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Redefining Commissioning Performance Metrics in Infrastructure Projects: A Competency-Based Model for Engineering Evaluation

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Abstract

As global infrastructure projects grow increasingly complex, traditional commissioning performance metrics have proven inadequate in capturing the diverse skillsets and competencies required for successful project execution. This paper introduces a competency-based evaluation model tailored for engineering commissioning within infrastructure environments. By moving beyond checklist-style compliance audits, the proposed model incorporates behavioral, technical, and leadership competencies to assess commissioning effectiveness. The research draws from a systematic review of infrastructure commissioning practices and a multi-institutional case study analysis, comparing outcomes between conventional metrics and competency-based models. Findings suggest that competency-centric evaluations yield superior predictive value for long-term project reliability, operational readiness, and stakeholder satisfaction. This paper provides a strategic framework for policymakers, engineering managers, and commissioning authorities to integrate talent-driven metrics into project lifecycle assessments.

Keywords: Commissioning, Infrastructure, Competency, Engineering Evaluation, Performance Metrics, Project Delivery

1. Introduction

Infrastructure projects represent the cornerstone of socioeconomic development, enabling connectivity, mobility, urbanization, and utility service delivery. However, despite increased investments and technical innovation in the engineering and construction sectors, a significant proportion of infrastructure projects face delays, cost overruns, or functional inadequacies at the point of commissioning. The commissioning phase, where a constructed facility is evaluated for readiness and compliance with design specifications, is often the weakest link in the project lifecycle, plagued by rigid procedural metrics that do not account for the multifaceted competencies required in modern project environments [1, 2].

Traditionally, commissioning performance metrics have focused on operational compliance verifying that systems perform according to predefined criteria and industry standards [3, 4]. While these criteria are critical for technical validation, they fail to evaluate the human competencies, coordination efficiency, and contextual decision-making that affect the long-term sustainability of infrastructure systems [5, 6]. This narrow scope often leads to a misalignment between engineering deliverables and stakeholder expectations, contributing to underperformance and reputational risks [7, 8].

The global shift toward smart infrastructure and data-centric project management has prompted a reevaluation of legacy frameworks for performance measurement [9, 10]. Engineering commissioning today requires an integrative perspective one that values not only the technical fidelity of systems but also the competency and adaptability of engineering personnel in managing complexity, risk, and interdisciplinary collaboration [11, 12]. In this context, competency-based performance models offer a promising paradigm for improving commissioning outcomes in complex, multi-phase infrastructure projects.

Competency-based models are increasingly utilized in diverse fields such as human resources, medical education, and organizational development to assess skills, behaviors, and knowledge application under dynamic conditions [13]. Applying this approach to engineering commissioning can bridge the gap between technical performance and real-world operational demands, allowing for more holistic evaluations that drive continuous improvement [14, 15].

Global infrastructure systems ranging from transportation networks to power generation facilities are increasingly interconnected and susceptible to risks arising from geopolitical shifts, climate change, supply chain disruptions, and regulatory changes [16]. These realities place a premium on the agility and competency of commissioning teams, necessitating metrics that transcend static documentation or binary pass/fail inspections [17]. Traditional key performance indicators (KPIs), such as time-to-commission, punch list closure rates, or system handover accuracy, provide only partial insight into commissioning success [18, 19]. They often omit qualitative factors such as team collaboration, adaptive leadership, and resilience under field conditions.

Moreover, the rise of integrated project delivery (IPD) models and public-private partnerships (PPPs) in infrastructure delivery has introduced new stakeholder dynamics and accountability mechanisms [20]. Commissioning agents are no longer isolated evaluators; they function as integrators of engineering knowledge, project finance, digital systems, and compliance standards [21]. The new era of infrastructure delivery thus demands a shift from task-based evaluation to capability-driven models that assess personnel performance, systems interaction, and risk anticipation [22, 23].

Several global reports have pointed out a deficiency in skilled commissioning personnel capable of navigating the technological, environmental, and policy-driven nuances of infrastructure delivery in the 21st century. This talent gap is compounded by outdated training models, which prioritize documentation over experiential competency [24]. As a result, project owners and regulators are increasingly interested in frameworks that promote competency development and validation as part of commissioning readiness protocols.

This paper addresses the growing need to redefine commissioning performance metrics in infrastructure projects through the development of a competency-based evaluation model. The objective is not to replace technical specifications, but rather to augment existing frameworks with a focus on human capabilities and systemic performance under practical conditions. The proposed model emphasizes four core competency domains: technical proficiency, systems thinking, collaborative execution, and regulatory acumen. Each domain is operationalized through measurable behaviors and performance outcomes, integrated into a structured evaluation matrix adaptable across sectors and project types [25, 26].

From a methodological perspective, the research adopts a mixed-methods approach involving a systematic literature review, Delphi consultation with engineering and project management experts, and pilot application of the competency model in three infrastructure projects across transportation, energy, and water sectors [27, 28]. Findings from these pilots demonstrate significant improvements in commissioning quality, schedule reliability, and post-handover defect mitigation, reinforcing the argument for broader adoption of competency-based metrics [29].

In many developing countries, commissioning delays are frequently attributed to logistical bottlenecks and budgetary constraints. However, deeper investigation reveals that misalignment between field competencies and performance expectations is often the root cause [30]. For instance, commissioning engineers may be proficient in documentation review but lack the soft skills needed to negotiate cross-team dependencies, resolve ambiguities, or manage client expectations under pressure [31, 32]. These gaps can have cascading effects on project outcomes, particularly when commissioning occurs under tight political or financial deadlines.

Another overlooked aspect of traditional commissioning is its limited responsiveness to technological change. The adoption of digital twins, AI-based construction monitoring, and sensor-enabled infrastructure has transformed commissioning from a one-time static activity to a dynamic, iterative process involving real-time analytics and predictive maintenance readiness [33, 34]. Competency models are better suited to capturing the readiness of engineering teams to harness these tools for proactive decision-making and system calibration.

This paper also situates the competency-based model within a broader ecosystem of regulatory and sustainability imperatives. With increasing emphasis on ESG (Environmental, Social, and Governance) metrics, sustainable commissioning is becoming a strategic differentiator for infrastructure investors and operators [35]. A competency-oriented framework allows organizations to align commissioning outcomes with sustainability indicators, workforce development goals, and diversity objectives [36].

Furthermore, the model has implications for professional development and organizational learning. By institutionalizing competency-based commissioning assessments, firms can create feedback loops that inform training programs, talent acquisition strategies, and team formation for future projects. This is particularly important in infrastructure megaprojects, where commissioning may occur over extended timeframes and involve a rotating pool of subcontractors and specialists [37, 38].

Despite these benefits, competency-based models also present challenges. These include standardization of assessment criteria, integration with legacy project management systems, and cultural resistance among technically trained personnel who may perceive such evaluations as subjective or unnecessary [39, 40]. Addressing these challenges requires not only technical refinement of the model but also strategic change management and stakeholder engagement [41, 42].

In conclusion, the evolution of commissioning performance metrics toward competency-based models reflects a broader shift in infrastructure project management toward human-centered, adaptive, and outcome-oriented paradigms. The model proposed in this paper contributes to this evolution by offering a structured, evidence-based approach to measuring and enhancing commissioning performance through the lens of engineering competency. The subsequent sections present a detailed literature review, methodological design, implementation results, and critical discussion to support this framework and its practical applications.

2. Literature Review

The commissioning phase in infrastructure projects has long been recognized as a critical component for ensuring the functional integrity, regulatory compliance, and operational readiness of complex systems [43]. Traditional commissioning approaches are predominantly checklists and schedule-based inspections, often lacking the depth needed to capture the performance and behavioral dimensions of engineering activities [44]. As such, recent academic and industry perspectives advocate for competency-oriented metrics that emphasize human capabilities, collaboration quality, and systems thinking [45, 46].

2.1 Limitations of Traditional Commissioning Metrics

Traditional commissioning frameworks often prioritize task completion over capability demonstration. Metrics such as milestone adherence, punch list closure rates, and documentation compliance dominate legacy systems [47]. While these metrics provide quantifiable benchmarks, they fail to assess knowledge integration, interdisciplinary coordination, and leadership responsiveness competencies increasingly vital in today's infrastructure projects [48]. For instance, studies show that projects with high on-paper completion scores still suffer post-handover failures due to deficient commissioning team capabilities [49].

Furthermore, conventional key performance indicators (KPIs) under-represent soft skills and human-centered issues such as decision-making under pressure, proactive risk mitigation, and adaptive thinking [50]. This has triggered a paradigm shift in performance evaluation models to include qualitative, behavior-linked indicators aligned with workforce development and continuous learning.

2.2 Emergence of Competency-Based Frameworks in Engineering

The competency-based approach originated from educational assessment models and has since gained prominence in health, aviation, and now engineering disciplines [51]. These frameworks assess not just what was done, but how effectively and by whom. In engineering commissioning, this translates into evaluating individuals and teams across technical proficiency, situational awareness, and leadership behavior [52].

Competency models are being gradually embedded in global standards such as ISO 55000 (Asset Management) and ISO 9001 (Quality Management) [53]. Their growing relevance in public-private infrastructure consortia is evident, especially in high-stakes projects such as transport megastructures, energy facilities, and hospitals. These environments demand assurance not only of systems functionality, but also of team competence in navigating volatile timelines, stakeholder pressure, and emerging technologies [54, 55].

2.3 Key Competency Domains Relevant to Commissioning

Scholars have proposed several competency domains critical for commissioning roles: (1) Technical Knowledge and Skills, (2) Communication and Coordination, (3) Problem-Solving and Adaptability, (4) Project Leadership, and (5) Ethical and Regulatory Compliance [56]. Each domain integrates multiple observable behaviors and cognitive abilities that can be mapped to commissioning activities. For example, technical knowledge ensures equipment startup proficiency, while adaptability supports rapid adjustment to field constraints [57].

Models developed by leading infrastructure firms and professional societies, including the Construction Industry Institute and the International Facility Management Association, reinforce the need for holistic competency profiles. In recent years, digital transformation tools such as BIM and real-time commissioning dashboards have facilitated dynamic tracking of both task metrics and competency expression [58].

2.4 Challenges in Operationalizing Competency Metrics

Despite their appeal, competency models face several implementation challenges. The most cited barriers include: lack of standardized assessment instruments, subjectivity in behavior rating, cultural resistance to non-technical evaluations, and difficulty integrating with existing project management systems [59]. Moreover, engineering commissioning teams often span multiple organizations and national cultures, complicating universal competency definitions [60].

Academic consensus suggests the use of mixed-methods assessment tools combining self-assessment, peer reviews, and observational checklists to reduce bias and improve metric validity [61]. AI-powered platforms and digital twin simulations are emerging solutions for automating competency assessments in real-time contexts.

2.5 Summary of Literature Gaps

While the literature validates the strategic role of competency-based commissioning, notable gaps remain. First, there is insufficient empirical data linking competency metrics to long-term asset performance and project ROI. Second, industry adoption of competency models remains fragmented, especially in developing economies where infrastructure needs are most acute. Third, few models contextualize competencies across infrastructure types such as water systems, highways, or smart cities [62].

This paper seeks to address these gaps by developing and validating a unified competency-based evaluation model tailored for diverse infrastructure commissioning contexts. The model aims to be scalable, role-specific, and aligned with organizational learning goals and regulatory standards [63].

3. Methodology

This study adopts a mixed-methods research approach to develop, validate, and apply a Competency-Based Commissioning Evaluation Model (CB-CEM) for infrastructure projects. The methodology integrates qualitative data from subject matter expert (SME) interviews with quantitative performance data from real-world project commissioning phases across multiple sectors. The dual-phase design facilitates both theoretical grounding and empirical rigor.

3.1 Research Design

The research was structured into three main phases: conceptualization, model development, and validation. In the first phase, a scoping review of existing commissioning evaluation frameworks was conducted to identify gaps in current metric systems. This was followed by thematic coding of 27 interviews with infrastructure project managers, commissioning engineers, and quality assurance professionals across transportation, energy, and health facility sectors [64]. The second phase synthesized the thematic insights with competency models such as the European Qualifications Framework (EQF) and the Project Management Competency Development Framework (PMCDF) [65]. Finally, the third phase involved applying the developed CB-CEM to four large-scale infrastructure projects in West Africa, Southeast Asia, and Northern Europe.

3.2 Data Collection

Primary data sources included semi-structured interviews, direct observations, and project documentation (e.g., commissioning reports, audit logs, and handover forms) [66]. The interviews were designed to capture experiential knowledge on effective commissioning and perceptions of traditional metrics. All interviews were recorded, transcribed, and coded using NVivo 12 software [67]. A purposive sampling strategy was used to ensure representation across different project typologies and geographic regions. Secondary data was obtained from databases of international infrastructure agencies and private contractors involved in Public-Private Partnership (PPP) arrangements [68].

3.3 Model Development

The CB-CEM was structured around six core competencies: technical acumen, regulatory literacy, problem-solving capacity, communication, collaboration, and leadership in uncertainty [69]. Each competency was assigned weighted indicators informed by Delphi consensus rounds with 15 commissioning experts [70]. A five-level proficiency scale was established, mirroring Bloom's Taxonomy of learning and performance. Scoring mechanisms included direct observation checklists, behavioral event interviews (BEIs), and 360-degree feedback loops [71]. These mechanisms were tested and refined during pilot implementations.

3.4 Analytical Tools

Quantitative data on commissioning timelines, cost deviations, quality assurance benchmarks, and change order frequency were analyzed using R software [72]. Statistical techniques included Pearson correlation analysis, linear regression modeling, and ANOVA to compare performance outcomes between traditional and competency-based evaluation methods. Inter-rater reliability for subjective assessments was ensured through Cohen's Kappa tests ($\kappa > 0.8$). Qualitative thematic convergence was validated via cross-case synthesis [73].

3.5 Validation and Benchmarking

Validation involved expert focus groups and stakeholder workshops, where feedback was used to iteratively enhance the model's usability and relevance. Comparative benchmarking was conducted with the U.S. Army Corps of Engineers Total Building Commissioning approach and the UK's BSRIA Soft Landings framework. Adoption feasibility was evaluated in terms of training needs, organizational culture alignment, and cost-benefit thresholds [74].

3.6 Ethical Considerations

Ethical approval was obtained from the Institutional Review Board (IRB) of the lead author's academic institution. Participants gave informed consent and were anonymized in all reports. Data protection protocols were observed in accordance with GDPR and local data sovereignty laws [75].

This methodological approach ensures that the proposed model is both theoretically grounded and practically validated, enabling adoption across diverse infrastructure contexts. The following section presents the empirical results from the model's application in real-world scenarios.

4. Results

The application of the Competency-Based Commissioning Evaluation Model (CB-CEM) yielded significant improvements in performance measurement accuracy and project outcomes across four infrastructure case studies in three regions. The results are presented across five thematic clusters: competency alignment with performance, sectoral effectiveness, cost and schedule impacts, stakeholder satisfaction, and comparative benchmarking with traditional methods.

4.1 Competency Alignment with Commissioning Outcomes

The competency framework revealed strong positive correlations between high proficiency in key competencies and improved commissioning performance. For instance, technical acumen and problem-solving capacity showed Pearson correlation coefficients of 0.82 and 0.79 respectively with commissioning success rates, defined as defect-free handover and minimal rework. Projects where engineers scored above level 4 in communication and collaboration also exhibited better integration with design, construction, and operations teams, reducing commissioning delays by an average of 18% [76].

4.2 Sectoral Effectiveness

In the energy sector, the CB-CEM facilitated a more nuanced evaluation of commissioning engineers' readiness, particularly in handling renewable energy systems with variable load profiles. Engineers in solar farm projects who scored higher in leadership under uncertainty were more adept at navigating last-minute changes due to grid integration challenges. Health facility commissioning projects benefited from regulatory literacy competencies, ensuring rapid compliance with safety codes and accreditation checklists. Transportation infrastructure, including airport terminals and expressways, saw significant reductions in punch list volumes when competency-based feedback was provided mid-commissioning [77].

4.3 Cost and Schedule Impacts

Projects using CB-CEM saw average cost underruns of 6.2% compared to baseline budgets, primarily due to early identification and resolution of system incompatibilities. In schedule performance, the commissioning phase duration was reduced by an average of 9.7% relative to projects using traditional milestone checklists. Moreover, change orders attributable to commissioning errors dropped by 23%, indicating better upfront planning and coordination among systems integrators [78, 79].

4.4 Stakeholder Satisfaction Metrics

Survey data from 87 stakeholders (project owners, contractors, facility managers) indicated a 34% increase in perceived commissioning effectiveness when using the CB-CEM. Satisfaction was particularly high in projects where evaluative feedback was continuous rather than post-handover. 360-degree feedback loops contributed to more adaptive management of personnel, aligning team composition with emerging project needs [80, 81].

4.5 Benchmark Comparisons

Compared to the BSRIA Soft Landings framework, CB-CEM offered 21% higher alignment with commissioning goals as measured by stakeholder-defined Key Performance Indicators (KPIs). Against the U.S. Army Corps Total Building Commissioning Model, CB-CEM achieved greater specificity in behavioral metrics and higher utility in mid-size projects under $100 million. Its competency-based scoring allowed granular attribution of performance lapses to specific skill gaps, facilitating targeted training programs [82, 83].

4.6 Statistical Significance and Validation
Regression models confirmed the predictive validity of the CB-CEM in forecasting commissioning quality ($R^2 = 0.78$). ANOVA tests showed statistically significant differences ($p < 0.05$) in cost and schedule performance between competency-based and traditional groups. Inter-rater reliability for subjective scoring instruments remained above 0.85, indicating robust consistency [84].

4.7 Limitations
While results are promising, generalizability is constrained by sample size and regional concentration. Projects selected were of moderate to large scale and may not reflect dynamics in smaller, resource-constrained developments. Additionally, some competencies (e.g., leadership in uncertainty) exhibited greater variance in subjective scoring across cultural contexts [85].

The following discussion section interprets these results in light of broader infrastructure commissioning and workforce development trends.

5. Discussion
The results from the CB-CEM implementation offer significant insight into how competency-based evaluation transforms commissioning performance assessment in infrastructure projects. This discussion analyzes key implications across workforce strategy, project governance, and policy alignment while situating findings within global debates on engineering professionalism and delivery excellence.

5.1 Elevating Workforce Development Through Competency Frameworks
A recurring theme in the results is the predictive power of core competencies, especially technical problem-solving and communication, in ensuring commissioning success. This supports earlier assertions that engineering performance is not merely technical but socio-technical in nature [86]. When mapped against global engineering competency frameworks such as those of the World Federation of Engineering Organizations the CB-CEM aligns closely with 21st-century skill domains [86]. Embedding this model into training programs offers potential to address the growing skills gap in infrastructure delivery [87].

5.2 Strategic Project Governance and Adaptive Evaluation
CB-CEM enables project managers and owners to adopt more adaptive governance mechanisms. By linking competency evaluations with project milestones, teams gain actionable insights for real-time personnel optimization [88]. This contrasts with traditional commissioning, which often relies on post-mortem checklists that fail to prevent in-progress performance degradation [89]. Importantly, the model fosters a culture of continuous improvement by introducing feedback loops between stakeholders, aligning with agile principles now popular in construction management [90].

5.3 Alignment with Sustainable Infrastructure Delivery Goals
Modern infrastructure projects are increasingly framed within the Sustainable Development Goals (SDGs), where delivery efficiency, regulatory compliance, and quality assurance are vital. The competency-based approach promotes these ideals by ensuring that commissioning agents possess not only technical ability but ethical reasoning, regulatory literacy, and systems thinking [91]. These attributes are critical in green building certifications, smart infrastructure rollouts, and climate-resilient systems commissioning.

5.4 Benchmarking and International Model Integration
Comparisons with existing models such as the BSRIA and USACE frameworks highlight the CB-CEM's added granularity in behavioral assessments. By allowing attribution of project performance lapses to specific skill deficiencies, the model introduces a level of precision absent in existing commissioning protocols [92, 93]. This invites potential for hybrid models where CB-CEM metrics are layered atop baseline commissioning protocols to improve both diagnostic and predictive capabilities.

5.5 Policy Implications and Standardization Prospects
Results from multiple sectors suggest the possibility of CB-CEM becoming a standard evaluation protocol in infrastructure governance. Adoption could be accelerated through integration with ISO commissioning standards (e.g., ISO 50001 for energy management) and local statutory requirements [94]. Furthermore, regulators could link funding eligibility or project approvals to demonstrated use of competency-based evaluation models, thus institutionalizing higher quality assurance benchmarks [95, 96].

5.6 Socio-Cultural and Organizational Change Management
One limitation raised in the results relates to cultural variance in subjective scoring. This necessitates capacity building for evaluators and possibly the introduction of calibration tools or AI-driven assistive scoring [97, 98]. Organizational change management must also account for potential resistance, particularly in traditionally structured engineering teams where seniority often overrides performance-based evaluation.

In sum, CB-CEM offers a transformative model for commissioning evaluation, with implications that extend beyond project sites to educational, regulatory, and policy-making institutions.

6. Conclusion
The evolution of infrastructure project delivery models has underscored the need for modernizing how commissioning performance is evaluated. Traditional metrics rooted in compliance and schedule adherence no longer suffice to measure the dynamic interplay between technical complexity, human behavior, and collaborative leadership inherent in large-scale infrastructure commissioning. In response to this gap, this paper has proposed a competency-based performance evaluation framework that integrates technical, behavioral, and managerial dimensions to provide a more nuanced and holistic assessment of engineering performance in commissioning environments.

The findings from the comparative case study and statistical validation provide strong evidence that competency-based evaluation models significantly enhance the predictive reliability of commissioning outcomes. Key competencies such as stakeholder communication, problem-solving under uncertainty, adaptability to change, and collaborative leadership have demonstrated substantial correlations with successful commissioning delivery and sustained infrastructure performance. In contrast, organizations that adhered strictly to conventional metrics showed higher rates of operational defects, delays in handover, and post-commissioning inefficiencies [99, 100, 101].

This model not only bridges performance measurement with human capital strategy but also aligns with international best practices on workforce development in technical fields. By prioritizing the assessment of skill application rather than task completion, it enables project managers and commissioning authorities to pinpoint critical training gaps, identify high-potential professionals, and drive a culture of continuous learning and accountability [102, 103].

Moreover, in a rapidly digitizing infrastructure ecosystem, this model can be further enhanced through the integration of digital commissioning tools, real-time analytics, and automated competency dashboards [15, 104]. Such tools enable seamless tracking of individual and team-based performance metrics against expected commissioning standards, making evaluations both adaptive and scalable across diverse infrastructure typologies and geographies.

However, the model's effectiveness is contingent upon organizational buy-in, particularly from senior engineering leaders and commissioning authorities. Without systemic integration into project governance structures, even the most robust evaluation frameworks risk marginalization. Therefore, future research must explore change management strategies, competency policy adoption pathways, and multi-stakeholder engagement frameworks to embed competency-based assessments as standard practice in infrastructure commissioning.

In conclusion, redefining commissioning performance metrics through a competency-based lens offers a transformative opportunity to align engineering evaluation with contemporary project demands. It lays the foundation for a resilient, high-performing infrastructure workforce and paves the way for more adaptive, inclusive, and outcome-driven commissioning practices. This approach represents not merely a technical shift, but a strategic reimagining of how we define and reward engineering excellence in complex infrastructure delivery [105].

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