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Multicriteria conceptual framework for maturity assessment of testing and calibration laboratories based on the ISO/IEC 17025: 2017 standard

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ABSTRACT
This study presents a novel multicriteria framework for assessing the maturity of testing and calibration laboratories in accordance with ISO/IEC 17025:2017 requirements. The research methodology comprised a systematic literature review spanning 2010–2023, followed by the development of an analytical framework integrating the Analytical Hierarchy Process (AHP) for weighting standard requirements and the Importance–Performance Analysis (IPA) for maturity assessment. The framework's empirical validation was conducted at the Brazilian Army Evaluation Center (CAEx) to evaluate laboratory compliance capabilities vis-à-vis the ISO/IEC 17025:2017 requirements regarding competence, impartiality, and operational consistency. The validation process involved senior laboratory managers and resulted in quantitative maturity assessments across standard requirements, enabling the identification of critical improvement areas and the development of targeted action plans for accreditation preparation. The primary contribution of this study is a comprehensive assessment framework that provides testing and calibration laboratories with robust decision-making support for accreditation processes. The empirical validation demonstrated the effectiveness of the framework in identifying critical compliance gaps and prioritizing improvement initiatives. This methodological advancement is a significant contribution to the field of laboratory quality management.

Section: RESEARCH PAPER

Keywords: testing and calibration laboratories; ISO/IEC 17025:2017 standard; accreditation; maturity model; multicriteria decision-making methods

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1. INTRODUCTION

Technological services constitute a strategic segment of national innovation systems, encompassing metrology, testing, calibration, inspection, certification, and accreditation services [1].

Organizations requiring these services can either conduct them internally or engage external providers, particularly independent laboratories. The increasing complexity of technological development and regulatory requirements has elevated the importance of laboratory competence and reliability in supporting innovation and quality assurance processes.

The ISO/IEC 17025:2017 standard [2] defines a laboratory as an entity that performs testing, calibration, or sampling activities followed by subsequent testing or calibration. This international standard serves as the primary reference for laboratories providing testing and calibration services globally, with operational effectiveness depending on both technical competence and consistent management practices. The standard's requirements address critical aspects of laboratory operations, including organizational structure, resource management, process control, and quality assurance.

Despite extensive literature addressing laboratory quality management systems, significant research gaps persist regarding comprehensive assessment models based on the ISO/IEC 17025:2017 requirements. These gaps are particularly evident in the context of maturity evaluation frameworks that could guide laboratories toward accreditation readiness. This study addresses these gaps by developing a multicriteria conceptual framework for evaluating laboratory maturity levels, specifically addressing the following research questions:

i. How can the maturity level of testing and calibration laboratories seeking accreditation be assessed against the ISO/IEC 17025:2017 requirements?

ii. What essential elements should comprise a conceptual framework for evaluating laboratory maturity levels toward accreditation?
iii. Which decision-making methodologies should be integrated to effectively assess laboratory maturity levels?
iv. What are the critical factors affecting laboratory competence, impartiality, and operational consistency in pursuit of accreditation?

This research presents an innovative multicriteria framework integrating established decision-making methods to assess laboratory maturity levels. The framework incorporates both an analytical hierarchy process and importance–performance analysis methodologies, providing a comprehensive approach to maturity assessment and improvement planning. The selection of the Analytical Network Process (ANP) over the Analytical Hierarchy Process (AHP) was motivated by ANP's superior capability to handle complex interdependencies among assessment factors. Unlike AHP's strictly hierarchical structure, ANP allows for feedback relationships and interactions between elements at different levels, which better reflects the interconnected nature of the ISO/IEC 17025:2017 requirements, where improvements in one area often influence performance in others. The framework's empirical validation was conducted at the Brazilian Army Evaluation Center (CAEx) ballistic testing laboratory, demonstrating its practical applicability in a complex testing environment.

The paper is structured as follows: Section 2 synthesizes relevant literature (2010–2023) focusing on the ISO/IEC 17025:2017 implementation and laboratory assessment methodologies.

Section 3 outlines the research methodology and the framework development process.

Section 4 presents the proposed multicriteria framework, including its structural elements and assessment protocols.

Section 5 discusses the integration of decision-making methods for enhanced self-assessment capabilities and empirical validation results, while Section 6 provides conclusions, research limitations, and future research directions.

2. LITERATURE REVIEW

A literature review was conducted focusing on the central research subjects and covered 15 previous works published between 2010 and 2023 by researchers from different contexts and countries, including Brazil [3]–[17]. This review reveals significant developments in the implementation and assessment of ISO/IEC 17025 in testing and calibration laboratories.

Early research by Abdel-Fatah [3] highlighted the gap between desired outcomes and practical realities in implementing ISO/IEC 17025, while Khodabocus and Balgobin [4] documented practical benefits of implementation, including improved documentation and technical competence.

Grochau and Caten [5] introduced a process-based approach to quality management system implementation, emphasizing the importance of systematic documentation and staff training. This was complemented by Ratseou and Ramphal's study [6], which demonstrated positive correlations between quality assurance standards and operational performance.

Significant contributions to performance measurement emerged with Catini et al. [7] developing quality indicators and indices for continuous improvement in accredited laboratories.

Albano and Faustini [8] specifically examined Brazilian laboratories, establishing a positive relationship between ISO/IEC 17025 implementation and proficiency testing performance in environmental analysis.

Karthiyayini and Rajendran [9] identified critical success factors and performance indicators for laboratory accreditation, while Middlebrook [10] provided empirical evidence that accredited laboratories generally outperform non-accredited ones in proficiency testing.

Al-Mijrab et al. [11] extended this research to Arabic countries, identifying region-specific implementation challenges.

Recent studies have focused on integration and systematic approaches. Dehouck et al. [12] addressed the integration of quality management systems, while Aqidawati et al. [13] developed a framework for strengthening internal laboratory environments. Belezia and Almeida [14] proposed a self-assessment model specifically aligned with the 2017 version of ISO/IEC 17025.

The most recent contributions focus on specialized aspects: Martínez-Perales et al. [15] proposed a quality management system model for research laboratories, Silva et al. [16] addressed risk management implementation, and Jesus et al. [17] documented the evolution of a quality management system through action research.

The analysis of these studies reveals several gaps relevant to the current research. A prominent limitation is the scarce integration of multiple decision-making methodologies for comprehensive evaluation. Additionally, while various studies address implementation and performance measurement, there is a notable absence of frameworks specifically focused on maturity assessment.

The literature also demonstrates a lack of systematic, quantitative approaches to evaluating laboratory compliance with the ISO/IEC 17025:2017 requirements. Furthermore, insufficient attention has been devoted to utilizing assessment results for strategic improvement planning.

In addition, reference works on organizational maturity models [18]–[20] were also analysed to support the definition of a maturity five-point scale to be integrated into the conceptual framework, as described in Section 4 (Item 4.5).

Process maturity models have evolved from basic quality assessment tools into comprehensive frameworks for organizational development and transformation. These models provide structured approaches for systematic process evaluation and enhancement, reflecting advancements in management theory and practice.

Key contributions to maturity model development include Jochem et al.'s framework for knowledge-intensive business processes, which emphasized systematic measurement methodologies [18].

De Bruin et al. [19] developed a significant methodological framework comprising six phases: scope definition, design, population, testing, deployment, and maintenance. Their approach emphasized stakeholder involvement and iterative refinement throughout the development process, establishing methodological rigor while maintaining domain specificity.

Duffy [20] conceptualized maturity models as blueprints for organizational evolution, highlighting the importance of structured progression through defined maturity levels while maintaining adaptability to specific contexts.

The evolution of maturity models reflects increasing sophistication in measurement techniques and evaluation criteria, addressing the complexity of organizational processes [21]. Contemporary literature emphasizes the importance of contextual adaptation, allowing organizations to customize these models while adhering to fundamental principles of systematic assessment and improvement.

These findings provide substantial support for the development of a multicriteria framework in several ways. The literature review highlights the critical need for integrated assessment approaches and identifies essential success factors and performance indicators. It also demonstrates the fundamental importance of systematic evaluation methods and provides empirical evidence supporting the benefits of comprehensive assessment systems.

The proposed multicriteria framework addresses these identified gaps by integrating established decision-making methods with maturity assessment concepts, ultimately providing a comprehensive approach to laboratory evaluation and improvement planning.

Table 1. Research design.

Phase	Stage	Research questions [Section]
Motivation (Why?)	Problem definition and the rationale for the research.	What theoretical and methodological foundations justify the development of a multicriteria framework for assessing laboratory maturity based on ISO/IEC 17025:2017 requirements? [Section 1].
Development (What and How?)	State of research on central themes, and identification of research gaps and unsolved problems.	What are the significant gaps in the existing literature regarding maturity assessment frameworks for testing and calibration laboratories under ISO/IEC 17025:2017? [Section 2]. How do current methodological approaches address laboratory maturity assessment in the context of accreditation requirements? [Section 2].
	Definition of the research methodology.	How can decision-making methods be integrated to create a comprehensive framework for assessing laboratory maturity levels? [Section 3] Which decision-making methods should be integrated into a conceptual framework to assist laboratories aiming to hold accreditation? [Section 3].
	Development of a multicriteria conceptual framework for maturity assessment of testing and calibration laboratories based on the ISO/IEC 17025: 2017 standard.	What critical assessment factors should comprise the analytical structure for evaluating laboratory maturity in the context of accreditation requirements? [Section 4] How can the framework systematically identify and prioritize improvement opportunities regarding laboratory competence, impartiality, and operational consistency? [Section 4].
Validation (How to demonstrate the applicability of the conceptual framework?)	Application of the multicriteria conceptual framework at one of the testing and calibration laboratories within the Brazilian Army Evaluation Center (CAEx), focusing on ballistic testing.	How does the empirical application at the Brazilian Army Evaluation Center's Ballistic Testing Laboratory demonstrate the framework's practical validity? [Section 5] What contributions emerge from the assessment of the Laboratory's current maturity level regarding critical operational challenges, strategic improvement opportunities, and accreditation readiness? [Section 5]
	Discussion of the empirical results and implications of the adoption of the model in other testing and calibration laboratories.	How does the proposed framework advance existing methodological approaches in laboratory maturity assessment? [Section 5] What are the theoretical and practical implications for laboratory quality management and accreditation processes? [Section 5]. How can this framework be extended through future research to address broader applications across laboratory types, integration with emerging quality management paradigms, enhanced quantitative assessment methodologies, and international harmonization of maturity evaluation approaches? [Section 6]

3. RESEARCH DESIGN AND METHODOLOGY

This section presents the methodological framework developed to address the research questions outlined in Table 1.

The research design follows a systematic procedural model adapted from Correia et al. [22], comprising three interconnected phases—motivation, development, and validation—each implemented via five sequential stages.

This comprehensive approach begins with an exploratory phase that establishes the research foundation through careful problem definition and justification. A systematic literature review spanning 2010–2023 [2], [3]–[17] provided crucial insights into existing methodologies and identified significant gaps in laboratory maturity assessment approaches, ultimately validating the need for an integrated multicriteria framework based on ISO/IEC 17025:2017 requirements.

The development phase represents the core methodological contribution, integrating three essential components that work in harmony. At its foundation lies the ISO/IEC 17025:2017 standard [2], which provides a robust structural framework comprising five standard clauses serving as network clusters and 28 assessment factors functioning as network elements. This structural foundation is enhanced through the implementation of the Analytical Network Process (ANP) [23], specifically chosen for its sophisticated ability to address complex interdependencies within the assessment framework.

The ANP implementation follows a carefully structured progression, beginning with network structure determination through interfactorial dominance analysis, followed by element and cluster importance weight determination, and culminating in limit matrix calculation for final weightings. This methodological choice proves particularly valuable due to its unique capability to represent complex interdependencies between assessment elements, accommodate feedback relationships within the network structure, and generate comprehensive supermatrix analyses incorporating eigenvectors of adjusted relative importance weights.

The framework's analytical capabilities are further strengthened by the integration of the Importance-Performance Analysis (IPA) method [24], which enables the systematic evaluation of assessment outcomes and facilitates improvement prioritization. Throughout the assessment process, Saaty's nine-point scale (Table 2) provides a robust foundation for systematic pairwise comparisons, ensuring consistent and reliable quantitative assessment capabilities.

Table 2. Saaty’s nine-point scale [23].

Scale	Linguistic scale
1	Equally important
2	Equally to moderately more important
3	Moderately more important
4	Moderately to strongly important
5	Strongly important
6	Strongly to very strongly more important
7	Very strongly more important
8	Very strongly more important to absolutely important
9	Absolutely important

The methodological framework incorporates sophisticated validation protocols for expert judgments and preferences. Central to this process is the consistency test, which employs consistency ratios (C.R.) derived from pairwise comparison matrices within the ANP methodology. This systematic approach ensures the reliability of expert assessments through the quantitative validation of comparative judgments.

The analytical process culminates in the development of a limit matrix, achieved through iterative power calculations of the weighted supermatrix. This mathematical framework encompasses 28 assessment factors, systematically aligned with the five fundamental clauses of ISO/IEC 17025:2017 [2]. These factors are strategically organized into corresponding clusters, creating a comprehensive evaluation structure (illustrated in Figure 1). The quantitative analysis employs the Super Decisions® software [25] to calculate precise factor weightings, ensuring computational accuracy and methodological consistency.

The framework's analytical depth is further enhanced through the integration of laboratory-specific assessment data, synthesized from expert judgments to determine maturity levels across individual assessment factors. This primary analytical approach is complemented by the incorporation of the Importance–Performance Analysis (IPA) method [24], which provides a strategic dimension to resource allocation decisions. This integrated methodology enables laboratories to demonstrate operational competence and result validity effectively, as detailed in Section 4.8.

4. MULTICRITERIA CONCEPTUAL FRAMEWORK FOR MATURITY ASSESSMENT OF TESTING AND CALIBRATION LABORATORIES BASED ON THE ISO/IEC 17025: 2017 STANDARD

Based on the methodology outlined in Section 3, a multicriteria conceptual framework comprising nine stages was developed for assessing the maturity of testing and calibration laboratories based on the ISO/IEC 17025: 2017 standard.

4.1. Stage 1: Development of hierarchical analytical structure aligned with the ISO/IEC 17025:2017 standard

The analytical framework for maturity assessment is structured according to the hierarchical structure of the ISO/IEC 17025:2017 standard, wherein its clauses serve as assessment dimensions, and their constituent requirements function as assessment factors, as illustrated in Table 3 and Figure 1. This hierarchical structure provides a comprehensive foundation for evaluating laboratory maturity levels.

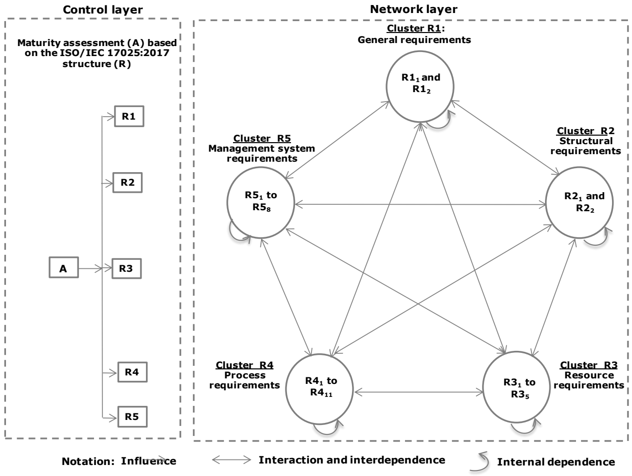

Figure 1. The network analytical structure based on the ISO/IEC 17025:2017 standard [2].

The interdependencies among assessment factors are systematically mapped through a zero-one interfactorial dominance matrix. This matrix captures the complex network of relationships between the 28 assessment factors, organized within five distinct clusters. Each matrix element is assigned a binary value (1 or 0), representing the presence or absence of influence between factors, thereby creating a comprehensive representation of the assessment framework's internal dynamics.

4.2. Stage 2: Designing the questionnaire for pairwise comparisons of assessment factors and dimensions

This stage encompasses the development and validation of a comparative assessment instrument designed to facilitate pairwise comparisons among 28 assessment factors and five dimensions. The instrument undergoes rigorous pretesting to evaluate multiple dimensions of its efficacy: (i) conceptual clarity and comprehensibility; (ii) respondent appropriateness and accessibility; (iii) temporal requirements for completion; and (iv) potential implementation constraints.

The comparative analysis employs Saaty's nine-point scale (Table 2), providing a standardized framework for quantitative assessment. This evaluation process engages key stakeholders directly involved in the laboratory's accreditation preparation, including senior management and technical personnel, ensuring comprehensive expertise in the assessment process.

4.3. Stage 3: Determination of weighted assessment criteria through expert evaluation

The analytical process begins with the consolidation of expert judgments and preferences, validated through consistency ratio (C.R.) analysis, to generate comprehensive pairwise comparison matrices for eigenvector derivation [23]. This process culminates in the construction of a sophisticated supermatrix that integrates all sub-matrices encompassing the five assessment dimensions (clusters) and their associated 28 assessment factors.

The weighted supermatrix emerges through the systematic integration of the unweighted supermatrix with the control hierarchy matrix, the latter derived from rigorous pairwise comparisons utilizing Saaty's standardized scale (Table 2). The final quantitative analysis employs the Super Decisions® software [25] to calculate precise weightings for all 28 assessment factors, ensuring computational accuracy and methodological consistency as detailed in Section 3.

Table 3. Analytical structure based on the ISO/IEC 17025:2017 standard [2].

Control layer		Network layer
Target	Assessment dimensions	Assessment factors
Maturity assessment (A) based on the ISO/IEC 17025:2017 clauses (R)	General requirements [R1]	Impartiality (R11)
		Confidentiality (R12)
	Structural requirements [R2]	Defined legal entity (R21)
		Laboratory scope, capabilities, and responsibilities of staff (R22)
	Resource requirements [R3]	Personnel (R31)
		Facilities and environmental conditions (R32)
		Equipment (R33)
		Metrological traceability (R34)
		Externally provided products and services (R35)
	Process requirements [R4]	Review of requests, tenders and contracts (R41)
		Selection, verification and validation of methods (R42)
		Sampling (R43)
		Handling of test or calibration items (R44)
		Technical records (R45)
		Evaluation of measurement uncertainty (R46)
		Ensuring the validity of results (R47)
		Reporting of results (R48)
		Complaints (R49)
		Nonconforming work (R410)
		Control of data and information management (R411)
	Management system requirements [R5]	Management system documentation (R51)
		Control of management system documents (R52)
		Control of records (R53)
		Actions to address risks and opportunities (R54)
		Improvement (R55)
		Corrective actions (R56)
		Internal audits (R57)
		Management reviews (R58)
One target	Five clauses	28 requirements

Table 4. Maturity scale to evaluate the competence, impartiality, and consistent operation of testing and calibration laboratories.

Maturity level	Description
1: Initial/Ad hoc	Organizational capabilities are either undefined or implemented through informal, reactive processes lacking standardization and systematic management. No structured approach to capability development exists.
2: Basic management	Organizational capabilities are established with fundamental management processes in place. Implementation shows evidence of basic structure but lacks a comprehensive systematic approach. Key processes are identified but not fully integrated.
3: Defined management	Organizational capabilities are proactively established with defined processes and management protocols. Standard operating procedures are documented and systematically implemented, though optimization opportunities remain.
4: Systematic management	Organizational capabilities are comprehensively established with integrated management systems. Processes are systematically monitored and controlled, demonstrating clear alignment with organizational objectives and continuous improvement practices.
5: Optimized management	Organizational capabilities are fully mature, characterized by systematic implementation, continuous optimization, and dynamic adaptation. Management processes integrate active monitoring, feedback mechanisms, and organizational learning for sustained excellence.

Source: Based on [19]–[21].

4.4. Stage 4: Computational analysis of limit supermatrix for assessment factor weight derivation

The limit supermatrix computation involves iterative power operations on the weighted supermatrix until convergence to stable values is achieved. This mathematical process systematically captures and consolidates the complex network of interdependencies and relative importance weightings among assessment factors.

The final quantitative analysis, executed through the Super Decisions® software [25], yields precise weightings for all 28 assessment factors, ensuring computational accuracy and methodological rigor in the evaluation framework.

4.5. Stage 5: Designing the maturity five-point scale for assessing test and calibration laboratories

A comprehensive five-point maturity assessment scale was developed through the systematic analysis of common characteristics identified across multiple maturity models examined during the research's exploratory phase [19]–[21]. This structured assessment framework synthesizes key developmental indicators from established maturity models, to create a robust assessment tool specifically tailored for testing and calibration laboratories.

The resultant maturity scale, presented in Table 4, provides clearly defined progression criteria that enable the systematic evaluation of laboratory capabilities.

4.6. Stage 6: Development of comprehensive assessment protocol

This stage involves the development of a comprehensive assessment instrument incorporating the 28 network assessment factors, five-dimensional clusters, and the established maturity scale (Table 4). The instrument undergoes rigorous validation through pretesting protocols before implementation with key stakeholders involved in the laboratory's accreditation preparation process.

The evaluation methodology accommodates multiple expert assessments through two distinct approaches: consensus-building through structured deliberation sessions, or quantitative aggregation utilizing fuzzy logic techniques for collective weighting determination [23]. This flexible approach ensures robust data collection

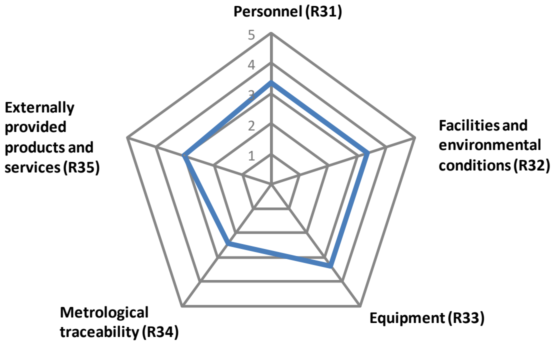

Figure 2. An illustrative example of a radar-type chart for the 'Resource requirements' dimension.

while maintaining methodological rigor in multi-evaluator scenarios.

4.7. Stage 7: Quantitative analysis of laboratory maturity index

Stage 7 encompasses the synthesis of assessment factor weightings (derived from stage 4) with maturity ratings (based on the scale in Table 4) to determine the laboratory's comprehensive maturity index. This analytical process generates composite indicators that quantify maturity levels across the five assessment dimensions aligned with standard clauses. The multidimensional assessment outcomes are visualized through radar-type charts (Figure 2), enabling the efficient comparison and analysis of dimensional maturity profiles.

The integration of weighted assessments and dimensional analysis provides a robust framework for evaluating overall laboratory maturity, while maintaining granular visibility of performance across individual assessment dimensions. This systematic approach facilitates both comprehensive and dimension-specific maturity evaluation.

4.8. Stage 8: Strategic analysis through decision zone mapping

This stage focuses on strategic analysis through the application of the Importance–Performance Analysis (IPA) [24], creating a systematic framework for identifying and prioritizing improvement opportunities across assessment dimensions.

The resulting decision-making zones provide a structured basis for developing targeted enhancement initiatives and action plans, translating assessment outcomes into actionable improvement strategies through an IPA matrix applied to each assessment dimension.

4.9. Stage 9: Synthesis of laboratory assessment outcomes and recommendations

The framework's final stage focuses on the synthesis of assessment outcomes through a comprehensive analytical report. This document consolidates quantitative evaluations, dimensional analyses, and strategic recommendations into an integrated improvement framework. The report establishes a systematic approach to enhancing laboratory maturity through clearly defined objectives, structured implementation plans, and specific performance targets aligned with accreditation requirements.

5. APPLICATION IN THE BALLISTIC TESTING LABORATORY (LEB) OF THE BRAZILIAN ARMY EVALUATION CENTER (CAEX)

The framework's empirical validation was conducted at the Ballistic Testing Laboratory (LEB) of the Brazilian Army Evaluation Center (CAEx) [26], providing a comprehensive assessment of the multicriteria framework's practical applicability in an operational laboratory context.

The empirical investigation addressed two primary research questions:

(i) What is the current maturity level of the LEB regarding competence, impartiality, and operational consistency?

(ii) What strategic challenges require management attention, and what recommendations should be presented to senior leadership to optimize accreditation-derived value?

5.1. Data collection

The data collection and assessment process engaged three senior experts with extensive qualifications in laboratory management and ISO/IEC 17025:2017 implementation, as follows:

- Expert 1: Laboratory Quality Manager with 15 years of experience in accreditation processes, certified lead auditor for ISO/IEC 17025, and Master's degree in Metrology;
- Expert 2: Technical Director with 12 years of experience in ballistic testing, certified in measurement uncertainty evaluation, and specialized training in calibration procedures.
- Expert 3: Senior Military Officer with 18 years of experience in defence testing laboratories, certified project manager, and extensive background in quality assurance systems.

Initial data collection focused on establishing the hierarchical control matrix (5 × 5 standard clauses), presented in Table 5.

Subsequently, a comprehensive interfactorial dominance matrix (28 × 28 assessment factors) was developed, with binary values (1 or 0) assigned based on identified influence relationships between elements.

5.2 Quantitative analysis of assessment factor weightings

The analytical process employed the Super Decisions® software, following standardized protocols [25], to generate three sequential supermatrices. The process began with the original weightless supermatrix, derived from pairwise factor comparisons, followed by the development of a weighted supermatrix that incorporated cluster weights with unweighted matrix elements.

The analysis culminated in a stochastic limiting supermatrix, achieved through iterative power calculations until convergence. While space constraints preclude full matrix presentation, complete analytical details are available in [27].

5.3 Laboratory maturity assessment

The integration of factor weightings with maturity assessments enabled the construction of five Importance–Performance Analysis (IPA) matrices, systematically aligned with the core dimensions of the ISO/IEC 17025:2017 standard, namely: General requirements, Structural requirements,

Table 5. Hierarchy control matrix based on the ISO/IEC 17025:2017 clauses.

Hierarchy control matrix	R1	R2	R3	R4	R5
General requirements [R1]	0	1	1	1	1
Structural requirements [R2]	1	0	1	1	1
Resource requirements [R3]	1	1	0	1	1
Process requirements [R4]	1	1	1	0	1
Management system requirements [R5]	0	0	1	1	0

Resource requirements, Process requirements, and Management system requirements.

Each matrix provides a bidimensional representation in which importance (derived from calculated weights) is plotted on the horizontal axis, and performance (maturity level) is represented on the vertical axis. By segmenting results into four decision zones—appropriate, improve, urgent action, and excess [24]. So, the framework introduces a structured and transparent basis for prioritising managerial interventions.

The novelty of this approach lies in its ability to couple quantitative weighting with maturity assessments, thereby overcoming the limitations of conventional audit-based evaluations that often provide fragmented or descriptive findings. Validation was performed by comparing framework outcomes with nonconformities identified during LEB's internal audits. For example, requirement R33 (Equipment), within the 'Resource requirements' dimension, achieved a maturity level of 3.2. While calibration schedules and maintenance routines were in place, the laboratory lacked systematic performance monitoring and predictive maintenance mechanisms. The IPA analysis highlighted targeted improvement needs, such as the definition of key performance indicators (KPIs) for critical equipment, the establishment of predictive maintenance protocols based on usage patterns and performance trends, and the integration of automated alert systems for deviation detection. In addition, LEB was advised to enhance equipment validation protocols, implement real-time monitoring of environmental conditions affecting equipment reliability, and create comprehensive documentation linking equipment performance to measurement uncertainty.

The strong correspondence between the framework's results and audit findings demonstrates its validity in revealing genuine weaknesses and improvement opportunities across all ISO/IEC 17025:2017 dimensions. More importantly, the framework offers practical benefits by transforming complex maturity assessments into visual, decision-oriented tools that facilitate strategic priority setting and continuous improvement planning. Given its systematic nature, the proposed approach is transferable to laboratories operating in other regulated sectors, thus contributing to broader discussions on performance-based compliance, laboratory resilience, and quality assurance under international standards.

This analytical framework provided LEB managers with a comprehensive visualization of performance distribution across decision zones, facilitating strategic priority setting and improvement planning.

6. DISCUSSION

The multi-criteria framework developed in this study advances the field of laboratory quality management in several significant dimensions, particularly regarding maturity assessment methodologies for testing and calibration laboratories.

While previous studies by Abdel-Fatah [3] and Khodabocus and Balgobin [4] focused primarily on basic implementation aspects, the proposed framework provides a more sophisticated approach for testing and calibration laboratory assessment.

The integration of the ANP and IPA methods represents a notable advancement over the approaches documented by Grochau and Caten [5] and Ratseou and Ramphal [6], who employed single-method approaches focused on compliance verification. Although Catini et al. [7] introduced quality indicators for continuous improvement, the proposed framework provides a more comprehensive evaluation system that captures complex interdependencies between assessment factors.

The incorporation of a five-point maturity scale, derived from established organizational maturity models [18]–[21], enables a more effective evaluation of laboratory capabilities compared to the binary compliance assessments prevalent in earlier studies. The framework's systematic approach to weight determination through the ANP method [23] addresses significant gaps identified in studies by Albano and Faustini [8] and Karthiyayini and Rajendran [9], where assessment criteria were treated with equal importance.

This weighted approach provides a more accurate representation of the relative significance of different ISO/IEC 17025:2017 standard requirements, advancing beyond the uniform treatment of requirements observed in Middlebrook's study [10].

Although Al-Mijrab et al. [11] and Dehouck et al. [12] focused on regional implementation challenges and quality system integration, respectively, the proposed framework offers a more comprehensive methodology applicable across different laboratory contexts.

The approach builds upon the framework developed by Aqidawati et al. for internal environment strengthening [13], while adding sophisticated quantitative assessment capabilities.

Recent contributions by Martínez-Perales et al. [15] and Silva et al. [16] addressed specific aspects of quality management systems and risk management but lacked the integrated approach to maturity assessment presented in our framework.

The multi-criteria conceptual framework for maturity assessment of testing and calibration laboratories presented here extends beyond the action research approach documented by Jesus et al. [17], by providing a structured, quantitative basis for assessment and improvement planning.

The empirical validation at CAEx's Ballistic Testing Laboratory demonstrated the practical applicability of the framework in a complex testing environment, advancing beyond the theoretical frameworks presented in earlier studies. The implementation revealed capabilities not found in previous research, including quantifiable maturity assessments across multiple dimensions and the systematic identification of improvement areas through IPA matrices.

This framework provides laboratory managers with tools that address the limitations identified in previous studies. While Belezia and Almeida [14] proposed a self-assessment maturity model based on the Analytical Hierarchy Process (AHP) method, the proposed framework employed the ANP method because of its superior capability to handle complex interdependencies among assessment factors.

Unlike AHP's hierarchical structure, the ANP method allows for feedback relationships and interactions between elements at different levels, which better reflects the interconnected nature of the ISO/IEC 17025:2017 requirements. This is particularly relevant, as laboratory quality management systems exhibit numerous cross-dependencies, where improvements in one area often influence performance in others.

In this regard, the ability of the ANP method to capture these network relationships through its super-matrix approach provides a more accurate representation of the complex interactions between the standard's 28 assessment factors across its five main clauses. This enables more precise weight calculations compared to AHP's strictly hierarchical approach, resulting in a more realistic prioritization of improvement initiatives. Furthermore, ANP's capability to model both inner and outer dependencies makes it particularly suitable for evaluating laboratory quality management systems, where requirements often have bidirectional influences.

However, several limitations of this study warrant further investigation. The effectiveness of the framework depends significantly on expert judgment quality during the ANP weighting process, although the consistency ratio analysis helps mitigate subjective bias identified as problematic in previous studies [8], [9]. To address this limitation, future implementations should include expert training sessions on the assessment methodology and establish minimum qualification criteria for evaluators. Additionally, the five-point maturity scale may not capture all the nuanced variations in compliance levels. Empirical validation across multiple laboratory contexts will help refine scale granularity and identify sector-specific adaptations. The current single-laboratory validation, while demonstrating practical applicability, requires extension to multiple laboratory types and operational contexts to fully establish the framework's effectiveness across different scenarios [11], [13].

Several promising research trajectories emerge from this study as pointed out in the next section.

7. CONCLUSIONS

This study developed and validated a comprehensive multicriteria framework for assessing testing and calibration laboratory maturity levels based on the ISO/IEC 17025:2017 standard requirements, effectively addressing the research questions associated with the research gaps identified during the literature review (Section 2).

The framework offers a systematic approach for evaluating laboratory competence, impartiality, and operational consistency through the integration of the ANP and IPA methods.

Regarding the first research question on maturity level assessment, the study demonstrated that combining established decision-making methods with a structured maturity scale provides an effective mechanism for evaluating laboratory capabilities. The framework's empirical validation at the CAEx Ballistic Testing Laboratory confirmed its practical applicability and effectiveness in generating actionable insights for planning improvements.

The second research question, concerning essential framework elements, was addressed through the development of a hierarchical analytical structure comprising 28 assessment factors organized across five dimensions. This structure, derived from the ISO/IEC 17025:2017 requirements, provides a comprehensive foundation for maturity evaluation, while maintaining alignment with international standards.

The integration of the ANP and IPA methods, addressing the third research question, proved particularly valuable in capturing the complex interdependencies between assessment factors, and facilitating strategic improvement prioritization. This methodological combination enables a more nuanced evaluation than traditional binary compliance assessments.

The fourth research question, focusing on the critical factors affecting laboratory capabilities, was resolved through the framework's weighted assessment approach, which identified and prioritized key areas influencing laboratory competence, impartiality, and operational consistency.

Several promising research trajectories have emerged from this study. Firstly, cross-sectoral validation across different laboratory types can enhance the generalizability of the framework and identify sector-specific adaptations. Integration with broader quality management systems is another valuable direction, potentially creating more comprehensive assessment approaches that align with other relevant standards and practices. The development of automated assessment tools can streamline the evaluation process and enable more frequent monitoring of maturity progression. Similarly, adaptation to international laboratory networks could facilitate standardized assessment approaches across global operations, supporting international harmonization efforts. Longitudinal studies tracking maturity progression over time could provide valuable insights into the effectiveness of improvement initiatives and dynamics of organizational development in laboratory contexts. Investigation of the correlations between maturity levels and operational performance metrics could strengthen the business case for maturity enhancement programs and guide resource allocation decisions. Additional research opportunities include the following:

(i) Development of industry-specific benchmarking capabilities;
(ii) Integration of emerging technologies for data collection and analysis;
(iii) Exploration of cultural and regional factors affecting framework implementation;
(iv) Investigation of the relationship between maturity levels and accreditation outcomes;
(v) Development of predictive models for accreditation readiness.

These research directions could significantly advance the understanding of laboratory quality management and maturity assessment methodologies, while supporting the ongoing evolution of accreditation practices.

The successful validation of the proposed framework in a complex testing environment suggests its potential value for other laboratories seeking accreditation.

AUTHORS' CONTRIBUTION

Conceptualization: D. B. C., M. F. L. A.; methodology: D. B. C., M. F. L. A.; writing—original draft preparation: D. B. C..; writing—review and editing: M. F. L. A. All authors have read and agreed to the published version of the manuscript.

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