

Methodology for the Efficient Management of Current Repairs in Civil Infrastructure

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Abstract: Operational durability and economic sustainability of building assets depend heavily on the timing and organization of routine maintenance actions. Conventional maintenance management frequently relies on rigid time-based intervals or reactive repairs, producing high lifecycle expenditures and unmitigated structural deterioration under sharp environmental variations. This paper presents an integrated engineering methodology for the efficient planning, multi-criteria prioritization, and resource allocation of current repairs across civil and municipal buildings. The proposed framework combines continuous condition assessment, non-destructive testing (NDT) metrics, and an analytical Condition-Predictive and Risk-Priority Maintenance Index (CP-RPMI). By formulating a lifecycle cost optimization model, maintenance schedules are mathematically harmonized against stochastic degradation rates and budget constraints. Longitudinal validation across a forty-two-building experimental portfolio demonstrates that shifting from calendar-driven upkeep to condition-predictive planning lowers recurring repair outlays by 24.4%, curtails emergency structural interventions by 38.6%, and eliminates costly cascading envelope failures.

Keywords— current repairs, degradation modeling, facilities management, lifecycle cost analysis, non-destructive testing, structural durability

1. INTRODUCTION

Modern civil infrastructure components deteriorate continuously as a consequence of chemical attack, cyclic hygrothermal variations, solar ultraviolet radiation, and mechanical fatigue. In institutional, municipal, and multi-unit residential facilities, operational and maintenance expenditures systematically outstrip initial construction costs, often representing 60% to 80% of total lifecycle outlays over a fifty-year horizon [1],[2]. Within this operational continuum, current repairs—encompassing routine upkeep, protective sealing, cosmetic restorations, and localized non-structural replacements—serve as the first line of defense against compounding degradation [3],[4].

Despite substantial advances in Building Information Modeling (BIM) and facility operations software [5], maintenance management within municipal, institutional, and residential building sectors across transitional economies remains heavily tethered to deterministic, calendar-based regulatory cycles or unmitigated reactive repair strategies [6], [7]. Deterministic cycles fail to account for site-specific microclimates, structural occupancy spikes, and stochastic material fatigue. Reactive regimes, conversely, incur substantial direct economic penalties, tenant disruption, and structural reliability compromises [8].

Developing a robust engineering methodology for current maintenance organization requires addressing three interrelated structural domains:

Physical Degradation Mechanics: Formulating realistic condition decay functions across complex building envelopes, load-bearing frames, and finish systems under environmental exposure [3], [8].

Diagnostic Instrumentation: Deploying non-destructive testing (NDT) and visual multi-spectral inspection pipelines to quantify residual service margins [9], [10].

Economic and Operational Optimization: Deriving mathematical scheduling algorithms that determine optimal intervention points, minimizing cumulative life cycle costs while upholding statutory structural safety and comfort constraints [11], [12].

This study develops an empirical, scalable, and computationally transparent methodology for current maintenance execution.

The core research objectives comprise:

a-characterizing degradation vectors for critical exterior and interior asset sub-assemblies;

b-establishing a multi-criteria Condition-Predictive and Risk-Priority Maintenance Index (CP-RPMI);

c- deriving a life cycle optimization function balancing direct maintenance outlay against failure risks;

d-validating the operational model through a multi-year comparative field experiment across municipal building portfolios.

2. THEORETICAL FRAMEWORK AND PROBLEM STATEMENT

2.1 Evolution of Structural and Facilities Maintenance Paradigms

Building maintenance engineering has transitioned through three major paradigms over the past half-century:

Run-to-Failure (Corrective), Time-Based Maintenance (Preventive), and Condition-Based Maintenance (Predictive) [4], [7]. Classical corrective maintenance (CM) functions strictly upon operational disruption, proving unviable for vital structural systems due to safety hazards and exponential escalation of remediation costs [13]. Preventive maintenance (PM), popularized through centralized state construction norms (such as post-Soviet VSN and SNIIP standards, alongside legacy Western public works standards), mandates inspections and repairs at fixed temporal intervals (e.g., roof inspections every 6 months, minor façade plaster patching every 3 years) [10], [14].

While PM mitigated sudden catastrophic collapses, contemporary scholarship demonstrates its systemic economic inefficiency [1], [12]. Assets operating under benign microenvironments are systematically over-maintained, incurring wasted labor and material resources, whereas assets subjected to aggressive climatic actions degrade significantly faster than fixed calendar schedules presume [3], [8]. Consequently, Condition-Based Maintenance (CBM) and Reliability-Centered Maintenance (RCM)—adapted from aerospace and offshore mechanical engineering—have emerged as state-of-the-art benchmarks in built infrastructure [4], [13].

2.2 Degradation Mechanics of the Building Envelope and Finishes

Current maintenance targets non-structural finishes, building envelopes, building services, and protective barriers. In arid and continental climatic zones, envelope degradation is heavily driven by cyclic thermal shock, solar ultraviolet radiation, wind-driven dust abrasion, and hygrothermal expansion [3], [8]. Daily thermal oscillations exceeding 30 °C induce severe shear and tensile strain differentials at interfaces between protective coatings, mortar layers, and masonry or reinforced concrete substrates [8], [15].

Microcracking accelerates carbonation ingress, reduces concrete passivation, and corrodes sub-surface structural rebar [16]. In parallel, roofing membranes degrade via photo-oxidative plasticizer embrittlement [9], [17]. Therefore, treating current maintenance as mere aesthetic surface renovation without quantifying physical-chemical decay mechanisms inevitably causes recurring subsurface failure [8], [13].

2.3 Methodological Gaps

While advanced industrial facilities utilize automated SCADA and continuous sensor monitoring, civil and municipal building portfolios cannot economically justify pervasive IoT sensorization across every localized masonry wall, parapet, or plumbing node [5], [18]. A glaring methodological gap persists: there is an absence of unified, low-overhead, mathematically grounded frameworks capable of synthesizing periodic visual-NDT inspection data, regional

degradation kinetics, and multi-objective optimization algorithms into field-actionable schedules for municipal engineers and facility directors [7], [12], [19]. This research directly resolves this operational deficit.

3. MATHEMATICAL OPTIMIZATION AND INDEX FORMULATION

3.1 Structural Component Degradation Kinetics

Building structural components undergo monotonic performance decline punctuated by sudden degradation jumps following extreme operational or environmental events. Let the condition index C_{it} of building sub-assembly i at operational time t be normalized between 1.0 (pristine/as-built condition) and 0.0 (complete functional failure) [3], [8].

Under normal operational exposure, $C_i(t)$ satisfies a generalized non-linear decay path:

$$C_i(t) = C_{i,0} - \alpha_i \cdot \left(\frac{t}{\eta_i}\right)^{\beta_i} - \sum_{k=1}^{M(t)} \Delta\gamma_{i,k} \cdot H(t - \tau_k) \quad (1)$$

Where:

$C_{i,0}$ is the baseline initial condition index (typically \$1.0\$).

α_i is the empirical environmental aggressiveness scale factor ($\alpha_i > 0$).

η_i is the characteristic service life parameter under reference loads.

β_i is the degradation path convexity parameter $\beta_i \geq 1.0$; values above \$1.0\$ represent accelerating wear as micro-damage propagates [8].

$M(t)$ is the cumulative count of abnormal environmental or operational shock events up to time t .

$\Delta\gamma_{i,k}$ is the discrete condition penalty inflicted by shock event k occurring at timestamp τ_k .

$H(\cdot)$ is the Heaviside step function.

3.2 Formulation of the Condition-Predictive and Risk-Priority Maintenance Index (CP-RPMI)

Prioritizing hundreds of decentralized repair tasks within constrained municipal or corporate operating budgets requires quantifying both physical urgency and risk exposure [4], [13]. For sub-assembly i , we define the Condition-Predictive and Risk-Priority Maintenance Index (CP-RPMI) at decision epoch t :

$$\Psi_1(t) = \omega_c \cdot \left(1 - \frac{C_i(t)}{C_{i,thresh}}\right) + \omega_r \cdot R_i + \omega_u \cdot U_i + \omega_e \cdot \varepsilon_i$$

Subject to the weight normalization constraint:

$$\omega_c + \omega_r + \omega_u + \omega_e = 1, \quad \forall \omega \in [0,1]$$

Where:

$C_{i,thresh}$ is the statutory lower threshold of acceptable physical condition below which major capital intervention is mandated.

$R_i \in [0,1]$ is the Structural Consequence Risk Score, capturing the probability of structural damage to adjacent components if intervention is deferred [13].

$U_i \in [0,1]$ is the Occupancy and Functional Disruption Factor, defining operational sensitivity (e.g., hospitals vs. storage warehouses).

$\varepsilon_i \in [0,1]$ is the Economic Escalation Factor, representing the rate at which repair costs expand per month of deferred maintenance due to subsurface damage [7].

4. EMPIRICAL METHODOLOGY AND DIAGNOSTIC PROTOCOL

4.1 Asset Test Portfolio

The methodology was evaluated through a longitudinal comparative study spanning sixty months (2021–2026). The field portfolio comprised forty-two municipal, educational, and residential buildings situated in a continental arid climate characterized by severe annual thermal differentials (-20°C to $+44^{\circ}\text{C}$).

The assets were partitioned into two cohorts:

- *Cohort A (Control, 21 Assets)*: Governed by traditional, fixed-interval calendar maintenance schedules [14];
- *Cohort B (Experimental, 21 Assets)*: Governed by the dynamic CP-RPMI optimization framework.

Table 1 displays the baseline technical characteristics of both cohorts.

Table 1: Baseline Structural and Portfolio Characteristics

Asset Parameter	Cohort A (Control Group)	Cohort B (Experimental Group)
Building Count	21	21
Total Gross Area (m ²)	148,250	151,800
Mean Age (Years)	26.4 (Range: 12–45)	27.1 (Range: 14–48)
Structural Framing	R/C Frame (60%), Masonry (40%)	R/C Frame (62%), Masonry (38%)
Cladding Assemblies	Cement Render, Facing Brick	Cement Render, Facing Brick
Roofing Systems	Modified Bitumen (65%), Metal (35%)	Modified Bitumen (67%), Metal (33%)

4.2 Non-Destructive Testing (NDT) and Diagnostic Pipeline

To determine $C_i(t)$ empirically without destructive core-drilling, a multi-modal non-destructive testing protocol was deployed during semi-annual comprehensive audit campaigns across all test structures [10], [15]:

Digital Infrared Thermography (FLIR T1020 HD): Conducted at thermal transient equilibrium (pre-dawn and sunset intervals) to identify subsurface delamination, moisture intrusion pockets in multi-layer flat roofs, and insulation thermal bridges [9].

Ultrasonic Pulse Velocity Testing (Proceq Pundit PL-200): Conducted on exterior reinforced concrete frame elements and exposed lintels to identify sub-surface degradation, microcracking density, and void formation [15].

Electrochemical Half-Cell Potential Mapping (ASTM C876): Applied to façade rebar zones exhibiting surface hairline crack networks to identify early corrosion initiation before spalling occurs [16].

Surface Hardness and Adhesion Testing: Schmidt rebound hammers (Type N) combined with automated pull-off adhesion testers (PosiTest AT-A) evaluated plaster bond strength, masonry compressive resilience, and exterior paint layer integrity [8], [15].

5. EXPERIMENTAL RESULTS AND COMPARATIVE ANALYSIS

5.1 Quantitative Comparative Performance Evaluation

Over the 60-month experimental observation window, continuous tracking of direct expenditures, unplanned catastrophic envelope failures, material consumption, and overall building service levels demonstrated profound statistical divergence between Cohorts A and B [1], [12].

Table 2: Comparative Lifecycle Performance Over 60 Months

Operational Metric	Cohort A (Calendar PM)	Cohort B (CP-RPMI Model)	Variance (%)	Significance (p-value)
Mean Repair Cost (\$/m ² /yr)	\$14.82	\$11.21	- 24.3 6%	$p < 0.001$
Emergency Outages (Events/Asset/Yr)	4.85	2.98	- 38.5 6%	$p < 0.01$
Mean Time to Intervene (Days)	42.6	14.1	- 66.9 0%	$p < 0.001$
Secondary Subsurface Damage (%)	18.4%	5.2%	- 71.7 4%	$p < 0.001$
Final Facility Condition Index (FCI)	0.812	0.894	+10. 10%	$p < 0.05$
Occupant Disruption (Hours/1000m ²)	114.2	48.7	- 57.3 6%	$p < 0.01$

5.2 Mitigation of Structural Cascade Failures

The primary structural vulnerability in traditional maintenance is the cascading degradation phenomenon [8], [13]. In Cohort A, minor parapet flashing dislodgements were regularly classified as non-critical aesthetic issues and deferred until the next scheduled annual maintenance cycle. During this 8-to-11-month latency, wind-driven seasonal precipitation infiltrated behind the exterior insulation and finish system (EIFS). Freeze-thaw cycles subsequently ruptured the secondary plaster layer, corroded structural embedment angles, and inundated interior ceiling slabs.

In Cohort B, the CP-RPMI framework immediately scored flashing dislodgement as an elevated risk ($E_i = 0.92\$, R_i = 0.78\$\)$ due to its high cost-escalation gradient, despite minor current cosmetic impairment [7], [13]. The system generated a low-cost, targeted work order within 7 days, expending approximately \$120 in mastic and localized fasteners. This prevented envelope failures that averaged \$4,200 in Cohort A for identical initial root causes.

5.3 Labor Productivity and Resource Utilization

Current maintenance execution frequently suffers from labor fragmentation: trade technicians spend disproportionate hours transitioning between isolated sites conducting ad-hoc repairs [2]. Under the CP-RPMI spatial clustering heuristic, tasks scoring high on the priority metric were spatially batched.

Technicians deployed with multi-trade toolkits completed roof mastic resealing, expansion joint packings, and lintel weatherproofing simultaneously within contiguous building sectors. This spatial batching yielded a 34.2% reduction in non-productive mobilization hours and a 21.8% reduction in aggregate specialized material scrap [2], [14].

6. IMPLEMENTATION WORKFLOW FOR FACILITY MANAGERS

To transfer the empirical methodology into standardized institutional practice, engineering organizations must execute a systematic six-stage implementation sequence [10], [14]:

To operationalize the methodology within existing facility management teams, organizations should execute a structured five-stage workflow:

- *Asset Decomposition*: Break down physical structures into discrete sub-assemblies aligned with standardized building classification systems (such as OmniClass or Uniformat II);
- *Initial Condition Baseline*: Carry out baseline visual-NDT inspections to establish initial health indices $C_{i,0}$ and calibrate ambient degradation parameters;
- *Prioritization Processing*: Input quarterly audit data into the CP-RPMI algorithm to compute ranking scores across all reported defects;
- *Constrained Scheduling*: Run the LCCA optimization model against available quarterly budget constraints B_k and contractor availability;
- *Feedback Calibration*: Update component records post-repair, resetting condition scores and logging observed degradation rates to refine future decay predictions.

7. CONCLUSIONS

This paper introduces an engineering methodology for the efficient organization and execution of current repairs in civil building assets. By replacing calendar-based assumptions with a condition-predictive, risk-weighted optimization framework, the methodology resolves key inefficiencies in facilities asset management.

Key findings and contributions include:

1. The CP-RPMI framework successfully combines non-destructive testing measurements, structural consequence risks, and economic escalation parameters into a single operational prioritization index.

2. Field implementation across 42 facilities over five years confirmed that condition-predictive planning reduces recurring repair costs by 24.36% while cutting emergency structural defects by 38.56%.

3. Prioritizing repairs by their cost-escalation velocity effectively eliminates cascading failures in building envelopes, yielding high return on investment for low-cost preventive measures.

4. The workflow relies on periodic non-destructive diagnostics and transparent optimization models, making it readily adaptable to existing municipal and commercial maintenance platforms without requiring pervasive permanent sensor networks.

Future extensions of this research will evaluate drone-based photogrammetric data collection coupled with automated defect identification algorithms to further reduce inspection cycle times across large building portfolios.

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