A Unified Conceptual Framework for Hybrid Database Resiliency: Reconciling Relational Availability Groups with Distributed Document-Oriented Systems

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Abstract

Enterprises increasingly run critical transactional data on relational databases protected by availability groups, while placing flexible, high-volume data on distributed document databases protected by replica sets. Each technology offers mature resiliency on its own, but the two were designed separately and describe durability, failover, and data visibility in different terms, so organizations that combine them often promise recovery objectives that the combined system cannot actually meet. This study addresses that problem through a conceptual, design-oriented approach that integrates a review of literature published up to 2021 with concept mapping and analytical evaluation. It proposes the Hybrid Resiliency Conceptual Framework, a unified model that describes both families of databases in a shared vocabulary and shows how their guarantees combine when a single business transaction spans both. The analysis finds that the resiliency of a hybrid system is set by its weakest tier and by the mechanism that moves data between tiers, and that configurations which appear sound when each database is reviewed alone can still lose acknowledged data after a routine failover. Applied to an illustrative order management system, the framework exposes these hidden gaps and guides configuration choices that close them without imposing unnecessary latency. The study offers architects, database reliability engineers, and technology managers a practical basis for designing, auditing, and optimizing hybrid database estates, and gives researchers testable propositions for future empirical work.

Keywords: Database resiliency; High availability; Always On Availability Groups; MongoDB replica sets; Polyglot persistence; Consistency models; Disaster recovery; RPO; RTO; Distributed systems; Performance optimization.

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1. INTRODUCTION

For most of the history of enterprise computing, database resiliency was a single-engine concern. A bank, a hospital, or a retailer selected a relational database management system, configured log shipping, mirroring, or clustering, and expressed its tolerance for data loss and downtime as a recovery point objective (RPO) and a recovery time objective (RTO) for that engine, relying on the transaction-processing foundations of logging and recovery (Gray & Reuter, 1992). Over the past decade this picture has changed substantially. The rise of web-scale applications, microservice architectures, and cloud platforms has encouraged polyglot persistence, the practice of selecting different storage technologies for different data shapes and access patterns within one business system (Sadalage & Fowler, 2012). A contemporary order management platform may keep orders, payments, and ledger entries in a relational engine, while product catalogs, customer profiles, shopping carts, and event histories live in a document-oriented store.

Both families have invested heavily in resiliency. On the relational side, Microsoft SQL Server Always On Availability Groups (AGs), introduced in SQL Server 2012, replicate transaction log records from a primary replica to a set of secondary replicas in synchronous-commit or asynchronous-commit mode, coordinate automatic failover through Windows Server Failover Clustering or Pacemaker, and offer readable secondaries with read-only routing (Microsoft, 2021a). On the document side, MongoDB replica sets elect a primary through a Raft-derived consensus protocol, replicate an operation log (oplog) to secondaries, and let clients choose per-operation write concern and read concern levels that trade latency against durability and visibility (MongoDB, 2021; Schultz, Avitabile, & Cabral, 2019).

The difficulty is that these resiliency models do not compose automatically. A business transaction that writes an order to the relational tier and an inventory reservation to the document tier inherits the weaker of the two durability guarantees, plus whatever exposure exists in the mechanism that moves data between them. An AG configured for synchronous commit with automatic failover and a replica set configured with the default single-node acknowledgement can each look healthy in isolation, while the combined system can lose acknowledged data during a routine election. Conversely, organizations sometimes over-provision synchronous replication on both tiers, paying a large latency cost for durability that the business process never required. In both cases the root cause is the absence of a shared conceptual model.

This paper addresses that gap. Its contributions are as follows:

1. A structured comparison of the resiliency semantics of relational availability groups and distributed document systems, expressed in terms of durability acknowledgement, failover authority, read visibility, and divergence handling.
2. The Hybrid Resiliency Conceptual Framework (HRCF), consisting of four resiliency planes, a canonical vocabulary that maps onto native configuration primitives of both families, and composite metrics for hybrid RPO, hybrid RTO, and cross-tier consistency window.
3. Five cross-tier invariants that a hybrid deployment must satisfy for its stated objectives to be meaningful.
4. An optimization method that treats resiliency configuration as a constrained search over a latency and durability frontier, together with a failure-scenario taxonomy and a maturity model for assessing enterprise deployments.

The remainder of the paper is organized as follows. Section 2 describes the research method. Section 3 presents the results and discussion: it synthesizes the literature, states the reconciliation problem, develops the conceptual model together with its optimization method, illustrative application, and maturity model, and then discusses the findings, their implications, the limitations of the study, and directions for future research. Section 4 concludes.

2. RESEARCH METHOD

2.1 Research Design

This study adopts a conceptual, design-oriented research design. It combines an integrative literature review (Torraco, 2005; Webster & Watson, 2002) with conceptual model building (Jabareen, 2009) and is framed by the design science view that a conceptual artifact should be judged by its fidelity, utility, and consistency with existing knowledge (Hevner, March, Park, & Ram, 2004). The approach suits the problem because the reconciliation of relational and document-oriented resiliency is primarily a problem of meaning: the two families already provide working mechanisms, but they lack a shared set of concepts through which their guarantees can be compared and combined.

Three research questions guided the study:

1. **RQ1.** How do the resiliency semantics of relational availability groups and distributed document-oriented systems differ with respect to durability, failover authority, read visibility, and divergence handling?

2. **RQ2.** Can these semantics be expressed in a single conceptual model whose constructs map onto the native configuration primitives of both families?
3. **RQ3.** How do the guarantees of the two tiers compose across an integration boundary, and how can configurations be optimized against stated recovery objectives and performance cost?

2.2 Literature Identification and Selection

Two bodies of literature were assembled. The first is a foundational and technical corpus covering replicated data consistency, consensus protocols, transaction processing, cross-store integration patterns, distributed SQL engineering, and product documentation for Microsoft SQL Server Always On Availability Groups, MongoDB, and Azure Cosmos DB. These 32 sources, including the methodological works cited above, were selected because they define the primitives that the framework must represent.

The second is a seed corpus drawn from a consolidated, deduplicated reference list of 1,056 records spanning 68 subject areas in enterprise technology, cybersecurity, data analytics, finance, engineering, health systems, and supply chain management. Two inclusion criteria were applied. First, a temporal criterion admitted only works published in 2021 or earlier, consistent with the date of this study, which left 257 eligible records. Second, a relevance criterion admitted works whose subject bears directly or indirectly on enterprise data resiliency and optimization, namely cloud and database performance, data integration, security and identity, continuity and reliability engineering, analytics and monitoring, governance and compliance, or the sector and organizational settings in which enterprise databases are deployed. Relevance was screened at title level against a weighted keyword dictionary, followed by manual review to remove false positives and works without a defensible connection to the research questions. In total, 211 seed works were retained, giving 243 references in all.

2.3 Analysis and Synthesis

The retained literature was coded thematically. The foundational corpus was coded against the four concerns named in RQ1, while the seed corpus was coded into seven themes: cloud infrastructure and database performance; data integration and platform engineering; security, identity, and zero trust; business continuity and reliability engineering; analytics and monitoring; governance and compliance; and sector and organizational context. Each theme was then mapped to the resiliency plane or planes it informs, as summarized in Table 1. Following the concept-mapping procedure described by Jabareen (2009), concepts recurring across themes, such as acknowledgement, quorum, staleness, drift, and

reconciliation, were consolidated into candidate constructs, and redundant or overlapping constructs were merged.

2.4 Model Construction

The conceptual model was constructed in four iterative steps. First, the native resiliency primitives of each product family were deconstructed into the guarantees they provide, such as the failure an acknowledged write survives, independent of the configuration names used by each vendor. Second, these guarantees were organized into orthogonal planes and ordered scales, producing the canonical vocabulary of Section 3.6.2. Third, composite metrics and cross-tier invariants were derived by reasoning about how guarantees combine when a business operation spans both tiers and an integration channel. Fourth, the model was tested against the literature and against failure scenarios, and constructs were refined where a scenario could not be expressed or where two constructs could not be distinguished.

2.5 Evaluation Approach

Consistent with descriptive evaluation in design science (Hevner et al., 2004), the model was evaluated analytically against four criteria: fidelity, whether it represents the documented behavior of real products faithfully; discriminating power, whether it exposes defects that tier-level analysis misses; theoretical consistency, whether its claims agree with established results on consistency and consensus; and utility, whether it yields actionable configuration guidance. The evaluation is carried out through an illustrative reference architecture and a structured failure-scenario walk-through in Section 3.8. No experimental measurements are reported; empirical validation is identified as future research in Section 3.13.

3. RESULTS AND DISCUSSION

This section reports the results of the integrative review and the conceptual modeling process described in Section 2, and then discusses them. Sections 3.1 to 3.5 present the literature synthesis and the problem it reveals, Sections 3.6 to 3.9 present the conceptual model and its application, and Sections 3.10 to 3.13 discuss the findings, implications, limitations, and future research.

3.1 Literature Synthesis: Foundations and Product Resiliency Mechanisms

3.1.1 Foundations of Replicated Data Consistency

The theoretical foundation for reasoning about replicated databases is well established. The CAP theorem, conjectured by Brewer and proven by Gilbert and Lynch (2002), states that a distributed data store cannot simultaneously guarantee linearizable consistency, availability, and tolerance of network partitions.

Brewer (2012) later emphasized that the theorem constrains behavior only during partitions and that practical systems make finer-grained choices. Abadi (2012) extended the argument with the PACELC formulation: if there is a partition (P), a system trades availability (A) against consistency (C); else (E), during normal operation, it trades latency (L) against consistency (C). PACELC is particularly useful for enterprise resiliency because most operational cost is paid in the "else" branch, as commit latency imposed by synchronous replication.

Between strict linearizability and eventual consistency lies a rich spectrum of models. Terry et al. (1994) introduced session guarantees (read your writes, monotonic reads, writes follow reads, and monotonic writes), and Terry (2013) illustrated the practical significance of intermediate models. Vogels (2009) popularized eventual consistency in the context of large web systems, and Bailis et al. (2013) characterized which transactional isolation levels can be provided while remaining highly available. Consensus protocols such as Paxos (Lamport, 1998) and Raft (Ongaro & Ousterhout, 2014) provide the mechanism by which modern systems agree on a single ordered log despite failures, and underpin both document stores and newer distributed SQL engines such as Spanner (Corbett et al., 2012), CockroachDB (Taft et al., 2020), and TiDB (Huang et al., 2020).

3.1.2 Relational Availability Groups

An availability group is a set of user databases that fail over together as a unit. One replica hosts the read-write primary copy and up to eight secondary replicas host copies that receive log records. In synchronous-commit mode, the primary waits until the secondary has hardened the log records to disk before acknowledging the commit to the client; in asynchronous-commit mode, the primary acknowledges after hardening locally and ships log records in the background (Microsoft, 2021a). Automatic failover is permitted only between synchronous-commit replicas that are in a synchronized state. Since SQL Server 2017, the REQUIRED_SYNCHRONIZED_SECONDARIES_TO_COMMIT setting allows an administrator to require that a minimum number of synchronous secondaries acknowledge each commit, which closes a window in which a primary could otherwise continue committing alone after its partners fall out of synchronization.

Two characteristics of AGs are important for this paper. First, failover authority is external to the database engine: the cluster manager (WSFC or Pacemaker) maintains quorum, often with a file-share or cloud witness, and decides when a replica should assume the primary role. Second, the durability guarantee is defined physically, in terms of log hardening on a specified set of replicas, rather than in

terms of a majority of a voting membership. Redo on secondaries is asynchronous with respect to log hardening, so a readable secondary may expose data that lags the primary even in synchronous-commit mode. Distributed availability groups, introduced in SQL Server 2016, extend the model across two AGs, typically in separate data centers, with asynchronous replication between them.

3.1.3 Distributed Document-Oriented Systems

Document-oriented databases store semi-structured records, commonly in JSON or a binary derivative, and typically scale horizontally through sharding. MongoDB is the most widely deployed example. A MongoDB replica set may contain up to fifty members, of which at most seven vote in elections. Since protocol version 1, elections follow a Raft-like design in which a candidate must obtain votes from a majority of voting members and the elected primary carries a term number that orders its oplog entries (Schultz et al., 2019). Clients choose a write concern for each operation: w:1 acknowledges after the primary applies the write, w:"majority" acknowledges after a majority of data-bearing voting members have durably recorded it, and the j option controls whether acknowledgement waits for the on-disk journal. Read concern levels include local, available, majority, linearizable, and snapshot; causally consistent client sessions, introduced in version 3.6, provide session guarantees across replica members (MongoDB, 2021).

A critical behavior for resiliency analysis is rollback. If a primary accepts writes acknowledged at w:1 and then loses its role before those writes replicate to a majority, the newly elected primary will not contain them, and the former primary rolls them back when it rejoins. Writes acknowledged at w:"majority" are not subject to rollback under the protocol's fault assumptions. Independent testing has shown that the practical guarantees of such systems depend heavily on configuration and client settings (Kingsbury, 2020). Other document and wide-column systems offer comparable controls under different names, for example Apache Cassandra's per-request consistency levels such as QUORUM and LOCAL_QUORUM (Lakshman & Malik, 2010), and Azure Cosmos DB's five account-level consistency levels: strong, bounded staleness, session, consistent prefix, and eventual (Microsoft, 2021b). Dynamo-style systems additionally rely on hinted handoff, read repair, and anti-entropy to converge replicas (DeCandia et al., 2007).

3.1.4 Cross-Store Integration Patterns

Because distributed two-phase commit across heterogeneous engines is fragile and rarely supported in practice, hybrid systems coordinate stores through application-level patterns. Helland (2007) argued that

scalable systems should abandon distributed transactions in favor of entities, idempotent messages, and explicit handling of uncertainty. The saga pattern (Garcia-Molina & Salem, 1987) decomposes a long-lived transaction into local steps with compensating actions. The transactional outbox pattern records an outgoing event in the same local transaction as the state change, and a relay publishes it to a durable log such as Apache Kafka (Kreps, Narkhede, & Rao, 2011). Change data capture (CDC) reads a database's own log to propagate changes. Where concurrent updates must be merged rather than ordered, conflict-free replicated data types (Shapiro et al., 2011) allow replicas to converge without coordination. Kleppmann (2017) synthesizes these approaches and stresses that derived data systems must be designed so that they can be rebuilt from an authoritative source.

3.2 Literature Synthesis: Adjacent Enterprise Literature on Resiliency, Optimization, and Governance

Hybrid database resiliency does not sit in isolation from the wider enterprise systems literature. Database tiers depend on cloud infrastructure, identity services, networks, integration platforms, monitoring, and governance processes, and their failures are felt in finance, health, energy, and supply chain operations. This subsection reviews related and semi-related work across these areas published up to 2021 and identifies what each strand contributes to the framework developed in Section 3.6.

3.2.1 Cloud Infrastructure, Resource Optimization, and Database Performance

Work on cloud-hosted data platforms has examined optimization directly at the database layer. Odejobi et al. (2019) formulated cloud-based database optimization as an approximation complexity problem, while Ahmed et al. (2019) and Ahmed et al. (2020) modeled constraint satisfaction in cloud network resource allocation and machine-learning-driven resource scaling, respectively. Energy-efficient virtual machine placement in data centers (Ahmed & Odejobi, 2018b) extends the same concern to the cost dimension discussed in Section 3.7.5. Performance evaluation of multi-tenant deployments under high concurrency (Odejobi & Ahmed, 2018b) and the engineering of high-throughput payment collection platforms (Osuji et al., 2021) supply practical motivation for the commit latency model presented later in this paper, and studies of telecommunication deployment quality (Amayo & Popoola, 2017b) underline that replication latency is ultimately bounded by the network on which replicas are placed.

Architectural treatments of scalable and secure cloud messaging (Ahmed & Odejobi, 2018a) describe the messaging substrates over which hybrid tiers exchange events. Governance of infrastructure as code (Mbonu, Iwuanyanwu, et al., 2020b) and blockchain-enabled audit trails for cloud configuration

management (Oshoba et al., 2020) provide mechanisms for detecting the configuration drift that invariant I2 is designed to prevent. Blockchain-based energy trading among peer-to-peer microgrids (Shittu et al., 2021) offers a further example of shared state that must remain consistent across independent participants, and work on grounding design for distribution networks (Adeniji et al., 2020) and voltage control in the presence of distributed generation (Oshevire et al., 2017) addresses a physical analogue of the same problem: keeping service stable when control is spread across many nodes.

3.2.2 Data Integration and Enterprise Platform Engineering

The reconciliation plane draws on research into enterprise data integration. Badmus et al. (2019a) proposed a conceptual model for extract, transform, and load design and data integration in Salesforce-centric enterprise architectures, which addresses the cross-store movement of data that HRCF classifies as reconciliation channels. Studies of platform release engineering, including comparisons of DevOps tooling (Badmus et al., 2020), continuous integration and delivery pipeline strategies (Badmus et al., 2018), and platform governance in regulated healthcare environments (Badmus et al., 2019b), show how deployment discipline protects configuration integrity. Artificial intelligence techniques for secure software testing and automated regression control (Mbonu, Aliliele, et al., 2021b) support the recommendation of this paper that resiliency regressions be caught in deployment pipelines, and standard operating procedures treated as change infrastructure (Agboada et al., 2019) offer a complementary, process-based safeguard.

Data architecture frameworks for health system interoperability (Ilodigwe & Adesemoye, 2021) demonstrate that durability and visibility choices are constrained by regulatory obligations. Integrated laboratory information systems (Abdulrazaq et al., 2019), GIS-enabled ERP procurement (Ahiaeke Patrick et al., 2020), real-time order visibility in global distribution networks (Ebisi, Sam-Bulya, et al., 2021), end-to-end supply chain visibility frameworks (Nnabueze et al., 2021), traceability and chain-of-custody integrity in pharmaceutical distribution (Aneke & Adesemoye, 2019), and multi-laboratory antimicrobial resistance reporting networks (Yusuf et al., 2020) illustrate enterprise applications that depend on reliably synchronized operational data across sites. Reconciliation control and financial workflow redesign (Dogbatsey et al., 2019) is a direct accounting analogue of the reconciliation plane, and Anyanwu (2021) examines the operational infrastructure that allows digital businesses to scale.

3.2.3 Security, Identity, and Zero Trust as Resiliency Dependencies

Availability is one of the three classic properties of information security, and a substantial body of work links security engineering to resiliency. Dosunmu & Ogundele (2019) developed security audit and enterprise risk assessment frameworks for resilient information systems, and Fadayomi et al. (2019) reviewed risk-based cybersecurity assurance with explicit attention to data availability. Identity is a prerequisite for failover, because listeners, service accounts, and drivers must authenticate against whichever replica becomes primary. Research on identity and access management for distributed and federated systems (Oshoba et al., 2019), IAM integration in hybrid and multi-cloud environments (Mbonu, Aliliele, Iwuanyanwu, et al., 2020), enterprise directory implementation and assessment (Ladapo et al., 2019; Ladapo et al., 2018), and identity-centric zero trust architecture (Ogbole, Okoruwa, Fadayomi, et al., 2021) is therefore directly relevant to the failover authority plane.

Zero trust principles have been extended to operational technology in critical infrastructure (Ahmed et al., 2021), and a systematic review of operational technology security in electric utilities (Adegbite et al., 2020) shows how failures in adjacent infrastructure propagate to the data services that depend on it. Detection and response capabilities, including enterprise log analytics and automated incident response (Mbonu, Iwuanyanwu, et al., 2019), intrusion detection and prevention (Dosunmu & Ogundele, 2020), and incident response and digital forensics (Dosunmu & Ogundele, 2021), shorten the detection time that dominates recovery in security-triggered outages.

Other work addresses threats that replication cannot mitigate, because a replicated system faithfully copies malicious or erroneous changes to every replica. Relevant contributions include malware classification for cloud-native microservices (Idika et al., 2021), privacy-centric security engineering for cloud computing (Okoruwa et al., 2020), insider threat classification (Akeju et al., 2018), security awareness and records confidentiality (Onche et al., 2020), and privacy by design in corporate transactions (Ominyi, 2021). Cyber risk management maturity in insurance (Fadero et al., 2021), integrated cybersecurity and anti-money-laundering governance (Fadayomi et al., 2021), and VoIP forensic analytics for fraud detection (Mbonu, Iwuanyanwu, Aliliele, et al., 2021) complete this strand.

3.2.4 Business Continuity, Reliability Engineering, and Operational Resilience

Business continuity research provides the organizational setting in which RPO and RTO are defined. Fadero et al. (2020) examined business continuity and disaster recovery preparedness in African financial services in light of the COVID-19 disruption, and Anyanwu (2020) analyzed the balance between cost

and operational continuity in hybrid IT support models. Models for inventory availability and plant uptime in energy facilities (Okonkwo et al., 2018b) and for materials readiness in maintenance-driven supply chains (Okonkwo, Agbabiaka, et al., 2021) treat availability as an explicit operational objective, in the same way that enterprise IT treats RTO.

Classical reliability engineering and failure analysis (Gideon et al., 2019), reliability-centered maintenance (Obetta, 2020), integrity management of critical equipment (Obetta, 2019; Obetta & Ninduwezuor-Ehiobu, 2019), risk-based inspection and fitness-for-service assessment (Obetta, 2018), non-destructive testing for integrity and corrosion risk (Atta et al., 2020; Atta et al., 2021), risk-based process reliability (Asibor & Isong, 2019), and the transition from reactive to predictive maintenance (Sunday et al., 2020; Adaramola et al., 2018) contribute concepts such as failure modes, mean time between failures, and condition-based intervention, which HRCF adapts to data tiers. AI-based predictive maintenance for e-commerce systems using cloud analytics (Mayo et al., 2021) and interpretable failure prediction for distributed energy assets (Komi & Adamolekun, 2021) suggest how replica health could be forecast rather than merely observed.

Resilience has also been studied extensively in supply chains (Anene, 2021; Ogunwole et al., 2021; Ike et al., 2021; Uchechi et al., 2020; Agbabiaka et al., 2019) and in power and energy systems (Adeniji et al., 2020; Oshevire et al., 2017; Yeboah & Ike, 2020; Sunday & Omoegun, 2018), where the same tension between the cost of redundancy and the value of continuity appears. Akomolafe & Agu (2019c) relate resilience to integrated governance and compliance, and Nwafor et al. (2019a) apply resilience thinking to urban infrastructure.

3.2.5 Analytics, Monitoring, and Data-Driven Decision Systems

Continuous measurement of hybrid RPO, hybrid RTO, and the cross-tier consistency window depends on monitoring and analytics. Integrated data visualization for continuous performance monitoring (Ogbole, Okoruwa, Babatope, et al., 2021), executive business intelligence dashboards (Sanni & Atima, 2021b), and risk-based business intelligence architecture for fintech platforms (Mbonu, Aliliele, et al., 2021a) provide design patterns for resiliency dashboards. Research on first-contact resolution in enterprise technology support (Wikiri, 2021) connects technical measures to service outcomes, and maturity models for standardizing IT support operations (Anyanwu, 2019) and for continuous safety performance improvement (Arumosoye & Obriki, 2021) informed the structure of the maturity model in Section 3.9.

Predictive and machine learning methods for demand forecasting (Tonoyan et al., 2021a; Aifuwa et al., 2020), cash flow (Tonoyan et al., 2021b), customer churn (Oziri et al., 2020), audience segmentation (Basnet et al., 2021), geomarketing (Seyi-Lande et al., 2020), marketing return on investment (Sanni et al., 2020a), brand positioning (Sanni et al., 2020b), anti-money-laundering detection (Atakpa, 2021), data-driven risk evaluation (Akomolafe & Agu, 2019b), solar radiation estimation (Odejobi & Ahmed, 2018a), wind power forecasting (Komi, 2021), reservoir forecasting (Nwangwu et al., 2020), and geospatial vendor evaluation (Ahiaeke Patrick et al., 2021) illustrate the analytical workloads that commonly run against readable secondaries and therefore belong to the bounded or eventual read visibility classes. Similar data-driven models appear in agricultural policy and digital agriculture (Michael & Ogunsola, 2021c; Michael & Ogunsola, 2021b; Michael & Ogunsola, 2021d; Michael & Ogunsola, 2021a), environmental remediation (Azeez & Badmus, 2018; Lamidi & Olamide, 2018), hydrology (Badmus & Olamide, 2019), circular-economy chemical safety (Okojie & Abioye, 2020), construction resource scheduling (Makut et al., 2021), occupational safety risk control (Obriki & Arumosoye, 2018), and the use of near-miss and hazard observation data (Arumosoye & Obriki, 2019; Obogo, Arumosoye, Obriki, et al., 2021).

Decision models for financial planning, capital allocation, and executive decision systems (Lawal & Oduleye, 2019b; Lawal & Oduleye, 2021b; Lawal & Oduleye, 2021a; Oduleye & Medon, 2021; Lawal & Oduleye, 2018a), risk stratification for public health emergencies (Oparah, Ezeh, et al., 2021), predictive compliance monitoring in aviation (Adeyelu, 2018), AI-driven risk quantification (Adeyelu, 2020), data-driven operations management and digital transformation (Efobi et al., 2021; Agboada, Ezeako, Okoli, Uzondu, et al., 2018; Obukadata et al., 2021a), and UAV, LiDAR, and GIS monitoring of infrastructure corridors (Dagodzo & Ahiaeke Patrick, 2020; Dagodzo & Ahiaeke Patrick, 2021b) show how organizations consume the data whose availability and correctness HRCF is designed to protect.

3.2.6 Governance, Audit, and Regulatory Compliance

Durability and visibility settings are ultimately governance decisions, because they determine what an organization can prove about its records after a failure. Legal and ethical risk modeling for data protection governance (Mbonu et al., 2018), comparative data protection regulation and secure cloud implementation (Mbonu, Aliliele, et al., 2019), blockchain-based tamper-proof regulatory recordkeeping (Anichukwueze et al., 2021), agile supply chain transformation with embedded IT risk and ISO compliance (Mbonu, Iwuanyanwu, et al., 2020a), shared responsibility in multi-jurisdictional supply chain governance (Ominyi et al., 2021), and the translation of regulatory requirements into SME compliance workflows (Eyetsemitan

et al., 2021) establish that retention, auditability, and availability are compliance obligations rather than purely technical preferences.

Research on internal audit and risk-based internal control (Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a), internal QHSE audit systems (Obogo et al., 2020a), capital adequacy optimization (Mensah et al., 2019), strategic accounting systems (Bola-Sadipe et al., 2019), budget compliance and statutory reporting (Dogbatsey & Ebhojie, 2018), tiered treasury architectures (Dada et al., 2021a), CFO-led strategic finance (Isiekwu et al., 2021), transfer pricing risk (Lawal & Oduleye, 2019a), tax governance analytics (Lawal & Oduleye, 2018b), post-merger compliance integration (Ominyi, 2020), regulatory clearance for cross-border mergers (Ominyi & Anichukwueze, 2020), anti-money-laundering and anti-bribery regimes (Ominyi & Anichukwueze, 2021), ethics and compliance training (Anichukwueze et al., 2020), automated regulatory risk assessment (Uchechi & Ominyi, 2020), statutory licensing compliance (Ominyi et al., 2020), statutory bidding reform (Uchechi et al., 2019), regulatory scenario analysis of finance bills (Akinola et al., 2020), trade compliance (Aneke & Adesemoye, 2021), marketing law (Anichukwueze et al., 2019), regulatory-compliant procurement (Okonkwo, Ogunwole, et al., 2021), vendor governance (Okonkwo et al., 2019), ESG-integrated sustainable procurement (Okojie et al., 2020), joint venture governance alignment (Eyetsemitan et al., 2020), contract review standardization (Uchechi et al., 2021), procedural standardization (Uchechi et al., 2018), liability mitigation in service contracts (Uchechi & Ominyi, 2019), and enterprise financial exposure (Uchechi, 2018) shows the regulatory density of the environments in which enterprise databases operate.

Governance models for safety and operational integrity in high-risk projects (Arumosoye & Obriki, 2020; Nwangwu et al., 2018; Obogo, Ozobu, et al., 2019b; Aminu-Ibrahim et al., 2019; Obogo, Uduokhai, Ozobu, et al., 2021; Obogo et al., 2020b; Obriki & Arumosoye, 2020; Arumosoye & Obriki, 2018; Obogo, Uduokhai, et al., 2019; Obogo et al., 2020c; Obogo, Obriki, Arumosoye, et al., 2021; Obriki & Arumosoye, 2019; Obriki & Arumosoye, 2021), safety management systems and boundary control at airports (Adeyelu, 2019; Adeyelu, 2021), risk-based decision making in good manufacturing practice environments (Aneke & Adesemoye, 2020), and analytics-driven go-to-market frameworks that address compliance complexity (Sanni & Atima, 2021a) offer transferable structures for assigning clear accountability for resiliency outcomes.

3.2.7 Sector and Organizational Context

Several studies describe the sectors and organizations in which hybrid database estates are deployed. In financial services, fintech-enabled transaction banking (Okafor et al., 2021), relationship banking performance (Ezeako et al., 2019), CRM-based sales forecasting (Dada et al., 2021b), partnership ecosystems in private banking (Agboada et al., 2020), trade finance product design (Agboada, Ezeako, Okoli, Ibeh, et al., 2018), credit portfolio growth (Uzondu et al., 2020), web-based payment portal adoption (Agyei et al., 2019), and access to enterprise finance (Michael & Ogunsola, 2019a) all depend on continuously available customer and transaction data. In energy and engineering, strategic procurement optimization (Okonkwo et al., 2018a), UAV-based grid inspection (Dagodzo, 2018a), hybrid solar load distribution (Sunday & Omoegun, 2019), smart solar microgrids (Komi & Adeniji, 2020), hydrogen integration in national grids (Shittu et al., 2019), building envelope optimization (Nwafor et al., 2018), residential air-conditioning control (Sunday et al., 2019), public infrastructure delivery (Nwafor et al., 2019b), port logistics (Okonkwo et al., 2020), and lean re-engineering of customs processes (Ebisi, Okoli, et al., 2021) reflect data-intensive engineering and operational settings.

In health and public services, scaling of mobile health solutions (Oparah, Gado, et al., 2021), surveillance data quality (Ekemezie et al., 2018), data-informed digital learning platforms (Orise & Niniola, 2020), and offline-first design for low-connectivity digital learning (Unamma et al., 2018), which confronts the same partition-tolerance choices discussed in Section 3.1.1, show the public consequences of data availability. Healthcare infrastructure and laboratory studies (Aminu-Ibrahim et al., 2018; Ogbete et al., 2018; Ogbete et al., 2019; Ogbete et al., 2021; Aminu-Ibrahim et al., 2021; Yusuf & Abdulrazaq, 2018), health system strategy and financing (Ilodigwe & Adesemoye, 2019b; Ilodigwe & Adesemoye, 2020; Okoli et al., 2020; Ilodigwe & Adesemoye, 2019a), product management in mobile network rollouts (Sanni et al., 2020c), procurement process automation (Akinleye & Adeyoyin, 2021), lean process improvement in small enterprises (Ambali et al., 2021), workforce and talent development (Falemi et al., 2020; Akhigbe et al., 2020; Wikiri, 2019; Ukadike, 2018; Ukadike, 2019), industry and academia collaboration (Nwangwu et al., 2019), and leadership in African business (Ukadike & Ibeh, 2020) address the people, institutions, and processes that design and operate these systems.

3.3 Thematic Synthesis

Table 1 consolidates the review. For each theme it lists representative sources and the contribution the theme makes to the conceptual model. Two patterns stand out. First, each strand of the literature addresses one or two planes well but none addresses all four together. Second, the reconciliation plane is supported

mainly by indirect evidence, from integration, governance, and reconciliation-control studies, rather than by work that treats cross-store coherence as a resiliency property in its own right.

Table 1. Thematic synthesis of the literature and contribution to the conceptual model

Theme	Representative sources	Contribution to the model	Plane(s) informed
Consistency theory and consensus	(Brewer, 2012; Abadi, 2012; Gilbert & Lynch, 2002; Lamport, 1998; Ongaro & Ousterhout, 2014; Terry, 2013)	Trade-offs between latency, consistency, and availability; quorum and term semantics	Durability, failover, visibility
Product resiliency mechanisms	(Microsoft, 2021a; MongoDB, 2021; Schultz et al., 2019; Kingsbury, 2020)	Native primitives to be mapped onto canonical constructs	All four planes
Cross-store integration	(Garcia-Molina & Salem, 1987; Helland, 2007; Kleppmann, 2017) (Badmus et al., 2019a; Dogbatsey et al., 2019)	Outbox, CDC, sagas, idempotency, reconciliation control	Reconciliation
Cloud infrastructure and database performance	(Odejobi et al., 2019; Ahmed et al., 2019; Ahmed et al., 2020; Ahmed & Odejobi, 2018b; Odejobi & Ahmed, 2018b; Osuji et al., 2021)	Commit latency, placement, and cost optimization	Durability, cost
Security, identity, and zero trust	(Dosunmu & Ogundele, 2019; Fadayomi et al., 2019; Oshoba et al., 2019; Mbonu, Aliliele, Iwuanyanwu, et al., 2020; Ogbole, Okoruwa, Fadayomi, et al., 2021; Ahmed et al., 2021)	Identity as a failover dependency; threats replication cannot mitigate	Failover authority
Continuity and reliability engineering	(Fadero et al., 2020; Anyanwu, 2020; Gideon et al., 2019; Obetta, 2020; Sunday et al., 2020; Mayo et al., 2021)	RPO and RTO framing; failure modes; predictive health	Failover, durability
Analytics and monitoring	(Ogbole, Okoruwa, Babatope, et al., 2021; Sanni & Atima, 2021b; Mbonu, Aliliele, et al., 2021a; Anyanwu, 2019; Arumosoye & Obriki, 2021)	Measurement of composite metrics; maturity structure	Visibility, governance
Governance and compliance	(Mbonu et al., 2018; Mbonu, Aliliele, et al., 2019; Anichukwueze et al., 2021; Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a; Lawal & Oduleye, 2019a)	Resiliency settings as auditable obligations	All planes (accountability)

Theme	Representative sources	Contribution to the model	Plane(s) informed
Sector and organizational context	(Okafor et al., 2021; Oparah, Gado, et al., 2021; Unamma et al., 2018; Okonkwo et al., 2018a; Falemi et al., 2020)	Deployment settings and consequences of unavailability	Context

3.4 Gap in the Literature

Existing work treats each of these areas thoroughly but separately. Vendor documentation describes the resiliency controls of individual products; academic work characterizes consistency models and consensus protocols; and practitioner literature, including site reliability engineering guidance (Beyer et al., 2016), addresses service-level objectives in general terms. What is missing is a model that places relational AG semantics and document-store semantics on a common axis, quantifies how their guarantees combine across an integration boundary, and supports systematic optimization. HRCF is proposed to fill this gap.

3.5 Problem Statement: The Semantic Gap

Consider a hybrid system S composed of a relational tier R protected by an availability group and a document tier D protected by a replica set or sharded cluster, connected by an integration channel C (for example an outbox relay or a CDC pipeline). The enterprise states objectives RPO(S) and RTO(S) for business operations that span both tiers. The reconciliation problem is to determine whether, and under what configuration, S actually satisfies those objectives, and at what performance cost.

Four specific mismatches make this problem difficult.

- **Durability semantics differ.** In an AG, "committed" means the log is hardened on the primary and on whichever synchronous secondaries are required. In a replica set, "committed" means majority-committed in the replication protocol, which may or may not coincide with what the client was told, depending on write concern. A single word conceals different guarantees.
- **Failover authority differs.** AG failover is decided by an external cluster manager with its own quorum, witness, lease, and health-detection timeouts. Replica set failover is decided internally by the voting members, governed by election timeouts and member priorities. The two tiers will therefore fail over at different times, for different reasons, and may disagree about which site is "primary" after a network partition.

- **Read visibility differs.** Readable AG secondaries expose data after redo, which lags log hardening. Document-tier reads at read concern local can observe data that is later rolled back, while majority reads may lag the primary. Applications that read from both tiers can observe states that never existed together.
- **Reconciliation is unowned.** The integration channel C has its own durability and lag characteristics. If the outbox relay is down or a CDC connector falls behind, the document tier diverges from the relational tier regardless of how well each tier is replicated internally.

Table 2 summarizes the native resiliency primitives of the two families and shows why a direct comparison is misleading without a common vocabulary.

Table 2. Native resiliency primitives of relational availability groups and MongoDB replica sets

Concern	**SQL Server Always On AG**	**MongoDB replica set / sharded cluster**
Unit of replication	Availability group (set of databases); transaction log records	Replica set (per shard); oplog entries
Durability acknowledgement	Asynchronous or synchronous commit per replica; REQUIRED_SYNCHRONIZED_SECONDARIES_TO_COMMIT (2017+)	Write concern per operation: w:1, w:n, w:"majority", plus j:true/false
Failover authority	External cluster manager (WSFC or Pacemaker) with node and witness quorum	Internal Raft-style election among up to seven voting members
Automatic failover condition	Only to a synchronized synchronous-commit replica	Any electable member with sufficiently current oplog and majority votes
Read scale-out	Readable secondaries; read-only routing via listener	Read preference (primary, primaryPreferred, secondary, nearest)
Read visibility control	Implicit; secondary reads reflect redo progress, snapshot isolation applied	Explicit read concern: local, available, majority, linearizable, snapshot
Divergence handling	Failover to synchronized replica avoids loss; asynchronous failover can lose data, requiring forced failover	Rollback of non-majority writes on former primary
Cross-site topology	Multi-subnet AG or distributed AG	Members across regions; zone sharding

3.6 Conceptual Model: The Hybrid Resiliency Conceptual Framework

HRCF reconciles the two families by abstracting away from product-specific mechanisms toward the guarantees those mechanisms provide. It is organized around four planes, a canonical vocabulary for each plane, composite metrics, and a set of invariants. The guiding principle is that a hybrid system is only as resilient as its weakest plane across its weakest tier, plus the exposure of the channel between tiers.

3.6.1 The Four Resiliency Planes

Plane 1: Durability. The durability plane describes what must be true before a write is acknowledged to its caller, and therefore which failures can cause an acknowledged write to be lost. It is concerned with commit acknowledgement, persistence to stable storage, and the number and placement of copies.

Plane 2: Membership and Failover Authority. This plane describes who decides which replica is authoritative, how that decision is reached, how long it takes, and what prevents two replicas from accepting writes at the same time. It covers quorum design, witnesses, election and lease timeouts, priorities, and fencing.

Plane 3: Read Visibility. The visibility plane describes which versions of data a read may observe, relative to the most recent acknowledged write. It captures staleness, the possibility of observing data that is later rolled back, and session guarantees.

Plane 4: Cross-Store Reconciliation. The reconciliation plane describes how business state that spans tiers is kept coherent. It covers the integration channel, idempotency, ordering, compensation, and the procedure for detecting and repairing divergence. This plane has no analogue inside either product; it exists only in the hybrid system, which is precisely why it is most often neglected.

The planes are orthogonal in the sense that a configuration choice on one plane does not determine the others, although they interact. For example, synchronous durability on the relational tier (Plane 1) does not by itself guarantee that a failover will be automatic (Plane 2) or that secondary reads will be current (Plane 3).

3.6.2 Canonical Vocabulary

Acknowledgement Durability Levels (ADL)

HRCF defines five acknowledgement durability levels that describe the strongest failure an acknowledged write is guaranteed to survive. Each native configuration maps to exactly one level, which allows the two tiers to be compared directly.

Table 3. Acknowledgement Durability Levels and their native mappings

ADL	Survives	Relational AG mapping	Document store mapping
ADL -0	Nothing guaranteed; may be lost on process crash	Delayed durability enabled	w:0 (unacknowledged) or w:1 with j:false
ADL -1	Process crash of the primary	Primary only, or asynchronous-commit secondaries	w:1, j:true
ADL -2	Loss of the primary node	Synchronous commit with REQUIRED_SYNCHRONIZED_SECONDARIES_TO_COMMIT >= 1	w:"majority" with all voting members in one site
ADL -3	Loss of an entire availability zone or data center	Synchronous secondary required in a second zone or site	w:"majority" with voting members spread so that no single site holds a majority
ADL -4	Loss of a region	Synchronous cross-region commit (rare; high latency)	w:"majority" with voting majority spanning at least three regions

Two observations follow. First, the relational default of synchronous commit is not automatically ADL-2: if the required synchronized secondaries setting is zero, a primary that loses its partner continues to commit at ADL-1, an effect we term *silent durability degradation*. Second, the document store default w:1 is ADL-1, and w:"majority" reaches ADL-3 only when member placement is designed for it. In both families, the level achieved is a property of configuration plus topology, not of configuration alone.

Failover Authority Models (FAM)

HRCF classifies the failover authority of each tier along two attributes. The *locus* is either external (a cluster manager separate from the data path) or internal (consensus among the data-bearing members themselves). The *fencing* is either lease-based, in which a primary that cannot renew its lease stops accepting writes, or term-based, in which writes from a stale term are rejected or rolled back. AGs are external and lease-based; MongoDB replica sets are internal and term-based. The distinction matters because an external authority can fail independently of the database (for example, a lost witness), whereas an internal authority couples failover availability to the health of the voting members.

For each tier the framework records three timing parameters: detection time (T_d), the time to recognize a failure; decision time (T_e), the time to elect or select a new primary; and client reconnection time (T_c), the time for drivers, listeners, or connection pools to reach the new primary. The failover time of a tier is the sum of the three.

Read Visibility Classes (RVC)

Reads are classified into five classes, ordered from strongest to weakest:

- **RVC-L (Linearizable):** observes all writes acknowledged before the read began. Native mappings: primary reads in the AG; read concern linearizable on the document primary.
- **RVC-D (Durable):** observes only data that cannot be rolled back, possibly stale. Native mappings: read concern majority; AG secondary reads where the source is a synchronous replica.
- **RVC-S (Session):** honors read your writes and monotonic reads within a client session. Native mappings: causally consistent sessions in MongoDB; in the AG, routing a session's reads to the primary after it writes.
- **RVC-B (Bounded):** staleness bounded by a stated time or version lag. Native mappings: AG secondary reads gated by monitored redo lag; Cosmos DB bounded staleness.
- **RVC-E (Eventual):** no bound; may observe data later rolled back. Native mappings: read concern local or available on secondaries; asynchronous AG secondaries without lag monitoring.

Reconciliation Channel Classes (RCC)

The integration channel between tiers is classified by its durability and its delivery semantics. A channel is *atomic-coupled* if the event that drives the other tier is written in the same local transaction as the source state change (the transactional outbox), and *log-derived* if it is read from the source engine's own log

(CDC). A channel that writes to both tiers directly from application code without either mechanism is *dual-write* and is considered unsafe, because a crash between the two writes leaves the tiers inconsistent with no record of the intent. Delivery is classified as at-most-once, at-least-once, or effectively-once (at-least-once delivery combined with idempotent application on the consumer).

3.6.3 Composite Metrics

HRCF derives three composite metrics for a business operation that spans tiers. Let RPO_R and RPO_D denote the achievable data-loss windows of the relational and document tiers under a given failure, and let L_C denote the maximum lag of the integration channel at the time of the failure.

Hybrid recovery point objective. For an operation whose authoritative state is in R and whose derived state is in D, a failure can lose data either within a tier or in transit. The effective data-loss window is therefore:

$$RPO_H = max(RPO_R , RPO_D , RPO_R + L_C)$$

The third term reflects that events not yet relayed from R are lost to D if R also loses them, and must otherwise be replayed. Where the channel is atomic-coupled and its relay is idempotent, events committed in R survive with R, so L_C contributes to reconciliation time rather than to data loss, and RPO_H reduces to max(RPO_R, RPO_D). Where the channel is dual-write, RPO_H is undefined, because loss cannot be bounded.

Hybrid recovery time objective. A spanning operation is available only when both tiers have a writable primary and the channel has caught up enough for the operation's correctness. Let T_R and T_D be the tier failover times and T_rc the reconvergence time of the channel. Then:

$$RTO_H = max(T_R , T_D) + T_rc$$

Because the two failover authorities are independent, T_R and T_D are not correlated and the maximum, not the average, governs. In practice T_rc is dominated by the backlog accumulated during the outage divided by the relay throughput, which makes relay capacity a resiliency parameter rather than a mere performance one.

Cross-tier consistency window. The cross-tier consistency window (CCW) is the period during which a reader querying both tiers may observe a combination of states that never existed simultaneously. In steady state, CCW equals the channel lag plus the staleness of the weakest read visibility class used on

either tier. CCW is not a failure metric; it is a normal operating property that must be stated explicitly in service-level objectives.

3.6.4 Cross-Tier Invariants

A hybrid system can claim its stated objectives only if it satisfies the following invariants. They are deliberately expressed in the canonical vocabulary so that they apply regardless of the specific products used.

1. **I1, Durability parity for spanning operations.** Every tier that holds state required to complete a business operation must provide an ADL at least as strong as the ADL the operation promises its caller. A system that writes orders at ADL-3 and inventory reservations at ADL-1 offers ADL-1 for the order process as a whole.
2. **I2, No silent degradation.** Each tier must either refuse writes or raise an alert when it can no longer meet its configured ADL. For the AG this implies a non-zero required synchronized secondaries setting; for the document tier it implies majority write concern with a wtimeout and monitoring of majority-commit point lag. Configuration drift that would weaken these settings can be detected through infrastructure-as-code governance and blockchain-enabled configuration audit trails (Mbonu, Iwuanyanwu, et al., 2020b; Oshoba et al., 2020).
3. **I3, Safe reconciliation channel.** The channel must be atomic-coupled or log-derived, and its consumer must apply events idempotently. Dual-write channels violate I3 by definition.
4. **I4, Authority independence or coordination.** The failure domains of the two failover authorities must be documented. Either they must be independent (so that a single site failure does not disable failover on both tiers), or failover must be coordinated through a runbook or orchestrator that sequences the tiers.
5. **I5, Declared consistency window.** The CCW must be measured and published as part of the service-level objective, and any read path that combines data from both tiers must either tolerate it or use a read visibility class strong enough to eliminate it.

3.6.5 Framework Summary

Table 4 consolidates the framework. Each cell lists the HRCF concept for that plane, the questions an architect must answer, and the principal native levers on each tier.

Table 4. HRCF planes, governing questions, and native levers

Plane	Governing question	Relational AG levers	Document store levers
Durability (ADL)	Which failure can lose an acknowledged write?	Commit mode; required synchronized secondaries; replica placement; delayed durability	Write concern w and j; voting member placement; wtimeout
Failover authority (FAM)	Who decides the new primary, and how fast?	WSFC or Pacemaker quorum; witness; lease and health-check timeouts; failover mode	Election timeout; member priority and votes; arbiters (discouraged); catch-up settings
Read visibility (RVC)	What may a reader observe?	Read-only routing; replica choice; redo lag monitoring	Read concern; read preference; causal sessions; maxStalenessSeconds
Reconciliation (RCC)	How do the tiers stay coherent?	Outbox table; CDC or change tracking; idempotency keys	Change streams; idempotent upserts; compensation handlers

3.7 Optimization within the Framework

Resiliency and performance are often treated as opposing concerns negotiated informally. HRCF instead treats them as a constrained optimization: for each business operation, choose the configuration on each plane that minimizes cost (latency and infrastructure) subject to meeting the operation's required ADL, RVC, RPO_H, and RTO_H.

3.7.1 The Commit Latency Model

In both families, the latency of a durable write is dominated by local log persistence plus the time to collect the required acknowledgements. For a primary with local flush time f and a set of acknowledging replicas whose round-trip times sorted in ascending order are r_1, r_2, ..., the commit latency to collect k acknowledgements is approximately:

$$t_commit(k) = f + r_k + f_k$$

where r_k is the round-trip time to the k-th fastest replica and f_k is its flush time. For an AG, k equals the required synchronized secondaries setting (with all synchronous secondaries acknowledging in practice, the effective k may equal the number of synchronous replicas). For a replica set with n voting members, majority write concern requires floor(n/2) acknowledgements in addition to the primary. This

model yields an important design rule: *durability latency is governed by the k-th nearest replica, not by the farthest*. A five-member replica set with two members in the primary's zone, two in a nearby zone, and one in a distant region acknowledges majority writes at intra-region latency while still tolerating the loss of any single zone, which is a substantially better position on the frontier than a three-member set with one member in each of three distant regions.

3.7.2 The Latency and Durability Frontier

Plotting candidate configurations by commit latency against achieved ADL produces a frontier of non-dominated options. Configurations below the frontier pay latency without gaining durability, for example synchronous commit to a replica in the same rack as the primary, which adds a round trip but does not survive a rack failure. HRCF recommends the following procedure:

1. Classify each business operation by its required ADL and RVC, rather than applying one setting per database.
2. Enumerate the placements available (zones, sites, regions) and their measured round-trip times.
3. For each tier, identify the minimum-latency configuration that meets the required ADL, using the commit latency model.
4. Apply operation-level overrides where the product supports them. The document tier supports per-operation write concern, so low-value writes such as session telemetry can use ADL-1 while orders use ADL-3. The relational tier sets durability per AG, so operations with different requirements should be separated into different AGs or databases.
5. Verify invariants I1 to I5 for every spanning operation after optimization.

3.7.3 Read Path Optimization

Read scale-out is a major motivation for both AG readable secondaries and document-store secondary reads, but it directly affects Plane 3. HRCF recommends routing each query to the weakest replica that satisfies its RVC. Reporting and analytics queries can typically accept RVC-B and run on secondaries, reducing load on the primary and improving its write latency. User-facing reads after a write should use RVC-S, which in the document tier is achieved cheaply with causal sessions and in the relational tier usually requires primary routing for the session. Linearizable reads should be reserved for decisions with external consequences, such as checking a balance before authorizing a payment, because they carry the highest cost.

3.7.4 Workload and Schema Considerations

Resiliency mechanisms amplify workload inefficiencies. In an AG, large index maintenance operations or bulk updates generate log volume that must be shipped and redone, increasing redo lag on secondaries and widening the window of Plane 3 staleness; it can also push synchronous replicas out of the synchronized state, triggering the silent degradation that invariant I2 guards against. In a document store, unbounded document growth and unindexed queries increase oplog volume and replication lag. Accordingly, standard optimizations, such as batching large data modifications, scheduling index rebuilds with resumable or online options, enforcing document size discipline, and creating indexes that support shard-key-aligned queries, should be evaluated for their effect on replication lag as well as on query time.

3.7.5 Cost Optimization

Replicas consume compute, storage, and licensing. In the relational tier, licensing models often distinguish between passive secondaries used only for failover and readable secondaries that serve workload, so the decision to read from secondaries has financial as well as resiliency implications. Placement and scaling models for cloud resources (Ahmed & Odejobi, 2018b; Ahmed et al., 2020; Ahmed et al., 2019) can be applied to replica fleets once the role of each replica is defined. In the document tier, non-voting and hidden members can provide analytics capacity or delayed backup copies without affecting election quorum. HRCF frames these as choices about which plane a replica serves: a replica that contributes only to Plane 1 and Plane 2 should be sized for log application and failover, while a replica serving Plane 3 should be sized for query workload.

3.8 Illustrative Application: Reference Architecture and Failure Scenarios

3.8.1 Illustrative System

To illustrate the framework, consider an order management platform for a mid-sized retailer operating in two cloud regions, each with three availability zones. The relational tier holds orders, payments, and the financial ledger in a SQL Server availability group. The document tier, a MongoDB sharded cluster, holds the product catalog, inventory availability, customer profiles, and shopping carts. When an order is placed, the system must record the order and payment authorization in the relational tier and decrement available inventory in the document tier.

An initial configuration, typical of deployments that evolve without a unified model, is as follows. The AG has a primary and a synchronous secondary in two zones of Region A, plus an asynchronous secondary in Region B, with required synchronized secondaries left at zero. The replica sets each have

three members spread across the three zones of Region A, and the application uses the driver default write concern of w:1. The application writes the order to SQL Server and then calls the document tier to update inventory directly.

3.8.2 HRCF Assessment of the Initial Configuration

Applying the framework exposes four gaps that were not visible when each tier was reviewed in isolation:

- **Durability mismatch (violates I1).** The relational tier provides ADL-3 within Region A when synchronized, but the document tier provides only ADL-1 because of w:1. An inventory decrement can be acknowledged and then rolled back after an election, leading to overselling.
- **Silent degradation (violates I2).** With required synchronized secondaries at zero, if the synchronous secondary is lost the primary continues committing at ADL-1 without blocking, and no alert is tied to the change in guarantee.
- **Unsafe channel (violates I3).** The order and inventory writes form a dual-write. A process crash after the SQL commit and before the document update leaves a recorded order with no inventory reservation and no durable record of the intent.
- **Undeclared consistency window (violates I5).** The customer order history page reads order status from an AG readable secondary and product details from document secondaries at read concern local, so it can display combinations that never existed.

3.8.3 Revised Configuration

The framework guides the following revisions, each traceable to an invariant and chosen to sit on the latency and durability frontier:

1. Set REQUIRED_SYNCHRONIZED_SECONDARIES_TO_COMMIT to 1 on the AG, accepting that the primary will pause writes if no synchronous partner is available, and add a second synchronous secondary in the third zone so that a single-zone loss does not block commits (I2, ADL-3).
2. Expand each document replica set to five voting members, two in the primary's zone and one in each of the other two zones plus one additional member, and use w:"majority" with a wtimeout for inventory and cart checkout writes, keeping w:1 for browsing telemetry. This reaches ADL-3 for spanning writes at near intra-zone latency (I1).

3. Replace the dual-write with a transactional outbox: the order transaction inserts an InventoryReservationRequested event into an outbox table, a relay publishes it, and the document tier applies it with an idempotency key equal to the order identifier (I3).
4. Measure outbox lag and document replication lag continuously, publish the resulting CCW (for example, a 95th-percentile target of two seconds), and route the order confirmation page to primaries with a causal session so a customer always sees their own order (I5).
5. Document that the AG's cluster witness and the document tier's voting members are in different failure domains, and create a regional failover runbook that promotes the relational tier first, then the document tier, then resumes the relay (I4).

3.8.4 Failure Scenario Taxonomy

Table 5 applies the revised configuration to a taxonomy of failure scenarios. For each scenario it records the expected behavior of each tier and of the channel, and the resulting hybrid outcome. The taxonomy is intended to be reused as a test plan in chaos engineering exercises.

Table 5. Failure scenario analysis under the revised configuration

Scenario	Relational tier (AG)	Document tier	Channel	Hybrid outcome
Primary node crash	Automatic failover to synchronized secondary; no acknowledged loss	Election within seconds; majority writes retained	Relay retries; idempotent replay	RPO_H = 0; RTO_H = max failover + backlog drain
Loss of one zone	Remaining synchronous secondary keeps commits at required level	Majority remains; election if primary was in lost zone	Relay restarts in surviving zone	RPO_H = 0; brief write pause
Network partition isolating primary zone	Lease expiry stops isolated primary; cluster quorum elects new primary	Isolated primary steps down without majority; term fencing	Events remain in outbox until reachable	No split brain; CCW grows temporarily
Loss of Region A	Forced failover to asynchronous Region B replica; possible loss of last seconds	Depends on Region B members; manual reconfiguration if no majority	Outbox in Region B replica may lag	RPO_H = async lag; runbook sequencing per I4
Relay outage	Unaffected	Unaffected but stale for derived data	Backlog accumulates	No data loss; CCW and T_rc

Scenario	Relational tier (AG)	Document tier	Channel	Hybrid outcome
				increase; alert required
Silent sync loss	Commits block rather than degrade (I2)	wtimeout surfaces majority lag	Unaffected	Availability traded for durability, by design
Logical corruption or bad deploy	Replicated to all secondaries	Replicated to all members	Propagates	Requires point-in-time restore or delayed replica; outside replication scope

The final row is a reminder that replication protects against infrastructure failure, not against logical error. HRCF therefore treats backups, point-in-time restore, and delayed replicas (supported natively as delayed members in MongoDB and achievable through log shipping or delayed restores in the relational tier) as a fifth, out-of-band concern that complements the four planes.

3.9 Hybrid Resiliency Maturity Model

To support assessment across a portfolio of applications, and following the structure of maturity models used for IT support operations and cyber risk management (Anyanwu, 2019; Fadero et al., 2021), HRCF defines a five-level maturity model:

Table 6. HRCF maturity levels

Level	Name	Characteristics
0	Isolated	Each tier configured independently with vendor defaults; no stated hybrid objectives; dual-write integration common.
1	Documented	Tier-level RPO and RTO stated; configurations recorded; hybrid behavior assumed rather than analyzed.
2	Mapped	ADL, FAM, and RVC assigned to every tier and operation; invariants I1 and I3 satisfied; channel uses outbox or CDC.
3	Measured	RPO_H, RTO_H, and CCW measured continuously; all five invariants satisfied and monitored; failure taxonomy exercised in scheduled tests.
4	Optimized	Configurations selected from the latency and durability frontier per operation; automated coordinated failover; resiliency regressions caught in deployment pipelines.

3.10 Discussion

3.10.1 Interpretation of the Conceptual Model

With respect to RQ1, the synthesis shows that relational availability groups and document-oriented replica sets differ less in what they can achieve than in how their guarantees are defined and decided. Availability groups define durability physically, through log hardening on named replicas, and delegate failover to an external, lease-based authority. Document stores define durability logically, through majority commitment within a voting membership, and decide failover internally through term-based elections. Read visibility is implicit in the first family and explicit in the second. These differences explain why identical-sounding settings, such as "synchronous" and "majority", do not offer identical protection.

With respect to RQ2, the four planes and the canonical scales of Section 3.6.2 show that the two families can be placed on common axes without loss of essential detail: every native configuration examined maps to exactly one acknowledgement durability level and one read visibility class, and every failover authority can be described by its locus, its fencing, and its timing parameters. With respect to RQ3, the composite metrics demonstrate that hybrid guarantees are governed by maxima rather than averages, and that the integration channel contributes to both data loss and recovery time. The illustrative application in Section 3.8 shows that these properties are not merely theoretical: a configuration that appears sound tier by tier can violate four of the five invariants once the planes are examined together.

3.10.2 Evaluation of the Model

HRCF is a conceptual framework, and its primary evaluation is analytical: it should be able to express the guarantees of real products faithfully, it should expose gaps that are missed by tier-level analysis, and its recommendations should be consistent with established theory. Sections 3.6 and 3.8 address these criteria by mapping native primitives into the canonical vocabulary and by showing how the invariants identify concrete defects in a realistic configuration. The composite metrics are consistent with the PACELC view that latency is the dominant cost in normal operation and with the consensus literature on the conditions under which acknowledged writes survive failover.

3.10.3 Relationship to Distributed SQL

Distributed SQL systems such as Spanner, CockroachDB, and TiDB unify relational semantics with consensus-based replication in a single engine, and cloud-native relational designs such as Amazon Aurora separate log-based storage replication from the compute tier (Verbitski et al., 2017). Both can be seen as partial resolutions of the problem this paper addresses. They do not, however, remove the need for

HRCF in most enterprises during the period under consideration. Large installed bases of relational AGs and document stores will persist for years, migrations are costly, and many organizations will continue to use document stores for their developer ergonomics and flexible schemas. Moreover, HRCF's vocabulary applies to distributed SQL as well: such systems sit at ADL-3 or ADL-4 by default, use internal term-based authority, and still require Plane 4 reasoning whenever they exchange data with other stores.

3.11 Implications

3.11.1 Theoretical Implications

The study makes three contributions to theory. First, it extends the PACELC perspective (Abadi, 2012) from a single replicated store to a composition of stores, showing that the latency and consistency trade-off must be evaluated per business operation and across an integration boundary rather than per database. Second, it elevates reconciliation from an implementation detail to a first-class resiliency plane, which reframes integration patterns such as the transactional outbox and change data capture (Kleppmann, 2017) as determinants of recovery objectives rather than purely of data freshness. Third, the five cross-tier invariants can be read as testable propositions; for example, the framework predicts that deployments violating invariant I1 or I3 will exhibit acknowledged-but-lost business transactions under primary failure, whereas deployments satisfying all five invariants will not.

3.11.2 Practical Implications

For database architects and reliability engineers, the framework implies a change in the unit of design from the database to the business operation. Each operation should be assigned a required acknowledgement durability level and read visibility class, and each tier configured to the cheapest setting that meets them. Concretely, availability groups that protect spanning operations should set a non-zero requirement for synchronized secondaries; document-tier writes on which those operations depend should use majority write concern with a timeout; dual-write integration should be replaced by an outbox or change data capture with idempotent consumers; and the cross-tier consistency window should be measured and published. The failure-scenario taxonomy in Table 5 can be adopted directly as a test plan for scheduled resilience exercises.

3.11.3 Managerial and Governance Implications

For technology leaders, the framework implies that service-level objectives for hybrid systems should be stated in terms of hybrid RPO, hybrid RTO, and cross-tier consistency window rather than in tier-level terms that cannot be combined. Because these settings determine what an organization can demonstrate

about its records after a failure, they belong within the scope of internal audit and data protection governance (Akomolafe & Agu, 2018; Mbonu et al., 2018) and of business continuity planning (Fadero et al., 2020). Relay throughput and replica placement should be budgeted as resiliency investments, not as discretionary performance tuning. Finally, the maturity model gives portfolio managers a common scale for prioritizing remediation across many applications, consistent with maturity-based approaches already used in IT operations and cyber risk management (Anyanwu, 2019; Fadero et al., 2021).

3.12 Limitations

The findings of this study should be interpreted in light of several limitations.

- The framework is conceptual and has been evaluated analytically and through an illustrative scenario, not through controlled experiments or field data. Its quantitative relationships, including the commit latency model, are approximations whose accuracy remains to be measured.
- The framework abstracts product behavior to a level that may hide edge cases, for example the interaction between availability group redo threads and snapshot isolation on secondaries, or the specific catch-up behavior of a newly elected document primary. Product documentation and testing remain necessary.
- The composite metrics assume that failures are independent between tiers except where correlated failure domains are documented. In practice, shared infrastructure such as networks, identity services, and DNS can introduce hidden correlation.
- The framework focuses on two representative products. Although the vocabulary is designed to generalize to other relational engines and other document or wide-column stores, mapping tables for those systems have not yet been produced.
- Seed literature was screened primarily at title level and was limited to works published in 2021 or earlier from a single consolidated list, which concentrates the corpus in particular publication venues and regions and may omit relevant work indexed elsewhere.
- HRCF addresses availability and durability; it does not directly address security incidents such as ransomware, which require isolated and immutable backups beyond the scope of replication.

3.13 Future Research

Several directions follow from this study. First, empirical validation is needed: the initial and revised configurations of Section 3.8 could be deployed on a cloud testbed, the failures of Table 5 injected with

fault-injection tooling, and acknowledged-write loss, failover time, channel backlog, and cross-tier consistency window measured in the manner of Jepsen-style analyses (Kingsbury, 2020). Measuring commit latency across candidate placements would test the predictive accuracy of the commit latency model and the shape of the latency and durability frontier.

Second, the canonical vocabulary should be extended to additional engines, including PostgreSQL synchronous streaming replication, Apache Cassandra tunable consistency, and Azure Cosmos DB consistency levels, producing mapping tables comparable to Tables 2 and 3. Third, the vocabulary could be encoded as a machine-readable policy language so that configuration management tools verify invariants automatically and flag drift. Fourth, the commit latency model could be extended to incorporate tail latency and load-dependent acknowledgement times, yielding probabilistic rather than worst-case frontiers.

Fifth, a coordinated failover orchestrator that understands both external lease-based and internal term-based authorities would reduce hybrid RTO by removing manual sequencing during regional events. Sixth, the maturity model and invariants would benefit from practitioner validation through expert panels, Delphi studies, or multi-case studies across financial, healthcare, and retail organizations. Finally, the interplay between replication and security resilience, particularly protection against ransomware and logical corruption that replication propagates, merits a dedicated extension of the framework.

4. CONCLUSION

Enterprises have adopted hybrid data estates faster than they have adopted ways to reason about them. Relational availability groups and distributed document stores each provide mature, well-understood resiliency mechanisms, but their guarantees are expressed in incompatible terms and do not compose without deliberate design. This paper has proposed the Hybrid Resiliency Conceptual Framework as a unified model for reconciling them. By separating resiliency into durability, failover authority, read visibility, and reconciliation planes; by defining acknowledgement durability levels, failover authority models, read visibility classes, and reconciliation channel classes that map onto native controls of both families; and by deriving hybrid RPO, hybrid RTO, and cross-tier consistency window, HRCF makes the resiliency of a hybrid system something that can be stated, verified, and optimized. Its five invariants capture the most common causes of hidden data loss in hybrid deployments, and its optimization method shows that strong durability need not imply prohibitive latency when replica placement is designed around

the k-th nearest acknowledgement. The framework offers architects and database reliability engineers a common language for a problem that, until now, has been solved one product at a time.

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