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Bridging the Cognitive-Psychomotor Gap in Competency-Based TVET Technology Education: A Multi-Cohort Study of Solar Photovoltaic Installation and Maintenance

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ABSTRACT

Within Technical and Vocational Education and Training (TVET) frameworks worldwide, Competency-Based Education (CBE) has become a foundational paradigm that prioritizes measurable student capabilities rather than traditional lecture-hour accumulation. Nonetheless, executing CBE successfully remains difficult, particularly in achieving and sustaining coherent alignment among cognitive, psychomotor, and affective learning domains. This article examines a five-cohort longitudinal dataset from the course BELS1245 (Solar PV Installation and Maintenance), situated within a Bachelor of Technology in Electrical Maintenance System program between the academic terms 2021/2022 and 2025/2026 (N = 185 total participants). Using John Biggs' Presage-Process-Product (3-P) framework alongside the principles of constructive alignment, we evaluate academic achievements across three distinct Course Learning Outcomes (CLOs) representing intellectual knowledge (LO01), physical installation skills (LO02), and professional ethics (LO03). The empirical results indicate a severe practical-cognitive disconnect. Although student attainment in psychomotor and affective domains was exceptionally strong, ranging from 96.0% to 100.0%, cognitive comprehension collapsed from 92.0% during the initial two cohorts to 51.0% in the third cohort, before leveling off at 55.0% in the fifth cohort. To remedy this performance imbalance and establish holistic professional competencies, several evidence-based Continuous Quality Improvement (CQI) measures are recommended, including Just-in-Time Teaching (JiTT), multidisciplinary engineering design initiatives, and targeted analytics within Learning Management Systems (LMS).

Keywords— Competency-based training, Constructive alignment, Pedagogical strain, Practical-cognitive mismatch, Solar energy education, Vocational instruction.

INTRODUCTION

Contemporary tertiary education is undergoing a major paradigm shift, migrating away from traditional instructor-led models and toward student-centric, results-oriented training frameworks [1, 7]. Prominent among these developments are Outcome-Based Education (OBE) and Competency-Based Education Systems (CBES), designed to align curriculum objectives directly with industrial requirements and societal needs [8, 21, 26]. In contrast to standard academic programs that rely on credit-hour accumulation and formal testing for evaluation, CBES demands that candidates exhibit measurable, verifiable mastery of both theoretical concepts and practical applications prior to graduation [12, 17, 27]. This focus on practical capability is highly critical within the Technical and Vocational Education and Training (TVET) sector [30].

In Malaysia, the fast-paced development of the sustainable energy sector has catalyzed an urgent need for proficient personnel capable of designing, installing, and servicing green energy systems, especially solar photovoltaic (PV) technologies. Technical institutions bear the responsibility of preparing engineering graduates who understand not only the physics of photovoltaic devices but also possess the hands-on psychomotor skills necessary to install, configure, inspect, and commission complex solar arrays safely and in accordance with regulatory frameworks. Nevertheless, executing competency-based frameworks in technical fields requires a careful balance between the three primary domains of human learning originally established by Benjamin Bloom: cognitive, psychomotor, and affective domains [23]. While TVET's highly hands-on environment inherently supports physical performance, industry partners frequently report that new graduates lack the underlying mathematical and theoretical knowledge required to troubleshoot system faults, synthesize complex technical structures, and resolve difficult engineering issues analytically [15].

This study investigates this practical-cognitive disconnect by examining student academic performance across five cohorts in the course BELS1245: Solar PV Installation and Maintenance, delivered at a Malaysian public technical university. Over five academic sessions (from 2021/2022 to 2025/2026), we monitor N = 185 students, uncovering a noteworthy pedagogical phenomenon: while candidates obtain near-flawless competency rates in practical construction and policy adherence, their capacity to mathematically utilize theoretical PV concepts undergoes a major decline, dropping by more than 40% as student enrollment doubles.

By evaluating this performance gap using John Biggs' Presage-Process-Product (3-P) model [16] and comparing it with global educational quality assurance standards [14, 20], this research diagnoses the underlying drivers of the cognitive bottleneck in technical vocational instruction. Ultimately, we propose actionable, data-driven continuous quality improvement (CQI) interventions to restore educational equilibrium.

Theoretical Framework And Literature Review

A. Outcome-Based Education and Constructive Alignment

The structural foundation of modern vocational and engineering programs is heavily rooted in Outcome-Based Education (OBE) paradigms [24]. OBE operates on the premise that educational programs must begin with clear, explicit descriptions of what students should know, comprehend, and perform upon graduation—known as Course Learning Outcomes (CLOs) or Expected Learning Outcomes (ELOs) [1]. To enhance the utility of these outcomes, Biggs and Tang introduced the theory of constructive alignment [16]. This principle suggests that to achieve optimal educational quality, the pedagogical delivery, practical laboratory tasks, and assessment methods must be systematically mapped to and aligned with the specified learning outcomes. Under a constructively aligned curriculum, the educator serves as an educational facilitator, and the learner's active engagement is prioritized over passive lecture delivery [16]. For instance, if a CLO requires students to 'apply' a concept (corresponding to a C3 application level in Bloom's Taxonomy), then both the instructional exercises and the assessment instruments must require active, practical problem-solving rather than rote memorization or simple knowledge retrieval [23].

B. The Presage-Process-Product (3-P) Model of Learning

To methodically inspect how vocational students navigate their educational experiences, this paper draws upon John Biggs' Presage-Process-Product (3-P) framework [16]. This pedagogical model portrays teaching and learning as a dynamic system divided into three integrated stages:

- **Presage Factors:** Conditions existing prior to the learning process, which are divided into individual Student Factors (such as academic preparation, cognitive capacity, learning styles, and motivation) and the institutional Teaching Context (including class size, course structures, laboratory resources, teaching techniques, and assessment styles).

- **Process Level:** The behaviors and activities that students employ when studying. Learners generally pursue either a deep approach (aiming to achieve profound understanding, evaluate concepts critically, and integrate theoretical details) or a surface approach (seeking to fulfill assessment tasks with minimal cognitive effort, typically through rote recall and passive memorization).

- **Product Level:** The character and depth of the educational outcomes, which can span from basic knowledge reproduction to complex, independent inquiry, critical analysis, and lifelong learning capabilities.

Within TVET contexts, the 3-P framework is highly useful for demonstrating how shifts in the teaching context—such as expanding enrollment numbers or poorly structured testing—can unintentionally push students from deep learning to surface memorization, consequently degrading the quality of the educational product [15, 30].

C. Competency-Based Evaluation and Grading Scales

A major hurdle in the widespread implementation of Competency-Based Education (CBE) has been the absence of standardized, diagnostic grading methods [12]. Traditional single-letter grades (e.g., 'A' or 'B') merge different aspects of student achievement into a single score, hiding individual student performance patterns across various competency areas [23]. To address this limitation, researchers have proposed multi-dimensional grading metrics, such as specialized 1-to-10 rating systems and structured Likert scales, to evaluate discrete capabilities such as content knowledge, communication, self-regulation, and written composition [12, 28]. Concurrently, technical educators have utilized detailed, rubric-based direct assessments [14]. By establishing explicit, measurable key performance indicators (KPIs) across progressive proficiency levels—ranging from beginner (1), approaching (2), meeting (3), to exceeding (4)—these analytical rubrics offer detailed, actionable feedback to students and faculty, enabling structured continuous quality improvement [14, 23].

D. Assessment Approaches in TVET: A Systematic Context

In vocational and practical settings, assessment strategies perform a dual role: verifying regulatory safety and technical proficiency for industrial certifications, and diagnosing student academic development [30]. A comprehensive PRISMA-guided review of TVET assessment methodologies across different countries documented twelve distinct evaluation approaches, highlighting competency-based assessment (CBA), performance-based assessment (PBA), and formative assessment (FA) as the most widely used methods [30]. This research concluded that although CBA is highly effective at certifying practical, industry-specific skills, these tools must be integrated with theoretical and reflective assessments. Such integration is essential to encourage deep cognitive processing and prevent candidates from merely executing rote, checklist-driven procedures without understanding the underlying concepts [30].

METHODOLOGY AND COURSE CONTEXT

A. Institutional and Course Context

This longitudinal study was conducted at a specialized technical university in Malaysia that specializes in engineering technology and TVET education. The focus of this research is BELS1245: Solar PV Installation and Maintenance, a mandatory, core subject within the Bachelor of Technology in Electrical Maintenance System with Honours (BELS) curriculum. According to the approved course syllabus, BELS1245 is designed to familiarize students with the technical vocabulary, core electrical principles, and engineering design standards governing solar energy systems. It prepares students to design, set up, test, and troubleshoot both stand-alone (off-grid) and grid-connected solar PV systems, ensuring strict compliance with local safety standards and guidelines established by the Sustainable Energy Development Authority (SEDA) Malaysia.

B. Course Learning Outcomes (CLOs) and Domain Mapping

The course BELS1245 features three Course Learning Outcomes (CLOs) designed to address three distinct learning domains—cognitive, psychomotor, and affective as illustrated in Table 1.

Table 1 Course Learning Outcomes And Domain Classifications For The Bels1245 Course

Outcome Code	Course Learning Outcome Statement	Learning Domain	Taxonomy Classification
LO01	Apply the principles of solar PV system technology	Cognitive	C3 (Application Level)

LO02	Build a stand-alone PV system configuration	Psychomotor	P4 (Mechanism Level)
LO03	Follow SEDA standards and policies in Malaysia	Affective	A3 (Valuing Level)

C. Constructive Alignment of Assessments

To maintain constructive alignment and ensure robust evaluation of all three learning domains, BELS1245 employs a comprehensive, structured evaluation framework:

1. Cognitive Assessment (LO01): This outcome is assessed through an individual, formal written Theory Test, which accounts for 20% of the overall course mark. The exam requires students to complete complex mathematical calculations, determine PV shading ratios, analyze thermal coefficients, and design functional solar arrays based on electrical parameters.

2. Psychomotor Assessment (LO02): Practical skills are evaluated via five continuous Laboratory Assessments (each weighted at 10%, totaling 50%) and two practical Laboratory Exams (each weighted at 10%, totaling 20%). This practical component represents 70% of the total course grade. Students are evaluated on safe working habits, appropriate use of Personal Protective Equipment (PPE), correct electrical wiring techniques, secure system integration of batteries, charge controllers, and inverters, and final system testing.

3. Affective Assessment (LO03): Professional attitudes and values are evaluated through a collaborative group report and presentation (weighted at 10%), which measures the students' ability to comply with and advocate for Malaysian solar PV guidelines.

D. Data Collection and Sample Size

Academic performance records were collected across five consecutive student cohorts over a five-year longitudinal window spanning from the 2021/2022 to the 2025/2026 academic years. The distribution of the student enrollment is as follows:

- Cohort 1 (2021/2022): n_1 = 25 students
- Cohort 2 (2022/2023): n_2 = 27 students
- Cohort 3 (2023/2024): n_3 = 31 students
- Cohort 4 (2024/2025): n_4 = 33 students
- Cohort 5 (2025/2026): n_5 = 69 students

This resulted in a total cumulative sample size of N = 185 students. Performance profiles for each course learning outcome were obtained from the institution's secure student database. The data were processed to compute the success rate for each outcome, where the threshold of competence was defined as achieving a score of 50% or higher on the respective assessments.

Quantitative Results And Longitudinal Analysis

A. Comparative Analysis of LO Attainment Across Cohorts

The five-year longitudinal dataset shows a clear divergence in student performance across different learning domains. While practical psychomotor skills (LO02) and affective development (LO03) remained exceptionally high throughout the study, academic achievement in the cognitive domain (LO01) dropped significantly. Table 2 displays the specific success rates of each learning outcome across the five cohorts.

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Table 2 Longitudinal Success Rates (%) By Learning Outcome Across Cohorts (2021/22 – 2025/26)

Evaluated Outcome	**Cohort 1 (2021/22)**	**Cohort 2 (2022/23)**	**Cohort 3 (2023/24)**	**Cohort 4 (2024/25)**	**Cohort 5 (2025/26)**
Sample Size (N)	**25**	**27**	**31**	**33**	**69**
LO01: Cognitive Domain (Theory Exam)	92.0%	92.0%	51.0%	52.0%	55.0%
LO02: Psychomotor Domain (Practical Work)	92.0%	96.0%	100.0%	100.0%	100.0%
LO03: Affective Domain (Policy Compliance)	96.0%	96.0%	100.0%	97.0%	98.0%

As illustrated by the empirical trends in Table 2, students in Cohorts 1 and 2 achieved balanced and high success, with more than 92.0% of candidates meeting competency standards across all three domains. However, in the 2023/2024 academic session (Cohort 3), LO01 performance plummeted, dropping 41 percentage points to just 51.0%. This theoretical bottleneck persisted in subsequent academic years, showing only minimal recovery to 55.0% by Cohort 5. In contrast, the success rates for LO02 and LO03 rose, with practical performance reaching a consistent 100.0% success rate from Cohort 3 onward.

B. Visualizing the Practical-Cognitive Mismatch

To better understand the relationship between student enrollment expansion and learning domain misalignment, longitudinal trends were plotted. Figure 1 illustrates the diverging trajectories of cognitive attainment (LO01) versus psychomotor (LO02) and affective (LO03) attainment, overlaid with the dramatic rise in class size (N).

The visual data in Figure 1 clearly shows that as the class size remains small ($N \leq 27$), the institution's teaching and assessment structure functions successfully, yielding balanced learning across all three domains. However, as class size rises, a severe gap opens. The gap is widest in Cohort 5, where class size more than doubles to 69 students: psychomotor attainment is at a perfect 100%, yet nearly half the class (45%) fails to achieve cognitive competence in basic solar PV principles.

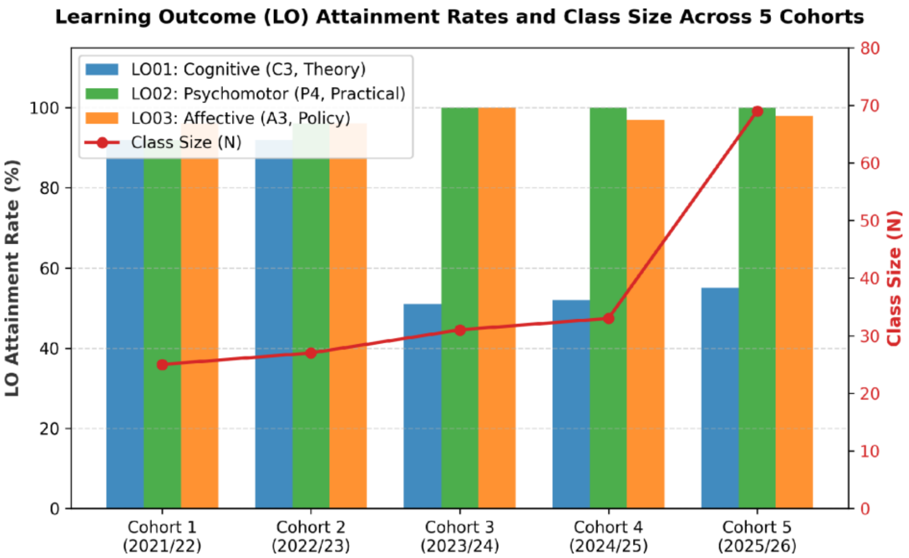

Figure 1: Diverging trajectories of cognitive, psychomotor, and affective learning outcome attainment rates overlaid with class size (N) expansion across five cohorts (2021/22 to 2025/26).

The trends show that when the student enrollment was small ($N \leq 27$), the course's instructional and assessment structures yielded high performance across all three learning domains. However, as the student population expanded, a significant gap emerged. This gap is most pronounced in Cohort 5, where the student count rose to

69: while psychomotor success reached a perfect 100.0%, nearly half the cohort (45.0%) failed to demonstrate basic cognitive competency in solar PV engineering principles.

DISCUSSION

A. The Cognitive Bottleneck: Analyzing the Misalignment

The empirical findings of this research highlight a notable pedagogical paradox in TVET-based engineering education which is how does a student cohort achieve a perfect 100.0% success rate in physical solar PV assembly (LO02), while nearly half the class fails to grasp the mathematical and engineering concepts behind it (LO01). Analyzing this through Biggs' 3-P model points to the nature of the assessment methods [16].

Practical laboratory work (LO02) is evaluated continuously using structured, step-by-step laboratory instructions and hands-on exams. In these sessions, students typically work in pairs or small groups. While such collaboration supports peer communication and collaborative work [30], it can inadvertently allow struggling students to rely on their peers to complete the actual electrical installations [15]. Additionally, this can lead to assessments reflecting checklist-completion rather than actual conceptual understanding [15]. Under these circumstances, students can follow the laboratory procedures like a 'recipe,' successfully completing the physical mechanism (P4) without executing high-level intellectual analysis (C3) [23].

Conversely, the cognitive outcome (LO01) is assessed through an individual, closed-book Theory Test. On this exam, students do not have group assistance, practical guides, or real-time mechanical feedback. To pass, a candidate must possess an independent, solid conceptual framework of the course material. The sharp drop in LO01 success indicates that many students adopted a surface learning approach—memorizing physical steps to clear the practical labs while failing to build the cognitive structures required to apply mathematical principles to theoretical engineering problems. This observation is consistent with findings by Ayadat et al., who reported that engineering students often perform poorest on learning outcomes that require individual, mathematical application of physical science concepts [14].

B. The Class Size Effect and Pedagogical Strain

The longitudinal results suggest that the sharp decline in cognitive performance is strongly linked to the rapid expansion of student enrollment. By Cohort 5, the class size had grown to 69 students. In a standard classroom setup, a single academic is unable to provide individual feedback, facilitate interactive discussions, or perform ongoing formative diagnostics for 69 individual learners [24].

Consequently, the educational delivery style frequently falls back onto traditional, passive lecturing. Within Biggs' 3-P framework, this represents a negative shift in the teaching context, moving from an active, deep-learning environment to a passive, surface-learning setting [16]. Under severe pedagogical strain, the instructor's time and energy are heavily consumed by logistical tasks, laboratory safety management, and resource allocation for a large student body, leaving theoretical lectures largely isolated from active, practical application.

CONTINUOUS QUALITY IMPROVEMENT (CQI) RECOMMENDATIONS

1) Transition to Project-Based, Crossed-Subject Design Projects

To discourage the rote, recipe-following approach during laboratory work and encourage deep-level learning, BELS1245 should implement a crossed-subject design project model, similar to the one introduced by Teo [29]. Instead of completing isolated, structured weekly lab tasks, students should work on open-ended, community-centered engineering challenges, such as designing and testing a solar-powered disaster-relief clean water system. This method forces students to synthesize their physical wiring skills with their theoretical knowledge of electrical load calculations.

2) Implement Just-in-Time Teaching (JiTT) and Active Learning

To mitigate the challenges associated with larger classes, course coordinators should transition away from traditional, passive lecture formats toward Just-in-Time Teaching (JiTT) and active, constructivist teaching strategies [24]. Under a JiTT approach, students complete brief, web-based diagnostic quizzes on core theoretical topics before attending class. The educator reviews these submissions prior to the lecture, adjusting the face-to-face session to focus on specific misconceptions. During class, students participate in group problem-solving, interactive tutorials, and peer-led instruction, which have been shown to develop analytical and critical thinking skills in larger class settings.

3) Leverage Learning Management Systems (LMS) for Personalized Analytics

As observed by Meng, contemporary LMS platforms provide powerful capabilities for personalized instruction and ongoing academic diagnostic monitoring [25]. To assist underperforming students in a large cohort, the LMS should be used to provide individualized learning activities, interactive simulations, and responsive feedback systems [25]. Faculty can use LMS analytics to identify students struggling with preparatory quizzes, enabling early and targeted interventions before students sit for the formal written Theory Test.

Conclusion

In conclusion, this five-cohort longitudinal analysis of the course BELS1245 (Solar PV Installation and Maintenance) highlights the practical-cognitive disconnect that can occur in competency-based vocational education. While physical psychomotor performance (LO02) and regulatory awareness (LO03) remained exceptionally high, individual cognitive competence (LO01) declined as student numbers doubled, creating a major educational bottleneck. This misalignment was exacerbated by a teaching context that allowed candidates to rely on surface, checklist-driven methods in the laboratory without fully integrating the mathematical and physical principles needed for engineering design.

To address this challenge and close the quality loop, technical universities must transition from isolated, repetitive lab exercises to constructively aligned, interdisciplinary design projects. These projects should be supported by active learning methods like Just-in-Time Teaching and robust learning technologies. By applying these structural quality improvements, vocational and technical institutions can ensure that their graduates possess both the hands-on proficiency and the analytical capabilities required to lead the clean energy transition safely and innovatively.

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