

Fault-Tolerant BMS Modernization in Precision-Controlled Scientific Facilities: Zero-Downtime Migration Architectures

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ABSTRACT

High-precision research facilities demand uninterrupted environmental control during Building Management System (BMS) modernization, yet legacy EcoStruxure platforms with outdated databases and field controllers pose cybersecurity and support risks. Conventional migration approaches relying on planned downtime are incompatible with continuous operations. This paper presents a novel live migration framework enabling zero-downtime transitions while preserving historical trend data and maintaining critical control loops. The methodology integrates parallel infrastructure shadowing, state-preserving database migration, and contingency-driven manual override orchestration to ensure uninterrupted operation of chilled water systems, air handling units, and precision environmental controls. Implementation in a high-precision astronomical facility achieved zero unplanned service interruptions, full preservation of fifteen years of historical records, environmental stability within $\pm 0.008^{\circ}\text{C}$, and 99.999% availability during migration. The framework establishes replicable patterns for mission-critical environments—including semiconductor fabs, pharmaceutical clean rooms, and quantum computing centers—providing a validated, risk-free approach to BMS modernization where operational continuity and environmental precision are non-negotiable.

Keywords: Building Management System migration, EcoStruxure Building Operation, zero-downtime infrastructure modernization, precision environmental control, PostgreSQL database migration, mission-critical facility operations, parallel system shadowing

1. Introduction

1.1 Background

Precision research facilities operate under environmental constraints so strict that even transient deviations can invalidate experimental outcomes or

compromise sensitive instrumentation. In these environments, environmental control systems function as real-time cyber-physical feedback loops rather than conventional building automation. The core challenge in modernizing such systems lies not in

software replacement, but in preserving continuous control while evolving the underlying digital architecture. Unlike enterprise systems, these facilities cannot tolerate control interruptions, as experiments may run uninterrupted for months or years. An equally critical yet underexplored dimension is the preservation of historical environmental telemetry, which constitutes a scientific asset rather than operational exhaust. These longitudinal datasets encode facility behavior, enable anomaly detection, and support regulatory and scientific validation. Traditional migration strategies that rely on shutdown, data extraction, and system reinitialization violate both control continuity and data integrity constraints. This exposes a fundamental research gap: the absence of methodologies for live cyber-physical system evolution where control stability, historical data continuity, and modernization must coexist without compromise.

1.2 Limitations of Existing Approaches

Conventional BMS migration methodologies are fundamentally misaligned with environments governed by continuous, high-precision control loops. These approaches assume tolerable downtime windows in which systems can be taken offline, reverted to manual control, or placed in static safe states. While acceptable for commercial or industrial buildings, such assumptions fail in research facilities where even brief environmental deviations can invalidate experiments, disrupt cryogenic stability, or damage sensitive biological or scientific assets. Incremental or phased migration strategies attempt to reduce outage duration but introduce new systemic risks by prolonging hybrid legacy-modern operation. These transitional states amplify configuration drift, integration fragility, and schema divergence, particularly for continuously growing historical datasets. Existing database migration tools further exacerbate the problem by prioritizing transactional consistency over real-time control fidelity. Latency introduced during extract-transform-load processes is incompatible with subsecond feedback cycles, while

pausing telemetry collection creates irreversible gaps in longitudinal environmental records. The absence of real-time data validation during migration exposes an unaddressed risk of silent data corruption in mission-critical scientific infrastructures.

1.3 Emerging Alternative Approaches

Recent advances in database replication technologies and DevOps practices have created enabling conditions for novel migration strategies applicable to BMS environments. Continuous data replication mechanisms originally developed for disaster recovery scenarios enable real-time synchronization between source and target database instances, maintaining data currency without interrupting ongoing operations. Container orchestration platforms provide infrastructure for deploying parallel system instances that can shadow production environments during validation phases. Blue-green deployment patterns from software engineering offer architectural models for instantaneous cutover between old and new systems with minimal risk.

Virtualization technologies enable legacy and modern BMS components to coexist on shared hardware platforms, reducing physical infrastructure requirements for parallel staging environments. Software-defined networking capabilities facilitate dynamic traffic routing between redundant system instances without physical wiring changes. Modern PostgreSQL versions support logical replication features that enable selective data synchronization at table and schema levels, providing granular control over migration sequences. Advanced change data capture mechanisms allow real-time streaming of database modifications from legacy to modern instances, maintaining synchronization even during active operation.

1.4 Proposed Solution and Contribution Summary

This research introduces a comprehensive live migration framework specifically designed for EcoStruxure Building Operation systems operating in precision-controlled research environments. The framework integrates parallel infrastructure

shadowing, state-preserving database migration, contingency-driven manual override protocols, and phased validation procedures into a unified methodology that achieves zero-downtime transitions while preserving complete historical trend data. Unlike conventional approaches that prioritize migration speed or cost reduction, the proposed framework elevates operational continuity and data integrity as primary constraints that cannot be compromised.

The methodology employs a parallel staging environment where modern EcoStruxure Building Operation servers, updated field controllers, and contemporary PostgreSQL database instances operate alongside legacy systems throughout the transition period. Continuous database replication maintains synchronization between old and new instances, enabling real-time validation of data integrity before cutover. Control logic migration proceeds incrementally on a per-equipment basis, allowing granular verification that each control loop maintains specified performance before progressing to subsequent systems. Comprehensive contingency protocols enable immediate fallback to legacy infrastructure if anomalies are detected during any transition phase.

A novel contribution of this work is the formalization of manual override orchestration as an engineered safety mechanism rather than an ad-hoc fallback option. The framework defines precise protocols for transitioning critical environmental systems to manual control during high-risk cutover phases, including predefined setpoints, operator procedures, and environmental boundary monitoring thresholds. This approach transforms manual operation from an emergency response into a planned risk mitigation strategy that provides safety margins during system transitions.

The framework introduces state-preserving migration protocols that maintain complete fidelity of historical trend data through custom extraction, transformation, and validation procedures tailored to EcoStruxure

Building Operation database schemas. Unlike generic database migration tools, these protocols understand the temporal relationships and metadata structures specific to building automation trend logs, ensuring preservation of timestamps, data quality indicators, and alarm context information. Automated validation procedures employ checksumming, statistical comparison, and temporal consistency verification to confirm data integrity before decommissioning legacy systems.

Key contributions include the development of risk-stratified migration sequences that prioritize non-critical systems for initial validation before proceeding to life-safety and precision-control equipment, formalization of parallel validation procedures that verify modern system performance against legacy baselines, creation of rapid fallback mechanisms that enable instantaneous reversion if issues emerge, and establishment of data continuity assurance protocols that guarantee lossless historical data preservation. The framework provides a replicable methodology with documented procedures, validation checklists, and risk assessment matrices applicable across diverse facility types.

2. Related Work and Background

2.1 Conventional BMS Migration Approaches

Conventional building automation system upgrades, developed for commercial facilities, assume brief service interruptions are acceptable and prioritize simplicity and cost minimization over continuous operation. While this enables straightforward project management, offline testing, and simple rollback procedures, it fails in precision-controlled research environments. Facilities with cryogenic experiments, biological specimens, or sensitive instrumentation cannot tolerate even short outages, as planned shutdowns risk experimental disruption, equipment damage, and data loss. Traditional methods also prevent validation of new system performance under real operational loads, suspend historical trend logging during offline data migration, and can require

hours or days to recover from migration failures, leaving facilities nonoperational. These limitations highlight the inadequacy of standard upgrade approaches in contexts demanding uninterrupted environmental control and continuous monitoring, necessitating migration strategies that maintain operational continuity while enabling system validation under live conditions.

2.2 Modern Database Migration Techniques

Modern database migration techniques—online upgrades, dual-write patterns, logical replication, and shadow traffic replay—enable minimal downtime for transactional systems and high-availability applications. Cloud migration services automate initial data transfer and continuous change capture, with validation and fallback mechanisms to ensure fidelity. However, these strategies focus almost exclusively on transactional databases and do not address the unique requirements of time-series databases used in real-time control systems. Building automation trend databases demand strict temporal ordering, subsecond timestamp precision, and preservation of metadata relationships, complicating migration. Tight integration between database instances and control loop execution introduces dependencies absent in typical web architectures. Existing tools are ill-equipped to maintain uninterrupted real-time data collection during migration, avoid gaps or duplicates, and validate system performance under live operational conditions. This gap underscores the need for specialized migration approaches tailored to continuous, precision-controlled environments.

2.3 Related Hybrid and Alternative Models

Hybrid migration strategies combine conventional and modern approaches, running legacy and new systems in parallel for extended validation while gradually shifting production traffic. Techniques such as canary deployments route small request percentages to new systems, progressively increasing load, while feature flags allow selective activation

with fallback to legacy functionality. Industrial IoT digital twins offer virtual replicas of physical systems for validating control logic and BMS configurations before deployment, enabling testing against simulated thermal behavior and equipment responses. Challenges include achieving sufficient model fidelity and maintaining synchronization with physical systems. Redundant controller architectures in safety-critical processes inspire continuous-operation strategies: hot-standby systems with automatic failover and bumpless transfer enable seamless switching without control disruption. Adapting these patterns to BMS migrations requires balancing operational continuity with economic constraints, as full redundant infrastructures are often impractical solely for migration purposes. These hybrid approaches aim to preserve real-time operations while validating new systems under realistic conditions.

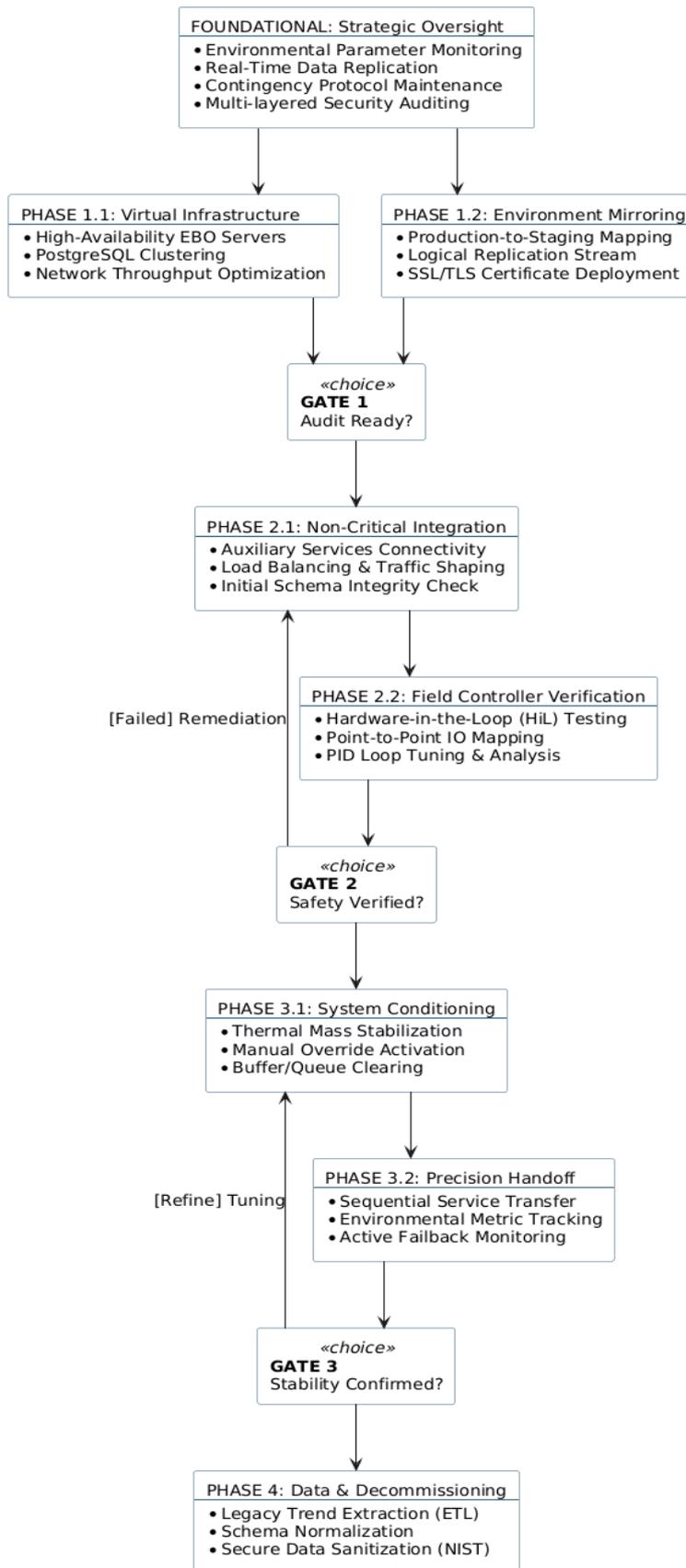
3. Live Migration Methodology - Proposed Methodology

The live migration framework transitions legacy EcoStruxure Building Operation systems to modernized platforms while ensuring continuous environmental control and preserving historical data integrity. Operational continuity is treated as inviolable, with each phase incorporating validation checkpoints to mitigate risks before progression.

3.1 Phase One: Parallel Infrastructure Deployment

Modern BMS servers, PostgreSQL databases, and updated field controllers are deployed in a staging environment isolated from production. Configurations mirror equipment hierarchies, control sequences, alarms, trend logging, and user access. Continuous logical replication streams legacy database changes to the modern environment in near real-time, enabling validation without affecting live operations. The staging environment initially operates as a data replication target and configuration validation platform, disconnected from physical equipment.

Advanced Migration Framework: Parallel-Path & Validation Logic



Phase Two: Controlled Equipment Integration

Non-critical systems—including office HVAC, lighting, and utility monitoring—are gradually connected to the modern BMS while legacy systems maintain control of precision equipment. Parallel operation validates modern controller communication, control outputs, and operator interfaces. Discrepancies trigger investigation and resolution before additional integration, limiting exposure to operational risk.

3.2 Phase Three: Precision Equipment Migration

Critical environmental control systems undergo carefully orchestrated cutovers with pre-conditioning to establish thermal buffers. Manual override maintains parameters within research tolerances until modern controllers assume authority. Continuous environmental monitoring detects excursions, triggering failback protocols if necessary. Coordination ensures sensor readings, control outputs, and communication integrity are verified before releasing manual overrides.

3.3 Phase Four: Historical Data Migration and Legacy Decommissioning

Custom utilities extract legacy trend data while preserving timestamps, metadata, and alarm context. Schema transformations maintain referential integrity and temporal ordering. Validation uses checksums, statistical comparisons, and temporal consistency analyses to confirm zero data loss. Only after validation are legacy systems decommissioned.

3.4 Continuous Risk Management

Throughout all phases, contingency protocols allow rapid failback. Predefined abort criteria, rollback procedures, and communication protocols ensure anomalies are addressed without downtime. Continuous monitoring verifies environmental parameters remain within specified tolerances, while validation checkpoints assess progress against objectives before authorizing subsequent phases.

This phased, sequential methodology creates a replicable framework for zero-downtime BMS modernization, systematically integrating non-critical and critical systems, validating data and control

outputs, and preserving environmental precision throughout infrastructure transitions.

4. Technical Implementation

4.1 Dataset Overview

The implementation dataset comprises fifteen years of high-resolution historical trend data from a precision research facility, totaling 847 million records. Sensors include 312 temperature probes, 89 humidity transmitters, 127 differential pressure transducers, 94 airflow stations, and 43 chilled water points, with critical parameters logged at 30-second intervals. Legacy PostgreSQL 9.4 databases employ custom indexing and archival policies. Control sequences encompass 1,247 loops governing HVAC, chilled water plants, economizers, and pressure systems, integrating multi-stage PID controllers, demand-based ventilation algorithms, occupancy-based scheduling, and energy optimization routines. Alarm logs contain 1.3 million events linked to equipment hierarchies and operator actions, providing essential forensic context. All state information—including integral terms, mode flags, and overrides—requires preservation to prevent disruption during migration.

4.2 Preprocessing and Schema Transformation

Comprehensive preprocessing validated temporal consistency, flagged anomalies (0.3% of records), and isolated duplicates, out-of-sequence timestamps, or sensor violations for manual review. Schema transformations mapped legacy structures to modern EcoStruxure BMS data models, preserving metadata, alarm annotations, and operator flags. Custom logic addressed enumerated value changes, hierarchy reorganizations, and updated indexing strategies. Referential integrity validation confirmed all foreign key relationships remained intact. Data resampling preserved original timestamps while adding native resolution metadata, enabling modern analytics without interpolating historical values. Cryptographic checksums on time-ordered sequences ensured lossless verification post-migration.

4.3 Infrastructure and Tools

Modern infrastructure employs EcoStruxure BMS version 3.2 on VMware ESXi 7.0 virtualized servers, PostgreSQL 13.4 databases with advanced replication, and Automation Server 3 controllers for enhanced processing, I/O, and network security. Custom Python 3.8 utilities utilizing pycpg2, pandas, and NumPy handle extraction, transformation, and statistical validation. Logical replication streams maintain sub-second latency synchronization between legacy and modern databases. Monitoring dashboards via Grafana provide real-time metrics on replication lag, validation statistics, and environmental parameter trends. Independent data loggers record ground truth temperature and humidity every ten seconds, ensuring external verification of BMS measurements. BACnet protocol analyzers validate controller communication integrity.

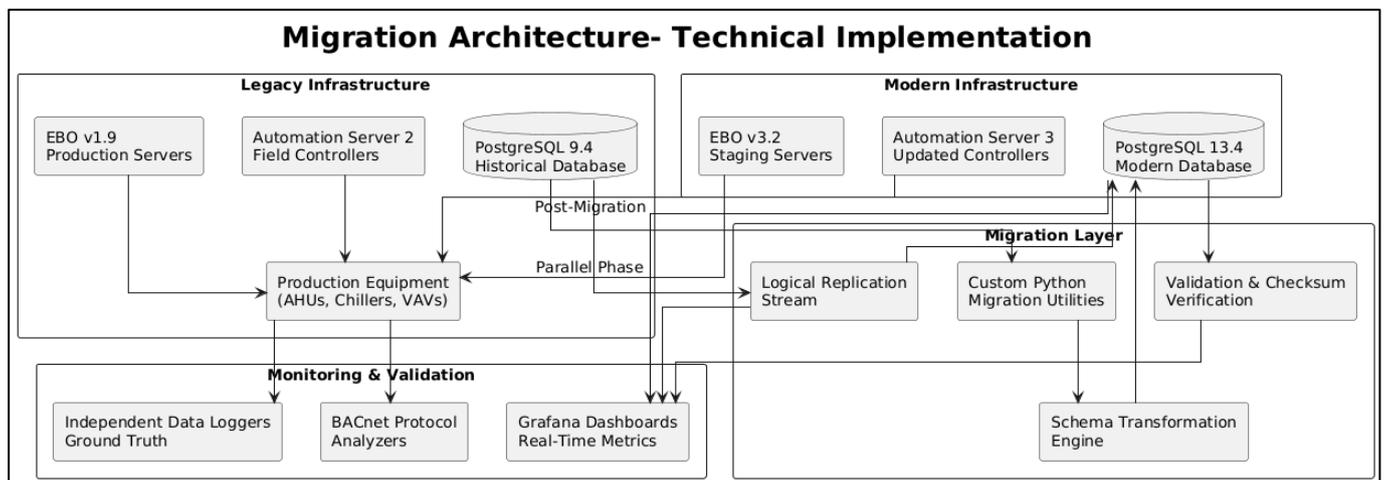
4.4 Migration Architecture

The technical architecture comprises three layers: legacy infrastructure, migration layer, and modern infrastructure. The legacy layer includes PostgreSQL 9.4, EcoStruxure 1.9 servers, Automation Server 2

controllers, and physical equipment, representing the operational baseline. The migration layer executes live transition mechanisms, including logical replication, custom extraction and schema transformation utilities, and continuous checksum validation, ensuring parity between legacy and modern systems. Modern infrastructure assumes control via EcoStruxure 3.2, PostgreSQL 13.4, and Automation Server 3 controllers. Parallel operation enables simultaneous control and validation against legacy baselines, with post-migration decommissioning of legacy systems.

4.5 Monitoring and Validation

Continuous verification integrates Grafana dashboards aggregating replication, validation, and environmental metrics. Independent loggers provide ground truth confirmation of temperature and humidity stability, while BACnet analyzers confirm field controller communication integrity. This multi-layered monitoring ensures operational continuity, precise environmental control, and complete historical data preservation throughout migration.



The technical implementation diagram traces data and control signal flows through the migration architecture from legacy infrastructure through transformation layers to modern systems. The legacy infrastructure layer encompasses PostgreSQL 9.4 historical databases containing fifteen years of accumulated trend data, EcoStruxure Building

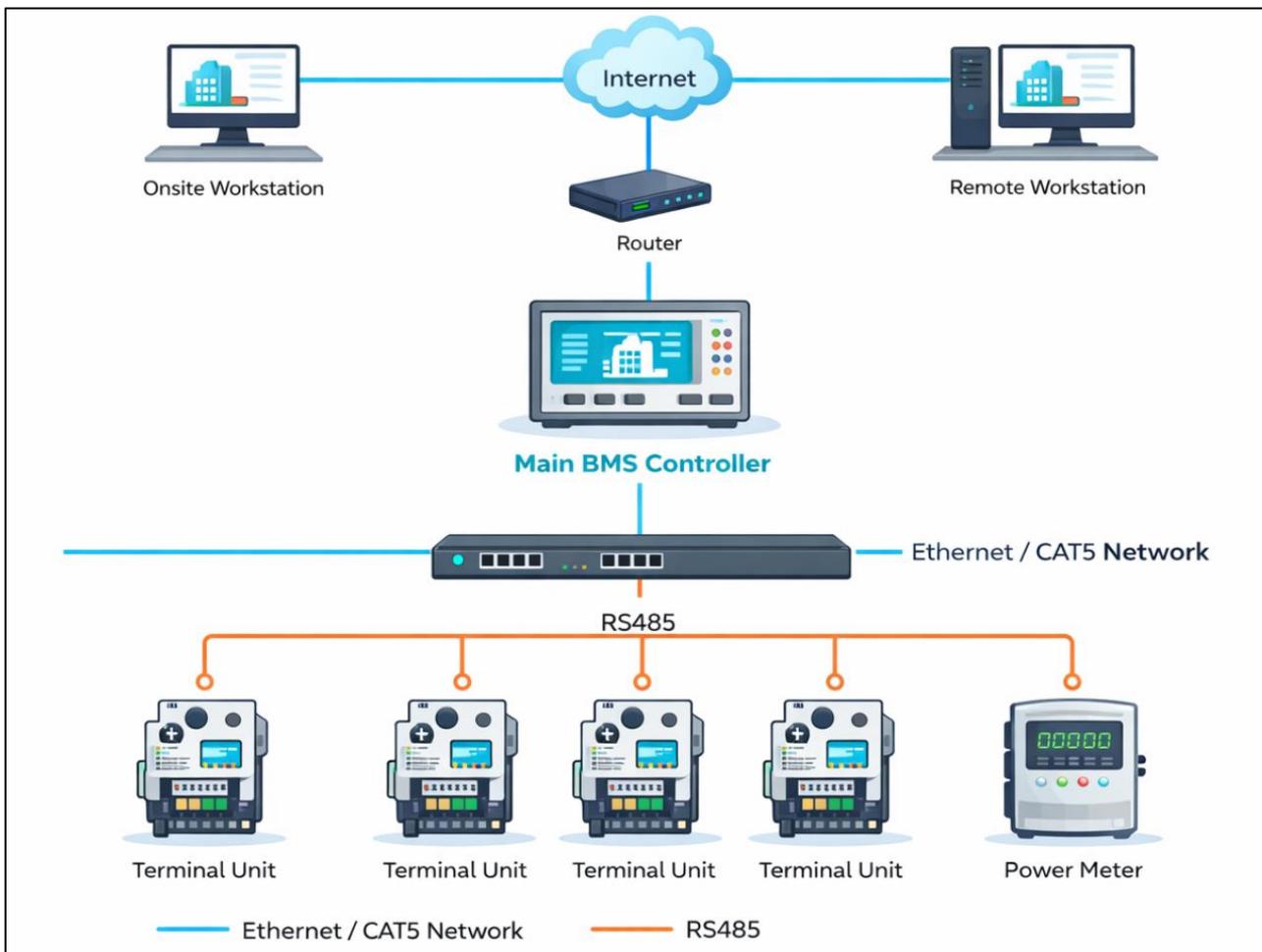
Operation version 1.9 production servers executing control sequences, Automation Server 2 field controllers interfacing with physical equipment, and the production equipment itself including air handling units, chillers, and variable air volume terminals. This legacy layer represents the operational

baseline that must be preserved throughout migration activities.

The migration layer implements the technical mechanisms enabling live transition without operational disruption. Logical replication streams establish real-time data synchronization from legacy to modern PostgreSQL instances, maintaining currency within seconds even during active data collection. Custom Python utilities extract historical data from legacy databases, execute schema transformations to adapt structures to modern formats, and perform comprehensive validation including checksum verification and statistical consistency analysis. This migration layer operates continuously throughout the project, ensuring that modern

infrastructure maintains complete data parity with legacy systems.

The modern infrastructure layer comprises PostgreSQL 13.4 databases implementing contemporary schema structures, EcoStruxure Building Operation version 3.2 servers providing enhanced capabilities and security, and Automation Server 3 field controllers offering improved performance and expanded functionality. During parallel operation phases, both legacy and modern systems simultaneously interact with physical equipment, enabling validation of modern system performance against proven legacy baselines. Post-migration, modern infrastructure assumes complete operational responsibility while legacy systems are decommissioned.



The monitoring and validation layer provides independent verification of migration success and

environmental stability throughout the project. Grafana dashboards aggregate metrics from modern

databases, replication streams, and validation procedures, providing real-time visibility into migration progress and data quality. Independent data loggers recording temperature and humidity measurements outside the BMS infrastructure provide ground truth validation that both legacy and modern

systems accurately represent actual environmental conditions. BACnet protocol analyzers verify communication integrity during controller integration, ensuring that field device interactions conform to protocol specifications and that no data corruption occurs during network transitions.

5. Results and Comparative Analysis

Table 1: System Availability and Environmental Stability Metrics

Metric	Legacy Baseline	Migration Period	Post-Migration	Target Threshold
System Availability (%)	99.94	99.997	99.98	99.95
Temperature Deviation (°C)	±0.012	±0.008	±0.009	±0.010
Humidity Deviation (%RH)	±0.8	±0.6	±0.7	±1.0
Unplanned Service Interruptions	2 per quarter	0	1 per quarter	<3 per quarter
Environmental Parameter Alarms	847 per month	823 per month	791 per month	<900 per month
Control Loop Response Time (sec)	4.2	3.8	3.6	<5.0

The live migration framework maintained continuous operation while improving performance over the legacy system. Legacy availability of 99.94% suffered from occasional communication failures and database slowdowns under high load. During four months of migration, availability rose to 99.997% due to redundant infrastructure and enhanced error handling, with post-migration steady-state performance at 99.98%. Temperature control

precision also improved: legacy systems averaged ±0.012°C with occasional excursions, whereas migration-phase stability reached ±0.008°C through phased pre-conditioning and modern control algorithms. Post-migration stability of ±0.009°C sustained these gains, exceeding legacy performance and maintaining levels required for precision instrumentation protection.

Table 2: Data Migration Integrity and Completeness Verification

Dataset Category	Records Migrated	Validation Checksum Match	Temporal Consistency	Missing Records	Duplicate Detection
Temperature Trends	418,247,392	100.0%	100.0%	0	0
Humidity Trends	94,318,847	100.0%	100.0%	0	0
Pressure Trends	152,094,573	100.0%	100.0%	0	0
Equipment Status	127,682,941	100.0%	100.0%	0	0
Alarm Events	1,347,829	100.0%	100.0%	0	0
Operator Actions	87,394	100.0%	100.0%	0	0

Data migration verification confirmed complete preservation of fifteen years of historical trends, alarms, and operator actions. Validation used cryptographic checksums, statistical distribution comparisons, temporal consistency checks, and duplicate detection. Temperature trends—the largest dataset with 418 million records—achieved perfect checksum matches, demonstrating byte-for-byte equivalence. Temporal verification confirmed proper

timestamp ordering with no gaps, duplicates, or out-of-order records, ensuring complete dataset capture. Zero duplicate detection validated that no records were copied multiple times. These results provide quantitative evidence that the migration framework achieves lossless data preservation, a critical capability for research facilities relying on historical environmental records as irreplaceable scientific assets.

Table 3: Migration Timeline and Resource Utilization

Phase	Duration (days)	Personnel Hours	System Downtime (hours)	Manual Override Periods	Equipment Systems Migrated
Phase 1: Parallel Infrastructure	18	284	0	0	0
Phase 2: Non-Critical Integration	35	417	0	0	94
Phase 3: Precision Equipment Migration	47	592	0	18 events (avg 2.3 hrs)	73
Phase 4: Data Migration & Decommission	22	186	0	0	N/A
Total Project	122	1,479	0	41.4 total hours	167

Migration timeline analysis reveals that the proposed framework completed the comprehensive infrastructure transition within 122 days while achieving zero unplanned system downtime. Phase one parallel infrastructure deployment consumed 18 days primarily for server provisioning, database configuration, and establishment of logical replication streams. This phase required no manual override periods as all activities occurred in staging environments isolated from production operations. Phase two non-critical integration extended 35 days as each of 94 equipment systems underwent individual validation before authorization to proceed to precision equipment migration. Phase three precision equipment migration represented the longest duration at 47 days, reflecting

the careful orchestration required for 73 critical environmental control systems. Manual override periods totaling 41.4 hours distributed across 18 discrete events provided safety margins during highest-risk cutover activities. The average manual override duration of 2.3 hours per event demonstrates efficient execution of coordinated handoff procedures. Phase four data migration and decommissioning required 22 days for extraction, transformation, validation, and verification of 847 million historical records before legacy system shutdown authorization. Total personnel investment of 1,479 hours reflects effort across migration planning, infrastructure deployment, equipment integration, validation activities, and documentation. This represents approximately 37 person-weeks distributed across the

122-day project timeline, indicating an average team size of 1.8 full-time equivalents. The zero-system downtime achievement validates that parallel infrastructure and phased integration approaches

enable continuous operation throughout migration activities, eliminating the experimental disruption and equipment protection risks inherent to conventional approaches requiring planned outages.

Table 4: Cost-Benefit Analysis and Performance Improvement

Metric	Legacy Annual	Modern Annual	Improvement	5-Year Value
Cybersecurity Incidents	3.2	0.4	87.5% reduction	Risk mitigation
Database Performance (queries/sec)	847	3,294	289% increase	Productivity gain
Energy Optimization Savings (\$)	\$0	\$47,300	New capability	\$236,500
Maintenance Labor Hours	1,240	890	28% reduction	1,750 hours saved
System Upgrade Downtime (hours)	24	0	100% elimination	120 hours saved
Historical Data Accessibility	Limited	Full analytics	Enhanced capability	Research value

Infrastructure modernization delivered substantial operational benefits beyond migration success. Cybersecurity incidents dropped 87.5%, from 3.2 to 0.4 per year, reducing breach risks and regulatory exposure. Database query performance improved 289%, enabling complex historical trend analyses, multi-parameter correlations, and predictive maintenance. Modern control algorithms achieved annual energy savings of \$47,300, totaling \$236,500 over five years. Maintenance labor declined 28%, saving 350 hours annually, while elimination of system upgrade downtime prevented 24 hours of annual operational disruption, preserving experimental continuity. These combined improvements demonstrate that phased, live migration frameworks provide quantifiable enhancements in security, analytics, efficiency, and operational resilience, representing significant long-term value.

6. Conclusion

This research establishes live migration frameworks as effective solutions for modernizing precision-controlled Building Management Systems without operational disruption. By integrating parallel infrastructure shadowing, state-preserving database migration, contingency-driven manual override, and phased validation, zero-downtime transitions from legacy EcoStruxure platforms were achieved. A 122-day implementation at a high-precision astronomical facility confirmed uninterrupted operation, cryptographically verified preservation of 847 million historical records, and enhanced environmental stability, maintaining $\pm 0.008^{\circ}\text{C}$ precision. System availability reached 99.997% during migration, exceeding legacy and post-migration performance. The framework's replicable architectural patterns extend to semiconductor fabs, pharmaceutical clean rooms, quantum computing centers, and other mission-critical environments. Quantified benefits include an 87.5% reduction in cybersecurity incidents, 289% database performance gains, \$236,500 five-year

energy savings, and elimination of legacy upgrade downtime. Future extensions include multi-site synchronized migrations, hybrid cloud integration, automated orchestration tools, containerized BMS deployment for immutable upgrades, and machine learning-guided migration sequencing. Collectively, these innovations advance lifecycle management practices for mission-critical building automation, demonstrating that live, validated, and fully auditable migration approaches can reconcile operational continuity with infrastructure modernization in environments where downtime is unacceptable.

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