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Policy-as-Code and Fine-Grained Data Access Governance in Multi-Tenant Financial Platforms

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Abstract

Multi-tenant financial platforms, including banking-as-a-service providers, payment processors, wealth and brokerage platforms, and core-banking SaaS, must enforce authorization decisions that are simultaneously fine-grained, tenant-isolated, auditable, and fast. To date, three converging forces reshaped how these platforms approach the problem: the maturation of declarative authorization languages and engines (Open Policy Agent and Rego, Cedar, and Zanzibar-style relationship engines such as OpenFGA); the extension of governance controls into the data plane through row-level security, column masking, and unified catalogs; and a regulatory calendar that placed explicit, testable obligations on access control, most notably the retirement of PCI DSS v3.2.1 and the run-up to the EU Digital Operational Resilience Act (DORA). This paper synthesizes the current state of practice into a taxonomy of five architectural models for policy enforcement: centralized decision service, distributed sidecar, embedded library, data-layer native enforcement, and relationship-graph authorization. It then analyzes them against a common set of security properties. We argue that no single model is dominant; the defensible design for regulated multi-tenancy is a layered hybrid in which tenant isolation is enforced as a non-negotiable invariant at the lowest layer, while business-level entitlements are expressed as versioned, analyzable policy higher in the stack. We identify the principal trade-offs (consistency versus latency, expressiveness versus analyzability, centralization versus blast radius, and fail-closed safety versus availability) and present a reference architecture, a threat model, and a verification regime suited to financial supervision.

Keywords: Policy-as-code, authorization, ABAC, ReBAC, multi-tenancy, Open Policy Agent, Cedar, Zanzibar, row-level security, data governance, financial services, DORA, PCI DSS

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INTRODUCTION

Background and Motivation

Authorization has quietly become one of the hardest problems in financial platform engineering. Authentication is largely solved by federated identity standards; encryption at rest and in transit is a configuration exercise. Deciding, for every request, whether *this* principal acting for *this* tenant may perform *this* action on

this record, under *these* conditions, is not. The OWASP Top 10 has ranked broken access control as the most prevalent web application risk since its 2021 edition (OWASP Foundation, 2021), and in multi-tenant systems the failure mode is uniquely severe: a single missing predicate can expose one institution's customers to another. Studies of cyber risk governance in financial institutions consistently identify access governance as a central control domain (Aliliele & Iwuanyanwu, 2023b; Bello et al., 2024; Okafor, Osuji, et al., 2024).

Financial platforms intensify the problem in four ways. First, tenancy is nested: a banking-as-a-service provider hosts fintech tenants, which serve business customers, which have their own employees and delegated users. Second, entitlements depend on data attributes that change frequently, such as account ownership, transaction amount, jurisdiction, product type, and KYC status. Third, the data itself is regulated at field granularity (primary account numbers, tax identifiers, and personal data subject to GDPR or comparable regimes). Fourth, supervisors increasingly expect firms to *demonstrate* control effectiveness, not merely assert it.

Policy-as-code (PaC) is the practice of expressing authorization rules in a declarative, version-controlled language, evaluated by a dedicated engine decoupled from application logic. The premise is familiar from infrastructure-as-code: if rules are code, they can be reviewed, tested, diffed, analyzed, and rolled back. By 2024 this premise had moved from early adoption to mainstream architecture discussion, but the question of *where* policy is evaluated, and how it reaches down into the data layer, remained contested.

Problem Context

Three features of the operating environment shape the authorization problem in multi-tenant financial platforms: how tenants are isolated, which access control model is used to express entitlements, and which regulatory obligations attach to the resulting controls.

Multi-Tenancy Patterns in Financial Platforms

Multi-tenant architectures are conventionally described along a spectrum of isolation. The **silo** model provisions dedicated infrastructure (accounts, clusters, or databases) per tenant. The pool model shares infrastructure and separates tenants logically, typically by a tenant identifier on every row and every request. The bridge or hybrid model mixes the two, for example shared compute with per-tenant databases, or pooled storage for most tenants with silos for the largest or most regulated.

Financial platforms rarely sit at one point on this spectrum. Regulatory segregation requirements, customer contractual demands, and cost pressure push different data classes to different isolation levels. Card data in PCI scope may be siloed into a tokenization vault, while transaction metadata is pooled in an analytics warehouse. The authorization system must therefore operate correctly across *heterogeneous* isolation boundaries, which is a central reason a single enforcement point is rarely sufficient. Applied studies of multi-tenant SaaS and hybrid-cloud identity integration report the same heterogeneity in practice (Mbonu et al., 2020; Odejobi & Ahmed, 2018b; Ukadike, 2024).

Access Control Models

Three access control models dominate contemporary design. Role-based access control (RBAC) assigns permissions to roles and roles to users; it is simple to audit but suffers role explosion when permissions depend on context, a chronic problem in financial entitlements. Attribute-based access control (ABAC), standardized in NIST SP 800-162 (Hu et al., 2014), evaluates predicates over attributes of the subject, resource, action, and environment, offering high expressiveness. Relationship-

based access control (ReBAC) derives permissions from a graph of relationships between objects, an approach popularized by Google's Zanzibar system, which serves authorization for many Google products at very large scale (Pang et al., 2019). In practice, modern engines blend these: OpenFGA combines ReBAC with conditional ABAC (OpenFGA, n.d.), and Cedar supports RBAC-style groups, entity hierarchies, and attribute conditions in a single language (Cutler et al., 2024).

Regulatory Drivers in 2024

Several regulatory milestones made 2024 a pivotal year for access governance in finance:

- **PCI DSS v4.0.** Version 3.2.1 was retired on 31 March 2024, making v4.0 (and the limited revision v4.0.1, published June 2024) the operative standard (PCI Security Standards Council, 2024). Requirement 7 demands that access to system components and cardholder data be restricted by business need-to-know and defined in documented access control systems, with periodic review of user and application accounts. Several future-dated requirements become mandatory on 31 March 2025, making 2024 the final preparation year.
- **EU DORA (Regulation (EU) 2022/2554).** DORA entered into force in January 2023 and applies from 17 January 2025 (European Parliament & Council of the European Union, 2022). Its ICT risk management chapter requires documented information security policies and access controls, and the associated regulatory technical standards developed through 2024 set out expectations for logical access control procedures (Deloitte, 2023). DORA also brings ICT third-party providers into scope, which matters when an authorization engine is consumed as a managed service. Regional studies of continuity preparedness and cyber risk maturity in African financial services show that readiness for such obligations varies widely (Fadero et al., 2020; Fadero et al., 2021).
- **Data protection and data governance.** GDPR's principles of data minimization and purpose limitation translate directly into column- and purpose-level controls. The Basel Committee's BCBS 239 principles on risk data aggregation (Basel Committee on Banking Supervision, 2013) add expectations about lineage and accuracy that intersect with how masked or filtered data is consumed. Multi-jurisdictional platforms must reconcile these regimes with local laws such as Nigeria's data protection framework (Mbonu et al., 2022a; Mbonu, Aliliele, et al., 2019; Ominyi & Anichukwueze, 2022a).
- **Sectoral and national rules** such as SOX internal controls for financial reporting, GLBA safeguards in the United States, and central bank guidance in other jurisdictions (for example, the Central Bank of Nigeria's risk-based cybersecurity framework for deposit money banks) consistently require least privilege, segregation of duties, and evidence of periodic access review (Agu et al., 2023a; Akomolafe & Agu, 2019a; Mbonu et al., 2022).

The common thread is a shift from *control existence* to *control evidence*. A policy written in a general-purpose language and scattered through microservices is difficult to present to an auditor. A policy repository with tests, change history, and decision logs is not.

Contributions and Structure of the Paper

This paper makes four contributions:

- A structured synthesis of the 2024 policy-as-code landscape and of 208 applied studies on identity, cloud, data governance, financial compliance, and security operations, organized into eleven themes.
- A taxonomy and comparative analysis of five architectural models for enforcing policy-as-code in multi-tenant financial platforms, evaluated against security, performance, and governance properties relevant to regulated finance.
- A layered conceptual model, with testable propositions, that separates tenant

isolation invariants from business entitlements and attaches a governance plane that produces supervisory evidence.
- A discussion of the principal security trade-offs and their mitigations, with implications for practitioners, assurance functions, supervisors, and researchers.

The remainder of the paper is organized as follows. Section 2 describes the research method. Section 3 presents the results and discussion: the literature synthesis and research gaps (Section 3.1), the conceptual model and its propositions (Section 3.2), a discussion of security trade-offs and adoption choices (Section 3.3), implications (Section 3.4), limitations (Section 3.5), and directions for future research (Section 3.6). Section 4 concludes.

RESEARCH METHOD

Research Design

The study adopts a qualitative, two-stage design. The first stage is an integrative literature review, chosen because the topic spans heterogeneous sources (peer-reviewed systems research, open-source technical documentation, regulatory texts, and applied management and information systems research) that cannot be pooled statistically. The second stage is conceptual model building in the design-science tradition: findings from the synthesis are abstracted into a layered model, a set of propositions, and a verification regime that can be evaluated in subsequent empirical work. The unit of analysis is the authorization architecture of a multi-tenant financial platform, defined as the combination of enforcement points, decision points, policy and attribute sources, and governance processes that together determine whether a request is permitted.

Sources and Scope

Three bodies of evidence were used. Primary technical sources comprised peer-reviewed work on authorization languages and systems (for example, the Zanzibar and Cedar papers) and the official documentation of the principal engines and data platforms (Open Policy Agent, Cedar, OpenFGA, PostgreSQL). Regulatory and standards sources comprised DORA, PCI DSS v4.0.1, NIST SP 800-162, BCBS 239, and the OWASP Top 10. Applied research sources were drawn from a consolidated reference list of 1,056 deduplicated records spanning 70 subject areas, which served as the seed pool for the thematic synthesis. Selected factual claims about tooling and regulatory dates were verified against publisher or official pages. The temporal scope is restricted to material published in or before 2024, consistent with the paper's focus on the 2024 state of practice.

Inclusion and Exclusion Criteria

A record was included if it (a) was published in or before 2024, (b) carried a complete bibliographic record, and (c) addressed at least one of the following: identity and access control; cloud architecture or multi-tenancy; data protection and data governance; financial-sector technology risk and compliance; audit and internal control; fraud and financial crime analytics; payment infrastructure; security operations; critical infrastructure security as a design analogue; AI governance; or secure software delivery and IT service management. Records were excluded if their subject matter had no plausible bearing on authorization or governance (for example, agronomy, clinical medicine, livestock nutrition, or marketing attribution), if the record was truncated or unverifiable, or if it was published after the date of this review.

Screening Procedure

Screening proceeded in four passes. First, the 22 subject areas of the seed pool

closest to the topic, plus 14 individually relevant records from other areas, yielded 359 candidate records. Second, title-level relevance screening excluded 123 records whose contribution to the research question was marginal, leaving 236. Third, one truncated record was removed and 79 records dated after 2024 were excluded, leaving 156. Fourth, because the temporal restriction removed a substantial share of recent work, a supplementary screen of all remaining records published to date added 52 semi-related studies, chiefly on compliance workflows, traceability, treasury architecture, change management, and IT service delivery. The final applied corpus comprises 208 studies, complemented by 17 primary technical and regulatory sources, for a total of 225 references.

Table 1: Summary of the screening procedure.

Screening stage	**Records**
Consolidated seed pool (deduplicated)	1,056
Candidates from topic-relevant subject areas and individual relevant records	359
After title-level relevance screening	236
After removing incomplete records and records dated after 2024	156
Added through supplementary screen of records published to date	52
Final applied corpus	208
Primary technical and regulatory sources	17
Total references	225

Analysis

Analysis combined three techniques. Thematic coding assigned each applied study to one primary theme based on its title, abstract-level contribution, and subject area; the resulting eleven themes and their sizes are shown in Table 2. Comparative architectural analysis evaluated five enforcement models against a fixed set of properties (decision latency, consistency of revocation, coverage of non-API access paths, blast radius on compromise, availability dependency, auditability, policy portability, and fit for nested tenancy) derived from the primary technical sources. Trade-off analysis framed each security concern as a tension between two desirable properties, identified the associated failure modes, and recorded mitigations reported in the literature. The outputs of these techniques were then integrated into the conceptual model in Section 3.2.

Rigor and Trustworthiness

Credibility was supported by triangulating technical claims across independent sources, for example by checking statements about engine semantics against both the peer-reviewed papers and the project documentation. Transparency was supported by reporting the screening counts and inclusion rules explicitly. Because the study does not collect primary data, no ethics approval was required. Performance characteristics are reported qualitatively or attributed to their sources rather than measured, and the propositions in Section 3.2.4 are offered for empirical testing rather than as findings.

RESULTS AND DISCUSSION

This section presents the results of the review and analysis and discusses their meaning. Results are reported in two parts: the literature synthesis (Section 3.1) and the conceptual model derived from it (Section 3.2). The discussion then examines

Table 2: Thematic distribution of the applied research corpus

Theme	*Studies*	*Primary role in the argument*
Identity, access control, and zero trust	16	Identity and context layer; IAM integration
Cloud architecture, multi-tenancy, and infrastructure as code	14	Tenancy patterns; infrastructure governance analogue
Data protection, privacy, and data governance	18	Classification-driven column and purpose controls
Financial-sector cyber risk, regulatory compliance, and resilience	28	Supervisory context and risk prioritization
Audit, internal control, and continuous control monitoring	28	Evidence model; segregation of duties
Fraud, anti-money laundering, and financial crime analytics	12	Risk attributes for decision tiers
Payment infrastructure and distributed ledgers	20	Availability and tamper-evident logging
Security operations and enterprise cyber defense	19	Threat model; continuous validation
Operational technology and critical infrastructure security	9	Layered isolation analogue
AI governance, model risk, and agentic systems	13	Non-human principals; future research
Secure software engineering, DevOps, and IT service management	31	Governance plane; change control
Total	208	

security trade-offs and adoption choices (Section 3.3), followed by implications (Section 3.4), limitations (Section 3.5), and future research (Section 3.6).

Literature Synthesis

The literature synthesis covers the 2024 policy-as-code landscape (Section 3.1.1), the architectural models and data governance techniques through which policy is enforced (Sections 3.1.2 and 3.1.3), and the applied research corpus (Section 3.1.4), and closes by identifying research gaps (Section 3.1.5).

Policy-as-Code Foundations: The 2024 Landscape

Core Concepts

Policy-as-code architectures inherit the vocabulary of XACML: a policy enforcement point (PEP) intercepts a request and asks a policy decision point (PDP) for a decision; the PDP consults policies from a policy administration point (PAP) and attributes from policy information points (PIPs). What distinguishes modern PaC from earlier XACML deployments is the developer experience: policies live in Git, are tested in CI pipelines, are distributed as signed bundles, and are evaluated by engines designed for low latency.

Open Policy Agent and Rego

Open Policy Agent (OPA) is a general-purpose policy engine that graduated within the Cloud Native Computing Foundation in 2021 and is widely used for Kubernetes admission control, API authorization, and infrastructure policy (Open Policy Agent, n.d.). Policies are written in Rego, a Datalog-inspired query language that operates over arbitrary JSON input and data. OPA's generality is its main strength: it can authorize HTTP requests, validate Terraform plans, and gate deployments with the same toolchain. OPA 1.0, released in December 2024, made the stricter Rego v1 syntax the default, reducing a class of ambiguous-policy mistakes.

Two OPA capabilities are especially relevant to data governance. Bundles allow policies and reference data to be distributed to many engine instances with

signatures and versioning. Partial evaluation allows OPA to evaluate a policy with some inputs unknown and return residual conditions, which can be translated into SQL predicates or search filters (Sandall, 2018). This is the foundation of "query-time" authorization, discussed in Section 3.1.3.

Cedar

Cedar is an open-source authorization language released by AWS in 2023 and used by Amazon Verified Permissions and AWS Verified Access (Amazon Science, 2023). Cedar policies have a constrained structure: each permits or forbids a principal to perform an action on a resource, optionally under conditions. The design deliberately trades some expressiveness for analyzability. Its policy validator uses optional typing against a schema, and its semantics admit a sound and complete logical encoding, enabling automated questions such as "does this refactoring change any authorization outcome?" (Cutler et al., 2024). Cedar was presented at OOPSLA 2024, where its authors reported that it compared favorably with OpenFGA and Rego on performance in their evaluation (Cutler et al., 2024). A companion FSE 2024 paper described the verification-guided development process behind it, combining machine-checked proofs of a formal model with differential random testing against the production Rust implementation; proofs surfaced four soundness bugs in the validator and testing found 21 further bugs (Disselkoen et al., 2024).

For financial platforms, Cedar's two most valuable properties are *forbid-overrides-permit* semantics, which make guardrails such as "no access across tenants" expressible as standalone policies that cannot be overridden by a permissive rule, and the ability to analyze policy changes before deployment.

Zanzibar-Style Relationship Engines

Zanzibar, described by Pang et al. at USENIX ATC 2019, stores authorization as relationship tuples (for example, "user U is an owner of account A") and answers permission checks by traversing a schema-defined graph (Pang et al., 2019). Its key contribution to consistency is the *zookie*, an opaque consistency token that lets clients request evaluation at least as fresh as a given write, addressing the "new enemy" problem in which a permission revocation and a subsequent content change are observed out of order.

OpenFGA, originally developed by Auth0 and Okta, implements this model as open source and was accepted into the CNCF Sandbox in September 2022 (OpenFGA, n.d.). SpiceDB is another prominent open-source Zanzibar implementation. ReBAC engines fit naturally with the nested tenancy of financial platforms: "a user can view an account if they are a signatory of the account, or an administrator of the business that owns it, or an operator of the fintech tenant that owns that business."

Data-Plane Policy Primitives

In parallel, the data platforms themselves acquired richer policy primitives. PostgreSQL has supported row-level security (RLS) policies since version 9.5 (PostgreSQL Global Development Group, n.d.). Cloud warehouses offer row access policies, dynamic data masking, and tag-based policies that apply masking to every column carrying a classification tag. Databricks open-sourced Unity Catalog in June 2024 (Databricks, 2024), signaling that catalog-level governance (lineage, tags, grants) was becoming an interoperable layer rather than a proprietary feature. These primitives matter because they enforce policy *where the data lives*, independent of which application path reaches it.

Architectural Models of Enforcement

We identify five recurring architectural models. Each describes where the PDP runs relative to the PEP and the data, and how policy and attributes reach the

Table 3: Principal policy engines and data-plane primitives in the 2024 landscape

Engine / primitive	*Model*	*Policy style*	*Analyzability*	*Typical role in finance*
OPA / Rego	ABAC, general	Datalog-like over JSON	Testing; limited formal analysis	API gateways, service authorization, infra and deployment guardrails
Cedar	RBAC + ABAC + hierarchy	Structured permit/ forbid	Schema validation; SMT-based equivalence analysis	Application entitlements, tenant guardrails
OpenFGA / SpiceDB	ReBAC + conditions	Schema + relationship tuples	Model tests; graph queries	Nested tenancy, delegated and shared access
Database RLS / masking	Row and column predicates	SQL policies	Limited; tested via queries	Last-line tenant isolation, PII and PAN masking
Catalog tag policies	Classification-driven	Tags + grants	Inventory and lineage reports	Analytics, data sharing, regulatory reporting

decision. Real platforms combine several; the models are presented separately to isolate their properties.

Model A: Centralized Decision Service

A single logical authorization service, often replicated for availability, receives decision requests from all services over the network. Policies and entitlement data are managed centrally. Managed offerings such as Amazon Verified Permissions follow this pattern.

Strengths. One place to change policy, one decision log, consistent semantics across services, and simple evidence for auditors. Revocation takes effect globally as soon as the service's state changes.

Weaknesses. Every authorization adds a network round trip; the service is on the critical path of every transaction and becomes a high-value target and a single point of failure. In multi-region deployments with data residency requirements, a central service may need to be regionalized, which erodes the "single place" benefit.

Model B: Distributed Sidecar or Host-Local Agent

A policy engine runs next to each service, as a sidecar container or host daemon, and evaluates policy locally. A control plane distributes signed policy bundles and reference data. This is the canonical OPA deployment in Kubernetes environments (Open Policy Agent, n.d.).

Strengths. Sub-millisecond local decisions, no central runtime dependency, and graceful operation during control-plane outages. Blast radius of an engine compromise is limited to one workload.

Weaknesses. Policy and data are eventually consistent across the fleet; during rollout, different services may run different policy versions. Large entitlement datasets do not fit comfortably in every sidecar, forcing either external data lookups (reintroducing latency) or data partitioning by tenant.

Model C: Embedded Library

The policy engine is linked directly into the application as a library. Cedar's Rust implementation and its bindings, and OPA compiled to WebAssembly, both support this pattern.

Strengths. Lowest latency and simplest runtime topology; the application can pass rich in-memory entities without serialization.

Weaknesses. Engine upgrades require application releases; decision logging and policy distribution must be re-implemented per service; and the boundary between "policy" and "application" can blur as developers pass pre-filtered or

application-computed attributes, weakening auditability.

Model D: Data-Layer Native Enforcement

Policy is enforced inside the database, warehouse, or catalog through RLS, masking functions, and tag-based grants. The application sets session context (tenant, user, purpose) and the data platform filters and masks accordingly.

Strengths. Enforcement holds regardless of access path, including ad hoc SQL, BI tools, and data pipelines that bypass application APIs. This makes it the strongest model for tenant isolation and for regulated fields, and it aligns with lakehouse and privacy-preserving analytics architectures proposed for regulated industries (Atakpa & Abolaji, 2022).

Weaknesses. Policy languages are platform-specific, so the same rule may be written several times for different stores. Session context is a trust boundary that is easy to get wrong, particularly with connection pooling. Complex relational predicates can degrade query plans, and testing and formal analysis tooling is weaker than for dedicated policy languages.

Model E: Relationship-Graph Authorization

A Zanzibar-style service stores relationship tuples and answers check, list-objects, and list-users queries. Applications write tuples as business events occur (an account is opened, a signatory is added) and query the graph for decisions.

Strengths. Natural expression of nested and delegated access; efficient "which accounts can this user see?" queries; explicit consistency tokens (Pang et al., 2019).

Weaknesses. The authorization graph is a second source of truth that must be kept synchronized with the system of record. Drift between them is a correctness and security risk, and dual writes require outbox patterns or change-data-capture pipelines. The model is less natural for purely attribute-driven rules such as transaction limits. Identity-centric zero trust models suggest combining relationship graphs with machine-identity governance so that service principals are first-class nodes (Ogbole et al., 2021).

Comparative Summary

The table makes one pattern clear: models that excel at fine-grained business entitlements (A, B, C, E) are weak at covering every path to the data, while the model that covers every path (D) is weak at expressing and analyzing business policy. This tension motivates the layered design in Section 3.2.

Table 4: Qualitative comparison of architectural models.

Property	*A. Central*	*B. Sidecar*	*C. Embedded*	*D. Data-layer*	*E. ReBAC graph*
Decision latency	Network hop	Local, very low	In-process, lowest	Inside query	Network hop + graph traversal
Consistency of revocation	Strong	Eventual (bundle lag)	Eventual (release lag)	Strong per store	Tunable (consistency tokens)
Coverage of non-API paths	Low	Low	Low	High	Low
Blast radius if PDP compromised	Platform-wide	One workload	One service	One data store	Platform-wide
Availability dependency	High	Low	None	Coupled to data store	High
Auditability	High	High with central logs	Medium	Medium	High
Policy portability	High	High	High	Low	Medium
Fit for nested tenancy	Medium	Medium	Medium	Low	High

Fine-Grained Data Access Governance

Granularity Levels

Fine-grained governance operates at several levels, each with a different enforcement mechanism:

- **Resource or API level:** may this principal call this endpoint or perform this action on this object type?
- **Row (record) level:** which accounts, transactions, or customers is the principal permitted to see?
- **Column (field) level:** which attributes of a permitted record may be seen in clear, masked, tokenized, or not at all?
- **Cell or value level:** conditions on specific values, for example showing a balance only if below a threshold for a given role.
- **Purpose level:** the same data may be permitted for fraud investigation but not for marketing, reflecting GDPR purpose limitation.

The Filtering Problem

Point checks ("may user U read account A?") are straightforward for any engine. The hard problem in financial data is *filtering*: "return all transactions user U may see, page 3, sorted by date." Evaluating a point check for every candidate row is prohibitively slow at scale. Three techniques are used:

- **Pre-filtering through the authorization engine.** A ReBAC engine's list-objects query returns the set of permitted identifiers, which the application passes into the data query. This works when permitted sets are modest, but degrades for administrators who can see millions of objects.
- **Policy compilation to query predicates.** The engine partially evaluates policy with the resource unknown and emits residual conditions, which are translated to SQL WHERE clauses or search filters. OPA's partial evaluation supports this (Sandall, 2018), and Cedar has been explored for similar partial evaluation. This keeps policy authoritative while letting the database do the filtering.
- **Native data-layer enforcement.** RLS policies apply the filter inside the database, typically keyed on session variables set by the application.

An illustrative example of technique 2: a Rego policy permitting relationship managers to see accounts in their assigned branch within their tenant can be partially evaluated with the account unknown, yielding a residual such as the predicate below, which the data access layer appends to every query.

```
# Residual after partial evaluation (conceptual)
account.tenant_id = "t-4821"
  AND account.branch_id IN ("br-07", "br-12")
  AND account.status != "restricted"
```

The security risk in compilation is translation fidelity: if the translator mishandles a construct, the generated predicate may be broader than the policy. Translators should therefore fail closed on unsupported constructs and be covered by differential tests that compare engine point-check results with query results on sampled data.

Tenant Context Propagation

Every model depends on a trustworthy assertion of "which tenant is this request for." In financial platforms that assertion should originate from a verified token claim or mTLS identity, never from a request parameter, and should be propagated through service calls as signed context. Common failure modes include services that accept tenant identifiers from request bodies, background jobs that run without tenant context and default to unrestricted access, and pooled database connections that retain the previous request's session variables. The last is

particularly insidious with RLS: if a session variable is set with a session-scoped command rather than a transaction-scoped one, a pooled connection can leak another tenant's context to the next request. Federated IAM models emphasize that identity assertions must be verified at every hop rather than inherited (Mbonu et al., 2022b; Oshoba et al., 2019).

Column Protection and Classification

Column-level governance is most robust when driven by classification rather than by enumerating columns. Tag-based policies (for example, any column tagged as a primary account number is masked for all roles except a tokenization service) scale with schema evolution and give auditors a single control to inspect. For PCI-scoped data, masking is a complement to, not a substitute for, tokenization and scope reduction: the strongest column control is that the column never exists in the general-purpose store. Sensitivity classification and regulatory traceability frameworks provide the tagging discipline this approach requires (Aliliele & Iwuanyanwu, 2024a; Mbonu et al., 2018; Okoruwa et al., 2020).

Thematic Synthesis of Applied Research

This paper builds on a broad body of applied research spanning identity governance, cloud security, data protection, financial-sector compliance, fraud analytics, payment infrastructure, security operations, and AI governance, restricted to work published in or before 2024. The studies below are grouped by theme, and each is cited individually where its contribution bears on the argument of this paper.

Identity, access control, and zero trust. The closest antecedents to this paper address identity and access management (IAM) as an architectural layer. Reviews of IAM integration in hybrid and multi-cloud environments (Mbonu et al., 2020) and of access governance optimization in large AWS estates (Mbonu et al., 2022b) document the operational difficulty of keeping entitlements consistent across providers, which motivates the externalized policy decision points discussed in Section 3.1.2. Models for secure IAM in distributed and federated systems (Oshoba et al., 2019) and identity-centric zero trust governance (Ogbole et al., 2021) align with the identity and context layer (L1) of the reference architecture. Attribute-based encryption for access control in supply chain systems (Shittu & Nabil, 2023) and a systematic review of privacy-driven access control policies in BYOD settings (Ladapo, Jooda, et al., 2023b) illustrate cryptographic and attribute-based alternatives to purely policy-engine enforcement. Work on role-based security architecture with privacy by design in Salesforce environments (Badmus & Anunagba, 2024) offers a CRM-platform view of field-level protection, while zero trust for operational technology (Ahmed et al., 2021) shows how the same principles transfer to other regulated sectors. Studies of Active Directory attack techniques, offline assessment of security-critical directory systems, and directory implementation for enterprise networks (Ladapo et al., 2018; Ladapo et al., 2019; Ladapo, Dosunmu, et al., 2023a) underline that directory misconfiguration remains a leading source of privilege escalation. Privacy-focused digital identity verification for financial inclusion in Africa (Kumuyi et al., 2024b) is directly relevant to KYC attributes that feed authorization decisions. Behavioral studies of BYOD risk in administrative offices (Onche et al., 2023), password practices and data-protection compliance (Onche & Ogbonna, 2022), records confidentiality and security awareness (Onche et al., 2020), and the effect of awareness training on insider-threat behavior (Onche et al., 2024) remind designers that human factors bound the effectiveness of any technical control.

Cloud architecture, multi-tenancy, and infrastructure as code. A second group examines the cloud substrate on which multi-tenant platforms run. Continuous cloud misconfiguration monitoring (Aliliele & Iwuanyanwu, 2023a) and

infrastructure-as-code governance for Terraform deployments (Mbonu et al., 2020b) parallel the policy-as-code argument at the infrastructure layer, and a blockchain-backed audit trail for cloud configuration management (Oshoba et al., 2020) addresses the same evidentiary need as signed policy bundles. Performance evaluation of multi-tenant Microsoft 365 deployments under high concurrency (Odejobi & Ahmed, 2018b) and a framework for scaling B2B SaaS ventures across multiple clouds (Ukadike, 2024) speak directly to tenancy and isolation trade-offs, and orchestration of multi-vertical digital ecosystem platforms (Osuji et al., 2024) illustrates the shared-platform, many-participant structure that drives nested tenancy. Secure cloud architectures for enterprise messaging (Ahmed & Odejobi, 2018a) and malware classification for cloud-native microservices (Idika et al., 2021) inform the threat surface of distributed sidecar deployments. Best practices for enterprise cloud migration (Ladapo, Jooda, et al., 2022) show that authorization logic is frequently rewritten during migration, which is the natural moment to externalize it as policy. Machine-learning models for cloud resource scaling (Ahmed et al., 2020) and for rightsizing and long-term usage forecasting (Upreti & Oteri, 2023) bear on capacity planning for PDP clusters, and an approximation-complexity model for cloud database optimization (Odejobi et al., 2019) is relevant to the query-plan cost of injected row-level predicates. MuleSoft integration patterns in multi-cloud Salesforce architectures (Badmus et al., 2022b) describe integration layers through which tenant context must be propagated intact, and secure data center lifecycle management (Amayo et al., 2024a) addresses the physical layer beneath silo deployments.

Data protection, privacy, and data governance. Fine-grained data access governance depends on knowing what data is sensitive and why. A framework for enterprise data sensitivity classification and regulatory traceability (Aliliele & Iwuanyanwu, 2024a) underpins the classification-driven column controls of Section 3.1.3, and legal and ethical risk modeling for enterprise data protection governance (Mbonu et al., 2018) frames the obligations those controls serve. Data protection impact assessment models for multi-cloud financial infrastructure (Mbonu et al., 2022a), comparative reviews of data protection regulation and secure cloud implementation across jurisdictions (Mbonu, Aliliele, et al., 2019), and a framework for harmonizing compliance across GDPR, NDPR, and United States privacy regimes (Ominyi & Anichukwueze, 2022a) are especially pertinent to platforms serving tenants in several jurisdictions, including Nigeria. A privacy-preserving data architecture for regulated analytics under GDPR and HIPAA (Atakpa & Abolaji, 2022), privacy-centric security engineering for cloud systems (Okoruwa et al., 2020), real-time compliance pipelines for enterprise data governance (Uchechi et al., 2022), and privacy governance for cross-border digital platforms (Annan, 2022) complement the data-layer model (Model D). Privacy by design in corporate restructuring (Ominyi, 2021) is relevant when tenants merge or split and entitlements must be re-partitioned, and blockchain-based cross-border data exchange for regulatory transparency (Kumuyi et al., 2023) addresses verifiable data sharing between jurisdictions. Research from health and life sciences on HIPAA-compliant data architecture (Aliliele & Iwuanyanwu, 2024b), data integrity failures and controls in regulated life sciences (Aneke et al., 2023), comparative health information governance frameworks (Peteranaba et al., 2022), HIPAA-compliant digital documentation workflows (Peteranaba et al., 2023a), structured clinical record protection (Nnaji & Akinlolu, 2024a), blockchain and cryptographic strategies for privacy-preserving health data (Afrihyia & Akinse, 2024), and ethical data practices in healthcare EdTech (Orise & Niniola, 2023) provides transferable lessons on auditable, field-level protection and purpose limitation.

Financial-sector cyber risk, regulatory compliance, and resilience. A large group of studies addresses how financial institutions govern technology risk. A

cybersecurity risk management and regulatory compliance framework for financial institutions (Bello et al., 2024), a review of API governance and risk prioritization in financial institutions (Aliliele & Iwuanyanwu, 2023b), and a framework for harmonizing risk governance, technology infrastructure, and compliance in future-ready banking (Okafor, Osuji, et al., 2024) frame the institutional context for the trade-offs in Section 3.3.1. Assessments of cyber risk maturity in Nigeria's insurance sector against NAICOM and NDPR requirements (Fadero et al., 2021) and of business continuity and disaster recovery preparedness in African financial services (Fadero et al., 2020) ground the analysis in emerging-market supervision. Risk-based business intelligence architecture for fintech platforms (Mbonu et al., 2021a) and data-driven risk evaluation for emerging-market financial institutions (Akomolafe & Agu, 2019b) describe the analytics estates whose access must be governed, while integrated governance for financial resilience (Akomolafe & Agu, 2019c) and quantitative compliance-risk assessment in emerging economies (Akomolafe & Bello, 2023b) supply methods for prioritizing which policies warrant the strongest verification. Capital adequacy and risk-weighted asset frameworks (Mensah et al., 2019) and credit decisioning and governance in emerging-market corporate portfolios (Uzondu et al., 2020) matter because the data feeding capital and credit decisions is among the most sensitive in a bank. Digital transformation in capital markets operations (Sanni & Attah, 2023a) shows the same pressures in securities processing. Reviews of cybersecurity governance frameworks (Jimoh, Ahmed, et al., 2023) and of risk-based cybersecurity assurance and data availability (Fadayomi et al., 2019) frame the availability side of the fail-closed trade-off. Post-merger compliance integration in multi-jurisdictional banking (Ominyi, 2020), regulatory clearance for cross-border mergers in African financial markets (Ominyi & Anichukwueze, 2020), AML and anti-bribery regimes across emerging and developed markets (Ominyi & Anichukwueze, 2021), tax governance and cross-border compliance analytics (Lawal & Oduleye, 2018b), digital trade regulation harmonization (Jones & Ominyi, 2024b), and compliance frameworks for technology transfers between developed and emerging markets (Jones & Ominyi, 2023) show the jurisdictional complexity that tenant-aware policy must encode. Shared responsibility and multi-jurisdictional alignment in supply chain governance (Ominyi et al., 2021) offers a useful analogue for the shared-responsibility model between platform and tenant. Translating regulatory requirements into compliance workflows (Eyetsemitan et al., 2021), automated risk assessment for regulatory deliverables (Uchechi & Ominyi, 2020), regulatory-compliant procurement in high-risk environments (Okonkwo et al., 2021), regulatory readiness maturity models (Eze et al., 2022b), and ethics and compliance training design (Anichukwueze et al., 2020) support treating policy-as-code as a shared artifact between engineering and compliance. Evidence on cyber risk pricing in technology platforms (Adebayo & Ozowara, 2023) and on the financial impact of cybersecurity investment (Ozowara et al., 2022) helps justify investment in layered authorization.

Audit, internal control, and continuous control monitoring. Policy-as-code is ultimately a control technology, and the audit literature supplies the vocabulary for evaluating it. AI-enabled IT general controls and SOX audit automation (Mbonu et al., 2022) maps closely to the evidence model in Table 6. A comparative review of SOX compliance frameworks in cross-border financial auditing (Agu et al., 2023a), risk-based internal control models for insurance and banking (Akomolafe & Agu, 2019a), and technology-enabled internal audit quality (Akomolafe & Agu, 2018) inform the segregation-of-duties invariants of Section 3.2.2. Risk-based auditing in strategic financial management (Akomolafe & Bello, 2023a) and security audit and enterprise risk assessment frameworks (Dosunmu & Ogundele, 2019) define what an auditor will expect to test in a policy pipeline. Reconciliation control and

workflow redesign (Dogbatsey et al., 2019), audit liaison and corrective action planning in multinational organisations (Ebhojie & Oyeleye, 2023a), budget compliance and statutory reporting in Sub-Saharan Africa (Dogbatsey & Ebhojie, 2018), data-driven tax compliance and financial reporting in banks (Bola-Sadipe & Odihi, 2022), and data-driven auditing of payroll and receivables (Okoli et al., 2022) describe the corrective and reporting processes that consume access-review findings. Strategic accounting systems for regulatory compliance (Bola-Sadipe & Eboh, 2019), automated financial consolidation in multinationals (Bola-Sadipe & Odihi, 2023), and comprehensive financial reporting for organizational accountability (Medon & Oduleye, 2022) all depend on strictly partitioned, role-restricted financial data, and integrated data management for forecasting (Agu et al., 2023b) represents the analytical consumers whose access is governed by column- and purpose-level policy. Traceability and chain-of-custody integrity (Aneke & Adesemoye, 2019), end-to-end visibility for compliance and traceability (Nnabueze et al., 2021), and blockchain-driven smart compliance for automated reporting (Abioye et al., 2023) correspond to the tamper-evident decision logs of Section 3.3.1. Risk-based decision-making in GMP environments (Aneke & Adesemoye, 2020) and CAPA effectiveness in quality management (Aneke et al., 2022a) offer mature models of control remediation. Embedded IT risk and ISO controls in digital transformation (Mbonu et al., 2020a), standardized compliance controls for high-volume distribution networks (Uchechi et al., 2023), data-driven procurement risk management (Bello & Agu, 2023), data-led cost governance in technology-intensive enterprises (Adesuyi, Kalu, et al., 2023), standardized contract review workflows (Uchechi et al., 2021), AI-supported revenue assurance (Sakyi et al., 2023), and audit analytics in multilateral healthcare finance (Abetoh & Atakpa, 2024) extend control design to adjacent operating contexts, and adaptive control models for AI-driven automation in financial compliance environments (Sanni et al., 2022) show how lifecycle controls can be made machine-verifiable.

Fraud, anti-money laundering, and financial crime analytics. Authorization and fraud controls meet at the transaction boundary: a request can be both authorized and fraudulent. A systematic review of machine learning for fraud detection in banking (Atakpa & Abetoh, 2022), predictive analytics for AML in commercial banking (Atakpa, 2021), an adaptive fraud risk scoring model for real-time transaction monitoring at scale (Fadayomi et al., 2024), and an integrated cybersecurity and AML governance framework (Fadayomi et al., 2021) inform the risk-tiered decision classes proposed in Section 3.3.1. Synthetic identity fraud detection (Elebe et al., 2023) and predictive fraud prevention in public systems (Adelanwa & Anene, 2023b) show signals that can enrich authorization context. Anomaly detection in financial time series (Atakpa & Fobellah, 2023), VoIP forensic analytics for fraud detection and compliance monitoring (Mbonu et al., 2021), and financial forensics for cyber-enabled fraud in telemedicine (Ekechi et al., 2022) describe post-hoc detection that depends on complete decision logs. AI for healthcare payment fraud detection (Atakpa et al., 2024), analytics for venture capital and private equity fraud risk (Eboh & Aliliele, 2024), and machine learning in insurance underwriting (Oluwo & Isiekwu, 2024) illustrate how the same data assets are reused across purposes, reinforcing the need for purpose-level controls.

Payment infrastructure and distributed ledgers. Multi-tenant financial platforms increasingly operate payment rails on behalf of tenants. Controls for cross-border payment operations and correspondent banking risk (Okafor, Farounbi, et al., 2024) and the engineering of high-throughput collections platforms for large payment ecosystems (Osuji et al., 2021) are directly relevant to the availability and fail-closed trade-off in Section 3.3.1. Blockchain-based architectures for tamper-proof regulatory recordkeeping and audit readiness (Anichukwueze et al., 2021) offer an alternative design for tamper-evident decision logs. Interoperability models

for distributed ledger cross-border payments (Adesuyi, Akomolafe, et al., 2023) raise the question of how authorization context travels between ledgers operated by different parties. AI-driven risk scoring for cross-border trade payments (Adesuyi et al., 2024) and predictive remittance liquidity optimization (Akomolafe et al., 2023) supply attributes that payment authorization policies may consume. A scalable blockchain payment gateway architecture (Akomolafe et al., 2024a), smart contract automation for supplier payments (Akomolafe et al., 2022), smart contract-based dispute resolution (Akomolafe et al., 2024b), and blockchain-enabled smart contracts for verifiable workflows (Sanni et al., 2024) encode authorization rules in contract code, a form of policy-as-code with immutable deployment, and blockchain-based supply chain coordination (Ekwunife et al., 2024) shows the same pattern outside payments. Tiered treasury architecture for multinational cash consolidation and FX risk control (Dada & Oluwo, 2021a) illustrates hierarchical entitlements over pooled funds. Work on fintech-enabled transaction banking (Okafor et al., 2021), customer data platforms for emerging-market banks (Ukadike, 2022), digital banking transformation in Sub-Saharan Africa (Agboada et al., 2022), CRM-based forecasting for lending institutions (Dada & Oluwo, 2021b), and relationship banking performance (Ezeako et al., 2019) situates these platforms in the markets they serve. Regulatory compliance adaptation for cross-border payment products (Olaogun et al., 2023) and determinants of web payment portal adoption in Sub-Saharan Africa (Agyei et al., 2019) contextualize adoption, while blockchain-assisted secure data exchange in power systems (Shittu et al., 2022) shows ledger-backed access in a different regulated domain.

Security operations and enterprise cyber defense. The threat model of Section 3.3.1 draws on research into adversary behavior and defensive validation. Insider threat classification and risk modeling (Akeju et al., 2018) is directly relevant to confused-deputy and privileged-access abuse. Breach and attack simulation for continuous validation of security controls (Dosunmu & Ogundele, 2024a), enterprise-scale continuous security validation for regulated infrastructures (Dosunmu & Ogundele, 2024c), and threat-informed defense engineering for measuring control effectiveness (Dosunmu & Ogundele, 2024d) support the cross-layer adversarial testing recommended in Section 3.2.3. Enterprise log analytics with SIEM platforms (Mbonu, Iwuanyanwu, et al., 2019), integrated network and security operations centers (Ladapo, Dosunmu, et al., 2024), and cyber risk quantification for prioritizing security investment (Dosunmu & Ogundele, 2024b) relate to decision-log consumption and risk-based prioritization. Intrusion detection and prevention models (Dosunmu & Ogundele, 2020) and incident response and digital forensics for rapid containment (Dosunmu & Ogundele, 2021) depend on authorization decision logs as a forensic source. Threat intelligence integration (Dosunmu & Ogundele, 2022) and threat actor analysis for strategic security planning (Dosunmu & Ogundele, 2023) inform the threat model behind tenant-targeted attacks, and analysis of NTP amplification DDoS attacks and mitigation (Jimoh & Ahmed, 2024) is a reminder that a centralized PDP is also an availability target. Multi-layered quantitative risk architecture (Ike et al., 2024a), real-time ML-based risk dashboards (Filani et al., 2022), predictive risk analytics for early warning in technology estates (Okwesa et al., 2024), and reviews of enterprise threat evolution (Okoruwa, Fadayomi, et al., 2024) frame governance reporting. Secure and scalable supply chain systems (Okonkwo et al., 2024b), IoT security in critical transport infrastructure (Jimoh, Abolle-Okoyeagu, et al., 2023), and federated learning for secure cross-organizational data management (Sanni et al., 2023) address the integration boundaries where tenant isolation is most often weakened.

Operational technology and critical infrastructure security. Although outside finance, research on critical infrastructure offers mature thinking about layered

isolation and fail-safe design. Security architecture for IT and OT convergence in regulated energy networks (Adegbite et al., 2022) and vulnerability governance from exposure mapping to remediation verification (Adegbite et al., 2024a) provide transferable patterns for defense in depth and for presenting control effectiveness to regulators. Adversarial machine learning threat modeling for AI-enabled OT (Adebayo & Ahmed, 2022) and AI-augmented ICS threat detection (Adebayo & Ahmed, 2023) show how ML-based controls can themselves be attacked, a caution for risk-scored authorization. NERC CIP compliance and architecture for utility OT networks (Adegbite et al., 2020), SIEM and NDR detection architectures for ICS (Adegbite et al., 2023), and AI-driven utility SOC architecture (Adegbite et al., 2024b) offer mature examples of regulator-facing control evidence. Physics-informed OT ransomware defense (Ojukwu & Nwakamma, 2023) and digital substation resilience (Shittu & Shittu, 2024) reinforce the argument for independent lower-layer isolation.

AI governance, model risk, and agentic systems. As AI agents begin to act on behalf of users, authorization must extend to non-human principals. Securing agentic AI enterprise workflows against prompt injection, tool poisoning, and excessive agency (Nwakamma & Oyesiji, 2024b) and the argument that autonomous agents demand a new interaction paradigm (Ogundairo & Ayivi-Donkor, 2024b) are the most direct precursors to the future direction outlined in Section 3.6. Reviews of algorithmic accountability and model risk management in financial services (Ominyi & Anichukwueze, 2023), responsible AI governance for automated decision systems in regulated industries (Ominyi & Anichukwueze, 2024), comparative governance of AI-driven management with executive oversight and accountability (Afrihyia & Ojukwu, 2024), and organizational readiness for the EU AI Act (Ominyi & Uzougbo, 2024b) frame the governance obligations that would attach to AI-mediated access decisions. AI-assisted compliance monitoring and anomaly detection in high-volume transactions (Ominyi & Uzougbo, 2024a) represents an AI system that itself requires scoped, policy-governed data access. LLM-as-a-judge for automated model governance and release gating (Nwakamma & Oyesiji, 2024a) and context-aware data curation for fine-tuning (Oyesiji et al., 2024) are relevant because AI pipelines must apply tenant and row filters before content reaches a model. Human-in-the-loop machine learning (Ladapo, Dosunmu, et al., 2022) and human-centered automated annotation with generative AI (Ladapo, Jooda, et al., 2024) support keeping human approval in the loop for high-impact policy changes. Algorithmic accountability and trade secret protection (Annan, 2024) defines legal limits on explainability of automated decisions, and structuring business problems into AI-ready requirements (Alieme et al., 2024) addresses the organizational dimension.

Secure software engineering, DevOps, and IT service management. The governance plane (L5) depends on disciplined delivery pipelines. Systematic reviews of CI/CD pipeline strategies (Badmus & Ozowara, 2018) and comparative evaluation of DevOps tooling (Badmus et al., 2020), Git-based version control and code review governance (Badmus et al., 2022a), AI techniques for secure testing and regression control (Mbonu et al., 2021b), AI applications in software testing (Borah et al., 2022), and structured user acceptance testing for technology deployment (Eyetsemitan et al., 2023b) map to the policy review, testing, and staged rollout practices of Section 3.2.3. Governance models for change, incident, and problem management in mission-critical IT (Olagunju et al., 2023) and IT service management practice and ServiceNow platforms (Ladapo, Dosunmu, et al., 2023b; Ladapo, Jooda, et al., 2023a) address the operational processes around policy change, as do supply chain automation on service management platforms (Okonkwo et al., 2024f) and integration of IT systems engineering with operations (Okonkwo et al., 2023). ETL design in Salesforce-centric architectures (Badmus

& Ozowara, 2019a) and Salesforce platform governance in regulated healthcare (Badmus & Ozowara, 2019b) address platform-specific permission models that must be reconciled with central policy. Data-integrated ERP migration (Chibwaye & Oteri, 2023), change management in digital transformation (Eyetsemitan et al., 2023a), standard operating procedures as change infrastructure (Agboada et al., 2019), standardization of reporting and decision workflows (Alieme et al., 2022), digital transformation of operations management (Agboada et al., 2018), and measurement of change program success (Obukadata et al., 2022) describe the organizational change that accompanies a move to policy-as-code. Project governance in multinational programs (Amayo et al., 2023a), digital supply chain governance (Okonkwo et al., 2024a), automation-led risk reduction in service delivery (Sakyi et al., 2024b), process automation for procurement transparency (Akinleye & Adeyoyin, 2021), and integrated digital platforms for procurement transparency (Okoruwa, Babatope, et al., 2024) show governance-by-workflow in adjacent domains. Executive dashboards and data-driven decision systems (Lawal & Oduleye, 2019b; Sanni & Atima, 2021b), IT support maturity and hybrid support continuity (Anyanwu, 2019; Anyanwu, 2020), predictive capacity planning for IT portfolios (Edivri & Oteri, 2022), KPI-driven IT service delivery (Edivri & Oteri, 2024), and performance optimization for high-demand technology programs (Olagunju et al., 2024) inform how the operational health of the authorization service itself should be measured and reported.

Synthesis and Research Gaps

Read together, the technical and applied literatures reveal five gaps that motivate the conceptual model.

- **Disconnected literatures.** Systems research on authorization languages emphasizes semantics, analyzability, and performance, while applied research on financial-sector governance emphasizes frameworks, maturity, and compliance (Bello et al., 2024; Okafor, Osuji, et al., 2024). Few studies connect declarative policy engines to the evidentiary expectations of supervisors.
- **Tenant isolation treated implicitly.** Applied IAM and cloud studies address identity integration and misconfiguration (Aliliele & Iwuanyanwu, 2023a; Mbonu et al., 2020) but rarely treat cross-tenant isolation as an explicit, independently verifiable invariant in multi-tenant SaaS settings (Odejobi & Ahmed, 2018b; Ukadike, 2024).
- **Cross-layer consistency.** The literature discusses API-level policy and data-layer controls separately; there is little guidance on keeping them consistent or on testing each layer independently.
- **Emerging-market supervision.** Studies of cyber risk maturity and continuity in African financial services (Fadero et al., 2020; Fadero et al., 2021) and of multi-regime data protection (Ominyi & Anichukwueze, 2022a) are rarely linked to concrete authorization architectures.
- **Non-human principals.** Work on agentic AI security and AI governance (Nwakamma & Oyesiji, 2024b; Ominyi & Anichukwueze, 2023) has not yet been integrated with fine-grained data access models for regulated platforms.

Conceptual Model

Layered Authorization Model

Based on the synthesis, we propose a layered conceptual model organized around a single principle: tenant isolation is an invariant enforced at the lowest feasible layer, independent of business policy; business entitlements are policy enforced higher in the stack, where they can be expressive, analyzed, and explained.

Three design choices deserve emphasis. First, L2 and L4 both enforce tenant isolation, using different mechanisms and ideally different implementations, so

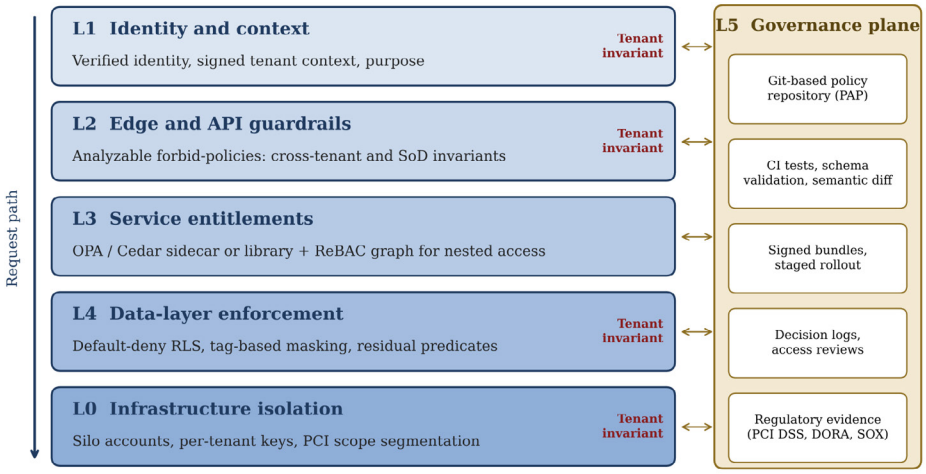


Figure 1: Layered conceptual model: tenant invariants enforced redundantly at L0, L1, L2, and L4; business entitlements at L3; and a governance plane (L5) that controls and evidences every layer.

that a defect in one does not compromise the other. Second, L3 is where most business change happens, and it is deliberately the layer with the richest tooling (tests, analysis, staged rollout). Third, the governance plane (L5) treats policy changes with the same rigor as production code changes, which is precisely the evidence that PCI DSS Requirement 7 reviews and DORA ICT risk management expect, and mirrors infrastructure-as-code governance practice (Aliliele & Iwuanyanwu, 2023a; Mbonu et al., 2020b).

Example Guardrail Policies

The following Cedar-style policy illustrates an L2 invariant. Because forbid overrides permit, no permissive business policy elsewhere can override it.

```
// Invariant: principals may never act on resources owned by another tenant
forbid (principal, action, resource)
when { principal.tenant != resource.tenant };

// Invariant: segregation of duties on payment approval
forbid (principal, action == Action::"ApprovePayment", resource)
when { resource.initiatedBy == principal };
```

The corresponding L4 control is an RLS policy that returns no rows unless the transaction-scoped tenant setting matches the row's tenant column, with no bypass role available to application connections.

Assurance and Verification Regime

Policy-as-code is only as trustworthy as the process that changes it. We recommend a verification regime with five components, ordered roughly from cheapest to strongest:

- **Unit tests for policy.** Every policy has positive and negative test cases, including explicit cross-tenant negative tests. OPA and Cedar both provide native testing workflows.
- **Schema validation.** Policies are type-checked against an entity schema so that references to non-existent attributes fail at build time rather than evaluating to silent denials or errors. Cedar's validator has machine-checked soundness proofs for this purpose (Disselkoen et al., 2024).
- **Semantic diff.** Before deployment, compute which requests change outcome between the old and new policy sets. For analyzable languages this can be

Table 5: Layered reference architecture for multi-tenant financial authorization.

Layer	*Enforcement mechanism*	*What it decides*	*Failure behavior*
L0. Infrastructure isolation	Silo accounts, per-tenant encryption keys, network segmentation for high-tier tenants and PCI scope	Physical and cryptographic separation	Hard boundary; no policy evaluation
L1. Identity and context	Federated identity, mTLS workload identity, signed tenant context propagated on every call	Who is acting, for which tenant, for what purpose	Request rejected if context missing or inconsistent
L2. Edge and API guardrails	Gateway PEP calling an analyzable engine (e.g., Cedar) with forbid-policies for cross-tenant and SoD invariants	Coarse permit/deny; invariant enforcement	Fail closed
L3. Service entitlements	Sidecar or embedded engine (OPA or Cedar) plus ReBAC graph for nested and delegated access	Fine-grained business authorization	Fail closed; scoped degraded read modes
L4. Data-layer enforcement	RLS default-deny keyed on tenant; tag-based column masking; residual predicates from L3 policies	Row and column visibility on every access path	No rows returned without valid context
L5. Governance plane	Git-based PAP, CI testing and semantic diff, signed bundles, decision logs, access-review reporting	Change control and evidence	Blocks deployment on failed checks

done symbolically; for others, by replaying a corpus of recorded production requests (shadow evaluation).

- **Invariant proofs.** For guardrail policies, prove properties such as "no permit is reachable when principal.tenant differs from resource.tenant" using SMT-based analysis where the language supports it.
- **Cross-layer adversarial testing.** Periodically test with upper layers disabled to confirm that lower layers enforce isolation on their own, and include authorization scenarios in DORA threat-led penetration testing where in scope. Breach and attack simulation and continuous security validation frameworks provide the methodology (Dosunmu & Ogundele, 2024a; Dosunmu & Ogundele, 2024c; Dosunmu & Ogundele, 2024d).

These components map directly to evidence that auditors and supervisors request: documented policies (the repository), approval of changes (pull request history), testing of controls (CI results and shadow-evaluation reports), and monitoring (decision logs and alerts). This shift from periodic audit to continuous control is well documented in the audit literature (Akomolafe & Agu, 2018; Mbonu et al., 2022).

Propositions

The conceptual model implies the following propositions, stated so that they can be tested in field studies, controlled experiments, or incident analyses.

- **P1 (Redundant isolation).** Platforms that enforce tenant isolation independently at both the edge (L2) and the data layer (L4) will experience fewer and less severe cross-tenant exposure incidents than platforms that rely on a single enforcement layer of comparable maturity.
- **P2 (Analyzable invariants).** Expressing tenant and segregation-of-duties invariants in an analyzable policy language, with pre-deployment semantic diffs, will reduce the rate of authorization regressions introduced by policy changes.
- **P3 (Risk-tiered consistency).** Assigning explicit staleness bounds by decision class, with strongly consistent checks for money movement, will reduce

Table 6: Mapping regulatory expectations to policy-as-code evidence

Regulatory expectation	*Policy-as-code evidence*
PCI DSS v4.0 Req. 7: access restricted by need-to-know, defined in an access control system	Versioned policy repository; role and attribute definitions; generated access reports
PCI DSS v4.0: periodic review of user and application accounts and privileges	Automated entitlement reports from the ReBAC graph and policy evaluation; review attestations
DORA ICT risk management: documented information security policies and access control	Policy repository, architecture records, control register of enforcement points
DORA: change management and ICT security testing	CI pipelines, semantic diff reports, staged rollout logs, penetration test findings
GDPR: data minimization and purpose limitation	Purpose attributes in policy; column masking by classification; redacted decision logs
SOX: segregation of duties over financial reporting	Forbid-policy SoD invariants with proofs and test cases

exposure from delayed revocation without materially increasing median transaction latency.

- **P4 (Governed pipeline).** Treating the policy pipeline as a governed artifact, with version control, testing, signed distribution, and decision logging, will improve audit outcomes and reduce the effort required for periodic access reviews (Akomolafe & Agu, 2018; Mbonu et al., 2022).
- **P5 (Context integrity).** Deriving tenant context exclusively from verified identity, rather than request parameters, will eliminate the tenant-context-injection class of vulnerabilities irrespective of the enforcement model chosen (Ogbole et al., 2021; Oshoba et al., 2019).

Discussion

Security Trade-Offs

This section presents the principal trade-offs a platform must resolve. Each is framed as a tension between two desirable properties, followed by the failure modes and mitigations observed in practice.

Consistency versus Latency

Strongly consistent authorization requires every decision to observe the latest policy and entitlement state, which implies coordination and latency. Caching decisions, distributing data to sidecars, and replicating relationship graphs all introduce staleness windows during which a revoked permission may still be honored. In finance, the classic exploitation scenario is an employee terminated at 17:00 who initiates a payment at 17:01 against a sidecar whose entitlement data refreshes every five minutes.

Mitigations: tier decisions by risk, using strongly consistent checks for money movement and privileged actions and cached decisions for read-mostly views; adopt Zanzibar-style consistency tokens so writes can demand fresh reads (Pang et al., 2019); push revocations as events rather than waiting for periodic refresh; and set explicit, documented maximum staleness per decision class, which also serves as audit evidence. Real-time fraud scoring work shows that risk signals can likewise be computed within transaction latency budgets and passed to the PDP as attributes (Fadayomi et al., 2021; Fadayomi et al., 2024).

Expressiveness versus Analyzability

A general-purpose language such as Rego can express nearly any rule, including ones that call external data or perform complex computation. That expressiveness

makes it harder to answer questions such as "can any principal in tenant X ever read data in tenant Y?" Cedar's constrained design exists specifically to make such questions decidable (Cutler et al., 2024). Financial platforms face the same tension in their own policy design: a rule that consults a fraud-score service at decision time is powerful but non-deterministic and difficult to reason about.
Mitigations: use an analyzable language for the invariants that matter most (tenant isolation, segregation of duties), reserving more expressive engines for operational policy; keep decisions pure, with external attributes fetched by the PEP and logged as decision inputs; and require formal or exhaustive analysis for changes touching guardrail policies.

Centralization versus Blast Radius

Centralizing the PDP simplifies governance but concentrates risk. A compromised or misconfigured central service can grant access across all tenants at once; an outage halts every transaction. Distribution limits blast radius but multiplies the surfaces that must be patched, configured, and monitored.
Mitigations: cell-based deployment in which a central service is sharded by tenant group or region so a fault affects one cell; signed policy bundles with verification at the enforcement point so a compromised control plane cannot push arbitrary policy; and independent, lower-layer tenant isolation (Section 3.2) so that even a fully compromised business PDP cannot cross tenant boundaries. Zero trust architectures for critical infrastructure apply the same segmentation logic (Adegbite et al., 2022; Ahmed et al., 2021).

Fail-Closed versus Availability

When the PDP is unreachable or returns an error, the PEP must choose between denying the request (safe but disruptive) and allowing it (available but unsafe). DORA's emphasis on operational resilience makes availability a regulatory concern, not merely a commercial one, yet fail-open authorization on payment initiation is indefensible.
Mitigations: fail closed by default, with narrowly scoped, pre-approved degraded modes (for example, read-only balance views from cached decisions during a PDP outage); treat the PDP as critical infrastructure with its own resilience testing; and ensure engine errors are distinguished from denials in logs so outages are not misread as attacks or vice versa (Okafor, Farounbi, et al., 2024). Cedar's semantics, in which a policy that errors during evaluation is ignored, illustrate why guardrails should be expressed as forbid policies: an erroring permit cannot accidentally grant access, but an erroring forbid can silently stop protecting, so forbid policies require the most validation (Cedar Policy, n.d.; Cutler et al., 2024).

Policy Centralization versus Duplication Across Layers

Layered enforcement (Section 3.2) means some rules exist in more than one place: tenant isolation may appear in the API policy, the RLS policy, and the warehouse row access policy. Duplication provides defense in depth but creates drift, where layers disagree and one silently becomes the only effective control.
Mitigations: generate lower-layer policies from a single source where possible (for example, emitting RLS predicates from the same tenant model the API policy uses); continuously test layers independently, with a deliberately disabled upper layer, to confirm each holds on its own; and inventory every enforcement point in a control register.

Multi-Tenancy-Specific Threats

Auditability versus Privacy and Cost

Decision logs are the evidentiary backbone of PaC: they record the principal, action, resource, inputs, policy version, and result. In finance they are also sensitive, since

Table 7: Threats specific to multi-tenant authorization and their mitigations.

Threat	*Description*	*Primary mitigations*
Tenant context injection	Attacker supplies another tenant's identifier in a request field that a service trusts.	Derive tenant only from verified identity; reject mismatches between token and payload; forbid-policy guardrail.
Cross-tenant cache poisoning	Decision or data caches keyed without tenant, so one tenant's cached result is served to another.	Include tenant and policy version in every cache key; per-tenant cache namespaces.
Confused deputy	A shared platform service with broad privileges acts on behalf of one tenant against another's data.	Propagate end-user and tenant context to downstream PDPs; avoid service-wide super-roles; on-behalf-of tokens.
Connection-pool context leakage	Pooled DB sessions retain previous session variables used by RLS.	Transaction-scoped context; reset on checkout; RLS default-deny when context absent.
Policy supply-chain attack	Malicious or erroneous policy pushed through the PaC pipeline.	Signed bundles, two-person review, protected branches, pre-deploy semantic diff, staged rollout.
Relationship graph drift	Authorization graph diverges from system of record, leaving stale grants.	Outbox or CDC synchronization, reconciliation jobs, drift alerts.
Side channels in filtered queries	Counts, error messages, or timing reveal existence of other tenants' records.	Apply filters before aggregation; uniform not-found responses; avoid global unique-constraint leaks.

the inputs may include personal data and account details, and they grow very large at transaction volumes. Logging everything conflicts with data minimization; logging too little undermines investigations and access reviews.

Mitigations: log policy version and decision identifiers for every decision, but redact or hash sensitive input fields; retain full inputs for privileged and money-movement decisions; route decision logs to tenant-partitioned, tamper-evident storage; and align retention with the longest applicable regulatory requirement rather than defaulting to indefinite retention. Blockchain-anchored audit trails have been proposed as one way to make such logs tamper-evident (Anichukwueze et al., 2021; Oshoba et al., 2020), and SIEM-based log analytics provide the consumption side (Mbonu, Iwuanyanwu, et al., 2019).

Choosing a Starting Point

Platforms rarely build all six layers at once. Our analysis suggests a pragmatic ordering. Begin with L1 and L4: trustworthy tenant context and default-deny data-layer isolation deliver the largest risk reduction for multi-tenancy, because they close the catastrophic cross-tenant failure regardless of application bugs. Next, introduce L2 guardrails and the L5 governance plane, which produce the evidence regulators want. Finally, migrate business entitlements to L3 engines incrementally, service by service, using shadow evaluation to compare legacy authorization with new policy before cutting over.

Build, Adopt, or Buy

Managed authorization services reduce operational burden but bring third-party risk considerations under DORA, including exit strategies and concentration risk (Adebayo & Ozowara, 2023). Self-hosted open-source engines avoid lock-in but require the platform to operate a critical, stateful service in the case of ReBAC engines. Standardizing on an open language, even when using a managed runtime, preserves portability; this is one practical argument for languages with multiple independent implementations or well-specified semantics.

Implications

Implications for Practice

For platform architects and engineering leaders, the central implication is to separate what must never happen from what is usually allowed. Tenant isolation and segregation of duties should be encoded as small, stable, analyzable invariants enforced at more than one layer, while business entitlements can evolve quickly in service-level policy. Teams should treat the authorization service as critical infrastructure, with explicit availability objectives, degraded modes approved in advance, and capacity planning, and should adopt the same infrastructure-as-code discipline for policy that they already apply to cloud configuration (Aliliele & Iwuanyanwu, 2023a; Mbonu et al., 2020b). Migration should be incremental and evidence-led, using shadow evaluation to compare legacy and new decisions before cutover.

Implications for Risk, Compliance, and Internal Audit

For second- and third-line functions, policy-as-code changes the object of assurance from screenshots and periodic attestations to a continuously observable control system. Auditors can sample policy changes from version history, inspect test coverage for negative cross-tenant cases, and reconcile decision logs against access reviews, consistent with moves toward continuous auditing and automated IT general controls (Agu et al., 2023a; Akomolafe & Agu, 2019a; Mbonu et al., 2022). Compliance teams should participate in policy review as co-owners of invariant policies, which converts regulatory interpretation into reviewable artifacts rather than informal guidance.

Implications for Regulators and Supervisors

For supervisors, including those overseeing emerging-market banking and fintech sectors, the model suggests a shift in examination questions from whether access controls exist to whether they are independently layered, tested, and evidenced. Supervisors could ask firms to demonstrate that tenant isolation holds with upper layers disabled, to show semantic diffs for recent changes to critical policies, and to state maximum staleness bounds for revocation. Where authorization engines are consumed as managed services, the third-party risk provisions of DORA and comparable national frameworks imply attention to exit strategies and concentration risk (Adebayo & Ozowara, 2023; Fadero et al., 2020).

Implications for Research

For researchers, the paper offers a vocabulary and a set of testable propositions that bridge systems research and information systems governance research. The taxonomy of architectural models provides a common frame for comparing case studies, and the propositions identify measurable outcomes (incident rates, regression rates, revocation exposure windows, and audit effort) that are rarely reported in the applied literature.

Limitations

Several limitations qualify the findings. First, the study is a literature-based synthesis and conceptual modeling exercise; it does not report controlled experiments, benchmarks, or field data, and the propositions remain untested. Second, the applied corpus was drawn from a single consolidated reference list, which introduces selection bias: many of its studies are conceptual frameworks published in regional journals, and themes such as payments and audit are better represented than, for example, formal verification of data-layer policies. Third, the restriction to sources published in or before 2024 deliberately excludes later developments in engines, standards, and supervisory guidance, so the analysis

reflects a point in time. Fourth, thematic coding was performed at the level of titles and stated contributions and assigned each study to a single primary theme, which simplifies studies that span several themes. Fifth, the regulatory mapping is indicative rather than legal advice, and interpretations should be validated with compliance functions and supervisors. Finally, performance characteristics vary widely with policy complexity, data volume, and deployment topology, and qualitative comparisons should not be read as measurements.

Future Research

The analysis suggests six directions for future research.

1. **Empirical testing of the propositions.** Multi-case studies of financial platforms, or analyses of disclosed access-control incidents, could test whether redundant isolation (P1) and analyzable invariants (P2) are associated with fewer and less severe failures.
2. **Cross-layer policy equivalence.** Formal methods could be extended from single policy sets to proving that API-level policy and data-layer policy agree, for example by translating row-level security predicates into the same logic used to analyze Cedar or Rego policies.
3. **Benchmarks for filtering.** Controlled benchmarks comparing list-based pre-filtering, partial evaluation into query predicates, and native row-level security on realistic financial schemas would quantify the latency and correctness trade-offs discussed in Section 3.1.3.
4. **Authorization for AI agents.** As agents act on behalf of users across tools and tenants, research is needed on on-behalf-of delegation, short-lived scoped grants, and the confused-deputy problem in agentic workflows (Nwakamma & Oyesiji, 2024b), together with how such controls fit model risk and AI governance regimes (Ominyi & Anichukwueze, 2023; Ominyi & Anichukwueze, 2024; Ominyi & Uzougbo, 2024b).
5. **Interface standardization.** The AuthZEN effort to standardize the interface between enforcement and decision points, under way in 2024 (OpenID Foundation, 2024), invites study of portability, lock-in, and the security of the standardized interface itself.
6. **Emerging-market contexts.** Case studies in Nigeria and other emerging markets could examine how supervisory frameworks, data protection regimes, and infrastructure constraints shape authorization architecture choices (Fadero et al., 2021; Ominyi & Anichukwueze, 2022a).

CONCLUSION

By 2024, policy-as-code had matured from an infrastructure convenience into a credible foundation for fine-grained authorization in regulated, multi-tenant financial platforms. The engines diverged in philosophy: OPA optimizing for generality, Cedar for analyzability and speed, and Zanzibar-style systems for relationship-rich models at scale. Meanwhile, data platforms gained native policy primitives that enforce controls on every access path. The central finding of this paper is that these approaches are complementary, not competing. The defensible architecture treats tenant isolation as an invariant enforced redundantly at the identity, edge, and data layers; expresses business entitlements as versioned, tested, and analyzable policy; and treats the policy pipeline itself as a governed, evidence-producing system. The trade-offs among consistency, latency, expressiveness, blast radius, and availability do not disappear, but in a layered design they can be made explicitly, documented, and defended to auditors and supervisors, which in finance is the standard that matters.

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