2024). Related work on cost governance, variance analytics, financial planning, benchmarking, cost optimization, procurement and vendor risk, lending forecasts and capital structure shows that management information depends on the same reconciled underlying data, so investment in reconciliation also improves decision support (Adesuyi, Kalu, et al., 2023; Aliliele et al., 2024; Anene et al., 2023; Bello et al., 2023; Dada et al., 2021b; Lawal & Oduleye, 2023a; Medon & Oduleye, 2023; Oduleye & Medon, 2023b; Okoli et al., 2024; Tonoyan et al., 2022b; Tonoyan et al., 2022c; Tonoyan et al., 2024a).

3.7.3 Policy and regulatory implications

For standard setters and supervisors, the findings suggest three priorities:

1. Develop common evidence standards for block-height snapshots and observation independence, aligned with the disclosure templates finalized in 2024.
2. Encourage interoperable conventions for counting multi-chain supply, building on frameworks such as the Guardian Funds Framework.

3. Recognize cryptographic attestations as supplementary evidence while clarifying their limits regarding liabilities and point-in-time manipulation.

4. Conclusion

The year 2024 did not invent real-time reconciliation for digital assets, but it made it an institutional obligation. This paper has shown how regulated exchange-traded products, tokenized funds, MiCA, the Basel disclosure framework, the approaching fair value standard and a high level of private key theft together raised the bar. It has documented the advances that responded, which shift integrity assurance upstream toward the point of data creation and outward toward third-party verification, and it has connected them to the wider literature on audit, payments, security and data governance.

The proposed conceptual model, comprising six architectural layers, five integrity properties and five propositions, offers institutions a basis for building and assessing their capability and offers researchers a basis for empirical testing. The remaining gaps, notably point-in-time proofs, liability-side verification, cross-chain counting conventions and evidence standards, are less about technology than about agreement, and closing them will require the multi-party collaboration among infrastructure providers, institutions and regulators that characterized the most productive 2024 initiatives.

4.1 Limitations

The study has several limitations. First, it is a structured narrative review rather than a formal systematic review; although inclusion criteria and screening steps were documented, the selection of industry sources involved judgment and may not be exhaustive. Second, much of the 2024 evidence comes from regulator announcements, pilot reports, vendor material and news coverage, which describe intentions and pilots more often than measured outcomes, and vendor claims were not independently verified. Third, the academic corpus was drawn from a single consolidated list and screened largely on titles; relevant studies outside that list were not considered, and some included studies are only semi-related to digital asset reconciliation. Fourth, the evidence window ends in December 2024, so requirements due to take effect later, such as the fair value standard and the Basel disclosure templates, are discussed as they were understood at that date. Finally, the conceptual model and its propositions have not been empirically validated.

4.2 Future research

The limitations and the open problems identified in the synthesis suggest an agenda for future research. Several problems remained unresolved at the end of 2024:

- **Point-in-time proofs.** Proofs of reserves are built from a snapshot of wallets and could be gamed by temporarily borrowed assets. Research is needed on continuous or randomized attestation that remains affordable at scale.
- **Liabilities and encumbrances.** Cryptographic techniques prove assets and user balances more readily than off-chain liabilities, rehypothecation or pledges. Methods that combine cryptographic and traditional audit evidence into a complete solvency view are an open question.
- **Cross-chain counting.** As fund shares and stablecoins proliferate across networks, conventions are needed to ensure bridged and native supply are each counted once, particularly during in-flight transfers.
- **Oracle and model dependency.** On-chain reference data concentrates reliance on interoperability layers and data providers, and multi-model

consensus does not eliminate shared errors. The systemic risk of these dependencies has not been studied.

- **Regulatory fragmentation.** Project Guardian participants noted that divergent national frameworks hinder cross-border distribution of tokenized assets. Comparative work is needed on how definitions of custody, segregation and cut-off differ, building on research on privacy by design in transaction structuring, statutory compliance strategy, compliance culture, legal risk education, automated regulatory risk assessment, contract review standardization, AI authorship, consumer protection law and ESG disclosure obligations.
- **Evidence standards.** Auditors and supervisors have not converged on what constitutes sufficient evidence of a block-height snapshot, how long it must be retained, or how node independence should be demonstrated.

Beyond these problems, three methodological directions follow from the study. First, empirical testing of propositions P1 to P5 through case studies, surveys of operations and audit teams, or analysis of break and incident data. Second, design science research that builds and evaluates reference implementations of the six-layer architecture, including measurement of detection latency. Third, systematic reviews with broader database searches to extend the academic evidence base beyond the corpus used here.

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