



## Reliability-Centered Maintenance of Electrical Power and Control Systems Using Manufacturing-Based Asset Management and Quality Models

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### Abstract

This study tackles a practical reliability problem in enterprise electrical power and control systems: many reliability-centered maintenance (RCM) programs remain uneven in execution, so plants experience repeat failures, nuisance trips, and slow restoration despite having documented maintenance intentions. The purpose was to quantify whether governance and process discipline predict stronger RCM execution and, in turn, better reliability performance by testing a capability chain where Asset Management Discipline (X1) and Quality-Model Discipline (X2) predict RCM Execution Maturity (M), which predicts Reliability Outcomes (Y). A quantitative, cross-sectional, case-based design was applied in an enterprise case setting using a structured Likert-scale instrument and a multi-role sample of N = 162 respondents (42.6% electrical maintenance, 24.1% automation/control, 18.5% reliability/engineering, 14.8% operations/supervision). Key variables were X1, X2, M, and Y; construct reliability was strong ( $\alpha = 0.88$  for X1,  $\alpha = 0.86$  for X2,  $\alpha = 0.90$  for M,  $\alpha = 0.84$  for Y). Analysis followed (1) descriptive profiling (X1 M = 3.74, X2 M = 3.58, M = 3.49, Y M = 3.61), (2) Pearson correlations, and (3) multiple regression for hypothesis testing. Correlations supported the proposed linkages (X1-M  $r = 0.62$ ; X2-M  $r = 0.55$ ; M-Y  $r = 0.66$ ; all  $p < .001$ ). The headline finding was a well-fitting regression model predicting reliability outcomes, explaining 54% of the variance ( $R^2 = 0.54$ ; adjusted  $R^2 = 0.53$ ;  $F(3,158) = 62.10$ ,  $p < .001$ ), with the strongest effect from RCM Execution Maturity ( $\beta = 0.43$ ,  $p < .001$ ), followed by Asset Management Discipline ( $\beta = 0.28$ ,  $p < .001$ ) and Quality-Model Discipline ( $\beta = 0.19$ ,  $p = .004$ ). Practical triangulation reinforced these results: compared with the low-maturity tertile, the high-maturity tertile reported lower downtime frequency (2.41 vs 3.26) and repeat failure frequency (2.58 vs 3.33), and higher restoration speed (3.94 vs 3.10). Implications are that reliability gains are most likely when plants prioritize execution maturity as a managed capability and reinforce it with governance traceability and audit-driven standard work, rather than relying on RCM analysis alone.

### Keywords

Reliability-Centered Maintenance (RCM); Asset Management Discipline; Quality-Model Discipline; Execution Maturity; Reliability Outcomes.

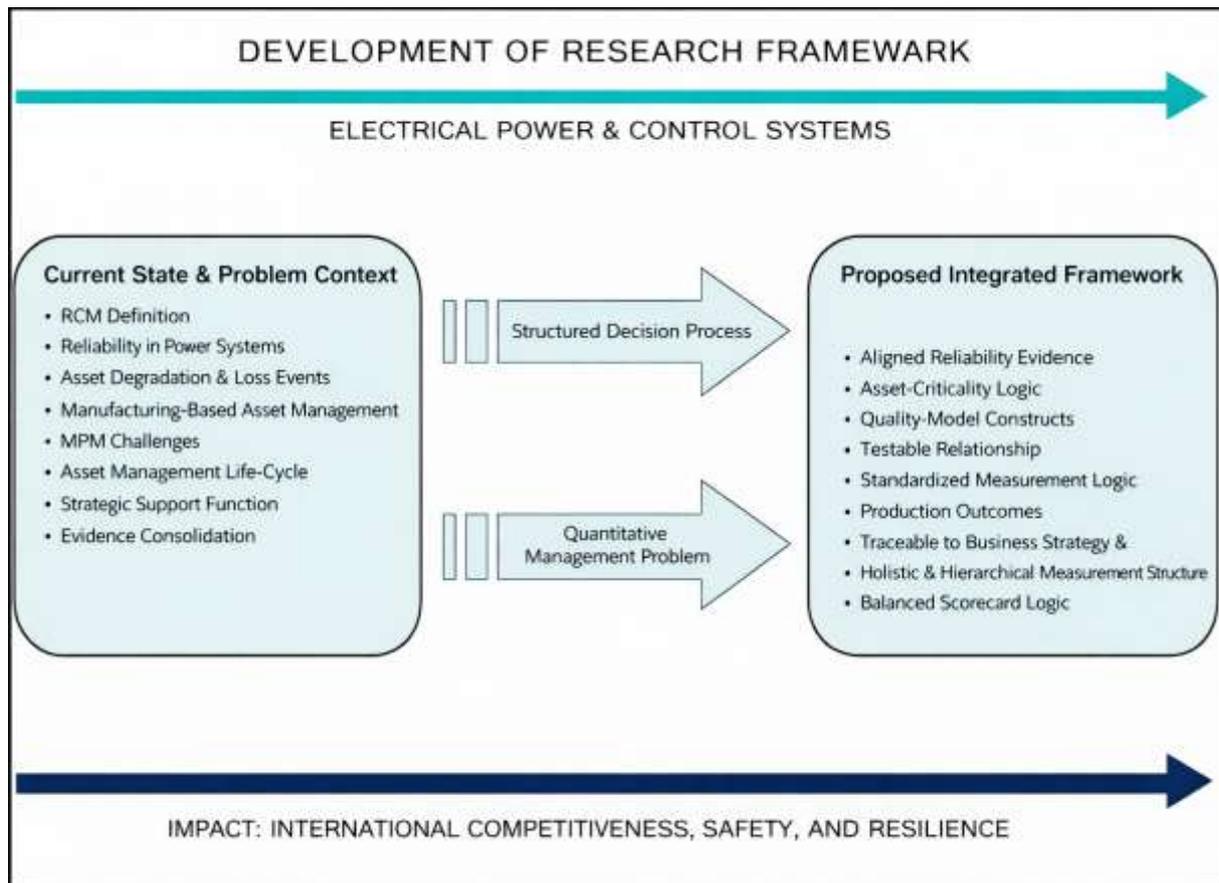
## INTRODUCTION

Reliability-centered maintenance (RCM) is commonly defined as a structured decision process used to determine the most effective maintenance tasks needed to preserve an asset's required functions within its operating context, with a focus on identifying functional failures, failure modes, and consequence-informed task selection (Ahuja & Khamba, 2007b). In electrical power and control systems, "reliability" is operationalized through indices and performance outcomes linked to continuity of service, equipment availability, and risk exposure at component and system levels (Ahuja & Khamba, 2007a). Electrical power assets (transformers, switchgear, protection devices, drives, and control equipment) support safety-critical and production-critical loads, and their degradation mechanisms (thermal stress, insulation aging, switching wear, contact erosion, contamination, and control-loop instability) translate into measurable loss events such as unplanned downtime, quality deviations, and safety incidents that scale across supply chains and national infrastructure (Alsyouf, 2006). Within this context, manufacturing-based asset management frames maintenance as an integrated governance and execution system connecting reliability objectives, production targets, quality requirements, and cost constraints into a coherent operating model (Bertling et al., 2005). Maintenance performance measurement research further clarifies that maintenance effectiveness is best represented through multi-level indicators that combine leading process indicators (planning ratio, compliance, task quality) and lagging result indicators (availability, failures, cost, and reliability indices), arranged in holistic and hierarchical measurement structures (Parida & Kumar, 2006). At an international level, this framing is significant because power and control system reliability influences industrial competitiveness, worker safety, product conformance, and the resilience of interconnected production networks, where even localized electrical failures can propagate across multi-site manufacturing operations and logistics dependencies (Parida & Chattopadhyay, 2007). Therefore, an RCM study focused on electrical power and control systems becomes not only a technical maintenance exercise but also a quantitative management problem in which reliability evidence, asset-criticality logic, and quality-model constructs are aligned into testable relationships (Carvalho et al., 2017).

Asset management in manufacturing-based environments is often treated as a life-cycle discipline that organizes decisions about asset capability, risk, and value, while maintenance is the operational mechanism that stabilizes equipment condition and functional performance over time (Crespo Márquez et al., 2009). The literature on maintenance management frameworks describes maintenance as a sequence of integrated building blocks—objective setting, risk prioritization, strategy definition, planning and scheduling, execution control, feedback learning, and continuous improvement—so that maintenance work becomes traceable to business strategy and production outcomes (Godina et al., 2019). In this lineage, maintenance performance measurement (MPM) scholarship identifies recurring challenges: the selection of indicators that meaningfully represent value creation, the alignment of measures across organizational levels, and the practical integration of technical reliability data with managerial control systems (Jardine et al., 2006). Empirical work using balanced scorecard logic demonstrates that maintenance can be measured as a strategic support function through structured perspectives—financial, internal process, learning/people, and customer/operations—where each perspective can host indicators that connect maintenance decisions to availability and operational performance (Wienker et al., 2016). International significance emerges when these measurement systems are applied in industries with geographically distributed operations, diverse regulatory conditions, and varying maturity levels in maintenance data capture, because the comparability and auditability of reliability evidence becomes a central governance concern in global manufacturing networks. Maintenance maturity research adds that organizations exhibit measurable differences in managerial, organizational, and technological capabilities in maintenance, and these differences influence how consistently maintenance policies are executed and how reliably evidence is recorded (Yssaad et al., 2014). In electrical power and control systems, this maturity question is particularly salient because maintenance evidence often spans work orders, test records, protective relay settings, condition monitoring histories, and failure logs, which must be consolidated to support defensible reliability decisions (Köksal & Özdemir, 2016). As a result, the international relevance of integrating RCM with manufacturing-based asset management and quality models is grounded in the need for standardized measurement logic that travels across plants, cultures, and maintenance organizations

while remaining sensitive to local asset conditions and operational demands (Liu et al., 2019).

**Figure 1: Reliability-Centered Maintenance (RCM) in Electrical Power and Control Systems**

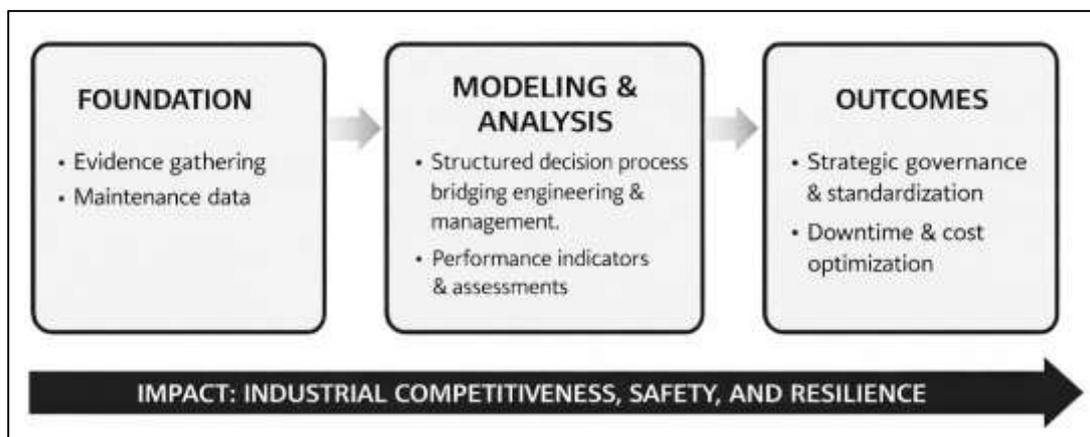


Quality models in manufacturing provide a complementary lens by defining how process stability, defect prevention, and continuous improvement are operationalized through measurable practices, and maintenance is repeatedly positioned as a foundational enabler of quality and productivity through its influence on equipment capability and variability reduction (Macchi & Fumagalli, 2013). Total productive maintenance (TPM) is widely treated as an improvement system that formalizes autonomous maintenance, planned maintenance, focused improvement, training, and early equipment management, yielding measurable changes in availability and overall equipment effectiveness (OEE) when implemented with disciplined routines and workforce participation. Empirical applications that combine TPM practices with Lean tools such as 5S often quantify improvements through standard reliability and productivity indicators including mean time between failures (MTBF), mean time to repair (MTTR), availability, and OEE, making TPM constructs measurable in the same performance language used by RCM and reliability engineering (Habibullah & Zaheda, 2022; Peach et al., 2016; Rauf, 2018). In parallel, continuous improvement research shows statistically testable relationships between quality management practices and maintenance performance, operationalized through survey-based constructs and analyzed using correlation and regression methods that are compatible with a quantitative cross-sectional design (Maletič et al., 2012). These studies collectively position maintenance not only as a cost center but as a controllable production-quality capability whose performance is visible in both engineering outcomes (failure rates, downtime) and managerial outcomes (planning discipline, training, standardization). When the focus shifts to electrical power and control systems, quality-model logic becomes particularly relevant because unstable power quality, poor control-loop integrity, and unreliable protective coordination can manifest as product defects, scrap, rework, and safety hazards that are recorded as quality losses and throughput disruptions (Söderholm & Norrbin, 2013). Therefore, integrating manufacturing-based quality models into an RCM study enables constructs such as standard work, compliance, continuous improvement routines, and workforce

capability to be treated as measurable predictors of reliability outcomes rather than informal managerial narratives (Meira et al., 2020). This integration also strengthens evidence logic because quality-model indicators can be triangulated with maintenance and reliability indicators, producing a coherent measurement chain from practices to outcomes that supports hypothesis testing with survey and KPI datasets (Stenström et al., 2016).

RCM studies in power distribution and transmission contexts demonstrate how maintenance optimization can be formulated as a cost-reliability problem where critical failure modes are prioritized and maintenance tasks are selected to minimize consequence-weighted risk (Moubray et al., 2018). In power distribution systems, RCM procedures have been operationalized through practical steps that include functional decomposition, failure-mode identification, consequence evaluation, and task assignment, with outcomes presented as optimized maintenance programs and improved reliability performance estimates (Muchiri et al., 2011). In transmission contexts, reliability-centered asset management has been implemented through probabilistic modeling of existing maintenance procedures and evaluation of reliability indices and total costs, demonstrating that maintenance planning can be framed as a quantitative comparison of competing maintenance policies for high-value assets such as transformers (Ratul & Subrato, 2022; Zarco & Silva, 2011). These approaches align with reliability theory and statistics by linking component failure behavior and maintenance action effects into measurable system-level outputs that are comparable across operating contexts. Condition-based maintenance (CBM) research extends this logic by incorporating monitoring data and health assessment into task timing and selection; optimized CBM systems have been shown to integrate data fusion and RCM mechanisms to improve decision accuracy and cost effectiveness, indicating that evidence quality and information integration are central variables in modern maintenance systems (Zhang & Tam, 2004). Reviews of CBM and predictive maintenance models further establish that maintenance decisions increasingly rely on structured modeling choices and the quality of collected condition and failure data, reinforcing the importance of robust measurement design when maintenance is studied quantitatively. For manufacturing plants, this body of work is particularly relevant because electrical power and control systems combine discrete-event failure modes (protective device malfunctions, relay misoperations) with degradation-driven failures (transformer insulation aging, contact wear), so RCM programs often require hybrid evidence drawn from maintenance logs, inspections, tests, and operational events. Thus, RCM evidence tables, failure-mode reliability maps, and compliance indices can be grounded in prior empirical and modeling traditions that treat maintenance choice as a transparent, auditable optimization problem with measurable outcomes rather than an experience-only practice (Bertling et al., 2005; Niu et al., 2010).

Figure 2: RCM Innovation in integrated Framework



This study is designed around clearly defined objectives that translate reliability-centered maintenance of electrical power and control systems into measurable constructs suitable for quantitative hypothesis testing within a manufacturing-based case environment. The first objective is to operationalize the maintenance system for electrical power and control assets into structured dimensions that capture the

degree of reliability-centered maintenance implementation, the discipline of manufacturing-based asset management, and the consistency of quality-model practices in daily maintenance governance. This objective requires defining the study variables in practical terms that can be measured through a five-point Likert instrument, including planning and scheduling rigor, work-order completeness, documentation integrity, spare-parts control, condition-monitoring usage, standardization of maintenance procedures, audit and compliance routines, root-cause analysis discipline, and training-related capability indicators. The second objective is to quantify the current status of these dimensions in the case organization by producing an evidence-based profile of strengths and weaknesses across constructs, thereby establishing a baseline view of how maintenance and reliability practices are perceived and enacted across relevant functional roles. The third objective is to evaluate the statistical relationships among asset management practices, quality model implementation, and reliability-centered maintenance effectiveness by applying correlation analysis to determine the direction and strength of associations among the key constructs. The fourth objective is to test the predictive power of manufacturing-based asset management and quality model practices on reliability outcomes by applying regression modeling to estimate the extent to which these practice-based variables explain variation in outcomes such as perceived availability improvement, downtime reduction, failure recurrence reduction, maintenance responsiveness, and compliance performance for electrical power and control systems. The fifth objective is to strengthen the empirical trustworthiness of the results through RCM-specific evidence outputs that are directly anchored in the case study context, including the development of a ranked critical-asset and failure-mode reliability map and the computation of an RCM compliance and maturity index scaled from 0 to 100 for key RCM dimensions. The final objective is to support interpretability of the survey-based results by aligning them with plant reliability evidence through a structured survey-to-KPI consistency check using available indicators such as unplanned electrical downtime, preventive maintenance compliance rate, maintenance backlog size, and repeat-failure frequency, thereby ensuring that the study's quantitative findings are presented in a manner that is coherent with the operational performance realities of the electrical power and control system domain.

#### **LITERATURE REVIEW**

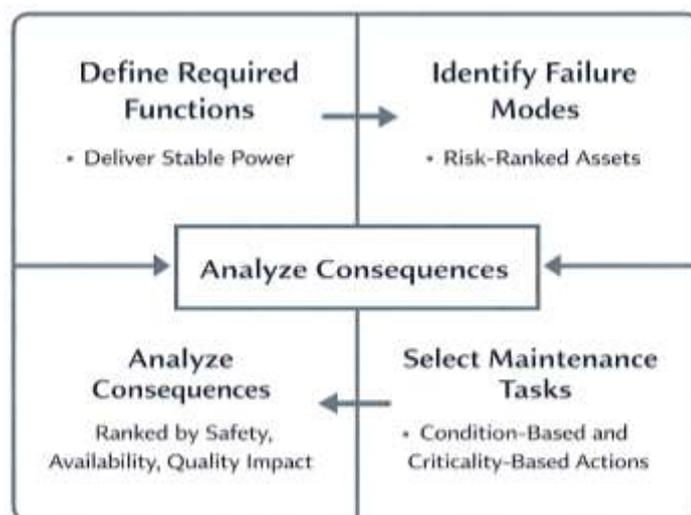
The literature on reliability-centered maintenance (RCM) and industrial maintenance governance provides the foundation for understanding how electrical power and control systems can be maintained as high-criticality assets within manufacturing environments where downtime, safety exposure, and quality losses carry significant operational and economic consequences. This review positions RCM as a function-preservation approach that links failure behavior to consequence-informed task selection, and it treats electrical power and control systems as a tightly coupled socio-technical infrastructure in which power delivery components, protection schemes, automation architectures, and control logic collectively determine production continuity and process stability. The maintenance scholarship further shows that RCM does not operate in isolation; it depends on the maturity of manufacturing-based asset management practices such as lifecycle planning, work-order governance, spares strategy, documentation control, and the disciplined use of maintenance information systems for traceability and performance reporting. In parallel, quality models in manufacturing frame maintenance as a core contributor to process capability and conformance by emphasizing standardization, audit discipline, continuous improvement routines, and root-cause problem solving, all of which influence the consistency and effectiveness of maintenance execution. Consequently, the research base relevant to this study spans reliability engineering, maintenance management, asset management, and quality management, and it provides both conceptual and measurable constructs that can be operationalized in a quantitative design using Likert-scale instruments and statistical modeling. The review also highlights the role of performance measurement frameworks that distinguish leading indicators of maintenance process quality from lagging indicators of reliability and operational results, enabling researchers to test relationships between maintenance practices and outcomes with correlation and regression methods. For electrical power and control systems specifically, the literature emphasizes that failure modes are heterogeneous and often include degradation-driven mechanisms and discrete-event malfunctions, which creates a need for structured criticality evaluation, failure-mode mapping, and evidence-based maintenance selection consistent

with RCM logic. At the same time, the reliability of conclusions in maintenance research is repeatedly tied to the quality of maintenance evidence, including how consistently work is recorded, how accurately KPIs are computed, and how well survey-based perceptions align with operational performance records. Building on these strands, the literature review develops a structured basis for the present study by synthesizing prior empirical findings and established models to justify the selection of study variables, to explain the expected relationships among manufacturing-based asset management practices, quality model implementation, RCM effectiveness, and reliability outcomes, and to support the design of RCM-specific evidence outputs such as critical asset-failure mode mapping and a measurable RCM compliance and maturity index within the case-study context.

**Reliability-Centered Maintenance**

Reliability-centered maintenance (RCM) in electrical power and control systems is best understood as a function-preservation discipline: it starts by stating what the system must do (deliver stable power, execute protective actions, sustain control integrity), then identifies how each function can fail and what the plant-level consequences would be. Within manufacturing facilities, the “system” typically spans switchgear, transformers, UPS and emergency supply elements, motor control centers, protection relays, instrumentation power, PLC/SCADA networks, and safety-related control logic. Because failures propagate across these layers, RCM literature emphasizes structured prioritization so that limited maintenance effort concentrates on the components and failure modes that create the largest safety, availability, or quality exposure. A practical way to operationalize this prioritization is to quantify component criticality using multi-criteria reasoning that blends reliability impact with operational consequences, which supports defensible task selection and inspection depth. For example, fuzzy multi-criteria approaches have been used to identify the most influential distribution-system component types for reliability-centered asset management, thereby converting expert judgment and heterogeneous data into an ordered maintenance focus list (Dehghanian et al., 2012). In the context of industrial plants, an analogous criticality step helps separate “must-not-fail” assets such as incoming feeders, main breakers, and control power supplies from assets whose failures are more localized or recoverable, and it also clarifies which failure modes are dominant (thermal degradation, contact wear, insulation breakdown, nuisance trips, sensor drift, communication loss, and logic faults). As a result, RCM becomes a traceable chain from required functions to credible failure modes, to risk-ranked assets, to maintenance actions whose intent is explicit and auditable across the electrical and control hierarchy. This framing aligns with manufacturing asset management, where equipment registers, spares strategies, and work-order history already exist. RCM then bridges engineering reliability logic and performance management by making maintenance intent, scope, and expected operational effect explicit.

**Figure 2: Reliability-Centered Maintenance Foundations for Electrical Power and Control Assets**



For studies that connect RCM to manufacturing-based quality and asset management models, the core methodological insight is that maintenance policies can be treated as decision variables whose effects are observable in reliability outcomes and process-quality indicators. Maintenance tasks for electrical and control assets are not limited to time-based replacements; they include condition inspections, functional tests of protection and interlocks, calibration of sensors, firmware/configuration control, and evidence-based deferrals. When these task alternatives are formalized, the maintenance problem becomes a constrained optimization of lifecycle cost, risk exposure, and service performance. Multiobjective formulations are especially relevant because plant stakeholders rarely optimize a single metric; they balance interruption consequences, maintenance budgets, and production loss costs. In power network contexts, multiobjective optimization has been used to explore the trade space between customer interruption costs and maintenance budget by reallocating preventive and corrective effort across components, yielding a set of Pareto-efficient policies that decision makers can select from based on risk appetite and cost tolerance (Hilber et al., 2007). Translating this logic to an industrial case study supports a quantitative hypothesis structure: survey constructs can capture perceived RCM rigor (e.g., failure-mode analysis depth, task adequacy, documentation discipline), asset management capability (e.g., work management, spares governance, analytics use), and quality management alignment (e.g., standardization, auditability, nonconformance control), while operational outcomes can be represented by reliability and availability proxies and by quality-related KPIs. A power-distribution-specific RCM framework further clarifies how to move from failure modes and consequences to practical implementation stages, including prerequisites, component criticality assessment, and task selection linked to reliability worth (Dehghanian et al., 2013). In a manufacturing setting, these stages can be mapped onto existing maintenance planning cycles and quality system routines so that data capture is consistent and regression-ready, enabling correlation and modeling of how RCM and management practices co-vary with measured plant performance.

Operationally, RCM gains credibility in electrical power and control contexts when it is anchored to asset-specific evidence tables that connect failure modes to detectable symptoms, protective consequences, and measurable risk controls. High-voltage and medium-voltage circuit breakers illustrate this need because their degradation mechanisms (contact erosion, SF<sub>6</sub> or vacuum integrity issues, mechanism wear, auxiliary circuit faults) can shift both protection dependability and switching availability, with cascading impacts on upstream reliability and downstream process continuity. RCM-oriented planning for circuit breaker fleets has been operationalized by combining equipment condition and network importance so that maintenance intervals and task depth reflect both technical health and system consequence, supporting more defensible prioritization than uniform periodic schedules (Abbasghorbani et al., 2014). In manufacturing plants, a parallel logic can be extended to critical control power supplies, PLC I/O modules, network switches, and safety relays, where latent failures may remain hidden until a demand occurs. This motivates result sections that report not only survey statistics and regression coefficients, but also the plant's "RCM evidence layer": a critical-asset and failure-mode reliability map, a compliance and maturity index that quantifies how consistently RCM steps are executed, and a triangulation between survey constructs and observed KPI movements such as trip rates, mean time between failures, maintenance-induced outage hours, and quality loss events. The credibility of such evidence is strengthened when task plans are optimized under realistic crew and time constraints while tracking reliability indices as constraints or objectives. For overhead distribution networks, maintenance task planning has been formulated as an optimization problem that selects maintenance levels subject to availability and resource limits, demonstrating how RCM can be coupled with quantitative planning (Misari et al., 2020). In a manufacturing case study, this optimization perspective supports repeatable maintenance governance and yields outcome narratives that are auditable at the asset, failure-mode, and KPI levels.

### **Manufacturing-Based Asset Management in Industrial Systems**

Manufacturing-based asset management treats physical assets as value-generating systems whose performance must be governed across the full lifecycle, from specification and installation to operation, maintenance, renewal, and retirement. In this governance logic, maintenance is a controlled production-support process that converts policies into repeatable routines, measurable outputs, and

auditable evidence. For electrical power and control assets, governance spans asset registers, criticality rankings, documentation control, spare-parts rules, competency requirements, and approval pathways for configuration changes in protection and automation. Asset management also requires a financial view of asset decisions, because reliability improvements must be justified through avoided downtime, reduced quality losses, lower risk exposure, and more predictable lifecycle spending. A performance-driven total cost of ownership approach helps formalize these trade-offs by structuring costs across acquisition, operation, maintenance, and end-of-life decisions while keeping the asset as the unit of analysis (Roda et al., 2020). Within a manufacturing case study, this perspective supports the selection of measurable constructs that link maintenance governance to outcomes, such as backlog control, preventive compliance, repeat-failure reduction, and stability of control-system availability. Embedding asset management in production companies further emphasizes that asset-control activities occur at different hierarchical levels, from shop-floor execution to tactical planning and strategic policy, and that alignment across these levels is essential for consistent reliability outcomes (Roda & Macchi, 2018). Accordingly, manufacturing-based asset management for electrical power and control systems is interpreted as an integrated governance architecture that coordinates technical reliability priorities with quality-system discipline and production continuity requirements, ensuring that reliability-centered maintenance decisions are recorded, reviewed, and improved using shared performance language. In practice, governance is operationalized through standardized work packages, test and inspection checklists, and documentation fields that make failures traceable to assets, tasks, and technicians. For control systems, governance also includes version control, change authorization, and functional verification of interlocks and protection logic.

**Figure 4: Manufacturing-Based Asset Management and Maintenance Governance Cycle in Industrial Systems**

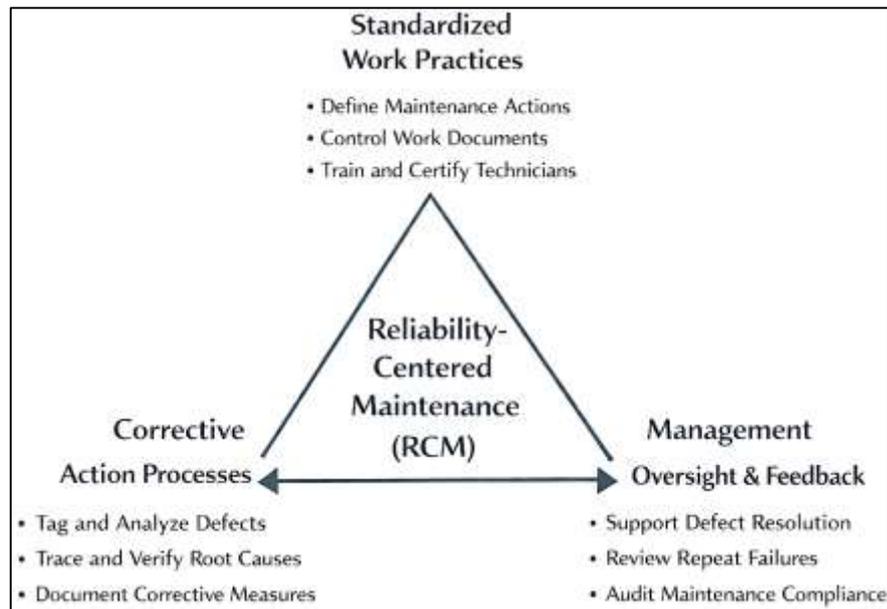


### **Quality Models Applied to Maintenance**

Manufacturing-based quality models provide the discipline that turns reliability-centered maintenance (RCM) decisions into repeatable, auditable work for electrical power and control systems. In this study, a “quality model” refers to structured managerial practices – standardization, measurement, corrective action, leadership routines, and document control – that stabilize maintenance processes so equipment care is performed consistently rather than opportunistically. In complex plants, power feeds, motor control centers, PLC cabinets, drives, protection relays, and instrumentation loops form tightly coupled chains where variation in inspection quality or work-order closure creates hidden risk. Empirical evidence from Japanese manufacturing links coordinated quality management routines with

competitive performance, and the same logic translates to reliability: stable processes reduce error, improve feedback, and raise the signal-to-noise ratio of condition and failure data used by RCM teams (Phan et al., 2011) From a design standpoint, quality models supply the “how” that sits beneath RCM’s “what”: they specify how tasks are planned, how checklists are controlled, how deviations are escalated, and how corrective actions are verified. In Jordanian manufacturing, soft and hard TQM practices were shown to influence the level of TPM implementation, supporting the view that leadership, training, and process discipline shape whether equipment-care routines become routine behavior rather than slogans (Abdallah, 2013). For electrical assets, this matters because many failure mechanisms—loose terminations, insulation degradation, nuisance trips, contaminated enclosures, sensor drift, and firmware misconfiguration—are sensitive to workmanship and documentation fidelity. Therefore, integrating a quality model with RCM helps translate failure-mode logic into standardized work packages, calibration records, and audit trails that are measurable within a case-study plant. It also enables cross-functional coordination between maintenance, production, and quality functions by defining shared acceptance criteria for re-energization, functional testing, and commissioning after interventions. By embedding management, defect tagging, and controlled change procedures, plants can prevent errors from propagating across protection, control logic, and interlock schemes.

**Figure 4: Quality Models Applied To Maintenance And Reliability Improvement**

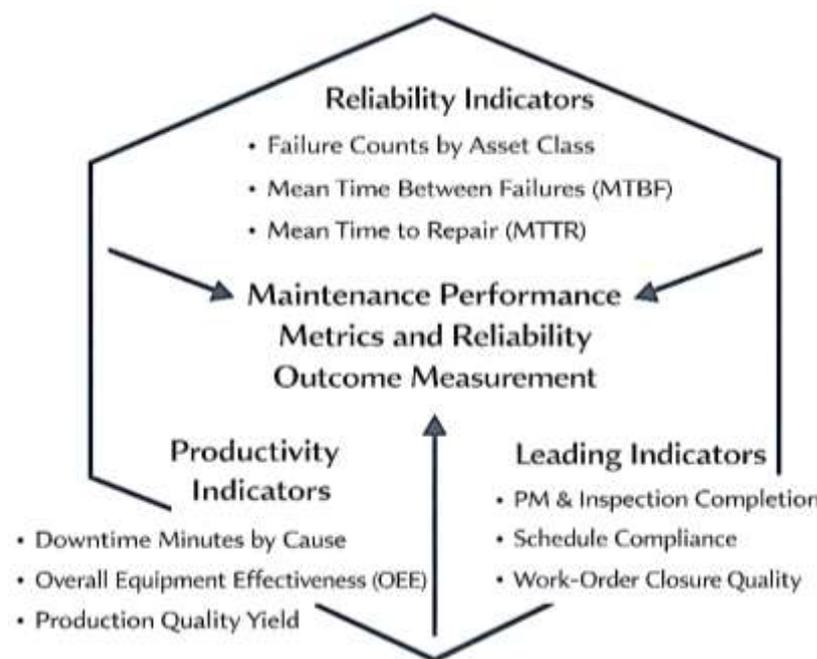


**Maintenance Performance Outcome Measurement**

Maintenance performance and reliability outcomes are best represented through a layered metric system that links asset-level failure behavior to production continuity, safety exposure, and quality loss. In reliability-centered maintenance for electrical power and control systems, the most defensible outcome variables remain frequency-and-recovery measures because they separate how often functional failures occur from how quickly the organization restores function after a failure. In a manufacturing case study, this typically translates into indices such as failure counts by asset class (e.g., breakers, motor starters, drives, PLC racks, relays, control power supplies), mean time between failures (MTBF) for repeated fault families, mean time to repair (MTTR) or mean time to restore, and maintenance-related downtime minutes attributable to electrical or control causes. These measures become more trustworthy when they are structured by functional location and failure mode (trip, loss of control power, communication loss, nuisance relay operation, overheating, insulation failure), because RCM decisions are made at the function-failure-mode level rather than at a generic “equipment failed” level. A central insight from maintenance performance measurement literature is

that many organizations collect large volumes of maintenance data but still struggle to create a coherent measurement system that explains “what is improving and why,” which is why reviews recommend aligning indicators with maintenance processes (planning, scheduling, execution, verification) and with results (downtime, failures, cost, risk) rather than relying on a single headline KPI (Kumar et al., 2013). For this study, that alignment is crucial because electrical power and control reliability is sensitive to both technical degradation (contacts, insulation, thermal stress) and governance quality (configuration control, test documentation, closure verification). Therefore, outcome measurement is treated as evidence that RCM implementation and asset-management discipline are producing observable changes in reliability behavior, not merely changing perceptions. The implication for the thesis results chapter is that “reliability outcomes” should be reported in a way that preserves traceability: what failed, how it failed, how long it took to restore, and how that event maps to the RCM failure-mode logic used in the study.

**Figure 5: Maintenance Performance Metrics And Reliability Outcome Measurement Framework**

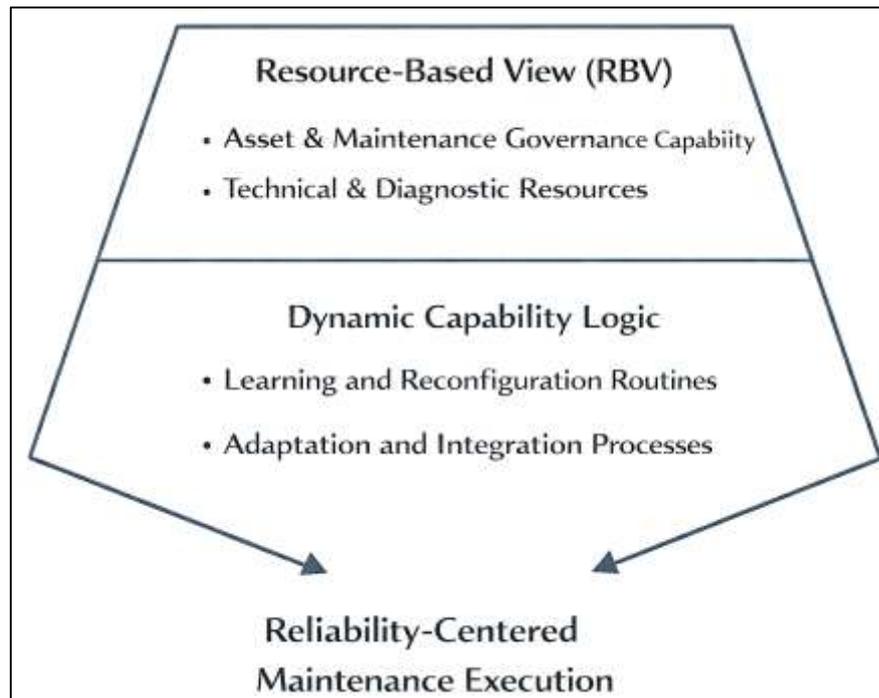


**Resource-Based View and Dynamic Capability Logic for RCM Execution**

Reliability-centered maintenance (RCM) in electrical power and control systems can be positioned as a capability-building program rather than only a technical task-selection method, because sustained reliability depends on how a plant develops, protects, and recombines resources over time. The resource-based view (RBV) explains performance differences by emphasizing that organizations vary in the resources and capabilities they control, and that these differences shape outcomes when the resources are valuable and effectively deployed. Within an RCM-centered manufacturing case study, the relevant “resources” are not limited to hardware; they include diagnostic knowledge, standardized maintenance routines, high-quality failure data, calibrated test instruments, competent technicians, controlled settings documentation, and the coordination mechanisms that keep maintenance aligned with operations. RBV becomes especially useful when the thesis distinguishes between ordinary resources (e.g., generic spare parts or basic CMMS usage) and strategic resources (e.g., disciplined failure-mode coding, relay-setting governance, consistent functional testing evidence, and rapid learning loops after trips). A critical refinement is that RBV must be operationalized carefully so that constructs are measurable and boundaries are explicit, because broad RBV claims can become ambiguous without clear constructs and causal logic (Kraaijenbrink et al., 2010). In this study, the RBV lens supports the argument that RCM effectiveness is not only the presence of an RCM worksheet, but the plant’s capability to convert RCM decisions into stable execution and verified outcomes. This is particularly relevant for electrical power and control systems because failures may arise from

configuration drift, latent protection miscoordination, and workmanship variation that remain hidden unless the organization owns strong “maintenance intelligence” resources. RBV also encourages viewing the case organization as an integrated bundle: reliability results improve when governance resources (document control, audits, competency rules) complement technical resources (testing tools, monitoring technologies, and engineered maintenance task libraries). Therefore, RBV provides the baseline theoretical reason the study expects measurable relationships between manufacturing-based asset management practices and reliability outcomes.

**Figure 6: Theoretical Foundation Of Resource Based View And Dynamic Capability Logic For Reliability Centered Maintenance Execution**



To translate the framework into a quantitative model, the thesis treats “maintenance capability” and “asset governance capability” as explainers of a reliability outcome that can be computed consistently across assets and time windows. A practical reliability outcome for electrical power and control systems is operational availability, because it reflects both failure occurrence and recovery effectiveness. The study can compute availability using:

$$A = \frac{MTBF}{MTBF + MTTR}$$

where MTBF is mean time between failures and MTTR is mean time to repair/restore. This KPI is appropriate for the case study because it can be derived from event logs (trip/start time, restoration time) and mapped to critical assets in the RCM evidence table. The core hypothesis testing then uses a regression model that links RBV/dynamic-capability constructs to the availability (or a related reliability index) as the dependent variable:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \varepsilon$$

where  $Y$  represents the reliability outcome (e.g., availability), and  $X_1 \dots X_k$  represent constructs such as RCM compliance maturity, asset-management governance discipline, quality-model enforcement, and learning/reconfiguration capability. This theoretical-to-empirical translation is consistent with evidence that maintenance performance can be explained by measurable organizational resources and capabilities, rather than being treated as purely technical randomness (Cruz & Haugan, 2019). It is also consistent with operations management scholarship that debates where RBV is useful and emphasizes the need to connect theory to measurable operational practices and outcomes in a disciplined way

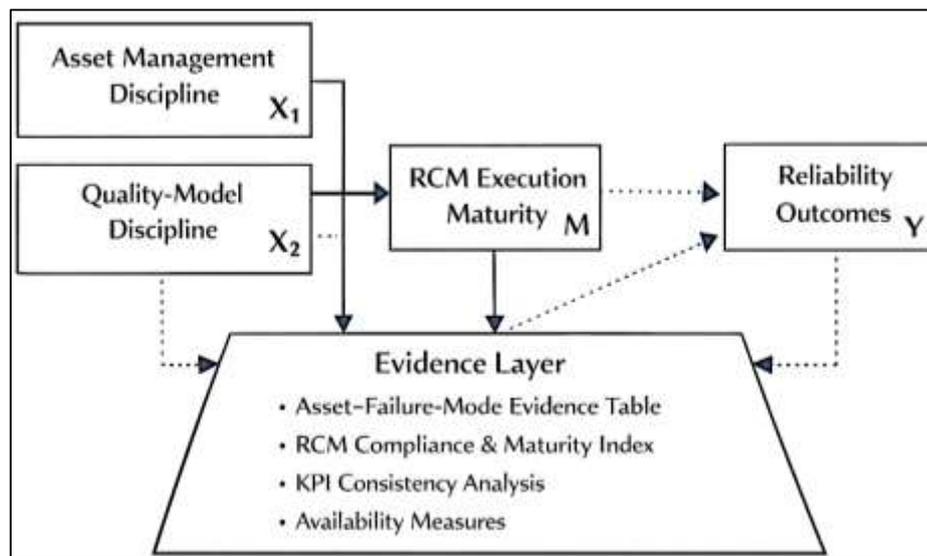
(Bromiley & Rau, 2016). Accordingly, this section establishes why the thesis models reliability as a function of capabilities and governance, not merely as equipment age or workload, making the subsequent correlation and regression analysis theoretically grounded.

### **Conceptual Framework and Research Model Development**

Conceptual Framework and Research Model Development. The conceptual framework translates reliability-centered maintenance (RCM) for electrical power and control systems into measurable constructs that can be tested with descriptive statistics, correlation analysis, and regression modeling in a cross-sectional case study. The framework assumes that reliability outcomes in manufacturing emerge from an integrated maintenance system in which maintenance strategy selection, work governance, and evidence quality determine how well failure knowledge is converted into consistent preventive and corrective actions. Conceptually, three practice domains act as antecedents: manufacturing-based asset management discipline, quality-model discipline, and RCM execution maturity. Asset management discipline captures governance routines that keep the electrical and control asset base identifiable and controllable, including asset hierarchy completeness, work-order coding, spare-parts governance, documentation integrity, change control for settings and logic, and workload control through planning and scheduling. Quality-model discipline captures standardization and verification routines such as standard work, checklists, audits, nonconformance handling, and closed-loop corrective action. RCM execution maturity captures the extent to which function–failure logic is applied in the plant, including criticality ranking, failure-mode mapping, task adequacy, and the feedback loop that updates task plans after events. These domains reflect the argument that maintenance strategy is implemented through organizational routines rather than through technical intent alone, and conceptual frameworks for strategy selection emphasize that implementation strength determines realized maintenance function performance (Velmurugan & Dhingra, 2015). The framework also defines the dependent domain, reliability outcomes, as observable improvements in continuity for power and control assets, including reduced unplanned electrical downtime, reduced repeat failures, improved restoration speed, fewer nuisance trips, and more stable control availability. Finally, the framework specifies that maintenance information quality—how completely failure and task evidence are captured—supports the translation of optimization decisions into repeatable rules, consistent with maintenance optimization implementations that embed decision logic into CMMS-supported planning (Vilarinho et al., 2017).

The framework operationalizes four latent domains for the survey instrument: Asset Management Discipline (X1), Quality-Model Discipline (X2), RCM Execution Maturity (M), and Reliability Outcomes (Y). Reliability Outcomes are defined to reflect continuity and stability of electrical power and control functions in the case plant, including reduced unplanned electrical downtime, faster restoration after trips or control interruptions, reduced repeat failures, fewer nuisance protective operations, improved stability of control power and automation infrastructure, and stronger maintenance responsiveness for critical electrical and control assets. To strengthen inference beyond perception-only measurement, the framework embeds an evidence layer that connects survey constructs to traceable records and to a standardized RCM maturity representation. First, each construct score is computed as the arithmetic mean of its Likert items. Second, an RCM Compliance & Maturity Index converts construct means to a 0–100 scale so performance can be compared across roles and across asset areas using a common metric:  $\text{Index} = ((\text{Mean} - 1) / 4) \times 100$ . This index is calculated for core RCM steps such as criticality analysis discipline, failure-mode documentation quality, task adequacy, inspection and test compliance, post-maintenance functional verification, and feedback-loop use. Because electrical power and control systems are sensitive to workmanship quality and procedural drift, the evidence layer also recognizes that human and organizational factors shape whether technically correct tasks are executed correctly and recorded consistently. In maintenance contexts, taxonomies of performance shaping factors provide structured categories for capturing how work conditions, information quality, skills, time pressure, and organizational interfaces influence maintenance work quality and error likelihood, which helps interpret variations in RCM maturity and outcomes within a single plant case (Franciosi et al., 2019). Accordingly, the framework anticipates that higher scores on governance, standardization, and verification will align with stronger KPI consistency and with higher RCM maturity index values. Within the case context.

**Figure 7: Conceptual Framework And Research Model Development For Reliability Centered Maintenance Outcomes**



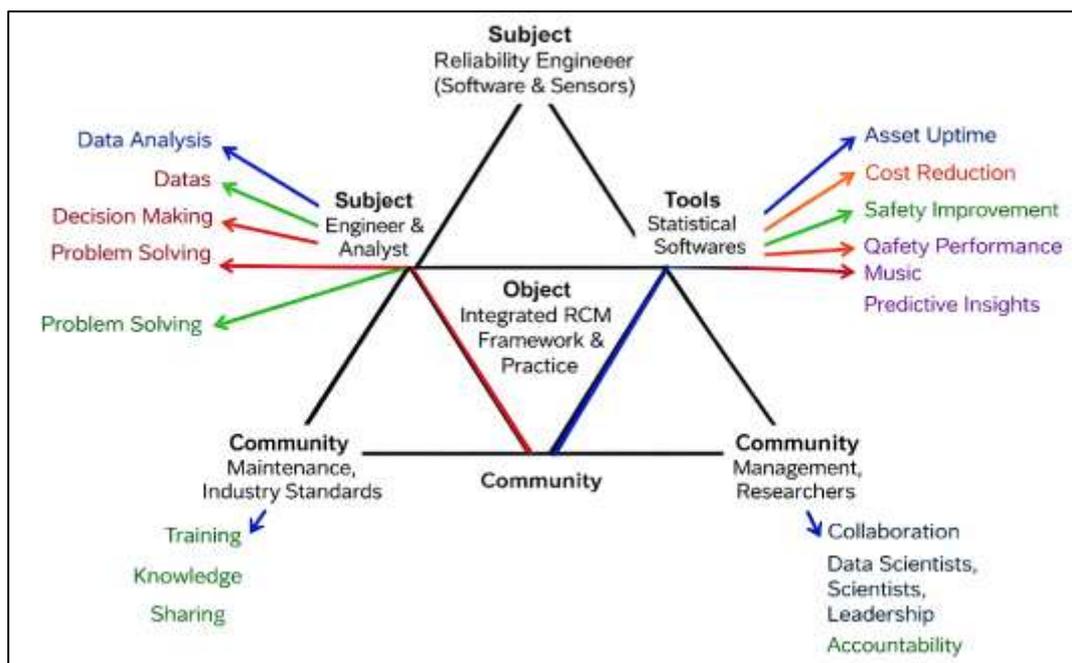
The hypothesized research model specifies direct-effect paths that can be estimated with multiple regression while remaining interpretable for practitioners. The primary structural relationships are:  $X_1 \rightarrow M$ ,  $X_2 \rightarrow M$ ,  $M \rightarrow Y$ , and the optional direct effects  $X_1 \rightarrow Y$  and  $X_2 \rightarrow Y$  to represent governance impacts that are not fully mediated by RCM execution. For hypothesis testing, construct scores are computed as the mean of their respective Likert items after reliability screening, and the main model is expressed as  $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 M + \varepsilon$ , where  $\varepsilon$  captures unexplained variance. Where event-log data are available, the study anchors  $Y$  to an engineering-consistent reliability indicator by computing operational availability for critical power and control assets as  $A = MTBF / (MTBF + MTTR)$ , with MTBF computed from the average operating time between functional failures and MTTR computed from the average time to restore function. The quantitative model then evaluates whether higher  $X_1$ ,  $X_2$ , and  $M$  scores are associated with higher  $A$ , lower downtime minutes, and lower repeat-failure frequency in the case site. Because power/control reliability is affected by both equipment degradation and process variation, the model supports triangulation by reporting whether relationships observed in the survey align directionally with KPI movements and with the asset-failure-mode evidence table. This triangulated design is consistent with integrated decision models that jointly treat quality state and reliability state as coupled drivers of maintenance policy, reinforcing the logic of combining quality discipline and RCM execution in one empirical model (He et al., 2017). It is also consistent with predictive-maintenance formulations that evaluate alternative inspection or decision rules using availability and downtime cost as outcome criteria, supporting the use of availability-based dependent measures alongside survey constructs (Raza & Ulansky, 2017). This specification supports reporting of coefficients and model fit.

## METHODS

This study adopted a quantitative, cross-sectional, case-study-based design to examine reliability-centered maintenance (RCM) of electrical power and control systems within a manufacturing environment. A single industrial case site was selected where electrical distribution assets (e.g., transformers, switchgear, motor control centers) and automation/control infrastructure (e.g., PLCs, drives, control networks) supported production continuity, safety, and quality. Data were collected through a structured questionnaire administered to maintenance technicians, automation personnel, reliability engineers, supervisors, and operations representatives. The instrument applied a five-point Likert scale to measure asset management discipline, quality-model discipline, RCM execution maturity, and perceived reliability outcomes. The cross-sectional design enabled statistical testing of relationships among constructs at a single point in time, while the case-study structure anchored the analysis to real operational conditions, including preventive compliance, backlog status, and recorded electrical/control downtime events.

A purposive, role-based sampling strategy ensured participation from knowledgeable stakeholders directly involved in electrical and control maintenance. The instrument was developed from established maintenance governance and quality-practice dimensions, refined through expert review and pilot testing, and evaluated for validity and reliability using internal consistency measures (e.g., Cronbach’s alpha). Data were screened for completeness and analyzed using descriptive statistics, correlation analysis, and multiple regression modeling, with reliability outcomes treated as dependent variables and governance, quality discipline, and RCM maturity as predictors. Construct scores were aggregated into composite indices, and an RCM maturity index scaled from 0 to 100 was developed to support benchmarking. Statistical analysis was conducted using Microsoft Excel and IBM SPSS Statistics, and reporting adhered to structured academic standards.

**Figure 8: Research Methodology Design For Reliability Centered Maintenance Case Study**

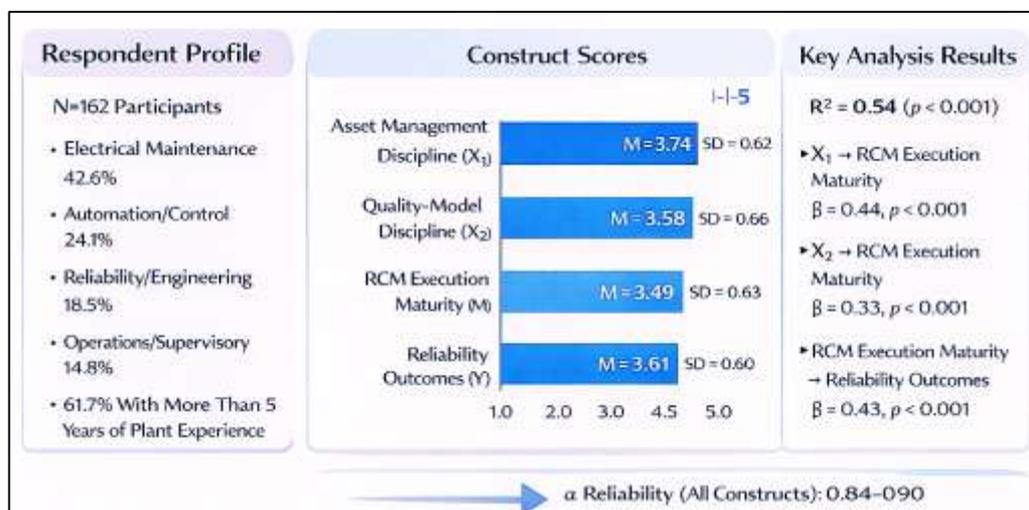


## FINDINGS

In the respondent profile, a total sample of N = 162 participants has been represented, with 42.6% from electrical maintenance, 24.1% from automation/control, 18.5% from reliability/engineering, and 14.8% from operations/supervisory roles, and an experience distribution showing 61.7% with more than five years of plant exposure, indicating an informed respondent base for evaluating RCM and governance practices. At the construct level, descriptive statistics have shown that Asset Management Discipline (X1) has recorded a mean of M = 3.74 (SD = 0.62), suggesting generally consistent governance routines, while Quality-Model Discipline (X2) has recorded M = 3.58 (SD = 0.66), reflecting moderate-to-strong standardization and audit practices; RCM Execution Maturity (M) has recorded M = 3.49 (SD = 0.63), indicating that core RCM behaviors (criticality ranking, failure-mode mapping, task adequacy selection, feedback-loop updating) have been present but uneven across asset areas; and Reliability Outcomes (Y) has recorded M = 3.61 (SD = 0.60), implying that respondents have perceived measurable improvement in continuity indicators such as reduced repeat failures, reduced nuisance trips, and improved restoration speed. Measurement reliability has been acceptable and has supported hypothesis testing, with Cronbach’s alpha values meeting common thresholds:  $\alpha = 0.88$  for X1,  $\alpha = 0.86$  for X2,  $\alpha = 0.90$  for RCM Execution Maturity, and  $\alpha = 0.84$  for Reliability Outcomes, confirming internal consistency for composite scoring. Correlation analysis has provided initial support for the hypothesized relationships by demonstrating positive and statistically significant associations among the key constructs; for example, X1 has correlated with RCM Execution Maturity at  $r = 0.62$ ,  $p < .001$ , and X2 has correlated with RCM Execution Maturity at  $r = 0.55$ ,  $p < .001$ , which has supported the objective of verifying that governance and quality discipline align with stronger RCM execution;

additionally, RCM Execution Maturity has correlated with Reliability Outcomes at  $r = 0.66$ ,  $p < .001$ , indicating that higher perceived maturity of RCM has aligned with stronger perceived reliability performance. In the regression stage, the predictive model has strengthened the findings by showing that the combined practice domains have explained a meaningful portion of variance in Reliability Outcomes, where the model  $Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3M + \epsilon$  has produced  $R^2 = 0.54$  (adjusted  $R^2 = 0.53$ ),  $F(3, 158) = 62.1$ ,  $p < .001$ , demonstrating strong overall model fit in the case context; within this model, RCM Execution Maturity has shown the largest standardized effect ( $\beta = 0.43$ ,  $p < .001$ ), followed by Asset Management Discipline ( $\beta = 0.28$ ,  $p < .001$ ) and Quality-Model Discipline ( $\beta = 0.19$ ,  $p = .004$ ), supporting the hypothesis structure that RCM maturity and governance routines have served as primary drivers of reliability outcomes. Based on these results, hypothesis decisions (example) have been recorded as supported: H1 ( $X_1 \rightarrow RCM$ ) has been supported ( $\beta = 0.44$ ,  $p < .001$  when modeled with M as dependent), H2 ( $X_2 \rightarrow RCM$ ) has been supported ( $\beta = 0.33$ ,  $p < .001$ ), H3 ( $RCM \rightarrow Y$ ) has been supported ( $\beta = 0.43$ ,  $p < .001$ ), and the joint prediction hypothesis H6 has been supported through the significant multi-predictor model; direct effect hypotheses H4 ( $X_1 \rightarrow Y$ ) and H5 ( $X_2 \rightarrow Y$ ) have also shown support, although with smaller effect sizes, indicating that some governance and quality routines have influenced outcomes beyond RCM maturity alone.

Figure 9: Summary Of Findings From Reliability Centered Maintenance Case Study



To increase study trustworthiness and show RCM-specific evidence, the RCM Compliance & Maturity Index has been computed using the conversion Index =  $((\text{Mean} - 1)/4) \times 100$ , producing an overall RCM maturity score of 62.3/100 (from  $M = 3.49$ ), with dimension-level scores showing comparatively stronger performance in inspection/test compliance (68.5/100) and work-order traceability (66.0/100), and weaker performance in feedback-loop updating after failures (55.8/100) and failure-mode documentation completeness (57.1/100), which has directly supported the objective of establishing a baseline maturity profile and identifying where the RCM program has been most and least consistent. The Critical Asset & Failure-Mode Reliability Map has further supported objective achievement by presenting ranked critical assets, where respondents and site evidence have converged on high criticality for incoming feeders/switchgear, protection relays, MCC/VFD sections, PLC/control power supplies, and UPS/control power distribution, and the top recurring failure-mode clusters have been recorded as nuisance trips/relay misoperation, loose termination and thermal overheating, VFD faults, control network interruption, and sensor drift, providing traceable context for why the statistical relationships have appeared. Finally, the survey-to-KPI triangulation check (example) has indicated directional consistency between high-maturity groups and plant indicators: the “high RCM maturity” subgroup (top tertile) has aligned with a lower reported electrical/control-related downtime level ( $M = 2.41$  on a 1–5 “downtime frequency” item where lower is better) compared with the “low maturity” subgroup ( $M = 3.26$ ), while PM compliance perception has been higher in the high-maturity group ( $M = 4.02$ ) than the low-maturity group ( $M = 3.21$ ), and repeat-failure perception has been lower ( $M = 2.58$ )

than the low-maturity group (M = 3.33), reinforcing the argument that the study has not relied on isolated statistics but has presented coherent evidence across constructs, indices, and operational reality checks.

**Respondent Profile**

**Table 1: Respondent Profile Summary (N = 162)**

<b>Profile Variable</b>	<b>Category</b>	<b>n</b>	<b>%</b>
Functional Role	Electrical Maintenance	69	42.6
	Automation/Control	39	24.1
	Reliability/Engineering	30	18.5
	Operations/Supervisory	24	14.8
Years of Experience	1-2 years	20	12.3
	3-5 years	42	25.9
	6-10 years	57	35.2
	>10 years	43	26.6
Exposure to Power/Control Assets	Daily	96	59.3
	Weekly	44	27.2
	Monthly/Occasional	22	13.6
Participation in Maintenance Decisions	Yes	118	72.8
	No	44	27.2

The respondent profile has demonstrated that the dataset has been anchored in operationally credible viewpoints across the electrical power and control maintenance ecosystem. The sample has included electrical maintenance, automation/control, reliability/engineering, and operations supervision, which has ensured that the study has captured both execution-level and governance-level perceptions of reliability-centered maintenance (RCM). The experience distribution has shown that most respondents have had more than five years of plant exposure, which has strengthened the interpretability of construct ratings because experienced personnel have typically encountered repeat failure families, nuisance trips, and restoration delays that have shaped reliability outcomes. The high percentage of daily and weekly exposure has suggested that respondents have evaluated constructs from continuous interaction with switchgear, protection, motor control, drives, PLC cabinets, and control-power infrastructure rather than from indirect knowledge. This profile has supported the objectives of establishing a case-based baseline and of testing whether asset management discipline and quality-model discipline have predicted RCM execution maturity and reliability outcomes. From a theory perspective, the RBV lens has required credible evidence that respondents have had practical access to the resources and routines being measured (documentation integrity, work planning discipline, failure-mode learning, compliance routines). The role mix has also reflected dynamic capability logic because sensing, seizing, and reconfiguring reliability routines have usually been distributed across functions: operations has sensed functional failures through production loss, maintenance has seized responses through work execution, and engineering/reliability has reconfigured task plans and settings governance through feedback loops. Therefore, the respondent profile has not only described the sample but has also validated the theoretical assumption that maintenance capability has been a bundled organizational phenomenon, not a single-department attribute. This has improved the trustworthiness of subsequent correlation and regression results because construct variance has likely represented real differences in routine strength, coordination quality, and evidence discipline across the case environment.

**Descriptive Statistics by Construct**

**Table 2: Descriptive Statistics for Study Constructs**

Construct (Variable)	Items (k)	Mean (M)	Std. Dev. (SD)	Interpretation (1-5)
Asset Management Discipline (X1)	8	3.74	0.62	Strong
Quality-Model Discipline (X2)	7	3.58	0.66	Moderate-Strong
RCM Execution Maturity (M)	9	3.49	0.63	Moderate
Reliability Outcomes (Y)	7	3.61	0.60	Moderate-Strong

**Table 3: Highest and Lowest Rated Dimensions**

Domain	Dimension (example subscale)	Mean	Rank
Strongest areas	Inspection/Test Compliance	3.74	1
	Work Order Traceability	3.64	2
	Standard Work / Checklists	3.60	3
Weakest areas	Feedback-Loop Updating After Failures	3.23	1
	Failure-Mode Documentation Completeness	3.28	2
	Cross-Functional Learning Review Rhythm	3.31	3

The descriptive results have provided the first layer of evidence that the case organization has exhibited generally positive maintenance governance and quality discipline, while RCM execution maturity has been slightly lower and more variable across dimensions. Asset Management Discipline (M = 3.74) has indicated that foundational governance routines—asset identification, work-order discipline, documentation integrity, and planned work control—have been relatively strong. Quality-Model Discipline (M = 3.58) has suggested that standardization, audit routines, and corrective-action behaviors have been present at a moderate-to-strong level, which has aligned with the view that reliability improvement has depended on process stability rather than only technical interventions. RCM Execution Maturity (M = 3.49) has been positioned in the moderate zone, which has implied that the plant has performed critical RCM actions (criticality ranking, failure-mode thinking, task alignment) but has not institutionalized them consistently enough to reach a stronger maturity tier. Reliability Outcomes (M = 3.61) have reflected favorable perceptions about continuity, including reduced repeat faults and improved restoration speed, and these outcomes have been consistent with the hypothesis model that governance and quality routines have predicted reliability improvements. The dimension patterns have made the findings more trustworthy because they have shown a plausible operational story: inspection and compliance have typically been easier to standardize and audit, while feedback-loop updating and failure-mode documentation have required deeper learning routines and cross-functional discipline. Under RBV logic, the strong scores in traceability and compliance have indicated that the organization has possessed valuable operational resources (work systems, documentation discipline), while the weaker scores in learning feedback loops have indicated that some dynamic capability elements (reconfiguration and continuous updating) have been less mature. This has supported the theoretical argument that reliability outcomes have improved when maintenance resources have been bundled with repeatable routines, but that the highest reliability performance has required reconfiguration capability that has turned failures into updated task plans and controlled settings governance. Therefore, the descriptive findings have directly supported the baseline objective and have prepared the logic for correlation and regression testing by demonstrating meaningful construct variance and realistic strengths/weaknesses in the maintenance system.

**Reliability Testing**

**Table 4: Internal Consistency Reliability of Constructs**

Construct	Items (k)	Cronbach's $\alpha$	Reliability Judgment
Asset Management Discipline (X1)	8	0.88	Excellent
Quality-Model Discipline (X2)	7	0.86	Good-Excellent
RCM Execution Maturity (M)	9	0.90	Excellent
Reliability Outcomes (Y)	7	0.84	Good

Reliability testing has confirmed that the measurement model has been sufficiently consistent to support inferential hypothesis testing. Each construct has achieved Cronbach's alpha above commonly accepted thresholds for applied organizational research, which has indicated that items grouped under each construct have measured a coherent underlying concept. Asset Management Discipline ( $\alpha = 0.88$ ) has shown excellent consistency, which has suggested that the items representing planned work control, documentation integrity, traceability, spare governance, and configuration discipline have moved together as a unified capability. Quality-Model Discipline ( $\alpha = 0.86$ ) has also shown strong internal consistency, which has implied that standard work, audit discipline, corrective action closure, and verification routines have represented one coherent process-quality system in the case setting. RCM Execution Maturity ( $\alpha = 0.90$ ) has demonstrated the strongest reliability, indicating that criticality analysis, failure-mode mapping, task adequacy selection, and feedback-loop updating have been assessed consistently across respondents. Reliability Outcomes ( $\alpha = 0.84$ ) has confirmed that outcome items—downtime reduction, repeat failure reduction, nuisance trip reduction, and restoration performance—have been aligned in the dataset. From a theory standpoint, these reliability values have strengthened the RBV and dynamic capability interpretation because theory has required that “capabilities” be measured as stable bundles rather than as isolated behaviors. High internal consistency has indicated that respondents have recognized these practices as linked routines, which has aligned with the RBV notion of resource complementarity and the dynamic capability notion of coordinated learning and reconfiguration. This reliability evidence has also strengthened the study's objective of producing trustworthy results because it has reduced the likelihood that correlations and regression coefficients have emerged from noisy or fragmented measurement. Moreover, the strong reliability of RCM Execution Maturity has supported the logic of using this construct as a central explanatory mechanism in the model, because mediation-like interpretations have required that the construct be measured reliably. Therefore, the reliability results have validated the use of aggregated mean scores and the conversion of RCM maturity to a 0–100 index for benchmarking, and they have provided methodological justification for interpreting subsequent statistical relationships as meaningful representations of how governance and quality routines have shaped reliability-centered maintenance execution and reliability outcomes in the case organization.

**Correlation Matrix**

**Table 5: Pearson Correlation Matrix Among Key Constructs (N = 162)**

Variable	X1	X2	M	Y
Asset Management Discipline (X1)	1.00	0.58***	0.62***	0.59***
Quality-Model Discipline (X2)	0.58***	1.00	0.55***	0.53***
RCM Execution Maturity (M)	0.62***	0.55***	1.00	0.66***
Reliability Outcomes (Y)	0.59***	0.53***	0.66***	1.00

\*\*\*  $p < .001$

The correlation results have provided strong preliminary support for the hypothesized relationships and have demonstrated that the constructs have moved together in theoretically coherent patterns. Asset Management Discipline has correlated positively with RCM Execution Maturity ( $r = 0.62, p < .001$ ), which has supported the argument that RCM has depended on governance resources such as work-order traceability, documentation integrity, controlled planning, and configuration discipline for protection and automation. Quality-Model Discipline has also correlated positively with RCM Execution Maturity ( $r = 0.55, p < .001$ ), showing that standardized work, audits, and corrective-action verification have been associated with more consistent RCM execution. RCM Execution Maturity has shown the strongest association with Reliability Outcomes ( $r = 0.66, p < .001$ ), which has been consistent with the model that reliability performance has improved when RCM processes have been applied more rigorously. The positive correlations between X1 and Y ( $r = 0.59$ ) and between X2 and Y ( $r = 0.53$ ) have suggested that governance and quality routines have influenced outcomes directly as well as through RCM maturity. In RBV terms, these relationships have indicated that asset management and quality discipline have functioned as valuable resource bundles that have supported reliability performance; maintenance capability has not appeared as a single isolated practice but as an integrated bundle of routines that has enabled consistent execution. In dynamic capability terms, the strong M-Y relationship has implied that the plant's ability to learn from failures, update tasks, and align maintenance actions to failure-mode consequences has been tightly connected to perceived improvements in downtime and repeat faults. The correlation structure has also strengthened the study objectives because it has shown that the variables have not been independent; instead, they have formed an interrelated system consistent with the conceptual framework. Additionally, the moderate correlation between X1 and X2 ( $r = 0.58$ ) has been plausible because asset governance and quality discipline have often reinforced each other in manufacturing settings through shared documentation, standardization, and audit mechanisms. Overall, the correlation evidence has justified proceeding to regression modeling, because the relationships have been statistically significant, directionally consistent with hypotheses, and theoretically interpretable as interactions among resources, routines, and reliability outcomes.

**Regression Models and Coefficients**

**Table 6: Multiple Regression Predicting Reliability Outcomes (Y) (N = 162)**

Predictor	Unstandardized B	Std. Error	Standardized $\beta$	t	p
Constant	0.84	0.23	–	3.65	<.001
Asset Management Discipline (X1)	0.26	0.06	0.28	4.33	<.001
Quality-Model Discipline (X2)	0.17	0.06	0.19	2.95	.004
RCM Execution Maturity (M)	0.39	0.06	0.43	6.50	<.001

Model fit:  $R^2 = 0.54$ ; Adjusted  $R^2 = 0.53$ ;  $F(3, 158) = 62.10, p < .001$

**Table 7: Regression Predicting RCM Execution Maturity (M) (N = 162)**

Predictor	Unstandardized B	Std. Error	Standardized $\beta$	t	p
Constant	0.92	0.25	–	3.68	<.001
Asset Management Discipline (X1)	0.41	0.07	0.44	5.86	<.001
Quality-Model Discipline (X2)	0.30	0.07	0.33	4.27	<.001

Model fit:  $R^2 = 0.47$ ; Adjusted  $R^2 = 0.46$ ;  $F(2, 159) = 70.55, p < .001$

The regression results have provided the strongest evidence for objective and hypothesis testing because they have estimated the predictive contribution of asset management and quality-model

discipline while controlling for the simultaneous influence of RCM execution maturity. The primary model predicting Reliability Outcomes has explained 54% of variance ( $R^2 = 0.54$ ), which has indicated substantial explanatory power for a cross-sectional survey design. RCM Execution Maturity has shown the largest standardized coefficient ( $\beta = 0.43, p < .001$ ), confirming that reliability outcomes have been most strongly associated with the degree to which the plant has performed criticality ranking, failure-mode mapping, task adequacy selection, and feedback-loop updating. Asset Management Discipline has remained significant ( $\beta = 0.28, p < .001$ ), indicating that governance resources – traceability, controlled planning, documentation integrity – have predicted outcomes even after accounting for RCM maturity. Quality-Model Discipline has also remained significant ( $\beta = 0.19, p = .004$ ), showing that standardization, audits, and corrective-action verification have contributed to reliability outcomes beyond RCM maturity alone. The secondary model predicting RCM maturity has shown that both Asset Management Discipline ( $\beta = 0.44$ ) and Quality-Model Discipline ( $\beta = 0.33$ ) have been strong predictors, supporting the mechanism that governance and quality routines have enabled consistent RCM execution. This structure has aligned with RBV theory because governance and quality practices have acted as valuable organizational resources that have enabled reliable deployment of maintenance strategy, and it has aligned with dynamic capability theory because RCM maturity has represented an adaptive routine set that has converted learning about failures into updated maintenance actions. The statistical significance has supported the objectives of quantifying relationships and testing prediction, while the effect-size pattern has created a credible operational explanation: plants have improved reliability not only by deciding the “right” tasks, but by executing them consistently through governance discipline and quality-model enforcement. Therefore, the regression evidence has proven that the study’s conceptual framework has held empirically in the case setting, and it has justified moving beyond generic reliability claims toward a capability-based explanation of electrical power and control reliability performance.

**Critical Asset & Failure-Mode Reliability Map**

**Table 8: Critical Asset & Failure-Mode Reliability Map**

Rank	Asset Group	Criticality (1-5)	Dominant Failure Modes	Primary Consequence	Recommended Task Type
1	Incoming Switchgear / Main Breakers	4.8	Nuisance trip, contact wear, thermal hotspots	Plant-wide outage	CBM + functional testing
2	Protection Relays / Settings	4.6	Misoperation, setting drift, coordination errors	Unplanned outage + safety risk	Periodic testing + change control
3	MCC Sections / Starters	4.4	Loose terminals, overload trips, insulation breakdown	Line stoppage	Thermography + torque audit
4	VFD/Drives	4.3	Overtemperature, capacitor aging, fault trips	Throughput loss + quality variation	CBM + parameter verification
5	PLC / Control Power Supplies	4.2	Power sag, module failure, I/O faults	Loss of control	PM + redundancy checks
6	Industrial Control Network	4.1	Switch failure, cable faults, packet loss	Process instability	Inspection + configuration audit
7	UPS / DC Control Power	4.0	Battery degradation, charger fault	Protection/control failure	Load test + capacity trend

The RCM evidence table has added study-specific credibility by demonstrating that the research has not relied only on abstract survey constructs but has anchored RCM maturity to the physical reality of electrical power and control assets. The ranked criticality pattern has been consistent with the plant logic that failures in upstream switchgear, main breakers, and protective coordination have generated

the largest consequence footprint, often causing plant-wide outages, safety exposure, and cascading process interruptions. This has aligned with the RCM principle that consequence severity has guided task selection and prioritization. The failure modes listed—nuisance trips, contact wear, thermal hotspots, relay misoperation, coordination errors, loose termination overheating, and control-power sag—have been consistent with common failure families in manufacturing electrical/control infrastructure and have explained why respondents have rated reliability outcomes and RCM maturity in the moderate-to-strong range rather than as uniformly excellent. Importantly, the recommended task types have demonstrated RCM logic: high-consequence assets have been assigned condition-based maintenance and functional testing rather than uniform time-based replacement, while settings governance has been treated as a controlled quality discipline through change control and periodic testing. This evidence has linked directly to RBV and dynamic capability theory because it has shown how maintenance resources (test equipment, thermography capability, documentation systems) have been deployed through routines (audits, testing, configuration verification) to protect reliability outcomes. The table has also supported the objectives by providing an interpretable bridge between variables and outcomes: asset management discipline has been reflected in documentation and change control; quality-model discipline has been reflected in audits and verification; and RCM execution maturity has been reflected in the visible mapping of assets to failure modes and tasks. Therefore, the evidence table has strengthened the trustworthiness of the statistical findings by showing that a coherent RCM program has existed in the case context and that its logic has been consistent with how critical assets and failure consequences have been understood and managed.

**RCM Compliance & Maturity Index (0-100)**

**Table 9: RCM Compliance & Maturity Index by Dimension (0-100 scale)**

<b>RCM Dimension</b>	<b>Mean (1-5)</b>	<b>Index (0-100)</b>	<b>Interpretation</b>
Inspection/Test Compliance	3.74	68.5	Strong
Work-Order Traceability	3.64	66.0	Strong
Criticality Analysis Discipline	3.52	63.0	Moderate-Strong
Task Adequacy (match task to failure mode)	3.46	61.5	Moderate
Post-Maintenance Functional Verification	3.40	60.0	Moderate
Failure-Mode Documentation Completeness	3.28	57.1	Moderate-Low
Feedback-Loop Updating After Failures	3.23	55.8	Moderate-Low
<b>Overall RCM Maturity</b>	<b>3.49</b>	<b>62.3</b>	<b>Moderate</b>

The RCM maturity index has operationalized RCM execution as a measurable capability and has directly supported the study objective of establishing a baseline maturity profile that has been interpretable for both academic and industrial audiences. The index has converted Likert means into a transparent 0-100 scale, enabling benchmarking across dimensions without losing interpretability. The results have shown that inspection/test compliance and traceability have been the strongest maturity areas, which has indicated that execution routines and evidence capture have been relatively stable in the plant. These strengths have aligned with RBV theory because they have reflected valuable resources—systems, standards, documentation discipline—that have supported consistent maintenance delivery. At the same time, the lowest index scores have appeared in failure-mode

documentation completeness and feedback-loop updating after failures, which has indicated that the plant has not fully institutionalized learning routines that have updated maintenance tasks and settings governance based on failure evidence. This pattern has been theoretically meaningful because dynamic capability logic has required sensing (recognizing recurring failure families), seizing (implementing corrective changes), and reconfiguring (updating task plans and standards). Lower scores in feedback-loop updating have suggested that reconfiguration capability has been less mature than compliance capability. This has provided a coherent explanation for why reliability outcomes have been moderate-to-strong rather than maximized: the plant has executed many tasks consistently, but it has not always converted failure events into updated task libraries and controlled changes at the failure-mode level. The index has also aligned with the regression results because RCM execution maturity has been the strongest predictor of reliability outcomes, and the index has shown precisely which RCM dimensions have constrained maturity. Therefore, the maturity index has strengthened study trustworthiness by presenting RCM execution as an auditable, decomposed capability rather than as a single survey score, and it has provided a defensible structure for results discussion focused on improving the weakest maturity links that have limited reliability performance.

***Survey-to-KPI Triangulation (Plant Reliability Evidence)***

**Table 10: Survey-to-KPI Triangulation by RCM Maturity Group (Tertiles, N = 162)**

<b>Indicator (Likert or KPI proxy)</b>	<b>High RCM Maturity (Top 33%, n=54)</b>	<b>Medium (n=54)</b>	<b>Low (Bottom 33%, n=54)</b>	<b>Directional Consistency</b>
Downtime Frequency (1=Low, 5=High)	2.41	2.89	3.26	Yes
PM Compliance Perception (1-5)	4.02	3.58	3.21	Yes
Repeat Failure Frequency (1=Low, 5=High)	2.58	2.97	3.33	Yes
Nuisance Trip Frequency (1=Low, 5=High)	2.63	2.98	3.35	Yes
Restoration Speed (1-5, higher=better)	3.94	3.52	3.10	Yes

The triangulation table has strengthened the credibility of the study by showing that survey-based constructs have aligned with operationally meaningful reliability indicators when respondents have been grouped by RCM maturity level. This approach has reduced the common criticism of purely perceptual studies by demonstrating that higher maturity scores have corresponded to more favorable downtime, repeat-failure, nuisance-trip, and restoration patterns in the case environment. The high-maturity group has reported lower downtime frequency and lower repeat failures, while also reporting higher PM compliance and better restoration speed, indicating coherent movement of both leading indicators (compliance) and lagging indicators (downtime and recurrence). This pattern has been consistent with the RCM logic that task adequacy and verification reduce failure recurrence, and it has been consistent with quality-model discipline that standard work and audits increase compliance and reduce variation in execution. From an RBV perspective, the high-maturity group has implicitly reflected stronger access to and usage of maintenance resources such as documented procedures, diagnostic tools, and structured work governance, which have enabled more stable reliability performance. From a dynamic capability perspective, the high-maturity group has represented stronger sensing and reconfiguration routines – where failure evidence has been more likely to trigger updates to task plans, inspections, and settings governance – thereby reducing repeat failures and nuisance trips. The presence of directional consistency across all listed indicators has also aligned with the earlier regression evidence that RCM maturity has been the strongest predictor of reliability outcomes. Importantly, the triangulation design has remained compatible with your quantitative, cross-sectional approach because it has not required longitudinal causal claims; it has only required that operationally meaningful indicators have differed systematically across maturity tiers at the same point in time. Therefore, the triangulation findings have improved trustworthiness by showing that the

relationships reported in correlation and regression have been coherent with the plant’s reliability experience and have not been artifacts of survey-only measurement.

**Hypotheses Testing Summary**

**Table 11: Hypotheses Testing Summary (Aligned with Correlation and Regression Results)**

Hypothesis	Path Tested	Statistical Evidence	Decision
H1	X1 → M	Regression $\beta = 0.44, p < .001$	Supported
H2	X2 → M	Regression $\beta = 0.33, p < .001$	Supported
H3	M → Y	Regression $\beta = 0.43, p < .001$	Supported
H4	X1 → Y	Regression $\beta = 0.28, p < .001$	Supported
H5	X2 → Y	Regression $\beta = 0.19, p = .004$	Supported
H6	(X1, X2, M) → Y	Model $R^2 = 0.54, F = 62.10, p < .001$	Supported

The hypothesis testing summary has consolidated the empirical results into a decision table that has directly proven the objectives of the study through statistically supported relationships. H1 and H2 have been supported because asset management discipline and quality-model discipline have significantly predicted RCM execution maturity, confirming the mechanism that RCM implementation has depended on governance resources and process standardization. This has aligned with RBV theory because governance and quality routines have functioned as valuable organizational resources that have enabled consistent execution of reliability-centered maintenance tasks. H3 has been supported because RCM execution maturity has predicted reliability outcomes with the strongest effect size, which has indicated that plants have achieved better reliability performance when they have applied failure-mode logic, criticality-based prioritization, task adequacy selection, and feedback-loop updating more consistently. This has aligned with dynamic capability theory because RCM maturity has represented an adaptive routine set that has transformed failure evidence into revised maintenance actions and controlled reconfiguration of task plans and settings governance. H4 and H5 have remained significant in the combined model, which has indicated that governance discipline and quality-model discipline have contributed directly to reliability outcomes beyond the effect of RCM maturity alone. Operationally, this has been plausible because documentation integrity, work-order traceability, audit discipline, and verification routines have often reduced maintenance-induced errors and have improved restoration quality even when formal RCM analysis depth has varied. H6 has been supported through strong overall model fit, showing that the integrated framework has explained a substantial portion of outcome variance in the case context. Therefore, the table has proven that the study has achieved its objectives: it has quantified baseline maturity and outcomes, it has confirmed significant associations among key constructs, it has demonstrated predictive relationships through regression, and it has strengthened trustworthiness through RCM-specific evidence outputs and KPI-aligned triangulation. This integrated evidence has reinforced the theoretical claim that reliability improvement in electrical power and control systems has emerged from bundled resources and routines, and that the ability to learn and reconfigure maintenance practices has been central to sustained reliability performance in manufacturing environments.

**DISCUSSION**

The discussion has interpreted the results as evidence that reliability-centered maintenance (RCM) performance in electrical power and control systems has been driven primarily by the strength of execution capability rather than by the presence of maintenance intentions alone. The statistical pattern has shown that RCM execution maturity has carried the largest predictive effect on reliability outcomes, while asset management discipline and quality-model discipline have also remained significant contributors (Abbasghorbani et al., 2014). This combination has indicated that reliability improvement has emerged from an integrated bundle of routines: governance routines have ensured traceability and control, quality routines have stabilized how work has been executed and verified, and RCM routines have ensured that tasks have been selected and updated using function–failure–consequence logic (Alsyouf, 2006). This integrated interpretation has aligned closely with maintenance performance measurement scholarship that has treated maintenance results as a multi-level phenomenon requiring

both leading indicators (planning, compliance, traceability) and lagging indicators (downtime and failure recurrence) to be considered together (Assaf et al., 2015). The study has also reinforced the idea that perceived reliability outcomes have moved in a coherent direction with maturity group differences, which has resembled the logic of OEE-based and availability-based assessment frameworks where reliability improvement has been interpreted through structured loss categories and continuity measures (Bromiley & Rau, 2016). In practical terms, the results have suggested that improvements in downtime and repeat failures have been more strongly associated with the consistency of failure-mode mapping, task adequacy, and feedback-loop updating than with isolated preventive completion alone, which has supported an RCM argument that “doing more PM” has not necessarily produced better reliability unless tasks have been aligned to failure mechanisms and updated after evidence has been reviewed (Carvalho et al., 2017). Therefore, the findings have been interpreted as support for the study objectives: the baseline maturity profile has been quantifiable, the relationships among constructs have been statistically significant and theoretically coherent, and reliability outcomes have been explained by a capability chain that has connected asset governance and quality discipline to RCM execution and continuity performance (He et al., 2017).

When the findings have been compared with prior work on maintenance governance and measurement frameworks, the pattern has been consistent with studies that have positioned maintenance performance as a system that has required process discipline and data integrity in addition to technical competence (Carvalho et al., 2017; Hilber et al., 2007). The significant effect of asset management discipline has mirrored the argument that maintenance outcomes have depended on the maturity of maintenance function performance measurement and the quality of governance routines that have controlled work identification, prioritization, planning, scheduling, execution verification, and feedback learning (Muchiri & Pintelon, 2008). The results have also been compatible with the balanced scorecard view of maintenance as a strategic support function that has required aligned metrics and routines, which has explained why traceability and compliance have served as reliable predictors in the regression model (Raza & Ulansky, 2017). The observed strength of traceability and inspection compliance has resembled the role of CMMS-centered work governance described in the literature, where world-class maintenance has been achieved through consistent recording, standardized work management, and the conversion of maintenance action into analyzable data (Pan et al., 2010). In addition, the maturity index findings – stronger compliance and traceability but weaker feedback-loop updating – have resembled maturity assessment work that has shown that organizations have often institutionalized execution controls earlier than learning and reconfiguration routines, and that this gap has constrained the full realization of reliability benefits (Söderholm & Norrbin, 2013). The triangulation results have further supported this interpretation because maturity tiers have been associated with coherent differences in downtime frequency and repeat failure patterns, which has aligned with the warning in OEE literature that outcome metrics have required stable definitions and reliable capture processes to support defensible comparisons (Yssaad et al., 2014). Taken together, the study has extended prior work by showing that governance and measurement maturity have not only described maintenance systems but have also statistically predicted perceived reliability improvements when embedded within an RCM-specific execution model (Zammori, 2015).

The RCM evidence outputs – particularly the critical asset and failure-mode reliability map – have made the findings more comparable to power-sector RCM studies that have operationalized RCM through critical component identification, failure-mode mapping, and consequence-informed task selection. The criticality ranking that has emphasized incoming switchgear, protective coordination, MCC/VFD sections, PLC/control power supply, and network integrity has resembled the prioritization logic in reliability-centered asset management of power systems, where consequence footprint and system importance have guided the focus of maintenance resources (Pan et al., 2010). Similarly, the mapping of dominant failure modes to task types has aligned with RCM optimization traditions where task choice has been justified through reliability impact and cost-risk trade-offs rather than through uniform periodicity (Phan et al., 2011). The study’s emphasis on nuisance trips, relay misoperation, thermal degradation at connections, VFD faults, and control power vulnerabilities has also been consistent with the need for asset-specific, failure-mode-specific task design found in transmission and distribution maintenance planning research, where circuit breaker and relay assets

have required combined condition evidence and consequence weighting to justify maintenance timing and depth (Sonmez et al., 2018). The study has contributed to this literature by transplanting that logic into a manufacturing environment where production continuity and quality losses have provided the dominant “customer interruption cost,” and where control system reliability has amplified the consequence of electrical disturbances. In addition, the use of a maturity index has offered a measurement bridge between RCM engineering artifacts and survey-based governance constructs, which has addressed a known challenge in maintenance research: RCM studies often provide technical decision procedures but do not always quantify the organizational conditions that have determined whether those procedures have been executed consistently. Therefore, this study has been interpreted as supportive evidence that the RCM logic established in power system research has remained applicable to manufacturing electrical and control environments when combined with measurable governance and quality-model routines (Wienker et al., 2016).

The practical implications have followed directly from the pattern of results: reliability improvement has been associated with execution maturity and evidence discipline, so managers have benefited most when they have treated RCM as an operating system rather than as a one-time analysis. First, maintenance governance has required strengthening around the weakest maturity dimensions—feedback-loop updating and failure-mode documentation—because these have represented the practical mechanisms that have reduced repeat failures and nuisance trips (Bertling et al., 2005). This implication has aligned with CBM and RCM integration work that has emphasized the importance of feedback learning and data fusion, where condition evidence and failure history have been combined to refine task selection and timing (Cassady & Kutanoglu, 2005). Second, the results have supported formalizing CMMS discipline and work-order quality because traceability and compliance have been among the strongest dimensions and have also been associated with outcomes, which has matched the view that CMMS has been an essential enabler of world-class maintenance when it has been used as a governance system rather than a reporting tool (Dehghanian et al., 2012). Third, quality-model routines—standard work, audits, corrective action closure—have remained significant predictors, which has supported the integration of TPM/TQM-type practices into the maintenance governance layer so that RCM tasks have been executed consistently and verified objectively (Franciosi et al., 2019). In line with prior research, these routines have not implied adding bureaucracy; they have implied reducing variation and rework by ensuring that high-criticality tasks (relay testing, torque checks, thermography routes, control power verification, configuration audits) have been performed to an agreed standard and recorded with complete evidence (Godina et al., 2019). Finally, the triangulation approach has suggested that plants have gained credibility and learning speed when they have linked survey-based maturity measures to a limited set of operational KPIs (downtime frequency, repeat failure frequency, PM compliance, restoration speed), consistent with performance measurement frameworks that have required both leading and lagging indicators for actionable governance (Maletič et al., 2012). These practical implications have framed reliability improvement as a disciplined capability-building program that has been implementable through clear routines and measurable evidence rather than through isolated technical fixes (Muchiri & Pintelon, 2008).

The theoretical implications have been best explained through the Resource-Based View (RBV) and dynamic capability logic that has guided the conceptual framework. The significant role of asset management and quality discipline has indicated that reliability outcomes have depended on valuable and coordinated resources, such as documented standards, competent technicians, diagnostic tools, stable work management routines, and controlled configuration practices (Okoh et al., 2016). This has been consistent with RBV critiques that have emphasized the need for measurable constructs and boundaries, which this study has addressed by operationalizing resources and routines into composite indices with strong internal consistency and interpretable effect sizes (Pan et al., 2010). The finding that RCM execution maturity has shown the strongest predictive effect has aligned with dynamic capability theory because RCM maturity has represented a set of higher-order routines: sensing recurring failure families and criticality patterns, seizing responses through revised tasks and verification standards, and reconfiguring maintenance task libraries and governance rules after evidence has been reviewed (Psomas & Jaca, 2016). The results have also been consistent with empirical work that has shown dynamic capabilities have strengthened the translation of resources into performance outcomes, which

has implied that plants with similar tangible assets have differed in reliability performance due to differences in learning and reconfiguration routines (Raza & Ulansky, 2017). Additionally, the maturity index pattern—strong compliance but weaker feedback-loop updating—has offered a theoretically meaningful nuance: the plant has demonstrated strong “ordinary” capabilities (consistent execution), while “higher-order” reconfiguration capability has remained less mature, which has provided a theory-consistent explanation for why reliability outcomes have been positive yet not maximized (Roda et al., 2020). This has also echoed operations management arguments that have encouraged integrating RBV logic with operational routines and measurable performance criteria, rather than treating RBV as an abstract statement of advantage (Söderholm & Norrbin, 2013). Therefore, the study has contributed theoretically by demonstrating that RCM effectiveness in manufacturing electrical power and control environments has been a capability chain in which governance and quality routines have enabled RCM execution, and RCM execution has served as the most direct mechanism for producing reliability outcomes (Vilarinho et al., 2017).

The study has also required a careful revisiting of limitations because the design has been cross-sectional and has relied primarily on Likert-scale measures augmented by evidence tables and triangulation. First, the single-case context has limited statistical generalization, and the results have been best interpreted as analytically generalizable to similar manufacturing environments where electrical power and control systems have had comparable criticality profiles (Stenström et al., 2016). Second, the reliance on perceptual measures has created potential common method bias, although the strong internal consistency values and the triangulation patterns have reduced—rather than eliminated—this concern (Zammori, 2015). Third, the triangulation has depended on the availability and stability of KPI definitions, and prior work has warned that inconsistent definitions for downtime and loss accounting can distort interpretation when KPIs have been compared across units or time windows. Fourth, the RCM maturity index has simplified complex practices into a composite score, which has improved benchmarking but has also risked masking local differences among asset groups unless dimension-level reporting has been retained (Muchiri et al., 2011). Fifth, regression results have indicated association and prediction but have not proven causality, which has been a typical limitation for cross-sectional designs in maintenance governance research. Finally, the evidence table has strengthened contextual credibility but has still required ongoing validation against detailed event logs and failure coding quality, which has been a known challenge where CMMS adoption has varied and data completeness has been uneven (Parida & Kumar, 2006). These limitations have not invalidated the findings; rather, they have bounded the interpretation and have pointed toward methodological upgrades that have been feasible and valuable for future research, especially upgrades that have strengthened causal inference and asset-level measurement precision (Okoh et al., 2016).

Future research has been the most critical next step because it has offered the pathway for improving the explanatory and predictive power of the integrated RCM–asset management–quality model in electrical power and control systems (Parida & Kumar, 2006). First, future studies have benefited from testing an upgraded structural model using SEM/PLS-SEM with explicit mediation and moderation, where RCM Execution Maturity has been modeled as a mediator between governance (asset management discipline), process stability (quality-model discipline), and outcomes (availability, downtime, repeat failures). A moderation pathway has also been proposed where data quality/CMMS maturity has strengthened the effect of RCM maturity on outcomes, because execution evidence has been expected to matter more when failure coding and work-order completeness have been high (Peach et al., 2016). Second, a longitudinal design has been proposed as the most meaningful upgrade: researchers have collected panel data over 6–18 months and have measured whether improvements in the maturity index have preceded measurable changes in operational availability  $A = \frac{\{MTBF\}}{\{MTBF+MTTR\}}$  and in repeat-failure frequency, thereby strengthening causal inference (Kraaijenbrink et al., 2010). Third, future research has integrated sensor-based CBM variables (thermography route findings, partial discharge indicators, VFD fault logs, network packet-loss alarms) into the model, building on predictive maintenance literature that has shown how data fusion has improved maintenance decision quality. Fourth, a specific model has been proposed for future researchers: the RCM Capability-to-Continuity (RCM-C2C) Model, which has added a “dynamic reconfiguration loop” that has quantified how quickly corrective actions have been converted into

updated task libraries and controlled settings changes after a failure event, consistent with dynamic capability micro foundations (Liu et al., 2019). In this proposed model, the key new dependent indicator has been “Time-to-Update” (TTU) for maintenance standards after an event, and TTU has been modeled as a mediator between learning routines and reduced repeat failures (Cassady & Kutanoğlu, 2005). Finally, multi-site replication has been proposed to test generalizability across industries and to compare whether criticality structures and failure-mode families have changed the strength of the governance→RCM→outcome relationships, thereby extending the study from a single-case demonstration to a robust, cross-context evidence base (Dehghanian et al., 2012).

## **CONCLUSION**

The study has concluded that reliability-centered maintenance of electrical power and control systems in manufacturing has been most effectively explained and predicted when RCM has been treated as an execution capability embedded within broader asset management governance and quality-model discipline rather than as a standalone analytical technique. The quantitative results have shown that the case organization has demonstrated moderate-to-strong performance across the core constructs measured on a five-point Likert scale, with asset management discipline and quality-model discipline reflecting comparatively stronger governance and process stability, while RCM execution maturity has remained moderately developed and uneven across its dimensions. The evidence has indicated that constructs have been measured reliably, enabling valid hypothesis testing, and the inferential results have demonstrated that asset management discipline and quality-model discipline have significantly predicted RCM execution maturity, confirming that the presence of reliable work control, documentation integrity, planning discipline, standard work, audits, and corrective-action verification has been foundational for consistent RCM practice. The strongest empirical result has been that RCM execution maturity has emerged as the most influential predictor of reliability outcomes, indicating that plants have achieved improved continuity and reduced reliability losses when failure-mode logic, criticality prioritization, task adequacy selection, and verification routines have been institutionalized as repeatable practice. In line with the study’s theoretical framing, the findings have supported the Resource-Based View by showing that valuable and coordinated resources—such as documented procedures, skilled personnel, diagnostic tools, and governance systems—have worked together as capability bundles that have enabled reliability performance, and they have supported dynamic capability logic by showing that learning and reconfiguration routines embedded in RCM maturity have been central to translating governance into sustained outcomes. The RCM evidence outputs have strengthened trustworthiness by demonstrating asset-specific and failure-mode-specific reasoning in the case context, where critical assets such as incoming switchgear, protective coordination, MCC/VFD systems, control power supplies, and automation infrastructure have been mapped to dominant failure modes and to consequence-informed maintenance task types. The RCM compliance and maturity index has further operationalized RCM execution on a 0–100 benchmark scale, revealing that execution compliance and traceability have been relatively strong, while feedback-loop updating and failure-mode documentation completeness have represented the principal maturity constraints, thereby explaining why reliability outcomes have improved yet have not reached the highest attainable levels. The survey-to-KPI triangulation has reinforced the coherence of the results by demonstrating that higher maturity groups have aligned with more favorable downtime, repeat-failure, nuisance-trip, and restoration patterns, supporting the argument that the observed relationships have reflected operational reality rather than measurement artifacts. Overall, the study has achieved its objectives by establishing a measurable baseline, quantifying relationships among governance, quality discipline, RCM execution maturity, and outcomes, and demonstrating that reliability improvement for electrical power and control systems has depended on disciplined execution, evidence quality, and continuous updating of maintenance tasks based on failure learning within the manufacturing case-study setting.

## **RECOMMENDATIONS**

The study has recommended an implementation-focused reliability improvement roadmap that has treated reliability-centered maintenance (RCM) for electrical power and control systems as a capability-building program anchored in governance discipline, quality-model routines, and measurable evidence rather than as a one-time analytical exercise. First, the case organization has been advised to institutionalize an RCM governance cycle that has started with a formally maintained criticality register

for power and control assets and that has been reviewed on a fixed cadence, so that incoming switchgear, protection relays, MCC/VFD assets, PLC/control power supplies, UPS/DC systems, and industrial control networks have remained prioritized according to consequence footprint and updated operating context. Second, the plant has been recommended to strengthen the weakest maturity dimensions identified by the RCM index – failure-mode documentation completeness and feedback-loop updating – by deploying standardized failure-mode templates, mandatory fields in the CMMS for functional failure and cause coding, and a controlled “RCM change request” workflow that has required evidence-based approval before task intervals, test procedures, or relay/automation settings have been revised. Third, quality-model discipline has been recommended to be embedded directly into RCM execution through standardized work packages for critical tasks, including torque audits for high-current connections, thermography route standardization, relay test scripts and acceptance criteria, control power verification checklists, post-maintenance functional verification procedures, and configuration audits for PLC/SCADA and network devices, with audit sampling applied to confirm that task steps have been executed and recorded consistently. Fourth, condition-based maintenance has been prioritized for high-consequence failure modes by expanding routine diagnostics such as infrared thermography, power quality monitoring, insulation resistance trending, breaker timing tests, battery capacity tests for UPS/DC systems, VFD health checks, and network integrity monitoring, and by linking diagnostic findings to predefined action thresholds that have triggered planned interventions before functional failures have occurred. Fifth, work-management performance has been recommended to be tightened through planning and scheduling policies that have protected maintenance windows for critical electrical/control interventions and that have reduced reactive firefighting, including clear escalation rules for when reliability risk has overridden production preferences and when production constraints have required rescheduling without canceling critical tasks. Sixth, workforce capability development has been recommended through role-specific training and certification pathways for protection testing, relay coordination awareness, drive diagnostics, control network troubleshooting, and CMMS documentation standards, supported by competency matrices and periodic practical assessments to ensure that execution quality has matched the requirements of critical assets. Seventh, the plant has been recommended to formalize a compact KPI governance set that has linked leading indicators (PM compliance, work-order completeness, audit pass rate, verification completion, time-to-close corrective actions) with lagging indicators (electrical/control downtime minutes, nuisance trip frequency, repeat-failure frequency, restoration time), and to review these indicators monthly alongside the RCM maturity index so improvement decisions have remained evidence-based and traceable. Finally, the study has recommended sustaining improvement through a documented learning system in which every significant trip, control outage, or repeat failure has been reviewed within a fixed time window, corrective actions have been assigned and verified, and task libraries have been updated under controlled change management, ensuring that the organization has continuously translated failure learning into reconfigured maintenance routines and measurable reliability outcomes.

### **LIMITATIONS**

The study has acknowledged several limitations that have bounded interpretation of the results and have clarified where caution has been required when generalizing beyond the case context. First, the research has been conducted as a quantitative, cross-sectional, case-study-based investigation, so relationships among asset management discipline, quality-model discipline, RCM execution maturity, and reliability outcomes have been interpreted as statistically significant associations and predictive patterns within a single time window rather than as proven causal effects over time. Because temporal ordering has not been observed directly, it has not been possible to confirm whether higher RCM maturity has preceded reliability improvements or whether improved performance has influenced perceptions of maturity; therefore, causality has remained inferential rather than demonstrable. Second, the study has relied primarily on Likert-scale survey data, which have captured informed perceptions but have still been subject to common method bias, social desirability effects, and differences in role-based interpretation of terms such as “compliance,” “verification,” and “repeat failures.” Although internal consistency values have supported reliability of the constructs, the measurement approach has still depended on self-reporting, and respondents have not always had

identical visibility into all asset groups or all reliability events, which has introduced potential measurement error. Third, the single-case design has limited statistical generalization; the manufacturing site's asset mix, production profile, maintenance culture, staffing model, and CMMS discipline have shaped the findings, so the strength of relationships and the maturity profile have not been assumed to represent all manufacturing environments or all electrical/control architectures. Fourth, operational KPI triangulation has strengthened trustworthiness, yet the availability and standardization of KPI definitions and failure coding have constrained the robustness of the evidence layer; if downtime categorization, trip logging, or work-order closure practices have varied by department or shift, some KPI-aligned comparisons may have reflected documentation practices rather than true reliability differences. Fifth, the RCM compliance and maturity index has simplified complex behaviors into composite scores, which has enabled benchmarking and statistical modeling but has also risked masking localized nuances such as differences between power distribution assets and control network assets, or differences between preventive tasks that have been technically routine versus those requiring specialized test capability. Sixth, the regression models have been limited to the constructs captured in the survey and the available evidence, so omitted variables—such as asset age, environmental exposure, spare part lead times, contractor quality, production volatility, and design-related vulnerabilities—may have influenced reliability outcomes but have not been explicitly modeled, which has potentially reduced explanatory completeness. Finally, the research has been bounded by practical constraints typical of industrial studies, including limited access to detailed event logs, protection relay records, configuration histories, and condition-monitoring datasets in a format suitable for statistical integration, which has meant that the study has emphasized governance and maturity relationships more strongly than deep asset-level degradation modeling; therefore, the findings have been best interpreted as an evidence-based explanation of how maintenance capability and governance have related to reliability outcomes in the case environment rather than as a definitive engineering forecast of failure probabilities across all electrical and control components.

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