



DESIGNING CONTROLLED DATA MIGRATION PIPELINES FROM ON-PREMISES TO CLOUD PLATFORMS FOR MISSION-CRITICAL ENTERPRISE SYSTEMS

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ABSTRACT

The migration of mission-critical enterprise systems from on-premises environments to cloud platforms has become a strategic priority for organizations seeking scalability, resilience, and operational efficiency. However, data migration in such contexts presents significant challenges, including maintaining data integrity, minimizing downtime, ensuring security, and complying with regulatory requirements. This paper proposes a structured and controlled framework for designing data migration pipelines that enable reliable and low-risk transitions to cloud environments.

The proposed approach emphasizes a hybrid and incremental migration model, incorporating initial bulk data transfer followed by continuous synchronization using change data capture mechanisms. The architecture integrates distinct layers for data extraction, transformation, secure transfer, cloud ingestion, and validation, ensuring end-to-end traceability and consistency. Key design principles such as idempotent processing, automated validation, rollback capability, and observability are incorporated to enhance reliability and fault tolerance.

Furthermore, the study outlines migration strategies suitable for mission-critical systems, including phased migration and parallel run approaches, supported by rigorous validation and reconciliation techniques. Performance optimization and security controls are also addressed to ensure efficient and compliant data movement. The paper provides a generalized, vendor-neutral blueprint that can be adapted across industries, enabling enterprises to execute controlled data migration with minimal disruption and high confidence in data accuracy and system continuity.

Keywords: Cloud Migration, Data Migration Pipelines, Mission-Critical Systems, Change Data Capture (CDC), Data Integrity, Hybrid Architecture, Incremental Data Load, ETL/ELT, Data Validation, Zero-Downtime Migration, Enterprise Systems, Secure Data Transfer

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I. INTRODUCTION

The increasing demand for scalability, flexibility, and cost optimization has driven enterprises to adopt cloud computing as a foundational component of their digital transformation strategies. Traditional on-premises systems, while reliable in controlled environments, often lack the elasticity and operational efficiency required to support modern, data-intensive applications. As a result, organizations are progressively migrating mission-critical workloads such as financial systems, healthcare platforms, and government applications to cloud-based infrastructures.

Despite its strategic importance, data migration remains one of the most complex and high-risk phases of cloud transformation. Mission-critical systems impose stringent requirements, including near-zero downtime, strict data consistency, high availability, and compliance with regulatory standards. Any disruption or inconsistency during migration can lead to significant operational, financial, and reputational consequences. Therefore, enterprises must adopt carefully designed and controlled data migration pipelines rather than relying on ad hoc or manual approaches.

A key challenge in this context is the seamless transfer of large volumes of heterogeneous data while ensuring integrity and synchronization between source and target systems. Legacy

environments often consist of tightly coupled architectures, fragmented data sources, and outdated schemas, which further complicate migration efforts. Additionally, the need to maintain continuous business operations necessitates strategies that minimize service interruption and support real-time or near-real-time data consistency.

To address these challenges, modern migration approaches emphasize hybrid architectures and incremental data movement techniques. Specifically, the combination of initial bulk data extraction with ongoing synchronization commonly implemented through change data capture (CDC) enables organizations to migrate data progressively while keeping source and target systems aligned. This approach reduces downtime during final cutover and allows for thorough validation before full system transition.

This paper focuses on designing controlled data migration pipelines tailored for mission-critical enterprise systems. It proposes a structured framework that integrates multiple stages, including data assessment, extraction, transformation, secure transfer, cloud ingestion, validation, and cutover. The framework is guided by key principles such as automation, idempotency, fault tolerance, and observability to ensure reliability and repeatability.

The main contributions of this paper are as follows:

- A generalized, vendor-neutral architecture for controlled data migration pipelines
- A phased migration framework incorporating incremental and hybrid strategies
- Comprehensive validation and reconciliation mechanisms to ensure data integrity
- Risk mitigation techniques, including rollback and parallel system operation
- Performance and security considerations for large-scale enterprise environments

By providing a systematic and practical approach, this study aims to support organizations in executing cloud migration initiatives with reduced risk and improved operational confidence. The proposed methodologies are applicable across various domains and can be adapted to different technology stacks and organizational requirements.

II. SYSTEMIC CHALLENGES IN MISSION-CRITICAL DATA MIGRATION

The migration of mission-critical enterprise data from on-premises systems to cloud platforms involves a complex interplay of technical, operational, and regulatory challenges. Unlike standard data transfer scenarios, mission-critical environments demand strict guarantees around availability, consistency, and security. This section examines the key systemic challenges that must be addressed when designing controlled data migration pipelines.

2.1 Legacy System Complexity and Constraints

Many enterprise systems are built on legacy architectures characterized by monolithic designs, tight coupling between application and database layers, and limited modularity. These systems often lack standardized interfaces, making data extraction and integration difficult. Additionally, undocumented dependencies and embedded business logic increase the risk of data inconsistencies during migration.

2.2 Data Volume, Variety, and Distribution

Mission-critical systems typically manage large volumes of data, ranging from structured relational datasets to semi-structured and unstructured formats. This data is often distributed across multiple databases, storage systems, and geographic locations. Migrating such heterogeneous datasets requires robust strategies for partitioning, parallel processing, and schema harmonization to ensure efficiency and consistency.

2.3 Downtime Sensitivity and Business Continuity

A fundamental requirement for mission-critical systems is continuous availability. Even short periods of downtime can result in significant financial losses and operational disruption. Therefore, migration pipelines must be designed to support near-zero downtime through techniques such as incremental synchronization, parallel system operation, and controlled cutover processes.

2.4 Data Integrity and Consistency Assurance

Ensuring data integrity during migration is a critical challenge. Issues such as data loss, duplication, and corruption can arise due to network failures, transformation errors, or synchronization delays. Maintaining referential integrity across related datasets further complicates the process. Effective validation mechanisms, including checksums, reconciliation processes, and audit trails, are essential to guarantee consistency between source and target systems.

2.5 Security and Regulatory Compliance

Enterprise data often includes sensitive information subject to strict regulatory requirements. Migration processes must ensure secure data transfer through encryption mechanisms and enforce robust access controls. Additionally, compliance with industry standards and regulations necessitates detailed logging, monitoring, and audit capabilities throughout the migration lifecycle.

2.6 Network and Performance Constraints

Transferring large datasets from on-premises environments to cloud platforms can strain network bandwidth and introduce latency issues. Inefficient data transfer can prolong migration timelines and impact system performance. Techniques such as data compression, parallel data transfer, and optimized scheduling are required to mitigate these constraints.

2.7 Dependency Management and System Interoperability

Enterprise applications often rely on interconnected systems, shared databases, and external integrations. Migrating data without properly managing these dependencies can lead to inconsistencies and functional failures. Ensuring interoperability between legacy systems and cloud-based platforms is essential for maintaining seamless operations during and after migration.

Table 1: Summary of Key Challenges in Data Migration

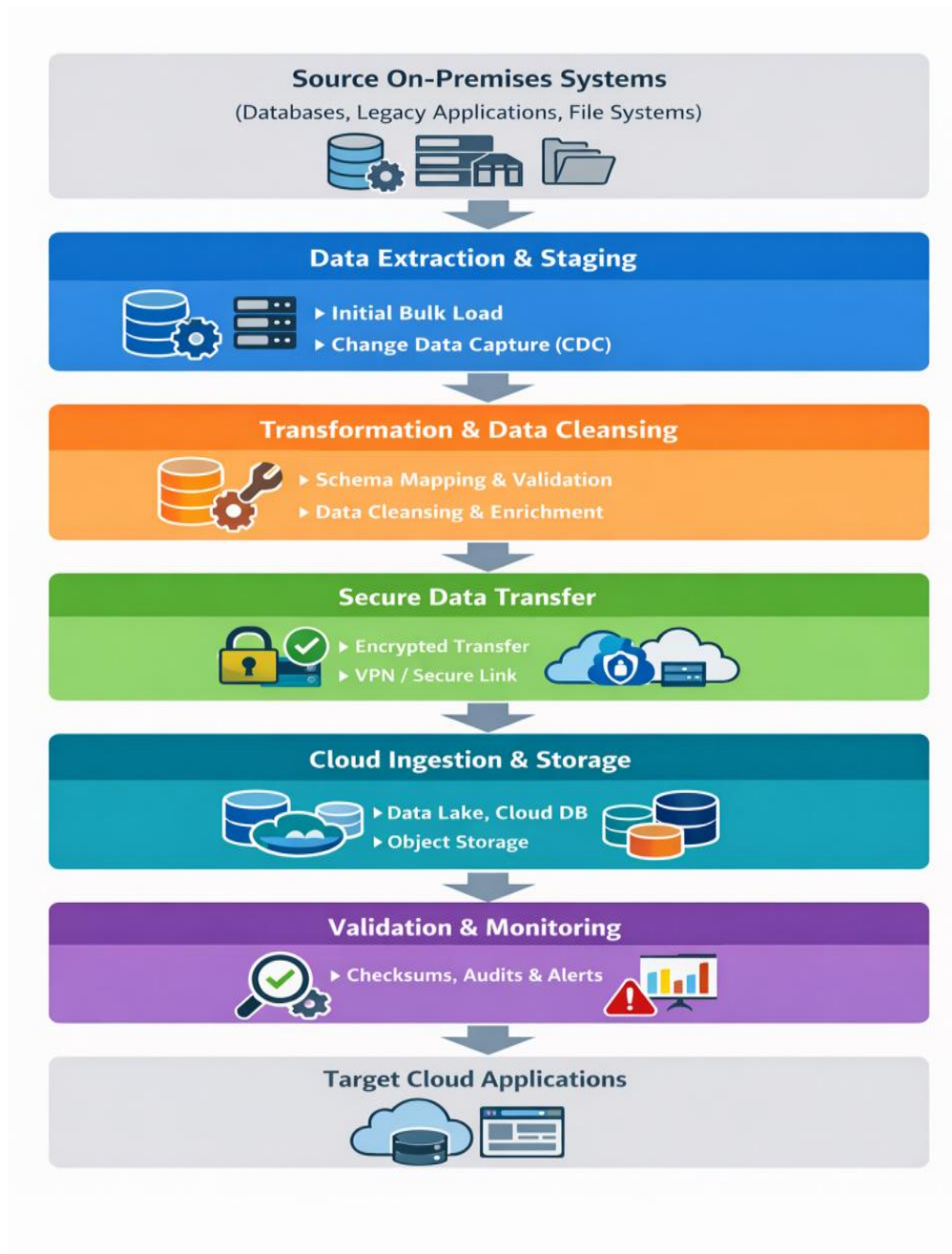
Challenge Category	Description	Impact on Migration
Legacy System Constraints	Monolithic, tightly coupled architectures	Increased complexity and risk
Data Volume & Variety	Large, distributed, heterogeneous datasets	Performance and scalability issues
Downtime Sensitivity	Requirement for continuous availability	Limited migration windows
Data Integrity	Risk of data loss or inconsistency	Trust and reliability concerns
Security & Compliance	Regulatory and data protection requirements	Need for secure and auditable flows
Network Constraints	Bandwidth and latency limitations	Slower data transfer
Dependency Management	Interconnected systems and integrations	Risk of system disruption

This analysis highlights that data migration is not merely a technical exercise but a multi-dimensional challenge requiring careful planning, robust architecture, and controlled execution.

III. LAYERED ARCHITECTURE FOR CONTROLLED DATA MIGRATION PIPELINES

Designing a controlled data migration pipeline for mission-critical enterprise systems requires a structured, modular, and fault-tolerant architecture. A layered approach enables separation of concerns, improves scalability, and allows independent validation at each stage of the pipeline. This section presents a generalized, vendor-neutral architecture that supports secure, incremental, and reliable data migration from on-premises environments to cloud platforms.

3.1 Architectural Overview



3.2 Design Principles

The effectiveness of the migration pipeline depends on several key architectural principles:

- **Decoupling of Components:** Each layer operates independently, reducing system dependencies and enabling flexible scaling.
- **Incremental Data Movement:** Continuous synchronization using change data capture minimizes downtime.

- **Idempotent Processing:** Ensures repeated executions do not introduce inconsistencies.
- **Fault Tolerance:** Failures in one layer do not propagate across the pipeline.
- **Automation and Observability:** Automated workflows with real-time monitoring improve reliability and traceability.

3.3 Data Extraction and Staging Layer

This layer is responsible for retrieving data from source systems and preparing it for downstream processing. It typically includes:

- **Initial Bulk Extraction:** A one-time full data snapshot
- **Change Data Capture (CDC):** Continuous tracking of inserts, updates, and deletes
- **Staging Area:** Temporary storage for raw data before transformation

The staging layer acts as a buffer, isolating source systems from downstream processing and reducing performance impact on production environments.

3.4 Transformation and Data Standardization Layer

Data extracted from legacy systems often requires transformation to align with cloud-native schemas and formats. This layer performs:

- Schema mapping and normalization
- Data cleansing (removal of duplicates, handling null values)
- Data enrichment and formatting
- Application of business rules

By standardizing data before transfer, this layer ensures compatibility with target cloud systems and improves data quality.

3.5 Secure Data Transfer and Integration Layer

This layer facilitates the movement of transformed data from on-premises environments to the cloud. Key considerations include:

- **Secure Communication:** Encryption using secure protocols
- **Hybrid Connectivity:** VPNs or private network links
- **Batch and Streaming Modes:** Support for both bulk and real-time data transfer
- **Message Queues and APIs:** Reliable and asynchronous data delivery

The design of this layer is critical for maintaining data confidentiality and ensuring reliable transmission across distributed environments.

3.6 Cloud Ingestion and Storage Layer

Once data reaches the cloud environment, it is ingested into scalable storage systems such as data lakes or cloud-native databases. This layer supports:

- High-throughput data ingestion
- Scalable storage for structured and unstructured data
- Partitioning and indexing for performance optimization

Efficient ingestion mechanisms ensure that large volumes of data can be processed without bottlenecks.

3.7 Validation, Reconciliation, and Monitoring Layer

To ensure data accuracy and completeness, this layer implements robust validation mechanisms:

- Record count comparison between source and target
- Checksum and hash-based validation
- Referential integrity checks
- Real-time monitoring and alerting

This layer provides visibility into the migration process and enables rapid detection and resolution of issues.

3.8 Target System Integration

The final layer connects the migrated data to cloud-based applications and services. This includes:

- Data access APIs
- Integration with analytics and reporting tools
- Support for transactional and operational workloads

Ensuring seamless integration with target systems is essential for maintaining business continuity post-migration.

3.9 Architectural Benefits

The proposed layered architecture offers several advantages:

- **Scalability:** Each layer can scale independently based on workload
- **Resilience:** Fault isolation improves system reliability
- **Flexibility:** Supports multiple migration strategies (batch, streaming, hybrid)
- **Traceability:** End-to-end monitoring ensures transparency
- **Reduced Risk:** Controlled execution minimizes migration failures

This layered architectural model provides a robust foundation for implementing controlled data migration pipelines in mission-critical enterprise environments. By combining modular design with strong validation and security mechanisms, it enables organizations to execute migrations with confidence and minimal disruption.

IV. MIGRATION STRATEGIES AND EXECUTION MODELS

Selecting an appropriate migration strategy is a crucial decision in designing data migration pipelines for mission-critical enterprise systems. The choice of execution model directly impacts system availability, risk exposure, migration duration, and operational complexity. This section presents commonly adopted migration strategies along with their characteristics, trade-offs, and suitability for different enterprise scenarios.

4.1 Big Bang Migration Approach

The Big Bang approach involves migrating the entire dataset from the on-premises environment to the cloud in a single operation, typically within a predefined maintenance window.

Key Characteristics

- One-time bulk data transfer
- Complete system switchover after migration
- Minimal coexistence between source and target systems

Advantages

- Simpler implementation
- Faster overall migration timeline

Limitations

- High risk of failure
- Requires extended downtime
- Limited rollback flexibility

This approach is generally unsuitable for mission-critical systems due to its inherent risk and downtime requirements.

4.2 Phased (Incremental) Migration Approach

In the phased approach, data is migrated in smaller, manageable segments over time. Each phase targets a specific dataset, module, or business function.

Key Characteristics

- Gradual migration of data and workloads

- Controlled validation at each stage
- Reduced operational risk

Advantages

- Lower risk compared to Big Bang
- Easier issue isolation and resolution
- Better alignment with business operations

Limitations

- Increased complexity in coordination
- Longer migration duration

This model is widely adopted for medium to large-scale enterprise migrations.

4.3 Parallel Run (Dual System) Strategy

The parallel run strategy involves running both the legacy (on-premises) system and the new cloud system simultaneously for a defined period.

Key Characteristics

- Dual data synchronization between systems
- Continuous validation and comparison
- Gradual transition to cloud

Advantages

- Near-zero downtime
- High confidence through real-time validation
- Safe rollback capability

Limitations

- Increased infrastructure and operational cost
- Complexity in maintaining data consistency

This approach is highly suitable for mission-critical environments where reliability is paramount.

4.4 Incremental Migration Using Change Data Capture (CDC)

This strategy combines an initial bulk data load with continuous synchronization of changes using CDC mechanisms.

Key Characteristics

- Initial full data extraction
- Ongoing replication of inserts, updates, and deletes
- Near real-time synchronization

Advantages

- Minimal downtime during cutover
- Efficient handling of large datasets
- Continuous data consistency

Limitations

- Higher implementation complexity
- Requires robust monitoring and conflict resolution

This is one of the most effective strategies for large-scale, mission-critical systems.

4.5 Hybrid Migration Model

The hybrid model combines multiple strategies (e.g., phased + CDC + parallel run) to achieve optimal results.

Key Characteristics

- Flexible combination of techniques
- Tailored to enterprise-specific requirements
- Supports complex system dependencies

Advantages

- Balanced risk and performance
- High adaptability
- Suitable for large, distributed systems

Limitations

- Requires advanced planning and governance
- Higher architectural complexity

Table 2: Comparative Analysis of Migration Strategies

Strategy	Risk Level	Downtime	Complexity	Best Use Case
Big Bang	High	High	Low	Small, non-critical systems
Phased	Medium	Medium	Medium	Modular enterprise systems
Parallel Run	Low	Low	High	Mission-critical applications
Incremental (CDC)	Very Low	Minimal	High	Large-scale data migration
Hybrid Model	Low	Minimal	Very High	Complex enterprise environments

4.6 Strategy Selection Considerations

Selecting the appropriate migration strategy depends on several organizational and technical factors:

- **Business Continuity Requirements:** Systems requiring 24/7 availability favor CDC or parallel strategies
- **Data Volume and Velocity:** Large datasets benefit from incremental approaches
- **System Dependencies:** Highly interconnected systems require phased or hybrid models
- **Risk Tolerance:** Lower tolerance necessitates controlled and reversible strategies
- **Regulatory Constraints:** Compliance requirements may influence migration design

4.7 Recommended Approach for Mission-Critical Systems

For mission-critical enterprise environments, a hybrid strategy combining phased migration, CDC-based synchronization, and parallel validation is recommended. This approach ensures:

- Near-zero downtime
- Continuous data consistency
- Controlled risk management
- High confidence before final cutover

This section highlights that there is no one-size-fits-all migration strategy. Instead, successful enterprise migrations rely on selecting and tailoring execution models based on system criticality, data characteristics, and organizational priorities.

V. END-TO-END CONTROLLED DATA MIGRATION PIPELINE DESIGN FRAMEWORK

A well-defined design framework is essential for executing data migration in a controlled, repeatable, and low-risk manner. For mission-critical enterprise systems, the migration pipeline must not only handle data movement but also ensure validation, synchronization, monitoring, and rollback readiness at every stage. This section presents a structured, phase-driven framework for designing and implementing controlled data migration pipelines.

5.1 Framework Overview

The proposed framework follows a multi-phase lifecycle approach, where each phase is independently validated before progressing to the next. This ensures early detection of issues, minimizes risk, and enables controlled execution.

5.2 Phase 1: Assessment and Planning

This phase establishes the foundation for migration by analyzing the source environment and defining migration objectives.

Key Activities

- Data profiling and classification
- Identification of critical datasets
- Dependency mapping across systems
- Risk assessment and mitigation planning
- Selection of migration strategy (CDC, phased, hybrid)

Outputs

- Migration roadmap
- Data inventory and prioritization
- Architecture design blueprint

5.3 Phase 2: Data Extraction and Initial Load

This phase focuses on extracting data from source systems and performing the initial bulk transfer.

Key Activities

- Full data snapshot extraction
- Data partitioning for parallel processing
- Loading data into staging or intermediate storage
- Initial bulk load into cloud target

Key Considerations

- Minimizing impact on source systems
- Ensuring completeness of extracted data

5.4 Phase 3: Incremental Synchronization (CDC Integration)

After the initial load, continuous synchronization ensures that changes in the source system are reflected in the target system.

Key Activities

- Capturing inserts, updates, and deletes
- Streaming or batching incremental data
- Conflict detection and resolution
- Maintaining ordering and consistency

Outcome

- Source and target systems remain synchronized in near real-time

5.5 Phase 4: Data Transformation and Standardization

This phase ensures that data conforms to target system requirements.

Key Activities

- Schema mapping and transformation
- Data cleansing and deduplication
- Data enrichment and normalization
- Application of business validation rules

Importance

This step ensures data quality and usability in the cloud environment.

5.6 Phase 5: Data Validation and Reconciliation

Validation is a critical control mechanism in the migration pipeline.

Key Activities

- Record count comparison
- Checksum/hash validation
- Referential integrity verification
- Sampling-based data quality checks

Automation

Validation processes should be automated to ensure consistency and repeatability.

5.7 Phase 6: Controlled Cutover and Deployment

This phase marks the transition from the on-premises system to the cloud system.

Key Activities

- Final synchronization (delta load)
- System readiness verification
- Switching application traffic to cloud
- Monitoring system stability post-cutover

Strategies

- Blue-green deployment
- Canary release for gradual transition

5.8 Phase 7: Post-Migration Monitoring and Optimization

After cutover, continuous monitoring ensures system stability and performance.

Key Activities

- Monitoring pipeline performance metrics
- Identifying and resolving anomalies
- Optimizing queries and storage structures
- Decommissioning legacy systems

5.9 End-to-End Workflow Representation



5.10 Key Benefits of the Framework

- **Controlled Execution:** Phase-wise validation reduces failure risk
- **Scalability:** Supports large-scale data migration
- **Flexibility:** Compatible with multiple migration strategies
- **Reliability:** Ensures data integrity and consistency
- **Auditability:** Enables traceability and compliance

5.11 Practical Implementation Considerations

- Automate pipeline orchestration using workflow engines
- Implement centralized logging and monitoring systems
- Use metadata-driven pipeline configurations
- Ensure rollback mechanisms are tested before cutover

This end-to-end framework provides a structured methodology for designing controlled data migration pipelines in mission-critical environments. By combining phased execution, continuous synchronization, and robust validation, it enables enterprises to achieve seamless and reliable cloud migration.

VI. DATA VALIDATION, INTEGRITY, AND QUALITY ASSURANCE

Ensuring data integrity and quality is a fundamental requirement in mission-critical data migration. Any inconsistencies introduced during migration can lead to incorrect business decisions, regulatory violations, and operational failures. Therefore, validation mechanisms must be embedded throughout the migration pipeline rather than treated as a post-migration activity.

6.1 Multi-Level Validation Framework

A robust validation strategy operates at multiple levels:

- **Schema-Level Validation:** Ensures structural consistency between source and target systems
- **Record-Level Validation:** Verifies row counts and individual record accuracy
- **Business-Level Validation:** Confirms that domain-specific rules and constraints are preserved
- **System-Level Validation:** Validates end-to-end data flow and integration correctness

6.2 Validation Techniques

Checksum and Hash Validation

- Generate hash values for datasets at source and target
- Compare hashes to ensure data consistency

Row Count Reconciliation

- Compare total records between systems
- Identify discrepancies in batch transfers

Data Sampling

- Perform random sampling for manual or automated verification
- Useful for large-scale datasets

Referential Integrity Checks

- Ensure relationships between tables are preserved
- Validate foreign key constraints

6.3 Automated Validation Pipelines

Automation plays a critical role in ensuring repeatability and scalability. Validation pipelines should:

- Run continuously during migration
- Trigger alerts on anomalies
- Maintain audit logs for traceability

Table 3: Validation Techniques and Their Use Cases

Technique	Purpose	Best Use Case
Checksum Validation	Detect data corruption	Large datasets
Row Count Comparison	Verify completeness	Batch migration
Data Sampling	Spot-check data quality	High-volume datasets
Referential Integrity	Maintain relationships	Relational databases

VII. PERFORMANCE OPTIMIZATION IN DATA MIGRATION PIPELINES

Performance optimization is essential for minimizing migration time and ensuring efficient resource utilization. Poorly optimized pipelines can lead to extended downtime and increased operational costs.

7.1 Parallel Processing and Partitioning

Dividing large datasets into smaller partitions enables parallel processing, significantly improving throughput.

- Horizontal partitioning (row-based)
- Vertical partitioning (column-based)

7.2 Data Compression and Transfer Optimization

Compressing data before transfer reduces network overhead and accelerates migration.

- Use of efficient compression algorithms
- Minimizing redundant data transfer

7.3 Incremental Data Processing

Instead of reprocessing entire datasets, incremental approaches focus only on changed data, reducing computational overhead.

7.4 Resource Scaling in Cloud Environments

Cloud platforms enable dynamic resource allocation:

- Auto-scaling compute resources
- Elastic storage provisioning

7.5 Performance Metrics

Key metrics to monitor include:

- Throughput (records per second)
- Latency (data transfer delay)
- Resource utilization (CPU, memory, network)

VIII. SECURITY AND COMPLIANCE IN DATA MIGRATION

Security is a critical concern when migrating sensitive enterprise data to the cloud. Migration pipelines must ensure confidentiality, integrity, and compliance with regulatory standards.

8.1 Data Encryption

- **In Transit:** Use secure communication protocols
- **At Rest:** Encrypt data stored in cloud systems

8.2 Access Control Mechanisms

- Role-Based Access Control (RBAC)
- Least privilege principle
- Identity and access management integration

8.3 Audit and Logging

- Maintain detailed logs of all migration activities
- Enable traceability for compliance audits

8.4 Regulatory Compliance

Migration pipelines must align with industry regulations such as:

- Financial compliance standards
- Healthcare data protection regulations
- Data residency requirements

8.5 Risk Mitigation

- Secure key management

- Continuous vulnerability assessment
- Data masking for sensitive fields

IX. MONITORING, OBSERVABILITY, AND OPERATIONAL GOVERNANCE

Continuous monitoring and governance are essential for ensuring the reliability and transparency of migration pipelines.

9.1 Observability Framework

An effective observability framework includes:

- Metrics collection
- Distributed logging
- Real-time alerting

9.2 Key Monitoring Metrics

- Pipeline success/failure rates
- Data latency and lag
- Error rates and retries
- Data throughput

9.3 Alerting and Incident Management

- Automated alerts for anomalies
- Incident response workflows
- Root cause analysis mechanisms

9.4 Governance and Control

- Policy-driven pipeline execution
- Data lineage tracking
- Compliance reporting

9.5 Operational Dashboards

Dashboards provide real-time visibility into migration progress and system health, enabling proactive issue resolution.

X. CONCLUSION

The migration of mission-critical enterprise systems from on-premises environments to cloud platforms is a complex and high-stakes undertaking. This paper presented a comprehensive, controlled approach to designing data migration pipelines that prioritize reliability, scalability, and security. By adopting a layered architecture, phased execution

framework, and robust validation mechanisms, organizations can significantly reduce migration risks and ensure data integrity throughout the process.

The study emphasized the importance of incremental migration strategies, particularly those leveraging change data capture, to achieve near-zero downtime and continuous synchronization. Additionally, performance optimization techniques, security controls, and observability frameworks were discussed as essential components for successful migration.

A key takeaway is that effective data migration is not solely a technical challenge but also an organizational and governance-driven process. Careful planning, automation, and continuous monitoring are critical to achieving predictable and repeatable outcomes.

As enterprises continue to modernize their IT landscapes, future advancements in automation, artificial intelligence, and real-time data processing are expected to further enhance migration capabilities. The framework and strategies presented in this paper provide a generalized and adaptable foundation for organizations seeking to execute controlled, efficient, and secure data migrations to cloud platforms.

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