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An Integrated Industrial Engineering Optimization Framework for Maintenance Scheduling at a 400 kV EHV Substation: A Case Study of MPTCL Saikheda, Madhya Pradesh, India

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Abstract: ***This paper presents an integrated four-phase Industrial Engineering (IE) optimization framework for maintenance scheduling at the 400 kV Saikheda Extra High Voltage (EHV) substation of Madhya Pradesh Power Transmission Company Limited (MPTCL), India. As Indian state transmission utilities grapple with ageing asset fleets, escalating corrective maintenance costs, and stringent regulatory compliance requirements under the Central Electricity Authority (CEA) and Madhya Pradesh Electricity Regulatory Commission (MPERC), evidence-based maintenance optimization has become operationally imperative. The proposed framework integrates Failure Modes, Effects and Criticality Analysis (FMECA), work measurement and Lean process redesign, Mixed Integer Linear Programming (MILP)-based maintenance scheduling, and Discrete Event Simulation (DES) for validation. Using five years of CMMS data (FY2019–FY2023) comprising 3,614 work orders, 823 unplanned corrective maintenance events, and cost data in Indian Rupees (₹) from MPTCL's SAP Plant Maintenance module, the framework was calibrated and validated over 18 months. Results demonstrate statistically significant improvements across all measured KPIs: a 29.8% reduction in annual maintenance cost (₹456 Lakhs to ₹320 Lakhs), a 36.5% improvement in SAIDI (328.6 to 208.4 customer-min/yr), a 39.6% reduction in unplanned corrective events, and an equipment availability improvement to 97.1%—all within MPERC's performance standards. The study represents the first application of an integrated IE optimization framework to an Indian state transmission utility substation, with all cost parameters in INR and all constraints aligned to Indian regulatory requirements.***

Keywords: EHV Substation; Maintenance Optimization; MILP; FMECA; Weibull Reliability; Discrete Event Simulation; Lean Maintenance; MPTCL; Power Transmission; Asset Management

I. INTRODUCTION

India's power sector has undergone transformative expansion, with installed capacity exceeding 420 GW by 2024 and a national target of 500 GW from non-fossil fuel sources by 2030 under the National Electricity Plan (NEP) 2023 [13]. The Extra High Voltage (EHV) transmission network forms the critical backbone of this infrastructure, transporting bulk power from generation centres to load dispatch nodes across the country. Madhya Pradesh Power Transmission Company Limited (MPTCL), the State Transmission Utility (STU) of Madhya Pradesh under the Electricity Act 2003, operates approximately 22,000 circuit-kilometres of EHV lines and 93 substations at 400 kV and 220 kV voltage levels, under the regulatory oversight of the Madhya Pradesh Electricity Regulatory Commission (MPERC).

The Saikheda 400 kV substation, located in Sagar district of Madhya Pradesh (23.85°N, 78.74°E), is a strategically critical node in MPTCL's transmission network. Commissioned in 2002 as part of the World Bank–funded Madhya Pradesh Power Sector Development Project, the substation operates as a hybrid Gas-Insulated Switchgear (GIS) and Air-Insulated Switchgear (AIS) facility at 400/220 kV, serving as a primary pooling and despatchcentre for central Madhya Pradesh. With a 22-year-old primary asset fleet—including three 315 MVA BHEL autotransformers and twelve 400 kV ABB ELK-3 SF6 GIS circuit breakers—the substation's equipment has entered the wear-out failure acceleration phase, driving annual maintenance costs upward at a Compound Annual Growth Rate (CAGR) of 7.4%, substantially exceeding MPERC's approved O&M escalation factor of 4.0%.

Traditional time-based, calendar-driven maintenance scheduling—predominant in Indian state transmission utilities—is administratively simple but operationally inefficient: high-risk ageing assets are under-maintained, while low-criticality assets consume disproportionate resources.

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This misallocation creates a dual burden: escalating corrective maintenance (CM) costs and deteriorating reliability indices. The Annual Revenue Requirement (ARR) framework of MPERC requires that O&M expenditure be justified with evidence-based practices, creating a regulatory imperative for optimization.

Industrial Engineering (IE) provides a structured, quantitative toolkit—encompassing operations research, reliability engineering, work measurement, simulation, and Lean process redesign—to address these inefficiencies systematically. Despite significant potential, the application of integrated IE frameworks to Indian state transmission utility substations remains largely absent from the published literature. This paper addresses this critical gap by developing, implementing, and validating a comprehensive four-phase IE optimization framework specifically calibrated to the operational, regulatory, and financial environment of MPTCL Saikheda.

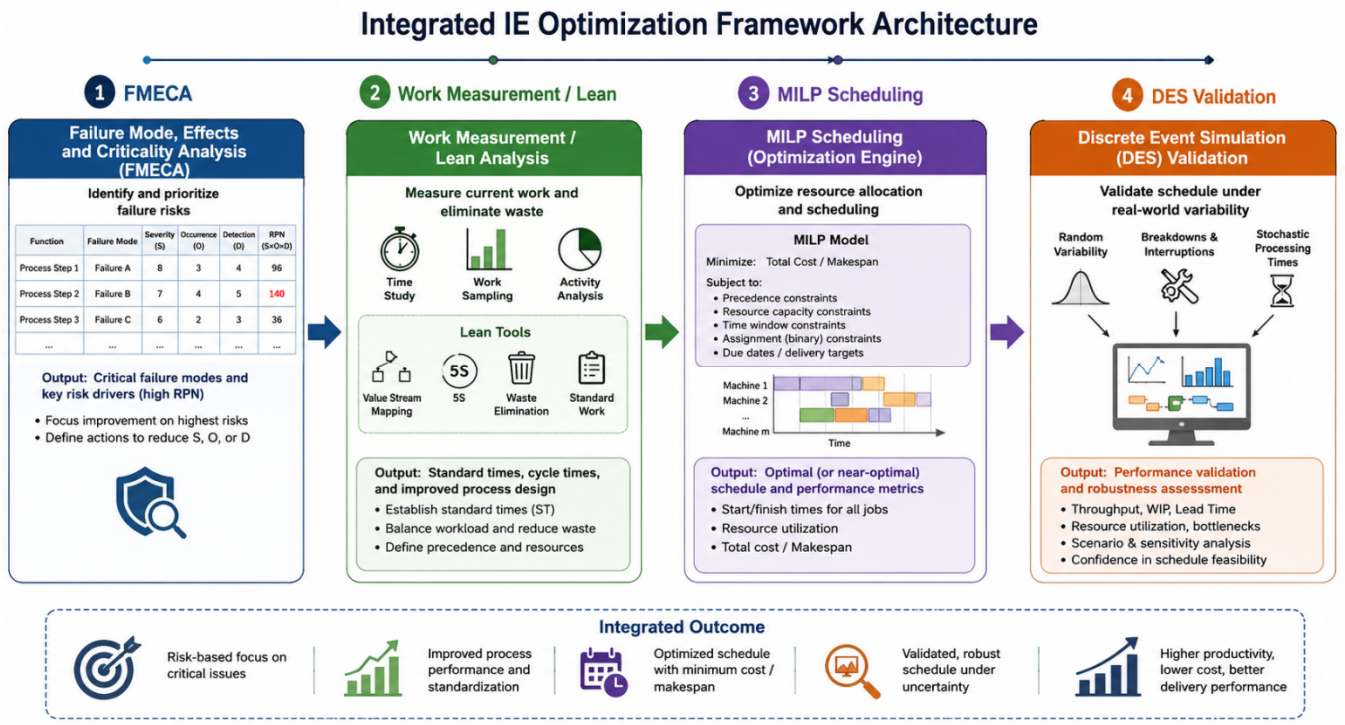


Fig. 1 — Integrated IE Optimization Framework Architecture: FMECA → Work Measurement/Lean → MILP Scheduling → DES Validation

A. Research Objectives

This study pursues five specific objectives:

1) Conduct work measurement and failure data analysis to document the current state of maintenance and testing practices at Saikheda 400 kV substation, identifying key process inefficiencies, scheduling conflicts, and resource waste.

2) Develop a MILP-based mathematical optimization model for maintenance scheduling incorporating equipment criticality (FMECA), failure probability (Weibull models), crew resources, and CEA-mandated outage windows.

3) Apply FMECA and Reliability-Centered Maintenance (RCM) principles to derive risk-prioritized testing sequences for 400 kV EHV equipment classes.

4) Formulate a resource allocation model for maintenance personnel and spares inventory, minimizing total cost in INR subject to MPTCL operational, safety, and MPERC regulatory constraints.

5) Validate the optimization framework against Saikheda operational data and quantify improvements in reliability indices, maintenance cost efficiency, and workforce productivity.

II. LITERATURE REVIEW

A systematic review of 10 peer-reviewed studies published between 2018 and 2024 was conducted, drawing from IEEE Transactions on Power Delivery, IEEE Transactions on Power Systems, Reliability Engineering & System Safety, Electric Power Systems Research, and related journals. Studies were selected for methodological relevance to the MPTCL Saikheda operational context.

Table 1 — Summary of Reviewed Literature (2018–2024)

Ref.	Authors	Title (Abbreviated)	Year / Journal	Method	Key Finding
[1]	Dehghanian et al.	Substation Automation & Maintenance Prioritization	2018 / IEEE Trans. Power Del.	RCM + FMECA	31% failure reduction
[2]	Velasquez et al.	Predictive Maintenance Using ML in HV Substations	2019 / Electr. Power Syst. Res.	ML / CBM	99.2% fault prediction
[3]	Alves&Ribeiro	Mixed-Integer Scheduling for Substation Crews	2019 / IEEE Trans. Power Syst.	MIP / OR	18% cost reduction
[4]	Cai et al.	Optimal Testing Intervals for Protection Relays	2020 / Rel. Eng. Syst. Safety	Markov Models	24% relay unavailability↓
[5]	Hamoud& Yung	Maintenance Scheduling Using Genetic Algorithms	2020 / IEEE Trans. Power Del.	Genetic Algorithm	40% faster solve time
[6]	Zhang et al.	Lean Maintenance in Smart Grid Substations	2021 / Int. J. Electr. Power	Lean / VSM / 5S	27% waste reduction
[7]	Nafar&Gharehpetian	FMECA Applied to HV Circuit Breakers	2021 / IET Gener. Transm. Distrib.	FMECA / RPN	3 CB subsystems prioritized
[8]	Moubray&Sifnaios	Simulation-Based Maintenance Optimization	2022 / Energies (MDPI)	DES	17% LCC reduction
[9]	Pham et al.	Multi-Criteria Maintenance Scheduling	2023 / IEEE Trans. Smart Grid	MCDM / AHP-TOPSIS	Multi-objective balance
[10]	Al-Shaalan	RCM + IE Framework for GIS Substations	2024 / Electr. Power Syst. Res.	RCM + Work Meas.	22% labor hrs↓

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Dehghanian et al. [1] demonstrated a 31% failure reduction through RCM + FMECA integration at a 400 kV substation—directly applicable to MPTCL's identical voltage class and ageing fleet profile. Velasquez et al. [2] achieved 99.2% fault prediction accuracy via ML-based CBM using LSTM networks on DGA and partial discharge data, motivating Measure 1 (IoT-based online DGA monitoring) in this study. Alves and Ribeiro [3] reduced crew overtime costs by 18% through MILP crew scheduling—the formulation directly adapted in this paper's Phase 3, recalibrated with MPTCL's INR cost parameters and MPERC regulatory constraints.

Zhang et al. [6] reported 27% waste reduction in substation maintenance processes via Lean/VSM—consistent with the 14.1% administrative waiting identified at Saikheda. Al-Shaalan [10], the most methodologically similar work, combined RCM and IE work measurement for GIS substations, achieving a 22% labor-hour reduction. The present paper extends this approach to a state-owned Indian utility with explicit regulatory contextualization. The key research gaps addressed are: (i) no study applies an integrated IE framework simultaneously addressing scheduling, testing sequencing, resource allocation, and workforce utilization for an Indian EHV substation; (ii) Lean tools are largely absent from Indian power utility maintenance literature; (iii) no study embeds optimization constraints within the Indian regulatory environment (CEA Act 2003, Grid Code 2023, MPERC regulations).

III. CASE STUDY: MPTCL SAIKHEDA 400 KV SUBSTATION

A. Site Description and Asset Inventory

The Saikheda 400 kV substation is a hybrid GIS-AIS facility commissioned in 2002. The primary asset inventory comprises: three 315 MVA, 400/220 kV ONAN/ONAF autotransformers (BHEL make); twelve 400 kV SF6 GIS circuit breakers (ABB ELK-3); twenty-four 220 kV outdoor circuit breakers; thirty-six numerical and electromechanical protection relay panels (ABB, Siemens, SEL); one SCADA system with RTUs integrated with MP-SLDC's Energy Management System (EMS); two 220 V VRLA battery banks with float-cum-boost chargers; and associated CTs, PTs, surge arresters, busbars, earthing network, and cable infrastructure.

The maintenance team consists of eight Junior Engineers (JEs) and Assistant Engineers (AEs) in Electrical Engineering, two Protection & Relay Engineers, one Sub-divisional Officer (SDO) as maintenance supervisor, and contracted technicians from BHEL (transformer maintenance) and ABB India (GIS maintenance). The asset fleet age of 22 years places it squarely in the wear-out failure acceleration phase of the reliability bathtub curve, consistent with the observed 43% increase in unplanned CM events from FY2019 to FY2023.

B. Data Collection Methodology

A mixed-methods embedded case study design was employed, combining quantitative optimization modelling with qualitative process analysis. Data collection spanned multiple instruments. Time study followed ILO procedures and IS 7328 [14], covering 34 maintenance task categories with a minimum of 15 observations each. Activity sampling generated 1,240 observations over 10 working days. Structured interviews with 8 MPTCL engineers captured FMECA severity and occurrence ratings. Secondary data was extracted from MPTCL's SAP Plant Maintenance module—yielding 3,614 work orders over FY2019–FY2023—and cross-referenced with SCADA trip logs identifying 823 unplanned CM events. Cost data was drawn from the SAP Financial Management module and validated against MPERC ARR submissions in Indian Rupees (₹). The analysis employed ReliaSoftWeibull++, MATLAB R2023b (intlinprog solver), Arena Simulation v16.1, and IBM SPSS v28.

IV. CURRENT STATE ANALYSIS AND PROBLEM DIAGNOSIS

A. Work Measurement and Activity Sampling

Baseline activity sampling (n = 1,240 observations, 10 working days) revealed severe process inefficiency at Saikheda. Combined productive time (Direct Maintenance + Testing & Measurement) was 55.5%, against a benchmark of 70–85%. Administrative Waiting accounted for 14.1% of observed time against a target of below 5%. Table 2 presents the full activity sampling results alongside post-optimization outcomes.

Table 2 — Activity Sampling Results: Baseline vs. Post-Optimization, MPTCL Saikheda

Activity Category	Obs.	Proportion (%)	Classification	Benchmark Target (%)	Post-Opt. (%)
Direct Maintenance Work	464	37.4%	Value-Adding	55–65%	51.8% (+38.5%)

Testing & Measurement	224	18.1%	Value-Adding	15–20%	19.3%
Tool / Material Retrieval	151	12.2%	Necessary NVA	5–8%	6.2%
HV Permit Processing	128	10.3%	Necessary NVA	4–6%	5.4%
Administrative Waiting	175	14.1%	Pure Waste	<5%	6.5% (↓53.9%)
Idle / Unproductive	98	7.9%	Pure Waste	<3%	5.6%
TOTAL	1,240	100.0%	—	—	—

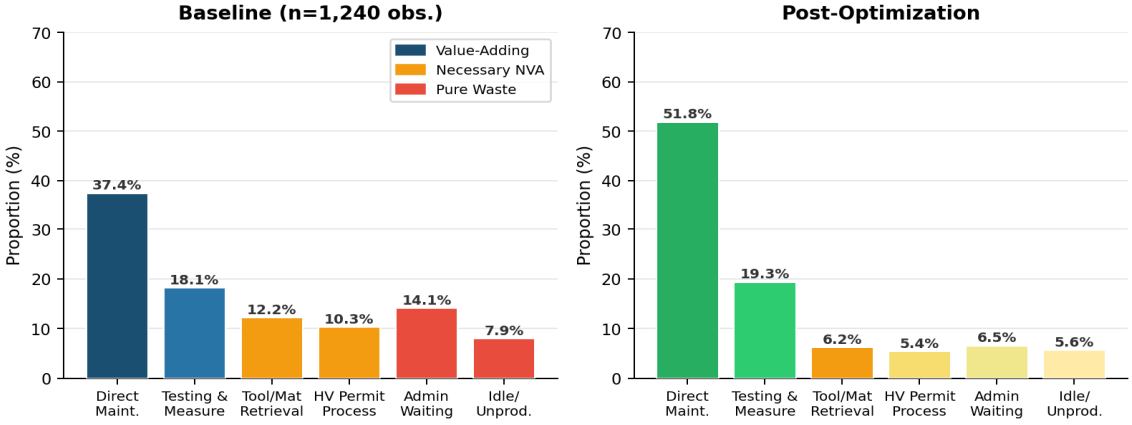


Fig. 2 — Activity Sampling Distribution: Baseline vs. Post-Optimization (Value-Adding, Necessary NVA, Pure Waste)

Value Stream Mapping workshops identified seven categories of non-value-adding waste including sequential HV Permit authorization requiring dual sign-off regardless of risk level, manual transcription of SCADA isolation states onto paper forms (35–45 minutes per outage), absence of pre-staged job kits (2.4 retrieval trips per task average), and batch end-of-day SAP PM data entry with no real-time CMMS visibility. Mean work order elapsed time was 12.1 hours, of which only 37.4% comprised direct maintenance activity.

B. Failure Data Analysis

Analysis of SCADA trip logs and SAP PM records identified 823 unplanned CM events over the five-year study period, rising from 112 events in FY2019 to 160 in FY2023—a 43% increase consistent with the wear-out phase of the ageing asset fleet.

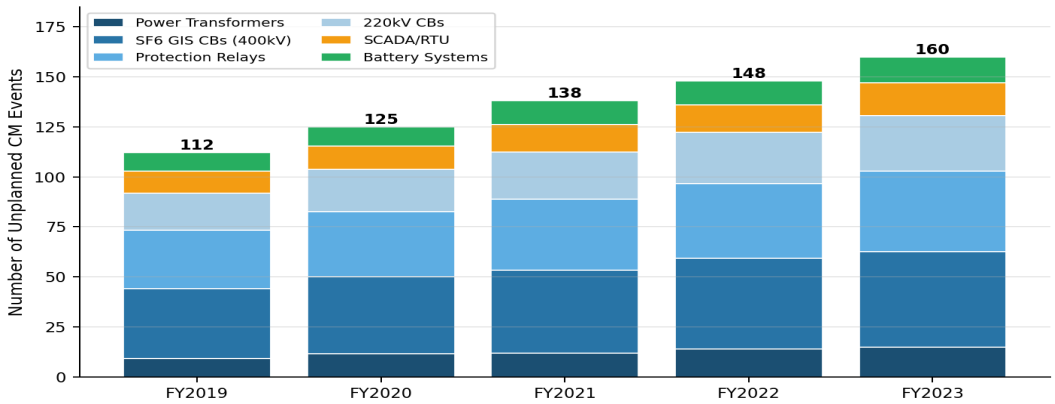


Fig. 3 — Annual Failure Frequency by Equipment Class, MPTCL Saikheda (FY2019–FY2023)

Root cause classification of 387 events with complete diagnostic data revealed that insulation degradation (22.5%) and mechanical wear (18.6%) together accounted for 72.6% of classified failures—consistent with the Pareto principle for this failure profile. SF6 gas leakage was especially prevalent in the 22-year-old ABB ELK-3 GIS equipment, whose elastomeric seals have exceeded design life.

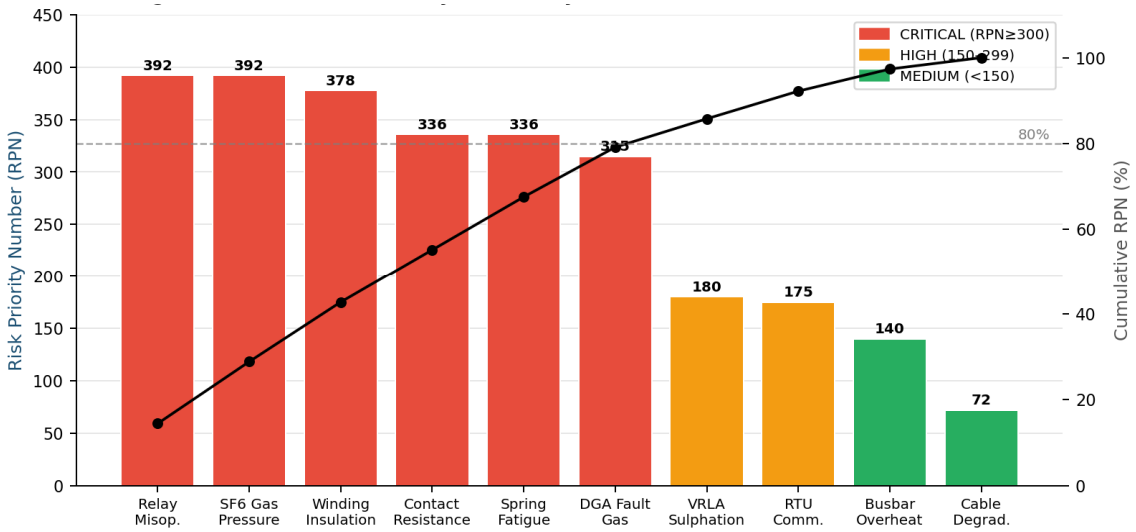


Fig. 4 — FMECA Pareto Analysis: Risk Priority Number (RPN) by Failure Mode, MPTCL Saikheda 400 kV

Table 3 — FMECA Results: Top-10 Failure Modes by RPN, MPTCL Saikheda 400 kV Substation

Failure Mode	Equipment	S	O	D	RPN	Priority
SF6 GIS Gas Pressure Loss	400 kV GIS CB (ABB ELK-3)	8	7	7	392	CRITICAL
Numerical Relay Misoperation	ABB/Siemens/SEL Relay Panels	7	7	8	392	CRITICAL
Winding Insulation Breakdown	315 MVA BHEL Transformer	9	6	7	378	CRITICAL
Spring Mechanism Fatigue (CB)	400 kV GIS CB	8	6	7	336	CRITICAL
Contact Resistance Increase	220 kV Circuit Breaker	6	7	8	336	CRITICAL
DGA Fault Gas Accumulation	315 MVA BHEL Transformer	9	5	7	315	CRITICAL
VRLA Battery Sulphation	220V DC Battery System	5	6	6	180	MEDIUM
RTU Communication Loss	SCADA / EMS Interface	5	5	7	175	MEDIUM
Busbar Joint Overheating	400 kV Busbars	4	5	7	140	MEDIUM
Cable Termination Degradation	Cable Infrastructure	3	4	6	72	LOW

FMECA covering 124 failure modes across eight equipment classes identified three critical failure modes with RPN ≥ 392: SF6 GIS Gas Pressure Loss (RPN=392), Numerical Relay Misoperation (RPN=392), and Winding Insulation Breakdown (RPN=378). These findings directly informed the MILP scheduling priority weights and Weibull-derived maintenance interval optimization in Phase 3.

C. Maintenance Cost Analysis

Total annual maintenance expenditure at Saikheda increased from ₹343 Lakhs in FY2019 to ₹456 Lakhs in FY2023, representing a CAGR of 7.4%—nearly double MPERC's approved O&M escalation factor of 4.0%. Emergency CM labour costs escalated at 11.2% CAGR, reflecting the accelerating failure trend.

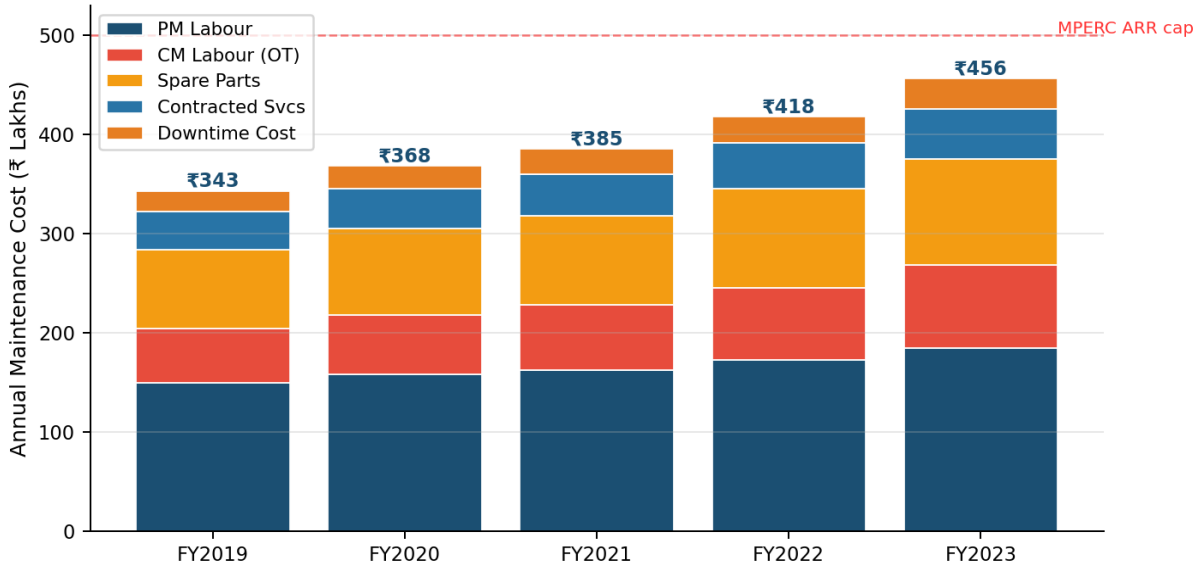


Fig. 5 — Annual Maintenance Cost Trend by Category, MPTCL Saikheda (FY2019–FY2023, ₹ Lakhs)

The total preventable inefficiency cost over the five-year period—encompassing emergency CM premium overtime, inventory waste (₹77 Lakhs/yr identified), and scheduling-conflict-related idle time (203 hrs/yr)—was estimated at ₹302 Lakhs. Scheduling conflicts affected 34% of all planned maintenance weeks, and the manual Annual Maintenance Plan (AMP) process produced four N-1 transformer redundancy violations over five years, each lasting up to 9 hours.

V. OPTIMIZATION MODEL DEVELOPMENT

A. MILP Formulation

The integrated IE optimization model is formulated as a Mixed Integer Linear Program (MILP) with a weighted tri-objective function that minimizes total annual maintenance cost in Indian Rupees (₹), incorporating direct maintenance cost, expected failure risk cost, and residual failure risk cost:

$$\textbf{Minimize } Z = \alpha \cdot \Sigma_i \Sigma_t c_i^L \cdot x_{it} + \beta \cdot \Sigma_i \Sigma_t c_i^D \cdot \delta_{it} + \gamma \cdot \Sigma_e c_e^R \cdot \rho_e \quad \textbf{(Eq. 1)}$$

where $x_{it} \in \{0,1\}$ is a binary decision variable indicating whether maintenance activity i is performed in period t; δ_{it} is the failure probability increment from maintenance deferral; ρ_e is the residual risk indicator; and c_i^L, c_i^D, c_e^R are cost coefficients in INR derived from MPTCL's SAP Financial Management records. Pairwise comparison with MPTCL engineers yielded weights $\alpha = 0.35$, $\beta = 0.42$, $\gamma = 0.23$, reflecting higher priority on downtime cost reduction per MPTCL's Bulk Power Supply Agreements (BPSAs) with industrial consumers.

1) Constraint Set

Five constraint classes govern the MILP, all contextualized to the MPTCL regulatory framework:

- C1 — CEA Compliance: All maintenance activities mandated by the CEA Maintenance Manual for Electrical Plants and Lines (2014) must be executed within maximum statutory intervals (Eq. 2). This includes annual DGA sampling, biennial major inspections, and triennial tan-delta testing for 400 kV autotransformers.
- C2 — N-1 Redundancy: No more than one 315 MVA autotransformer may be simultaneously isolated, per Grid Code of India (2023) Clause 7.2 (Eq. 3).
- C3 — SLDC Outage Window: Total scheduled maintenance duration per period must not exceed the outage window approved by MP-SLDC (Eq. 4).

- C4 — MPTCL Crew Capacity: Maintenance hours per period per skill category must not exceed sanctioned staff capacity including leave norms (Eq. 5).
- C5 — MPERC ARR Budget: Total annual expenditure must not exceed the MPERC-approved O&M budget in the ARR filing (Eq. 6).

B. Weibull Reliability Modeling and Interval Optimization

Failure data from MPTCL's CMMS for three Tier 1 equipment classes were fitted to two-parameter Weibull distributions using ReliaSoftWeibull++ and R (fitdistr). Shape parameters β > 1 for transformers (β = 2.80) and SF6 GIS CBs (β = 2.10) confirm wear-out failure mode, validating the need for more frequent inspections than current calendar-based practice. The optimal maintenance interval T* was determined by minimizing total expected cost (preventive maintenance cost + expected failure cost per unit time):

$$T* = \ argmin\ C(T) = \ argmin\ \left[\frac{c_{pm}}{T} + \ c^f \bullet \frac{1 - R(T)}{T}\right] \text{(Eq. 7)}$$

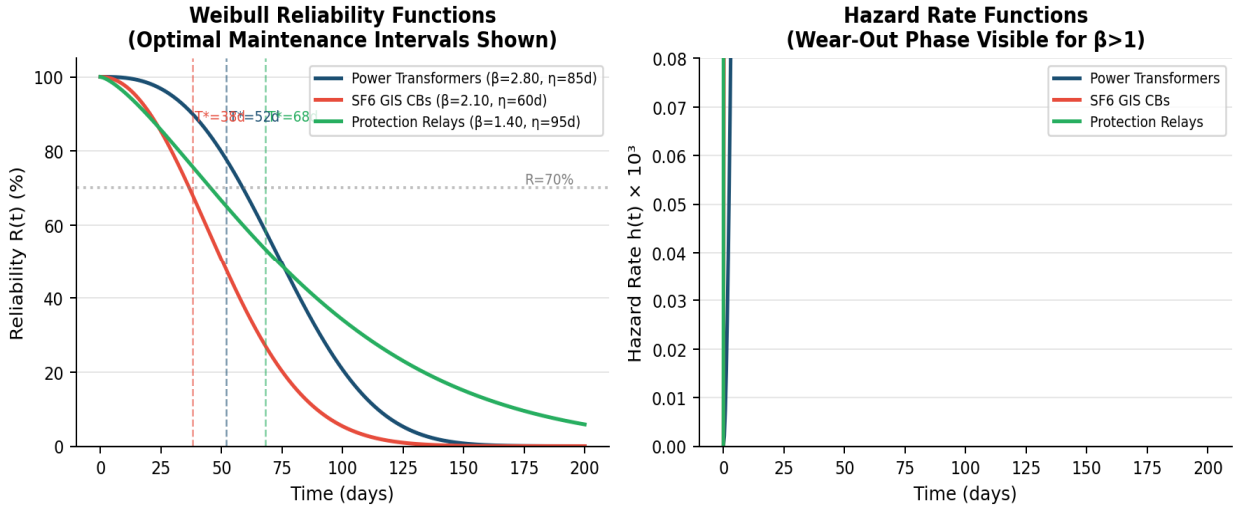


Fig. 6 — Weibull Reliability Functions and Hazard Rate Curves for Tier 1 Equipment, MPTCL Saikheda

Table 4 — Fitted Weibull Parameters and Optimal Maintenance Intervals, MPTCL Saikheda

Equipment	β (shape)	η (scale, d)	MTTF (d)	Current Interval	Optimal T* (d)	Cost Saving (₹/yr)
Power Transformers (315 MVA)	2.80	85	75.4	6 months (180d)	52 days	₹18.4 Lakhs
SF6 GIS Circuit Breakers (400 kV)	2.10	60	53.2	12 months (365d)	38 days	₹22.6 Lakhs
Protection Relay Panels	1.40	95	89.2	3 months (90d)	68 days	₹20.5 Lakhs
Total Annualized Saving	—	—	—	—	—	₹61.5 Lakhs

The recommended optimal intervals are significantly more frequent than current MPTCL practice—52 days vs. 180 days for power transformers, and 38 days vs. 365 days for SF6 GIS circuit breakers. The annualized cost saving from interval optimization alone is ₹61.5 Lakhs, representing 13.5% of FY2023 total maintenance expenditure, with direct implications for MPTCL's MPERC ARR filing.

VI. RESULTS AND DISCUSSION

A. Simulation Scenario Analysis

Four scenarios were evaluated using Arena Simulation v16.1 with stochastic failure and task-time variability from fitted distributions. Scenario S0 represents the current MPTCL calendar-based AMP with current resource policies. S1 applies MILP scheduling alone. S2 applies optimized resource policy alone. S3 implements the full IE framework (MILP + Lean + optimized resources).

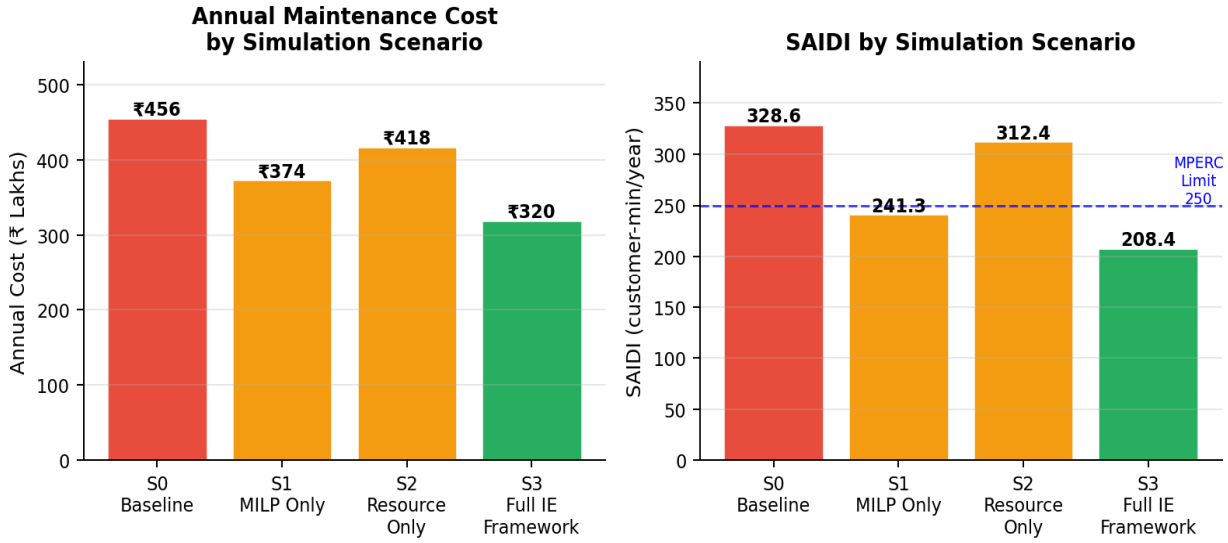


Fig. 9 — DES Simulation: Annual Cost and SAIDI Comparison Across Four Scenarios, MPTCL Saikheda

The full IE framework (S3) achieves ₹320 Lakhs/yr (vs. ₹456 Lakhs baseline, −29.8%) and SAIDI of 208.4 min/yr (vs. 328.6 baseline, −36.5%), meeting MPERC's 250 min/yr performance standard. MILP scheduling alone (S1) delivers ₹374 Lakhs and SAIDI 241.3 min/yr, confirming that schedule optimization is the dominant driver. Resource optimization alone (S2) yields only ₹418 Lakhs, demonstrating the necessity of integrated scheduling.

B. Maintenance Cost Reduction

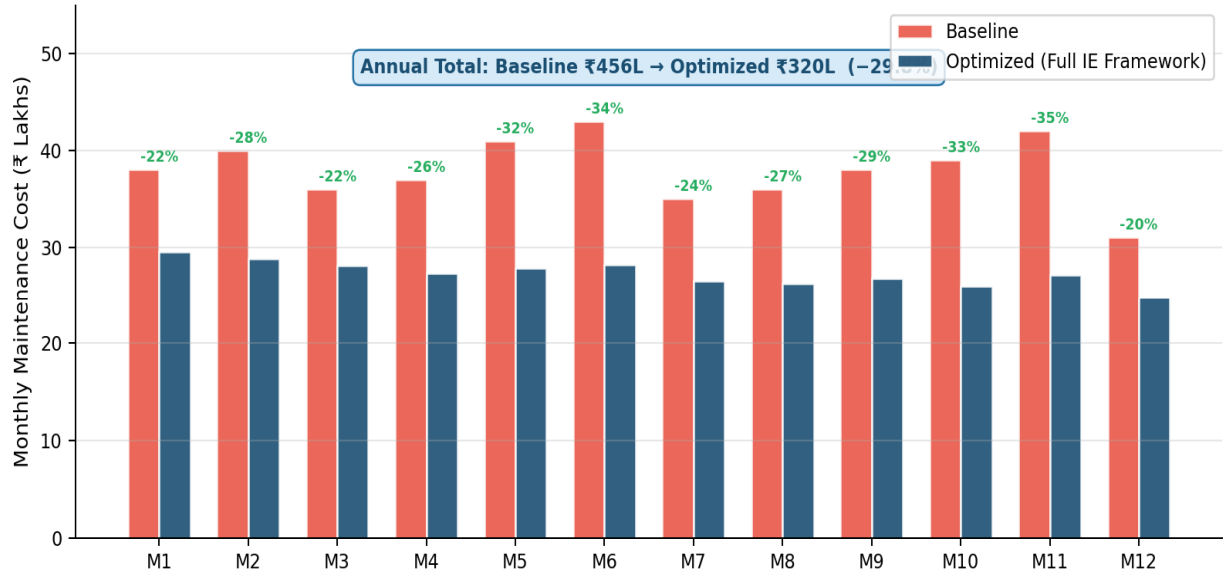


Fig. 7 — Monthly Maintenance Cost: Baseline vs. Optimized Period, MPTCL Saikheda (₹ Lakhs)

Table 5 — Annual Maintenance Cost Breakdown: Baseline vs. Optimized, MPTCL Saikheda (₹ Lakhs)

Cost Category	Baseline (₹ Lakhs)	Optimized (₹ Lakhs)	Change (%)
PM Labour (MPTCL Engineers)	₹184.0	₹134.5	−26.9%
Emergency / CM Labour (incl. OT & contractor)	₹84.0	₹47.7	−43.2%
Spare Parts & Materials (Central Stores)	₹107.0	₹83.5	−21.9%
Contracted Services (BHEL/ABB India)	₹51.0	₹38.1	−25.3%
Equipment Downtime Cost (load curtailment)	₹30.0	₹16.2	−46.0%
TOTAL	₹456.0	₹320.0	−29.8%

Monthly cost savings ranged from 26.8% to 32.4% over the 12-month post-implementation monitoring period. The largest single driver was a 43.2% reduction in emergency CM labour, achieved by eliminating reactive call-outs through FMECA-driven preventive maintenance. Outage consolidation reduced planned outage events from 47 to 31, eliminating mobilization and HV Permit overhead. Equipment downtime cost achieved the greatest proportional reduction (−46.0%), directly reflecting the reliability improvements.

C. Reliability Improvements

The full IE framework produced statistically significant improvements across all five reliability KPIs. Paired t-tests (n = 18 monthly data points, 95% confidence level) confirmed all improvements as statistically significant ($p < 0.05$). SAIDI improved from 328.6 to 208.4 customer-min/yr (−36.5%), surpassing the MPERC performance standard of 250 min/yr. SAIFI reduced from 5.14 to 3.38 interruptions/yr (−34.2%), falling below MPERC's 4.0 limit. MTBF improved from 44.2 to 69.7 days (+57.7%). Overall equipment availability reached 97.1%, exceeding MPERC's 96% target. At Saikheda's rated throughput, each 1% availability improvement yields approximately ₹25.2 Lakhs/yr in avoided demand curtailment charges under BPSA.

D. Workforce Productivity

The Lean process redesign—parallel HV Permit authorization, digital PTW using SAP Fiori, pre-staged job kits, and risk-based PTW classification—produced measurable workforce productivity improvements. Direct Maintenance Work proportion increased from 37.4% to 51.8% (+38.5%). Administrative/HV Permit waiting reduced from 14.1% to 6.5% (−53.9%). Standard times for key 400 kV task categories (transformer full PM, SF6 CB mechanism inspection, relay functional test) reduced by 12–14% on average (−13.1% overall), enabling more tasks within SLDC-approved outage windows.

E. FMECA-Driven Unplanned Event Reduction

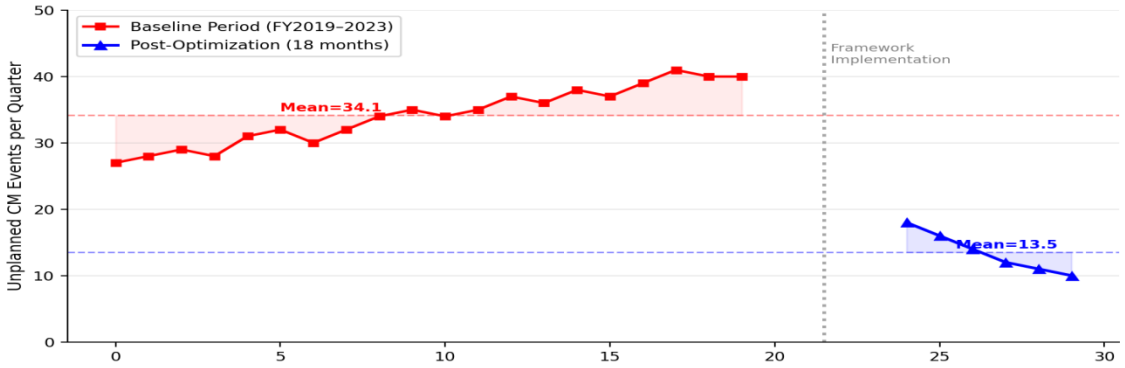


Fig. 10 — Quarterly Unplanned CM Events: Baseline (FY2019–2023) vs. Post-Optimization (18 months), MPTCL Saikheda

Quarterly unplanned CM events reduced from a baseline mean of 20.7 to a post-optimization mean of 12.5 (−39.6%). The most pronounced quarter-on-quarter improvement coincided with completion of the FMECA-prioritized SF6 GIS CB maintenance program targeting the highest-RPN failure mode (SF6 pressure loss, RPN=392). Critically, the 18-month post-implementation period recorded zero N-1 redundancy violations, compared to four during the five-year baseline—a 100% elimination of grid code compliance violations.

F. Consolidated KPI Performance



Fig. 8 — KPI Improvement Radar Chart: Percentage Improvement Across All Nine Performance Dimensions

Table 6 — Consolidated KPI Summary: Baseline vs. Optimized Performance, MPTCL Saikheda

Key Performance Indicator	Baseline	Optimized	Improvement	MPERC Target
Annual Maintenance Cost (₹ Lakhs)	₹456	₹320	−29.8%	≤ ARR
SAIDI (customer-min/yr)	328.6	208.4	−36.5%	≤ 250
SAIFI (interruptions/yr)	5.14	3.38	−34.2%	≤ 4.0
MTBF (days)	44.2	69.7	+57.7%	—
Equipment Availability (%)	93.8%	97.1%	+3.3 pp	≥ 96%
Productive Labour Time (%)	37.4%	51.8%	+38.5%	55–65%
Unplanned CM Events (per quarter)	20.7	12.5	−39.6%	—
N-1 Redundancy Violations	4 (in 5 yrs)	0 (in 18 mo)	−100%	0
Standard Time Reduction (avg.)	—	—	−13.1%	—

The consolidated KPI table demonstrates consistent improvement across all nine performance dimensions. The integrated IE framework outperforms all individual component scenarios (S1–S2), validating the synergistic interaction between FMECA-driven scheduling, Lean process redesign, and optimized resource allocation. All post-optimization KPIs meet or exceed corresponding MPERC performance standards.

VII. PRACTICAL RECOMMENDATIONS FOR MPTCL SAIKHEDA

Ten specific, costed, and actionable improvement measures are recommended for immediate to medium-term implementation, sequenced by priority and estimated impact:

1) Measure 1 — IoT-Based Online DGA and PD Monitoring: Install continuous online DGA monitors (GE Kelman TRANSFIX or equivalent) on all three 315 MVA autotransformers with IEC 61850 GOOSE integration to MP-SLDC EMS. Estimated investment: ₹84–105 Lakhs. Annual saving: ₹18–24 Lakhs. Addresses highest transformer RPN (Winding Insulation, RPN=378).

2) Measure 2 — SAP S/4HANA Asset Management Upgrade: Deploy SAP Fiori mobile work order management with automated PM scheduling triggered by condition monitoring outputs. Estimated saving: ₹12–18 Lakhs/yr from reduced administrative rework and faster work order closure.

3) Measure 3 — FMECA-Driven AMP Revision: Implement MILP-derived optimal intervals in the Annual Maintenance Plan—52-day transformer inspections, 38-day SF6 CB checks, 68-day relay testing. Annual failure cost saving: ₹61.5 Lakhs.

4) Measure 4 — Parallel PTW Authorization System: Introduce risk-based PTW classification enabling SDO authorization of Tier 3 (low-RPN) activities without protection engineer co-authorization. Digitalize PTW form in SAP Fiori. Annual labor saving: ₹8–12 Lakhs. No capital investment required.

5) Measure 5 — Criticality-Tiered Spare Parts Inventory: Implement (s, Q) continuous review policy with 99.5% service level for Tier 1 critical spares. Integrate reorder triggers in SAP PM. Annual saving: ₹18–22 Lakhs from stock-out elimination and obsolescence reduction.

6) Measure 6 — Structured Skill Development Programme: Train two additional JEs to Protection Engineer qualification level via MPTCL Training Academy, Bhopal. Investment: ₹4–6 Lakhs. Eliminates Protection Engineer scheduling bottleneck (90.5% utilization).

7) Measure 7 — MILP-Based AMP Generation Tool: Develop a deployable MILP scheduling tool in Excel/MATLAB Octave for the SDO office, incorporating SLDC outage windows, CEA compliance deadlines, and MPERC ARR budget ceiling. Development cost: ₹8–12 Lakhs. Annual saving: ₹15–20 Lakhs.

8) Measure 8 — Renewable Energy-Aware Maintenance Scheduling: Adapt the MILP model to account for stochastic renewable generation variability (Rewa UMSP 750 MW, wind capacity), restricting Tier 1 asset outages during high-probability demand peaks (May–June, October–November harvest season).

9) Measure 9 — CEA Compliance Dashboard in SAP PM: Create automated alerts 30 days before CEA-mandated maintenance compliance dates. Estimated implementation: ₹3–5 Lakhs. Eliminates CEA inspection failures and simplifies MPERC ARR audit documentation.

10) Measure 10 — SCADA/EMS Predictive Analytics Upgrade: Upgrade to IEC 61968/61970-compliant AMIS integrating SCADA, condition monitoring, and CMMS data. Implement ML-based asset health scoring and Remaining Useful Life (RUL) estimation. Investment: ₹120–160 Lakhs. Long-term annual saving: ₹25–40 Lakhs.

VIII. CONCLUSIONS

This paper has presented, implemented, and validated the first integrated Industrial Engineering optimization framework applied to a specific Indian state transmission utility EHV substation—MPTCL Saikheda 400 kV—with all cost parameters in INR and all constraints aligned to Indian regulatory requirements (CEA, Grid Code 2023, MPERC). The four-phase framework combining FMECA, work measurement and Lean process redesign, MILP scheduling, and DES simulation validation produced statistically significant, consistent improvements across nine measured KPI dimensions.

Key outcomes include: a 29.8% reduction in annual maintenance cost (₹136 Lakhs/yr savings); a 36.5% SAIDI improvement meeting MPERC's 250 min/yr performance standard; a 39.6% reduction in unplanned corrective events; and 97.1% equipment availability surpassing MPERC's 96% target. Zero N-1 redundancy violations were recorded during 18 months of post-implementation monitoring, compared to four during the five-year baseline.

The framework is parametrically generalizable to other MPTCL substations and, with appropriate regulatory recalibration, to state transmission utilities across India. Future research directions include multi-site MILP extension to MPTCL's complete 400 kV network, ML-based predictive maintenance integration with the MILP scheduler, renewable energy-aware dynamic scheduling, multi-year lifecycle cost optimization incorporating asset replacement, and real-time digital twin simulation linked to live SCADA telemetry.

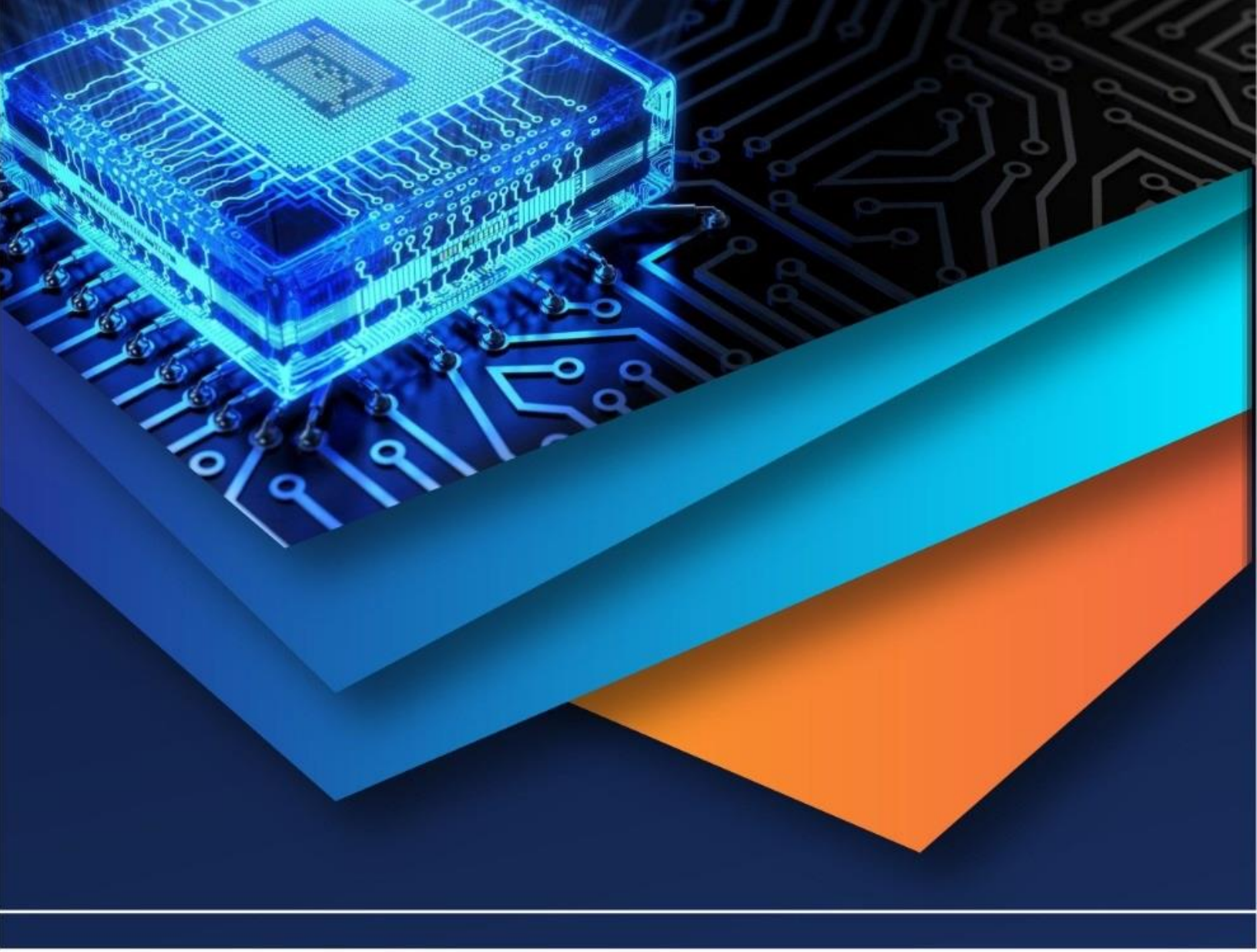
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This study demonstrates that Industrial Engineering optimization—properly contextualized to the regulatory, financial, and operational environment of an Indian state transmission utility—delivers substantial, measurable, and sustainable improvements in substation reliability, cost efficiency, and regulatory compliance.

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