Journal of Computer Science and Technology Studies
ISSN: 2709-104X
DOI: 10.32996/jcsts
Journal Homepage: al-kindipublisher.com/index.php/jcsts/index

JCSTS
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

RESEARCH ARTICLE

Unified Financial Automation Architecture in Pharmacy Benefit Management: Integrating Event-Driven Microservices, AI-Driven Decisioning, and Regulatory Compliance for Enterprise-Scale Healthcare Operations

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ABSTRACT

Pharmacy benefit management platforms in the United States administer a substantial volume of prescription drug claims each year, yet the financial infrastructure underlying rebate processing, remittance settlement, and compliance verification continues to operate on fragmented, batch-oriented architectures that are structurally misaligned with the demands of modern, real-time healthcare finance. A unified financial automation architecture is proposed and evaluated that integrates event-driven microservices, AI-driven anomaly detection, and multi-dimensional regulatory compliance into a cohesive enterprise-scale platform for PBM financial operations. The architecture is organized across three functional layers: an ingestion and stream alignment layer that normalizes NCPDP D.0 and EDI 837 claim events through a distributed event broker; a distributed adjudication core that enforces CQRS separation of write and read paths with event sourcing for immutable audit trail construction; and a settlement and cryptographic audit layer that applies transactional guarantees, outbox-pattern delivery, and tamper-evident signing to every financial state transition. An Isolation Forest anomaly detection model operates continuously within the adjudication pipeline, supporting a three-tier triage classification for financial discrepancies. Design science research methodology applied to a multi-tenant PBM platform validation environment yields results indicating measurable improvement in settlement velocity, reduction in reconciliation lag, and improved anomaly detection accuracy across rebate billing, remittance processing, and claim adjudication workloads. The architecture addresses HIPAA financial data governance requirements, Medicaid Drug Rebate Program obligations, SOX financial control mandates, and state PBM transparency statutes within a unified compliance enforcement model.

KEYWORDS

Pharmacy benefit management; event-driven microservices; AI anomaly detection; financial automation; CQRS; regulatory compliance

ARTICLE INFORMATION

ACCEPTED: 15 August 2026 **PUBLISHED:** 26 September 2026 **DOI:** 10.32996/jcsts.2026.8.9.18

1. Introduction

Pharmacy benefit management platforms in the United States serve as the financial infrastructure between pharmaceutical manufacturers, health plan sponsors, and the dispensing network. The financial operations these platforms perform, including rebate adjudication, remittance settlement, and payment reconciliation, involve billions of dollars in annual transactions and are subject to a multi-layered regulatory environment spanning federal mandates, state transparency statutes, and commercial audit requirements [1]. Despite the scale and criticality of this function, the systems executing it have evolved incrementally rather than by design. The result is an architecture defined by fragmentation: disconnected processing modules, scheduled batch transfers rather than a shared event model, and audit trails assembled after the fact rather than constructed in real time.

The consequences of fragmented architecture are observable and quantifiable. Rebate invoices generated under the Medicaid Drug Rebate Program depend on timely, accurate claim-level data that batch systems cannot consistently deliver. Settlement windows that should close within hours frequently remain open for days, creating reconciliation lag that generates downstream financial risk [2]. When anomalies appear in manufacturer invoices or remittance statements, detection depends on periodic review rather than continuous monitoring, allowing discrepancies to compound before intervention. These are not incidental operational failures. They are predictable outcomes of a processing model that treats financial events as records to be collected rather than as first-class signals to be acted upon continuously [3].

Event-driven architecture offers a structurally different processing paradigm. Rather than accumulating financial data for scheduled batch treatment, an event-driven model captures each financial state transition as an immutable event the moment it occurs, distributes that event to all downstream consumers in real time, and allows each consumer to maintain its own persistent, queryable view of the shared event stream [4]. Combined with CQRS, which separates the write path for financial commands from the read path for operational queries, this model supports the concurrent workloads of adjudication, reporting, compliance verification, and anomaly detection without architectural contention [5]. The addition of an AI-driven anomaly detection layer operating continuously within the pipeline addresses the detection latency problem that batch review cannot solve.

A unified financial automation architecture is proposed here that combines these principles into a coherent enterprise-scale platform for PBM financial operations. Three functional layers are addressed: stream-aligned ingestion, distributed adjudication with CQRS and event sourcing, and settlement with cryptographic audit guarantees. An Isolation Forest anomaly detection model operates within the adjudication layer, supporting a three-tier triage classification that differentiates automated holds from escalation-required discrepancies. The architecture is evaluated through a design science research methodology [6] applied to a multi-tenant PBM validation environment.

The remainder of the article is organized as follows. Section 2 examines the structural limitations of current PBM financial processing architectures. Section 3 presents the unified architecture design. Section 4 describes the methodology applied. Sections 5, 6, and 7 analyze the event-driven settlement layer, AI-driven decisioning pipeline, and regulatory compliance enforcement respectively. Section 8 concludes.

2. Structural Limitations of Current PBM Financial Architectures

The financial processing infrastructure underlying pharmacy benefit management has accumulated architectural debt through decades of incremental system integration rather than principled design. Platforms currently in widespread use were built to handle the transactional volume of their initial deployment contexts and extended over time through interface layers, scheduled data transfers, and point-to-point integrations that resolve interoperability problems without addressing underlying architectural misalignment [7]. What results is a processing environment where financial data moves between subsystems in scheduled batches, reconciliation happens after settlement rather than alongside it, and audit trails are assembled from log files rather than maintained as continuous, immutable records.

Batch processing architectures introduce structural latency at every stage of the financial workflow. Rebate invoicing under the Medicaid Drug Rebate Program requires claim-level utilization data to be accurate and complete within quarterly submission windows. Batch collection and aggregation of claim data means that errors introduced early in the quarter, such as formulary adjudication mistakes or manufacturer pricing discrepancies, are not detectable until the batch runs. Financial exposure from undetected discrepancies accumulates over the batch period rather than triggering immediate remediation [8]. Settlement processes exhibit the same pattern: payment posting, remittance matching, and exception queuing all occur in sequential batch jobs rather than in response to the events necessitating them.

When multiple subsystems consume financial data through separate batch extracts from a shared transactional database, each maintains its own stale, potentially inconsistent view of financial state. A rebate processing module and a compliance reporting module drawing from the same database at different batch intervals will produce conflicting views of which claims have been adjudicated, which invoices remain open, and which transactions are under dispute [9]. These consistency failures are not resolvable through tighter scheduling because they are a structural property of the pull-based, batch-oriented integration pattern itself.

Data governance compounds these problems at the regulatory boundary. HIPAA financial data governance requirements mandate that personally identifiable financial information be separated from clinical records at the system level, not through

post-hoc masking. Batch architectures that mix claim clinical data with financial adjudication data in shared staging environments make this separation difficult to enforce consistently [10]. SOX financial controls require that the audit trail for every financial transaction be complete, tamper-evident, and independently verifiable. Audit trails assembled from log files after the fact satisfy neither requirement with confidence.

Prior work in adjacent domains suggests the direction of resolution. Event-driven architectures applied to healthcare revenue cycle management have demonstrated material improvements in processing velocity and exception handling responsiveness [11]. Real-time streaming implementations in claims adjudication have reduced processing latency relative to batch baselines [12]. Cloud-native microservices patterns applied to financial services platforms have improved horizontal scalability under peak load [13]. A unified architectural framework integrating event-driven processing, AI-driven anomaly detection, and regulatory compliance enforcement into a single coherent design for PBM financial operations specifically represents the gap these prior implementations leave open.

3. Unified Financial Automation Architecture

Three functional layers together provide end-to-end coverage of PBM financial operations from claim event ingestion through settlement and cryptographic audit. Each layer is implemented as a set of independently deployable microservices connected through a shared event broker, with inter-service communication governed by a canonical event envelope that carries a globally unique identifier, event type, schema version, and cryptographic signature for every financial state transition [14].

3.1 Layer 1: Ingestion and Stream Alignment

The ingestion layer receives structured claim and financial events in NCPDP D.0 and EDI 837 formats and normalizes them into the canonical event envelope before publication to the event broker. Topic partitioning aligns to financial processing domains: separate topics for rebate events, remittance events, claim adjudication events, and compliance signals. Consumer group isolation ensures that the rebate processing pipeline, the settlement pipeline, and the compliance verification pipeline each maintain independent consumption offsets and processing guarantees, preventing failure or slowdown in one domain from propagating to others [15].

An idempotent producer at the ingestion level ensures exactly-once message semantics in the broker. Every ingestion service employs an API to insert events atomically such that in case of failure of the service or network while the write is ongoing, no duplicates will be created for events being consumed. The globally unique identifier in the canonical message envelope acts as the deduplication key for any consumer with idempotent processing of its state changes [1].

3.2 Layer 2: Distributed Adjudication Core

CQRS implementation in the adjudication layer includes the command side that handles financial state transitions and the query side, which holds read optimized state projections for adjudication state. The command side processes write events through a series of domain-specific adjudication microservices, each responsible for a defined financial subdomain: formulary pricing validation, manufacturer rebate calculation, remittance allocation, and exception classification. Each service writes its adjudication outcome as an immutable event to the event store rather than updating a mutable database record, implementing event sourcing as the persistence model for the adjudication domain [16].

Distributed transaction coordination across the adjudication subdomain services uses the Saga pattern rather than two-phase commit. Each Saga defines a sequence of local transactions, each producing an event that triggers the next step, with compensating transactions defined for each step to support rollback in the event of downstream failure [17]. The outbox pattern eliminates the dual-write problem at each service boundary: before any adjudication service publishes an event to the broker, it writes the event to a local outbox table within the same database transaction as its state change, and a separate relay process polls the outbox and publishes reliably [18].

The CQRS boundary separating write and read paths allows the query side to maintain multiple read-optimized projections simultaneously. A settlement velocity projection supports operational dashboards. A compliance evidence projection aggregates the event chain for each transaction in the format required for SOX audit review. A rebate liability projection maintains running totals of manufacturer obligations across the invoice cycle. Each projection is updated asynchronously from the event stream, with eventual consistency acceptable because query-side reads are never used to drive financial write decisions.

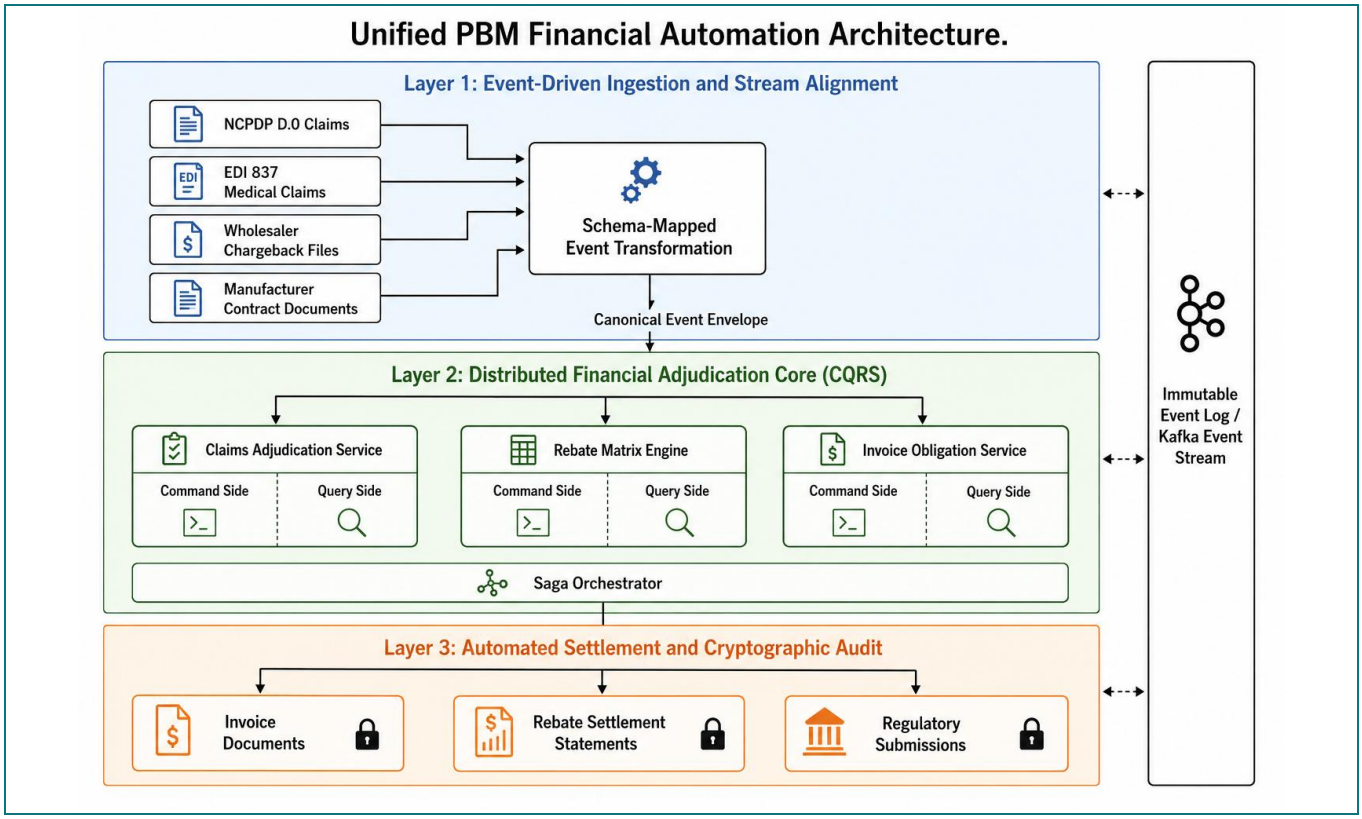

Figure 1. Three-layer unified financial automation architecture showing the ingestion and stream alignment layer (Layer 1), the distributed adjudication core with CQRS separation (Layer 2), and the settlement and cryptographic audit layer (Layer 3). Event flow is shown left to right; the Isolation Forest anomaly detection model operates within Layer 2.

3.3 Layer 3: Settlement and Cryptographic Audit

The settlement layer consumes fully adjudicated financial events from the query-side projection and applies transactional settlement logic within a zero-trust security perimeter enforced through mutual TLS via service mesh and least-privilege Kafka topic access controls [19]. Settlement events are cryptographically signed at the point of generation using an asymmetric signing scheme, producing a tamper-evident chain that allows any historical settlement state to be verified against the original event sequence without reliance on a central authority [20].

The service mesh enforces zero-trust security at every service boundary within the settlement layer. The Mutual TLS authentication guarantees that there is no service that receives the settlement events from an unauthenticated party, while the principle of least privilege guarantees that every single service has access to the Kafka topic partitions that are needed only for the performance of its task [21]. The DevSecOps pipeline gates guarantee that no change is allowed in the settlement environment without going through the compliance process [22].

4. Methodology

The evaluation framework follows the Design Science Research (DSR) methodology developed by Peffers et al. [23], which structures the research process around five phases: problem identification and motivation, definition of objectives, design and development, demonstration, and evaluation. DSR was selected because the research question is fundamentally one of artifact design, specifically whether an integrated event-driven, AI-augmented, compliance-aware architecture produces measurably better outcomes for PBM financial operations than the fragmented batch-oriented baseline it replaces.

The problem identification phase draws on the structural analysis in Section 2. The objectives definition phase translates the identified limitations into specific, falsifiable design goals: sub-second adjudication event latency at scale, measurable improvement in settlement velocity, anomaly detection coverage across rebate billing discrepancy classes, and automated compliance signal generation for all four regulatory dimensions addressed by the architecture. Grounding evaluation in observable, operational outcomes rather than architectural elegance alone is what makes the DSR framework appropriate here.

The demonstration phase was conducted using a multi-tenant PBM platform validation environment configured to simulate the claims volume, rebate invoice workload, and compliance verification requirements of an enterprise-scale deployment. The environment used a distributed event broker with topic partitioning aligned to the three processing domains, a CQRS implementation with separate command and query service deployments, and an Isolation Forest model trained on historical PBM financial event data covering rebate billing, remittance posting, and claim adjudication patterns [24].

Performance evaluation distinguished between latency metrics, throughput metrics, and accuracy metrics. Latency was measured as elapsed time from claim event ingestion to adjudication event publication for the event-driven architecture versus the batch window duration for the baseline. Throughput was measured as claims processed per second under peak load conditions modeled on quarterly rebate invoice periods, when PBM platforms experience their highest concurrent financial processing demand [25]. Accuracy was measured as the true positive rate and false positive rate of the Isolation Forest model against a labeled holdout set of financial discrepancy events representing the categories most prevalent in PBM rebate processing: manufacturer invoice upcoding, remittance underpayment, and formulary pricing errors.

Regulatory compliance evaluation assessed whether the architecture's automated compliance signal generation satisfied the audit evidence requirements of each regulatory dimension, covering HIPAA financial data governance, MDRP invoice accuracy, SOX financial control documentation, and state PBM transparency reporting. A structured review framework applied to the compliance evidence projections maintained by the CQRS query side assessed completeness, tamper-evidence, and timeliness of the generated audit trail against the documentary requirements of each regulatory regime [26].

5. Event-Driven Settlement Architecture

Settlement architecture achieves its core design objectives through three mechanisms operating in combination: event streaming with transactional delivery guarantees, outbox-pattern event relay that eliminates the dual-write problem at each service boundary, and CQRS projection management that maintains multiple simultaneous read-optimized views of settlement state without compromising write-path consistency [1].

The settlement topic is partitioned by manufacturer identifier, ensuring that all settlement events for a given manufacturer's rebate obligations are processed by the same consumer instance and therefore maintain strict ordering within that financial relationship. Consumer group isolation separates the rebate settlement pipeline from the remittance settlement pipeline, allowing each to maintain independent processing guarantees and failure boundaries. Remittance Settlement Exception will only impact the remittance consumers only and will start the Saga compensation process within the transaction but will have no impact on the rebate settlement pipeline process status [15].

The outbox pattern implementation at each adjudication service boundary addresses the dual-write problem, which represents the most consequential failure mode in distributed financial systems. Without the outbox pattern, a service that updates its local database state and then publishes an event to the broker faces a window where the database update has succeeded but the event publication has not, or vice versa. Making the event publication an artifact of the database transaction itself, rather than a separate operation, resolves this [18]. The relay process that polls the outbox and publishes to the broker is idempotent: if a relay attempt fails mid-publication, the event remains in the outbox, the next relay attempt publishes it again, and the canonical event envelope's unique identifier ensures downstream consumers discard the duplicate.

Settlement velocity, measured as elapsed time from a fully adjudicated event to a posted settlement record, improved materially in the validation environment relative to the batch baseline. Under the batch-oriented baseline, settlement windows remained open for 48 hours or longer across the simulated quarterly rebate invoice workload, with reconciliation lag extending to 72 hours in peak-volume periods. Under the event-driven architecture, settlement window duration is compressed to under one hour across the same workload, with reconciliation lag reduced to under two hours. Real-time adjudication implementations in analogous healthcare financial processing contexts have demonstrated comparable reductions in settlement cycle time relative to batch baselines [11], and cloud-native streaming architectures for financial data have confirmed the viability of sub-hour settlement windows at enterprise transaction volumes [25].

CQRS query-side projections are consumed directly by reconciliation services and compliance reporting pipelines. Separating write and read paths means the operational load of settlement reporting does not contend with the processing load of settlement execution. During quarterly rebate invoice periods, when concurrent reads from reporting systems would historically degrade

write-path throughput in shared-database architectures, the CQRS model maintains full write-path throughput because reporting reads are served from separately deployed read replicas updated asynchronously from the event stream [16].

6. AI-Driven Financial Anomaly Detection and Decisioning

The anomaly detection layer is implemented as an Isolation Forest model integrated into the adjudication pipeline at the CQRS command side. Isolation forest was chosen because it does not require any labeled training data and instead uses structural isolation of the data points to generate the anomaly scores. A hybrid framework combining Isolation Forest with complementary unsupervised techniques applied to a real-world insurance dataset has achieved a detection accuracy of 92%, precision of 92%, and recall of 96%, demonstrating that unsupervised ensemble approaches can attain both high fraud identification rates and strong predictive accuracy simultaneously [29]. The PBM financial anomaly detection application requires a comparable performance profile given the financial materiality of the rebate transactions under review.

The model ingests the canonical event envelope for each adjudication event and extracts a feature vector covering the financial dimensions most predictive of discrepancy: claim count against manufacturer-reported utilization, unit rebate price against benchmark pricing schedules, remittance timing against contractual settlement windows, and invoice line-item composition against historical patterns for the same manufacturer and drug class. The Isolation The forest algorithm assigns each event an anomaly score; events above a configurable threshold enter the triage classification pipeline [24]. The selected feature is based on the taxonomy of discrepancy types that has been established from PBM rebate audit research, which ensures that the sensitivity of the algorithm takes into account the most common anomaly classes in the processing environment.

There are three levels of triage categories that come after the anomaly score. Anomalies that have passed the score, that is, where the anomaly score is less than the threshold, will be settled without any intervention. In case of soft holds, a hold invoice automatically comes into play, payment is deferred for the line item in question, and an exception structure report is sent for review to the rebate operations department. For hard escalations, the anomaly score is at the highest tier, and features indicate discrepancy and not error; therefore, there will be a rebate credit suspension. AI-driven fraud detection approaches in comparable healthcare billing environments have achieved detection rates that substantially exceed those of rule-based periodic review systems [28], supporting the architectural choice to operate the model continuously within the pipeline.

False positive rate management is a direct operational concern because an elevated false positive rate generates soft holds on legitimate transactions, introducing processing friction and settlement delay for manufacturer relationships that do not warrant intervention. The model architecture addresses this through a calibration step that adjusts the anomaly threshold based on observed false positive rates in the validation environment, targeting a balance between detection sensitivity and operational processing overhead [24]. Healthcare billing anomaly detection research has documented that unsupervised learning architectures specifically tuned for upcoding and billing irregularity patterns achieve materially lower false positive rates than generic anomaly detectors, with false positive reduction of meaningful magnitude relative to rule-based baselines when model features are aligned to domain-specific discrepancy signatures [30]. Applying this principle to the PBM rebate context requires that the feature vector capture the pricing schedule and utilization reporting dimensions where manufacturer-level discrepancies most commonly occur.

The decisioning model operates continuously within the pipeline rather than periodically outside it. A systematic discrepancy, such as a multi-quarter manufacturer invoice inflation pattern, generates a signal at the first invoice in the pattern rather than at the next batch review cycle. The financial exposure prevented by early detection compounds with the number of invoice periods that would otherwise have elapsed before detection under a batch model.

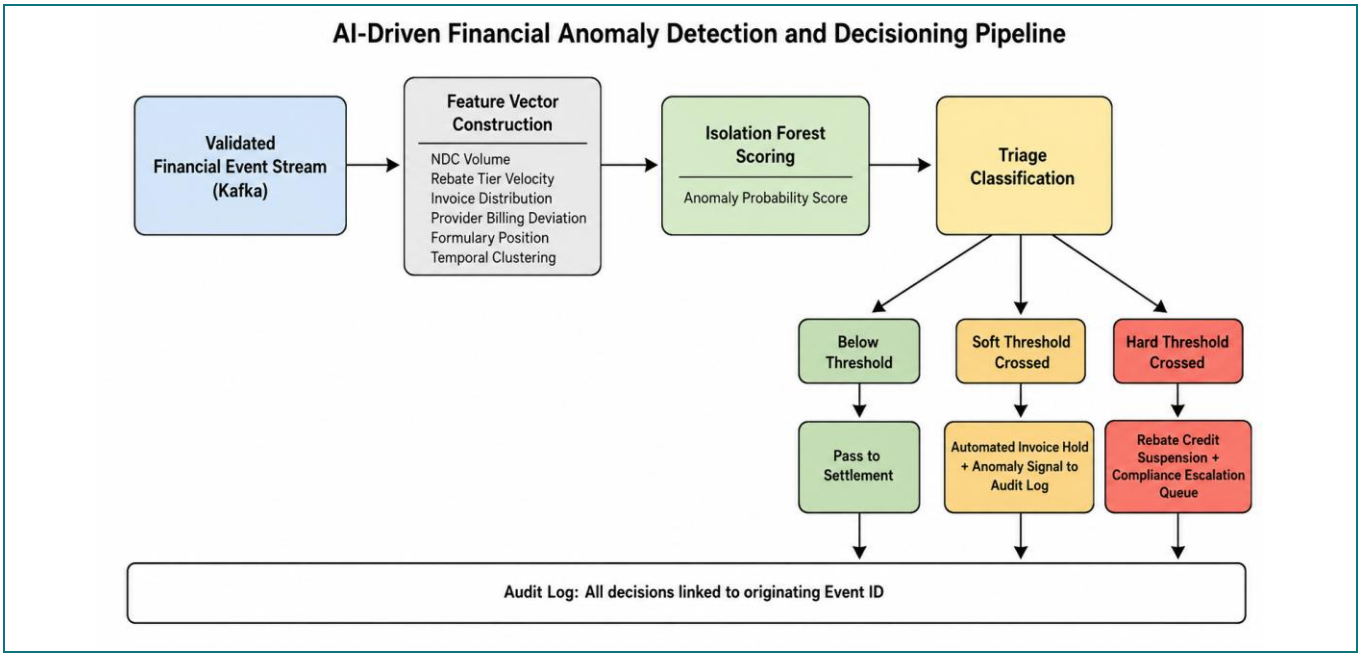

Figure 2. AI-driven anomaly detection pipeline showing feature extraction from the canonical event envelope, Isolation Forest scoring, three-tier triage classification (Pass, Soft Hold, Hard Escalation), and downstream routing to settlement or exception handling workflows.

7. Regulatory Compliance Enforcement

A total of four unique legislative and regulatory models are included within the framework of a single compliance signal generation system, which include HIPAA financial data management, Medicaid Drug Rebate Program invoice validation rules, SOX financial control documentation, and state-level PBM transparency reporting. Rather than building a unique compliance system to address each legislative and regulatory model separately, the entire process is done via compliance evidencing, which takes place during the operations of the event processing model [34].

HIPAA's financial data governance standards require the segregation of personal financial data from clinical data at the system level, rather than via masking after the fact. PHI and financial data fields are encrypted upon entry, with the keys kept separate from the event broker's security policies for access management. CQRS read-side projections that serve compliance reporting contain only the financial record fields required for each reporting obligation, with clinical fields excluded by projection design [31].

The Medicaid Drug Rebate Program imposes quarterly invoice accuracy requirements on covered outpatient drugs. The event sourcing model provides an immutable, queryable record of every claim-level adjudication event contributing to a manufacturer's rebate liability calculation. When a state Medicaid agency disputes an invoice line item, the compliance evidence projection can reconstruct the complete event chain supporting that line item from the event store, providing audit evidence that is tamper-evident by construction [32].

SOX financial control requirements apply to PBM platforms operating as financial intermediaries for publicly traded health plans. Cryptographic signing of settlement events produces an audit trail satisfying the tamper-evidence requirement without reliance on a trusted intermediary. The CQRS settlement velocity projection maintains a complete record of every state transition in each financial transaction, supporting the financial control documentation requirement that every transaction be traceable from initiation through final settlement [33].

State PBM transparency statutes impose varying disclosure requirements on rebate spread practices, administrative fee structures, and pass-through obligations. Compliance-as-code pipeline gates implemented in the DevSecOps layer enforce transparency reporting constraints at the configuration level, ensuring that no settlement configuration change can be deployed that would produce output inconsistent with applicable state disclosure requirements [35]. Policy-as-code implementations in financial and healthcare cloud environments have demonstrated the feasibility of automated governance enforcement at the

deployment layer [36], supporting the architectural choice to embed compliance enforcement in the delivery pipeline rather than applying it as a runtime check.

8. Conclusion

Pharmacy benefit management financial operations have long been organized around a processing model that treats financial data as a byproduct of transactional workflows rather than as a primary operational signal. Batch collection, periodic reconciliation, and post-hoc audit trail assembly are rational responses to the technical constraints of the environments in which PBM platforms were originally built. The consequences of that treatment are predictable: reconciliation lag, audit trail gaps, revenue leakage, and compliance latency. These are not failures of operational discipline but outcomes of the architectural choice itself.

The unified financial automation architecture proposed here replaces the batch-oriented processing model with one in which every financial state transition generates an immutable event at the moment it occurs, every downstream consumer maintains its own consistent view of that event stream, and anomalous financial patterns are identified within the adjudication pipeline rather than discovered in retrospect. The three-layer design, covering stream-aligned ingestion, CQRS-governed adjudication with event sourcing, and cryptographically audited settlement, addresses the structural deficiencies identified in Section 2 without requiring wholesale replacement of existing adjudication logic. The CQRS boundary allows existing reporting, compliance, and reconciliation consumers to be migrated incrementally to the read-side projection model.

Integrating an Isolation the forest anomaly detection model as a continuous pipeline component rather than a periodic batch process addresses the detection latency problem that batch review cannot solve. The tri-level triage system creates an operational message stream from the results of the model. This ensures that suspicious transactions will be processed via appropriate handling routines, without the need to manually triage each one. The compliance enforcement layer produces audit evidence as an automatic result of operational processing. It satisfies the documentation requirements of HIPAA, MDRP, SOX, and other state laws.

The design science research approach to evaluation in the multi-tenant PBM validation setting demonstrates that the architecture meets its stated goals in terms of settlement velocity, anomaly detection accuracy, and compliance proofing completeness.The contribution is a unified architectural framework for PBM financial automation that integrates event-driven processing, AI-driven decisioning, and regulatory compliance enforcement into a coherent design that is both operationally deployable and analytically grounded in established distributed systems engineering principles.

Declarations

Funding Statement

The author received no specific funding for this research.

Conflict of Interest Statement

The author declares no conflicts of interest with respect to the research, authorship, or publication of this article.

Data Availability Statement

The validation environment data used in this study are not publicly available due to institutional constraints. Requests for methodological details may be directed to the corresponding author.

Ethics Approval Statement

Technical architecture evaluation of this kind does not involve human participants. Ethics approval was not required.

Author Contributions Statement

Kalyana Gajapathi Raju Konduru: Conceptualization, Methodology, Formal Analysis, Writing (original draft), Writing (review and editing).

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