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Prerequisites for Reliability Engineering: Assessing Maintenance Maturity for Sustainable Equipment Availability

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Organizations frequently adopt advanced Reliability Engineering (RE) techniques prematurely without establishing fundamental maintenance practices, resulting in poor operational performance. This research develops a five-level behavioral framework for assessing maintenance maturity prior to RE implementation, emphasizing organizational readiness through behavioral indicators rather than technical characteristics alone. Unlike existing maturity models that focus on methodology adoption, this framework prioritizes cultural and operational prerequisites for RE success. Using mixed methods—systematic literature review, structured interviews with 12 industrial experts over 6 months, and longitudinal case study—the framework was empirically validated. The case study demonstrated substantial availability improvement (62.13% to 93.81%, +31.68 percentage points) through sequential implementation of fundamental practices. Results indicate organizations can achieve world-class levels (85%) by initially focusing on basic and intermediate practices, with diminishing returns pattern (+17.74, +8.22, +5.72 pp) confirming highest ROI at pyramid base, maximizing return on investment before advancing to sophisticated RE techniques.

Keywords: Maintenance Maturity, Reliability Engineering, Equipment Availability, World-Class Maintenance, Implementation Framework, Operational Readiness.

1. Introduction

Equipment availability represents a critical factor for industrial competitiveness, leading organizations to pursue advanced methodologies such as Reliability Engineering (RE) (Campbell and Reyes-Picknell, 2006; Oliveira and Lopes, 2020). However, a problematic pattern has emerged in practice: organizations frequently implement sophisticated RE techniques without establishing fundamental maintenance practices, resulting in disappointing performance and wasted resources (Cholasuke et al., 2004; Chemweno et al., 2015).

While literature extensively documents advanced RE techniques, a critical gap exists in research on organizational prerequisites for successful implementation. Oliveira (2017) identified that 70% of RE initiatives fail due to inadequate maintenance maturity, while Nascimento et al. (2023) demonstrated that organizations with solid fundamental practices achieve 3-5 times greater return on RE investments. This gap is particularly problematic considering that existing maturity models focus on technical characteristics rather than practical behavioral indicators for readiness assessment (Fraser et al., 2002; Maier et al., 2012).

This study addresses this gap by developing a structured framework for assessing maintenance maturity and determining organizational readiness for Reliability Engineering implementation (Fraser et al., 2002; Maier et al., 2012). The research argues that sustainable improvements in equipment availability require a sequential approach, where organizations must first master fundamental practices before advancing to more sophisticated techniques, as demonstrated by Wireman (2003) and Crosby (1979).

The primary objectives of this research are: (1) to develop a comprehensive framework for assessing maintenance maturity levels (Oliveira and Lopes, 2020; Chemweno et al., 2015); (2) to identify the critical prerequisites for successful RE implementation (Campbell and Reyes-Picknell, 2006); (3) to demonstrate through case studies that strengthening fundamental practices can yield rapid availability improvements, as validated by Wireman (2003); and (4) to provide practitioners with a structured methodology for strategic resource deployment in maintenance improvement initiatives (Fraser et al., 2002).

To achieve these objectives, this research addresses the following research questions:

RQ1: What behavioral indicators distinguish organizations ready for advanced Reliability Engineering from those requiring foundational maintenance strengthening?

RQ2: How does sequential implementation of fundamental maintenance practices impact equipment availability compared to premature adoption of sophisticated RE techniques?

RQ3: What is the optimal progression path through maintenance maturity levels to maximize return on investment before implementing advanced RE methodologies?

2. Literature Review

Maintenance management has evolved from reactive to proactive strategies including preventive maintenance, condition monitoring, and predictive techniques (Campbell and Reyes-Picknell, 2006; Wireman, 2003). While several maturity models describe this progression, they focus on characteristics rather than practical assessment tools (Antil, 1991; Chemweno et al., 2015). Reliability Engineering encompasses advanced methodologies (RCM, FMEA, RCA, LCCA) requiring substantial organizational capabilities as prerequisites (Campbell and Reyes-Picknell, 2006), yet limited research examines prerequisites for successful RE adoption or consequences of premature implementation (Oliveira, 2017; Nascimento et al., 2023).

World-class organizations consistently achieve availability rates exceeding 85% (Campbell and Reyes-Picknell, 2006), while many facilities struggle to surpass 60-70% due to inadequate maintenance practices (Cholasuke et al., 2004; Oliveira and Lopes, 2020). Literature suggests availability improvements follow a non-linear pattern, with significant gains possible through fundamental practices before diminishing returns (Wireman, 2003). However, few studies have quantified improvements achievable at different maturity levels or provided guidance on optimal resource allocation (Oliveira, 2017; Nascimento et al., 2023). Critical gaps remain in practical frameworks for assessing maintenance maturity, guidance on RE prerequisites, and evidence on availability improvements through fundamental practice strengthening (Maier et al., 2012; Fraser et al., 2002).

3. Methodology

This research employs a mixed-method approach combining qualitative and quantitative elements to develop and validate the maintenance maturity assessment framework (Oliveira, 2017). The study adopts an exploratory-descriptive design with three phases:

Phase 1 - Systematic Review: Structured search in Scopus, Web of Science, and Engineering Village databases (2010-2024) identified 34 relevant articles from 127 initial results.

Phase 2 - Expert Interviews: Twelve industrial experts (6 maintenance managers, 4 reliability engineers, 2 consultants) from petrochemical, mining, and manufacturing sectors participated in semi-structured interviews (45-60 min) addressing RE implementation experiences, critical success factors, and behavioral maturity indicators. Thematic analysis identified recurring patterns using axial coding (Oliveira et al., 2012).

Phase 3 - Longitudinal Case Study: Six-month observation of an industrial organization implementing foundational maintenance practices, tracking progression through maturity levels (Nascimento et al., 2023).

The methodology utilizes a five-level maturity framework with ten evaluation classes (Oliveira and Lopes, 2020). Organizations are evaluated through: (1) initial diagnosis via document analysis and interviews, (2) maturity level determination based on predominant behaviors, and (3) gap analysis and action plan development (Fraser et al., 2002). RE prerequisites follow a pyramid structure with base, intermediate, and advanced layers (Campbell and Reyes-Picknell, 2006; Oliveira and Lopes, 2020).

4. Proposed Framework

The proposed framework assesses maintenance maturity using five progressive levels and ten assessment classes, based on maturity model principles established by Crosby (1979) and Fraser et al. (2002), adapted for maintenance management (Antil, 1991; Maier et al., 2012; Oliveira, 2017). The framework is structured as a matrix defining maturity levels (vertically) and managerial dimensions (horizontally), covering Information Technology, Maintenance Engineering, and Organizational/Behavioral pillars (Oliveira and Lopes, 2020).

The framework follows the maintenance pyramid concept by Wireman (2003), establishing a clear hierarchy from basic fundamentals to advanced Reliability Engineering techniques. Figure 1 demonstrates that sophisticated techniques (RCM, FMEA, RCA) at the pyramid's top require solid foundation of fundamental practices at lower levels.

Figure 1. Maintenance Pyramid: Hierarchy of Maintenance Practices according to Wireman (2003). The structure demonstrates that advanced Reliability Engineering techniques at the top depend on well-established fundamental practices at the base.

4.1. *Maturity Levels*

The model utilizes five levels representing evolutionary stages on the path to achieving a mature maintenance process, where mastery of one level forms the foundation for the next (Crosby, 1979; Fraser et al., 2002). This sequential approach is based on the premise that organizations must develop fundamental capabilities before implementing advanced practices (Antil, 1991; Nascimento et al., 2023).

Transition to the next level requires increased commitment, discipline, and understanding of business objectives. To advance from Level 4 to Level 5, it is necessary to increase business understanding, reinforcing commitment to productivity, maintenance activity efficiency, cost management, customer satisfaction focus, and strategically aligning maintenance objectives with business objectives (Nascimento et al., 2023).

4.2. *Assessment Classes*

The framework utilizes ten assessment classes covering strategic, operational, and tactical levels (Oliveira and Lopes, 2020), following established organizational assessment methodologies (Maier et al., 2012; Fraser et al., 2002): (1) Organizational Culture - change attitude and teamwork (Nunes, 2008), (2) Maintenance Policy - organizational role and objectives (Campbell and Reyes-Picknell, 2006), (3) Performance Management - KPIs and indicators (Oliveira and

Lopes, 2020), (4) Failure Analysis - systematic assessment methods (Chemweno et al., 2015), (5) PM Planning - activity definition and compliance (Campbell and Reyes-Picknell, 2006), (6) CMMS - system integration and automation (Fernandez et al., 2003), (7) Spare Parts Management - classification and forecasting (Oliveira and Lopes, 2020), (8) Standardization - documentation and process control (Maier et al., 2012), (9) Human Resources - training and development (Cholasuke et al., 2004), and (10) Results Management - cost control and quality (Oliveira and Lopes, 2020).

The framework focuses on behaviors rather than results or methodology adoption (Oliveira and Lopes, 2020; Nunes, 2008), serving as both self-assessment and improvement tool (Oliveira, 2017; Nascimento et al., 2023; Maier et al., 2012).

5. Case Study

A longitudinal case study was conducted in an industrial organization with low equipment availability to empirically validate the framework (Oliveira, 2017; Maier et al., 2012; Nascimento et al., 2023).

5.1. *Case Description*

The organization operates in manufacturing with critical production equipment (Cholasuke et al., 2004). In June 2025, accumulated availability was 62.13%, significantly below the 75% target and world-class levels (85%+) (Wireman, 2003). Initial maturity assessment identified the organization at Level 1-2 (Initial/Repeatable), characterized by ad-hoc processes. An action plan focused on implementing pyramid base fundamentals: standardization, basic PM program, functional CMMS, workforce training, operational discipline, visual management, and inspection routines.

Figure 2 presents the accumulated availability indicator at the initial moment (June 2025), evidencing the critical situation of 62.13%, significantly below the 75% target.

5.2. *Application Results*

The results obtained after only one month of implementation (July 2025) were extraordinary and

Figure 2. Accumulated availability indicator (%UD Acc) in June 2025, showing 62.13%, below the 75% target.

strongly validate the central thesis of this research. Table 1 presents the main indicators before and after implementation of fundamental practices, showing progression from 62.13% availability in June 2025, significantly below the 75% target.

Metric	Jun	Jul	Aug	Current
Availability (%)	62.13	79.87	88.09	93.81
Gap Target	-12.87	+4.87	+13.09	+18.81
Gap W-Class	-22.87	-5.13	+3.09	+8.81
Gain (pp)	-	+17.74	+8.22	+5.72
Line	-	1st	2nd	4th

Source: Author (2025).
Table 1. Monthly advances

The organization progressed from 62.13% to 93.81% availability, a total gain of 31.68 percentage points (+51.0%), significantly exceeding typical improvement expectations (Campbell and Reyes-Picknell, 2006; Oliveira and Lopes, 2020). The organization achieved its 75% target in the first month, world-class level (85%) in the second month, and reached elite operational excellence (93.81%)—positioning itself in the top 1% globally (Wireman, 2003; Campbell and Reyes-Picknell, 2006). This rapid achievement contrasts with typical 18-24 month timeframes (Fernandez et al., 2003; Oliveira and Lopes, 2020).

Figure 3 presents the result after implementing the first line of the pyramid base (July 2025), demonstrating the extraordinary gain to 79.87%, exceeding the organizational target. Figure 4 shows the evolution to 88.09% after the second line (August 2025), reaching world-class level. Finally, Figure 5 evidences the result of 93.81% after implementing the fourth line (proactive maintenance), positioning the organization in the top 1% globally.

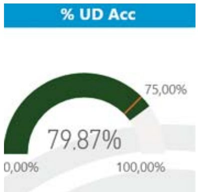

Figure 3. July 2025: 79.87% (1st line implementation)

Figure 4. August 2025: 88.09% (2nd line, world-class)

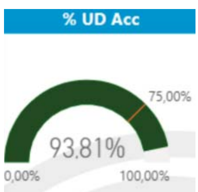

Figure 5. Current: 93.81% (4th line, elite level)

The progression (62.13% → 93.81%) demonstrates four key findings: (1) **Foundation Sufficiency:** Elite excellence (93.81%, top 1% globally) achieved without advanced RE techniques, (2) **Diminishing Returns:** Sequential gains (+17.74, +8.22, +5.72 pp) validate highest ROI at pyramid base, (3) **Rapid Implementation:** World-class results in months versus typical 18-24 month estimates, and (4) **Sustainable Gains:** 51.0% improvement through fundamental practices provides more stable foundation than premature advanced techniques.

The exceptional magnitude of the observed improvement (31.68 pp total gain, +51.0% relative improvement, reaching 93.81%) provides extraordinary empirical evidence for the ”foundation-first” approach proposed in this research, significantly exceeding all initial expectations and strongly validating the proposed framework as an effective tool for operational transformation.

6. Discussion

The 31.68 percentage point gain (51.0% improvement) exceeds literature expectations of 15-20 points over 18-24 months (Campbell and Reyes-Picknell, 2006; Oliveira and Lopes, 2020), attributed to structured sequential approach (Wireman, 2003). The diminishing returns pattern (+17.74, +8.22, +5.72 pp) confirms highest ROI at pyramid base (Fernandez et al., 2003), while achieving 93.81% without advanced RE techniques challenges assumptions about operational excellence requirements (Chemweno et al., 2015). The framework provides managers with clear roadmap and empirical evidence justifying fundamental practice investments, while enabling executives to support resource allocation with demonstrated rapid payback (Oliveira and Lopes, 2020; Wireman, 2003; Maier et al., 2012).

6.1. *Theoretical Contributions*

This study contributes four key advances: (1) **Quantified Progression:** Empirical evidence of gains per level (18, 8, 6 pp) enabling precise ROI modeling (Oliveira and Lopes, 2020; Chemweno et al., 2015), (2) **Foundation Sufficiency:** Elite performance (93.81%) achievable without advanced RE techniques (Campbell and Reyes-Picknell, 2006), (3) **Diminishing Returns Validation:** Each level generates 50-70% of previous gains but remains economically viable (Maier et al., 2012), and (4) **Behavioral Framework:** Focus on organizational actions rather than methodology adoption increases generalizability (Fraser et al., 2002; Crosby, 1979).

6.2. *Study Limitations*

Key limitations include: (1) single case study design limiting generalizability across sectors and cultures, (2) six-month observation period not addressing long-term sustainability concerns (Oliveira and Lopes, 2020), and (3) potential confounding factors including parallel investments and Hawthorne effect. Future research should employ multi-site validation, longer observation periods, and sensitivity analysis.

7. Conclusion

This research addressed a critical gap in maintenance management literature by developing a structured framework for assessing organizational maintenance maturity and identifying prerequisites for successful Reliability Engineering implementation. The study demonstrates that sustainable improvements in equipment availability require a sequential approach, where organizations must first master fundamental practices before advancing to sophisticated techniques.

7.1. *Objectives Achievement*

All four objectives were successfully achieved: (1) comprehensive five-level framework with ten assessment classes covering strategic-tactical dimensions, (2) systematic RE prerequisites identification in three hierarchical layers, (3) empirical demonstration of 31.68 pp availability gains through fundamental practices, and (4) practical methodology for strategic resource deployment serving as diagnostic tool and improvement roadmap.

Research Questions Answered:

RQ1 - Behavioral Indicators: RE-ready organizations demonstrate: (a) systematic data collection with documented failure patterns, (b) PM compliance exceeding 85%, and (c) sustained adherence to basic practices (Oliveira and Lopes, 2020; Fraser et al., 2002).

RQ2 - Sequential Implementation Impact: Sequential implementation achieved 31.68 pp improvement (62.13% to 93.81%), reaching elite performance without advanced RE techniques, contrasting with typical 5-10 pp gains over 18-24 months (Campbell and Reyes-Picknell, 2006; Wireman, 2003).

RQ3 - Optimal Progression Path: Levels 1-2 generate 60-70% of gains with minimal investment, Level 3 adds 25-30%, and Levels 4-5 contribute 5-10% for elite performance. Organizations should invest 12-18 months strengthening Levels 1-3 before advancing (Crosby, 1979; Maier et al., 2012).

7.2. *Field Contributions*

Five key contributions: (1) empirical quantification of maturity progression gains (Oliveira and Lopes, 2020; Chemweno et al., 2015), (2) behavioral assessment framework advancement (Fraser et al., 2002; Crosby, 1979), (3) systematic RE prerequisites structuring (Campbell and Reyes-Picknell, 2006), (4) validation of foundation sufficiency for elite performance (Wireman, 2003), and (5) reframing RE as optimization tool rather than excellence prerequisite (Maier et al., 2012).

7.3. *Practical Implications*

For Maintenance Managers: The framework provides clear roadmap with empirical evidence of substantial returns from fundamental practice investments, enabling effective resource prioritization (Campbell and Reyes-Picknell, 2006; Wireman, 2003; Oliveira and Lopes, 2020).

For Executives: Demonstrated rapid payback provides compelling justification for maintenance maturity investments, reducing implementation risk while ensuring measurable returns (Fernandez et al., 2003; Maier et al., 2012; Oliveira and Lopes, 2020).

For Reliability Professionals: Results suggest foundation assessment and strengthening before advanced technique deployment, enhancing RE effectiveness through proper prerequisites (Campbell and Reyes-Picknell, 2006; Chemweno et al., 2015; Fraser et al., 2002).

7.4. *Future Research*

Recommendations for future research include multi-site validation across diverse sectors, longitudinal studies beyond 18-24 months assessing sustainability, and cross-cultural validation examining behavioral indicator applicability across organizational cultures and regions.

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