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Article

Bridging the Cognitive-Execution Gap: The Impact of Professional Awareness on Safety Risk Prevention and Quality Control in Mechanical, Electrical, and Plumbing Engineering

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Abstract

This study examined how Mechanical, Electrical, and Plumbing (MEP) practitioners understand and apply quality and safety management in construction projects in Taiwan. It focused on the gap between what practitioners know about best practices and what they can carry out on site, defined here as the “Cognitive-Execution Gap.” A mixed-methods design combined a questionnaire survey of 130 MEP practitioners with semi-structured interviews with six senior experts. Practitioners with MEP-related academic backgrounds scored significantly higher in professional knowledge and practice than those from unrelated fields, with mean differences of roughly 30% in key indicators. In contrast, awareness of management optimization strategies was high and similar across all demographic groups. Interview findings suggested that schedule pressure, the lower organizational status of MEP compared with civil engineering, and persistent talent shortages prevent practitioners from applying the practices they recognize as necessary. The results support the existence of a Cognitive-Execution Gap and suggest that bridging it requires organization-level reforms, including contractually enforced BIM-based coordination, clearer standard operating procedures and performance indicators, and structured mentorship programs to strengthen professional capacity in MEP engineering.

Keywords: mechanical electrical and plumbing (MEP); construction management; cognitive-execution gap; building safety; quality control; organizational culture; Building Information Modeling (BIM)

1. Introduction

Mechanical, Electrical, and Plumbing (MEP) systems are central to building operation because they govern energy use, indoor comfort, and life safety. As buildings become larger and more complex, MEP installations account for a substantial share of total construction costs and often occupy a comparable portion of the project critical path [1]. However, MEP works are often planned and managed less systematically than structural and architectural works. Coordination between MEP systems and civil or structural elements is frequently postponed or treated as secondary to other project priorities [2,3]. This practice leads to spatial clashes, rework, and delays, and has been linked to substantial cost growth, with direct rework costs averaging around 5% of total construction costs in prior studies [4]. Hidden defects in plumbing, electrical, and HVAC systems may remain unnoticed during construction and only appear during operation, causing safety incidents, higher

maintenance costs, and reputational damage to developers and contractors. Recent studies indicate that MEP works contribute disproportionately to construction accidents, often in congested spaces with multiple trades and inadequate hazard awareness [1,5].

In recent years, the construction industry has invested heavily in digital tools to address coordination and safety problems. Technologies such as Building Information Modeling (BIM), Internet of Things (IoT) monitoring, and artificial intelligence-based platforms are promoted for clash detection and design verification. However, studies of behavior-based safety programs show that new safety initiatives do not automatically lead to better outcomes when human and organizational issues are not addressed [6]. Many projects still fail to meet their quality and safety targets, suggesting that the main constraint is no longer the availability of technology but the way projects are organized and managed.

This situation motivates the central focus of this study. We propose the concept of a “Cognitive-Execution Gap” in the MEP sector, defined as the mismatch between practitioners’ understanding of quality, safety, and management principles and their ability to apply these principles consistently in the field. In this framework, construction personnel may score highly on assessments of awareness and attitudes yet still struggle to implement the same practices on site. The key research question is whether MEP practitioners in Taiwan know the importance of quality management and safety best practices but fail to apply them because of systemic organizational barriers rather than a lack of individual knowledge.

Previous research on construction has often examined technical skills, safety climate, or technology adoption separately. Prior studies have documented differences in technical ability by education level and have shown that work and schedule pressure are important drivers of unsafe behavior and degraded safety performance [5,7,8]. Fewer studies have measured whether high levels of technical and managerial knowledge are translated into reliable implementation in the field, or how organizational hierarchies may prevent this. To address this gap, the present study evaluates professional awareness in three dimensions—Professional Knowledge, Professional Practice, and Management Optimization Awareness—and links these measures to demographic factors and organizational conditions. Previous studies have shown that organizational conditions and safety climate strongly influence safety performance. Building on this work, the present study identifies how schedule pressure, talent shortages, and the dominance of civil engineering over MEP work together to undermine quality control [9,10].

This research bridges that theoretical divide by comprehensively evaluating professional awareness across three interdependent dimensions: Professional Knowledge, Practical Execution, and Management Optimization Awareness. Through a triangulation of quantitative psychometric survey data gathered from active industry practitioners and deep qualitative narratives extracted from senior industry experts, this study aims to systematically quantify demographic disparities in professional competency. Furthermore, it seeks to expose the underlying mechanisms of the awareness-execution paradox, explicitly investigating how schedule pressures, severe talent shortages, and the structural dominance of civil engineering over MEP disciplines sabotage quality control. Ultimately, this paper proposes evidence-based, institutional optimization strategies designed to transcend individual training and fundamentally restructure construction project execution.

2. Materials and Methods

This study used a mixed-methods design to investigate the Cognitive-Execution Gap in MEP engineering. A quantitative questionnaire survey was conducted to measure professional awareness across different demographic groups, followed by qualitative interviews to explain and deepen the survey findings.

The quantitative phase used a structured questionnaire with items rated on a 5-point Likert scale from 1 (Strongly Disagree) to 5 (Strongly Agree). The draft instrument was reviewed by academic and industry experts in fire protection, structural engineering, and occupational safety, and content

validity indices were used to refine item wording and coverage. The final questionnaire included three dimensions:

1. Professional Knowledge (12 items) assessed understanding of basic engineering principles, relevant regulations and codes, design calculation logic, and common schematic symbols across the major MEP systems.
2. Professional Practice (10 items) measured self-reported ability to perform field tasks such as participating in coordination meetings, resolving on-site clashes, modifying CAD/BIM drawings, and supervising testing procedures.
3. Management Optimization Awareness (8 items) captured perceptions of the need for systematic management strategies, including BIM-based simulation, regular cross-departmental meetings, clear change-order responsibility, and early risk prevention.

The target population was practicing MEP-related personnel in Taiwan, including staff from large construction firms, specialized MEP subcontractors, and supervisory bodies. A non-probability convenience sampling approach was used, relying on professional networks and online distribution channels to reach respondents. A total of 130 valid questionnaires were collected. The sample was predominantly male (90.8%, $N = 118$), reflecting the gender distribution in the regional heavy construction industry. Regarding experience, 25.4% ($N = 32$) had less than 3 years in the industry, 13.1% ($N = 17$) had 3–6 years, and 61.5% ($N = 81$) had more than 6 years. In terms of job level, 22% ($N = 29$) were Assistant or Junior Engineers, 32% ($N = 42$) were Directors or Vice Directors, and 45% ($N = 59$) were Senior Managers or above. For education, 15.4% ($N = 19$) had high school or vocational training, 67.7% ($N = 88$) had a university or college degree, and 16.9% ($N = 23$) held a graduate degree. Academic majors were classified as relevant or unrelated to MEP; 38% ($N = 50$) held degrees in fields such as electrical, mechanical, HVAC, or fire safety engineering, while 62% ($N = 80$) came from other disciplines.

To interpret the survey results and explore underlying mechanisms, semi-structured interviews were conducted with six senior industry experts. Purposeful sampling was used to recruit Vice Presidents, Engineering Directors, and General Managers from major construction and MEP firms. On average, the experts had more than 30 years of industry experience. Interviews lasted 60–90 minutes and covered topics such as differences between corporate quality policies and site practice, the impact of talent shortages, relations between civil and MEP engineering units, and recommended strategies for improving management.

Quantitative data were analyzed using SPSS. Descriptive statistics were used to summarize central tendencies and variability. Internal consistency was evaluated using Cronbach's alpha coefficients. Independent-samples t-tests examined differences between binary groups such as gender and academic major relevance. One-way ANOVAs tested differences across multiple categories such as seniority, job level, and education level; Scheffé post hoc tests were used when ANOVA results were significant ($p < 0.05$) to locate specific group differences while controlling for unequal sample sizes. Qualitative interview data were coded and thematically analyzed to identify recurring patterns and to explain how organizational structures and site conditions contribute to the Cognitive-Execution Gap.

3. Results

3.1. Reliability Analysis

The questionnaire showed high internal consistency across all three dimensions. Cronbach's alpha values were 0.944 for Professional Knowledge, 0.952 for Professional Practice, and 0.925 for Management Optimization Awareness. The overall 30-item scale had an alpha of 0.943 (Table 1).

Table 1. Reliability Analysis (Cronbach's Alpha).

Dimension	Number of Items	Cronbach's alpha	Interpretation
Professional Knowledge	12	0.944	Excellent
Professional Practice	10	0.952	Excellent
Management Optimization Awareness	8	0.925	Excellent
Total Scale	30	0.943	Excellent

3.2. Descriptive Statistics of the Dimensions

Descriptive results indicated that Management Optimization Awareness had the highest mean scores among the 130 respondents. For example, the item “MEP engineering requires detailed interface coordination before construction to reduce future changes and conflicts” had a mean of 4.59 out of 5.00, and the item on prevention being better than remediation scored a mean of 4.57. By comparison, scores in the Professional Knowledge and Professional Practice dimensions were lower and more dispersed. The item on explaining design basis load calculations had a mean of 2.82, illustrating gaps in certain technical competencies.

3.3. The “Relevance” Gap: Impact of Academic Background

Academic major relevance was strongly associated with differences in professional awareness (Table 2). Practitioners with MEP-related degrees scored higher than those with unrelated degrees in both Professional Knowledge (means 3.81 vs. 2.94, $p < 0.001$) and Professional Practice (means 4.00 vs. 3.22, $p < 0.001$).

Table 2. Independent Sample t-test by Academic Major Relevance.

Dimension	Academic Background	N	Mean	SD	T-value	p-value
Professional Knowledge	Relevant Major	50	3.81	0.79	-5.792	<0.001*
	Unrelated Major	80	2.94	0.86		
Professional Practice	Relevant Major	50	4.00	0.79	-4.867	<0.001*
	Unrelated Major	80	3.22	0.94		
Management Optimization	Relevant Major	50	4.47	0.65	-0.276	0.783
	Unrelated Major	80	4.44	0.53		

Note: * indicates statistical significance at $p < 0.05$.

Item-level analysis showed that relevant majors reported better understanding of the basic principles of the main MEP pipelines, higher familiarity with testing and inspection standards, and greater ability to use CAD/BIM tools for spatial coordination. Management Optimization Awareness scores, however, were similar between the two groups (4.47 vs. 4.44, $p = 0.783$), indicating that both groups held comparable views on the importance of management strategies.

3.4. The Impact of Seniority and Job Position

When respondents were grouped by years of experience, ANOVAs showed no significant differences in overall Professional Knowledge or Professional Practice scores. However, item-level Scheffé tests revealed that those with more than 6 years of experience were more familiar with specific regulations, such as building technical rules and fire laws, and placed higher value on cross-departmental coordination to prevent structural problems. Job level showed clearer differences. Assistant and Junior Engineers had lower mean scores in Professional Practice than Directors/Vice Directors and Senior Managers (3.03 vs. 3.67 and 3.65, $F = 5.164$, $p = 0.007$). They also scored lower in Management Optimization Awareness compared with higher-level staff (4.16 vs. 4.49 and 4.58, $F = 5.346$, $p = 0.006$). Post hoc analysis indicated that Senior Managers were more likely than Junior

Engineers to report being able to lead coordination meetings, propose specific technical solutions to on-site issues, train junior staff, and recognize the importance of BIM and clear change-order responsibilities.

Table 3. Results by Job Level.

Dimension	Job Level	N	Mean	SD	T-value	p-value
Professional Practice	Assistant/Junior Engineer	29	3.03	0.99	5.164	0.007*
	Director/Vice Director	42	3.67	0.82		
	Senior Manager & Above	59	3.65	0.99		
Management Optimization	Assistant/Junior Engineer	29	4.16	0.69	5.346	0.006*
	Director/Vice Director	42	4.49	0.54		
	Senior Manager & Above	59	4.58	0.5		

Note: * indicates statistical significance at $p < 0.05$.

3.5. Gender and Educational Attainment Disparities

Gender and highest educational level were included as additional variables. T-tests showed that male practitioners had higher mean scores than female practitioners in Professional Knowledge ($p = 0.003$) and Management Optimization Awareness ($p = 0.022$). This pattern likely reflects the current division of labor in Taiwan, where male staff are more often assigned to on-site technical and supervisory roles, while female staff more often work in administrative and support roles. ANOVAs showed no significant differences in any of the three dimensions across levels of overall educational attainment (high school/vocational, university, graduate school). These findings suggest that the relevance of one’s major to MEP work is more important than the level of the degree for developing technical and managerial competence in this domain.

3.6. Qualitative Findings: Unearthing the Execution Gap

The qualitative analysis identified three main themes explaining why high management awareness does not reliably translate into field execution.

1. Theme 1: the gap between ideals and execution under schedule pressure, described how strong corporate statements on quality and safety are often overridden by tight deadlines on site. Under time pressure, inspection procedures are shortened or skipped, and engineers rely on improvised solutions rather than standardized processes.
2. Theme 2: the marginalization of MEP under civil engineering dominance, highlighted how civil and structural units usually control the project schedule and spatial layout, leaving MEP teams limited influence over early design decisions. As a result, MEP installations must adapt to constrained spaces, which increases the risk of hidden defects, such as problematic rerouting and penetrations that are difficult to detect until operation.
3. Theme 3: the talent fault line and succession challenges, reflected the difficulty of recruiting and retaining personnel with formal MEP training. Experts noted that many workers come from unrelated fields and lack the theoretical background to interpret complex drawings and anticipate system interactions. They argued that industry–academia partnerships and structured mentorship programs are needed to build and sustain professional capacity.

4. Discussion

4.1. The Cognitive-Execution Paradox

The findings confirm the presence of a Cognitive-Execution Gap in MEP engineering. Respondents reported high awareness of management optimization principles, including early coordination, standard procedures, and the use of BIM, with mean scores close to the upper end of the scale. At the same time, lower and more variable scores in knowledge and practice, together with

expert interviews, showed that many practitioners cannot consistently implement these practices. This pattern aligns with the “knowing–doing” gap discussed in organizational research, where understanding of good practice does not automatically translate into consistent behavior [7,8]. Suggesting that building failures result from workers “not knowing better” is a fallacy; they know better, but are structurally prohibited from acting on that knowledge.

4.2. Civil Dominance and Structural Inequality

The study also highlights the role of organizational hierarchies in creating risk. Experts described a “Civil First, MEP Support” culture in which civil engineering decisions often take precedence and MEP teams have limited power to enforce spatial or sequencing requirements. This imbalance pushes MEP work into a reactive position, where installations are adapted to remaining space rather than planned integrally, increasing the likelihood of hidden defects and long-term performance problems. Addressing this issue requires elevating MEP input in early design and planning and giving MEP teams stronger authority in coordination processes [2,3].

4.3. The Consequences of the Talent Fault Line

The quantitative result that practitioners from non-relevant majors score substantially lower in knowledge and practice provides a clear indicator of the sector’s talent challenges. With more than half of the surveyed workforce trained in unrelated fields, many practitioners lack the theoretical base needed to independently identify risks and evaluate design choices. Experts noted that the industry’s reliance on on-the-job learning is strained by schedule pressure and aging senior staff, which limits opportunities for systematic knowledge transfer. Without targeted strategies for recruitment, training, and succession, this talent fault line is likely to deepen.

4.4. Strategic Imperatives for Institutional Restructuring

Bridging the Cognitive-Execution Gap likely requires organization-level reforms beyond individual training. The data indicate that further gains from awareness training alone appear limited, given the already high awareness scores. Instead, the industry must deploy system-level mechanisms that help sustain good practice even under schedule pressure.

First, the integration of Building Information Modeling (BIM) must transition from an optional visualization aid to a mandatory, contractually enforced conflict-resolution protocol. BIM serves as a neutral, data-driven platform that forces cross-disciplinary spatial coordination before physical construction begins. By identifying clashes virtually, BIM neutralizes the traditional authority asymmetries between civil and MEP teams, preventing the “Civil First” hierarchy from dictating suboptimal field adaptations [3].

Second, organizations must systematically replace their reliance on individual, ad-hoc experience with rigid Standard Operating Procedures (SOPs) and Key Performance Indicators (KPIs). Quality control mechanisms must be deeply institutionalized and tied directly to project financing and performance reviews, ensuring they cannot be bypassed when schedule pressures mount.

Finally, to address the talent fault line, firms must heavily invest in and formalize structured mentorship (apprenticeship) programs. Given the massive influx of personnel from non-relevant backgrounds, tacit knowledge transfer must be prioritized and financially incentivized by corporate leadership. Structured mentorship ensures that the critical theoretical and practical knowledge of senior engineers whose imminent retirement threatens to deepen the fault line is systematically transmitted to junior staff before it is permanently lost.

5. Conclusions

This mixed-methods study examined how Mechanical, Electrical, and Plumbing (MEP) practitioners in Taiwan understand and implement quality and safety management principles in construction projects. Survey results showed that awareness of management optimization

strategies—such as early interface coordination, standardized procedures, and the use of BIM—was consistently high across demographic groups. In contrast, technical knowledge and practical execution varied more widely, particularly by academic major relevance and job level, with practitioners from MEP-related disciplines and those in senior positions reporting higher competence.

Qualitative evidence from senior experts indicated that tight schedules, the organizational dominance of civil engineering over MEP, and shortages of formally trained MEP personnel often prevent practitioners from applying the management practices they recognize as important. Together, these findings support the proposed concept of a Cognitive–Execution Gap, whereby knowledge of best practice exists but is not reliably translated into field behavior because of structural and organizational constraints.

To narrow this gap, the findings suggest that construction organizations should complement awareness-raising initiatives with reforms at the project and corporate levels. Priorities include making BIM-based multidisciplinary coordination a mandatory component of design and pre-construction processes, institutionalizing clear standard operating procedures and quality-related performance indicators, and developing structured mentorship and training systems to support staff from non-MEP educational backgrounds. Future research could extend this work by incorporating objective performance indicators, longitudinal designs, and cross-country comparisons to further validate and generalize the Cognitive–Execution Gap framework in MEP engineering and beyond.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
MEP	Mechanical, Electrical, and Plumbing

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