Developing an Industry-Aligned TVET Curriculum Framework and Authentic Assessment Blueprint for Automotive Checking Fixture Fabrication

Widodo W.S.*, Sulaiman S.N.

Faculty of Mechanical Technology and Engineering University Teknikal Malaysia Melaka (UTeM)

***Corresponding Author**

DOI: https://doi.org/10.47772/IJRISS.2026.100900764

Received: 04 October 2026; Accepted: 09 October 2026; Published: 23 October 2026

ABSTRACT

Modern automotive manufacturing depends on precise quality control, yet traditional Technical and Vocational Education and Training (TVET) curricula fall short. Conventional programs rely heavily on passive lectures and isolated 3D CAD exercises, an approach that leaves graduates ill-prepared for real-world Geometric Dimensioning and Tolerancing (GD&T), workholding mechanics, and shop-floor metrology. To address this gap, we developed and validated a 14-week project-based TVET framework and assessment blueprint centered on automotive checking fixture fabrication. Guided by Design-Based Research (DBR) and the Conceive-Design-Implement-Operate (CDIO) lifecycle, our approach integrates parametric CAD modeling, CNC machining, FDM 3D printing, and Coordinate Measuring Machine (CMM) verification with Measurement System Analysis (MSA). An expert panel of twenty industrial quality managers and TVET educators evaluated the framework, establishing strong content and construct validity with Item-Objective Congruence (IOC) scores above 0.80. The resulting 90-contact-hour curriculum features an authentic assessment rubric that ties 70% of the total grade directly to physical fabrication accuracy and metrological compliance (GRR < 30%). This model provides TVET institutions with an expert-validated, practical roadmap to align academic instruction with modern industrial quality standards

Keywords: TVET, Checking Fixture, CDIO Model, Geometric Dimensioning and Tolerancing (GD&T)

INTRODUCTION

Modern manufacturing assembly relies heavily on precise quality control, Geometric Dimensioning & Tolerancing (GD&T) standards, and specialized inspection tooling (Förster et al., 2026; Goetz et al., 2025; Sarıkaya et al., 2026; Sawant & Kadam, 2024; Sumasto et al., 2025). Checking fixtures and inspection jigs secure workpieces, establish datum references, reduce dimensional variation, and ensure component interchangeability across supply chains (Goetz et al., 2025; Sarıkaya et al., 2026; Sawant & Kadam, 2024). In industrial production, fixture inaccuracies cause roughly 40% of defective parts and account for 10% to 20% of total manufacturing costs (Niknam et al., 2021).

Despite these strict quality requirements, traditional Technical and Vocational Education and Training (TVET) curricula remain disconnected from modern assembly standards (Emmanuel, 2026; Metavia et al., 2026; Sarıkaya et al., 2026; Vázquez-Villegas & Borrego, 2026; Yoto et al., 2024). Industry evaluations show that only 26.14% of recent engineering graduates understand dimensional tolerancing, and merely 14.77% can properly apply international standards such as ASME Y14.5 and ISO Geometrical Product Specifications (ISO GPS) (Sarıkaya et al., 2026). This knowledge gap creates real financial damage: 79.55% of industry professionals report production delays, 78.41% incur rework costs, 73.86% deal with scrap generation, and 72.73% report material waste (Sarıkaya et al., 2026).

Most technical instruction relies on passive lectures, theoretical metrology, and standalone Computer-Aided Design (CAD) exercises (Agordah & Akrofi, 2026; ASEE, 2019; Nwoye et al., 2023; Sarıkaya et al., 2026;

Vázquez-Villegas & Borrego, 2026). These traditional methods fail to convey physical workholding mechanics, manufacturability, or practical quality verification (Culler, 2025; Sarıkaya et al., 2026; Sykes & Lenton, 2020; Vázquez-Villegas & Borrego, 2026). Compounding the problem, academic grading routinely awards passing marks to parts that factory quality managers would reject outright, reinforcing a low-stakes culture that undermines student readiness (ASEE, 2019)

While existing literature frequently discusses broad technical skills gaps (Agordah & Akrofi, 2026; Emmanuel, 2026; Sūtoová et al., 2026; Vázquez-Villegas & Borrego, 2026), few studies provide a practical, hands-on instructional framework for checking fixtures and precision inspection tooling in TVET environments (Sarıkaya et al., 2026; Sumasto et al., 2025; Vázquez-Villegas & Borrego, 2026). Most pedagogical research remains focused on software modeling, theoretical machine design, or abstract statistical process control (Farber et al., 2026; McPherson, 2019; Sarıkaya et al., 2026; Sumasto et al., 2025). Because these approaches isolate classroom theory from physical reality, students struggle to translate digital tolerance callouts into functional hardware (Culler, 2025; Sarıkaya et al., 2026; Sykes & Lenton, 2020; Vázquez-Villegas & Borrego, 2026). Additionally, vocational instruction lacks a standardized assessment blueprint to evaluate physical manufacturing precision alongside Measurement System Analysis (MSA), including Gage Repeatability and Reproducibility (GRR) (ASEE, 2019; McPherson & Reiter, 2019; Sumasto et al., 2025). Without an expert-validated workflow linking theoretical GD&T, physical fixture fabrication, and empirical GRR validation, institutions will continue producing graduates who require expensive post-graduation retraining (Agordah, 2026; Metavia et al., 2026; Nwoye et al., 2023; Zhang et al., 2026)

To bridge this gap, we developed and validated an industry-aligned, 14-week TVET curriculum framework and assessment blueprint centered on automotive checking fixture fabrication. Grounded in Design-Based Research (DBR) and the Conceive-Design-Implement-Operate (CDIO) educational model, our study bridges digital CAD modeling, physical tool fabrication, and closed-loop metrological verification.

Specifically, this study addresses two main objectives:

- To identify and map industry competency requirements for GD&T, checking fixture design, and Measurement System Analysis (MSA) in automotive manufacturing.
- To establish and structurally validate a 14-week CDIO curriculum framework and assessment blueprint through a formal expert panel of industrial quality managers and TVET educators.

To ensure methodological transparency, the scope of this study is intentionally focused on the theoretical synthesis, structural architecture design, and expert-panel validation of the 14-week TVET checking fixture framework. While full empirical deployment across active student cohorts lies beyond the immediate boundary of this design stage, establishing rigorous content and construct validity through industry and academic experts provides the necessary prerequisite blueprint prior to large-scale classroom implementation.

Significance of the Study

This study provides clear socio-technical, educational, and economic contributions:

- TVET Institutions and Pedagogy: By shifting classroom instruction from passive lecturing to active project-based learning (Peasura et al., 2025; Sawant & Kadam, 2024), the framework strengthens 3D-to-2D spatial visualization, critical thinking, and practical problem-solving capabilities (Sawant & Kadam, 2024).
- Manufacturing Sector: Grounding technical training in physical checking fixtures and structured MSA directly reduces measurement error (Sumasto et al., 2025). Implementing custom inspection fixtures can lower total Gage R&R variation from an unviable 100% down to an acceptable 26.27%, significantly curbing scrap generation, rework, and assembly line downtime (Sarıkaya et al., 2026; Sumasto et al., 2025).
- Educators and Infrastructure: The framework provides instructors with validated rubrics, low-cost additive manufacturing strategies, and industry-aligned modules (Niknam et al., 2021; Peasura et al.,

2025; Sawant & Kadam, 2024). This allows institutions to modernize their training offerings without requiring massive capital investments (ASEE, 2019; Emmanuel, 2026; Niknam et al., 2021).

- Graduate Employability: Hands-on experience with modern quality tools improves graduate workplace readiness, supporting higher job placement rates and starting salaries while strengthening national manufacturing competitiveness (Emmanuel, 2026; Metavia et al., 2026; Nwoye et al., 2023; Otu, 2026; Wahab et al., 2024).

LITERATURE REVIEW

Industry-Academia Competency Gap in Quality Control & Metrology

As global manufacturing rapidly undergoes the digital transformations driven by Industry 4.0 and Quality 4.0, a persistent and widening skills gap separates technical engineering graduates from real-world industrial needs (Agordah & Akrofi, 2026; Farber et al., 2026; Sūtoová et al., 2026; Vázquez-Villegas & Borrego, 2026; Yoto et al., 2024). Modern quality engineering roles demand a hybrid, versatile skill set; one that seamlessly integrates statistical process control and advanced physical metrology with digital thread literacy and practical shop-floor problem solving (Farber et al., 2026; Sūtoová et al., 2026; Trávníčková et al., 2024). However, recent empirical workforce surveys reveal staggering readiness gaps among early-career engineers, with deficiency rates reaching 64% to 69% in core technical skills and 74% to 75% in methodological application (Sūtoová et al., 2026).

At the core of this industrial disconnect is a widespread graduate struggle with technical drawing literacy, drawing interpretation, and strict adherence to Geometric Dimensioning and Tolerancing (GD&T) standards (Blacklock & Vanderbeek, 2022; Goetz et al., 2025; Sarıkaya et al., 2026; Schuldt et al., 2026). In mass production automotive assembly, checking fixtures and inspection jigs secure workpieces, establish datum reference frames, minimize dimensional variation, and ensure component interchangeability across global supply chains (Goetz et al., 2025; Sarıkaya et al., 2026; Sawant & Kadam, 2024). Industrial reports highlight that fixture inaccuracies account for roughly 40% of defective parts and contribute to 10% to 20% of total manufacturing costs (Niknam et al., 2021). Despite the criticality of these tools, a cross-national survey of manufacturing professionals revealed that only 26.14% rated new engineering graduates as proficient in dimensional tolerancing, and a mere 14.77% considered them competent with international standards such as ASME Y14.5 and ISO GPS (Sarıkaya et al., 2026).

These classroom shortfalls carry a severe financial and operational penalty on the factory floor. Graduate errors in drawing interpretation and GD&T callouts directly trigger production delays (79.55%), costly component rework (78.41%), scrap generation (73.86%), and material waste (72.73%) (Sarıkaya et al., 2026). When graduates fail to establish accurate datum references, apply geometric tolerances correctly, or grasp workholding mechanics, final product quality degrades sharply (Goetz et al., 2025; Sawant & Kadam, 2024; Sumasto et al., 2025). Technical and Vocational Education and Training (TVET) institutions struggle to keep pace with evolving modern tooling standards, leaving programs hindered by obsolete equipment and outdated static curricula (Emmanuel, 2026; Muoghalu & Ahmad, 2025; Nwoye et al., 2023; Wahab et al., 2024). Consequently, employers have little choice but to allocate substantial financial and time resources toward post-graduation industrial retraining simply to teach foundational quality verification (Agordah, 2026; Emmanuel, 2026; Metavia et al., 2026; Sūtoová et al., 2026; Vázquez-Villegas & Borrego, 2026).

Limitations of Current TVET Curricula and the 'CAD Black Box' Phenomenon

Traditional engineering and TVET education relies heavily on passive lectures, isolated 3D CAD modeling, and theoretical metrology (Agordah & Akrofi, 2026; Bondin & Zammit, 2025; Culler, 2025; Zhang et al., 2025). In practice, standard CAD coursework operates as a procedural 'black box' where students generate 3D geometries on screen without comprehending physical manufacturability, kinematic locating, tolerance stack-ups, or inspection feasibility (Sarıkaya et al., 2026; Sykes & Lenton, 2020; Zhang et al., 2025). Compounding this issue, academic grading routinely awards passing marks to 'C-grade' work that factory quality managers would reject outright, fostering a low-stakes culture that tolerates physical non-conformance (American Society for Engineering Education [ASEE], 2019; McPherson & Reiter, 2019).

A major structural flaw in modern technical curricula is the deep divide between theoretical GD&T instruction

and physical tool fabrication or inspection hardware (Blacklock & Vanderbeek, 2022; Gani et al., 2024; Sawant & Kadam, 2024; Sumasto et al., 2025). Students seldom gain practical, hands-on experience with physical checking fixtures, kinematic locating mechanics (such as the 3-2-1 principle), or specialized clamping systems needed for flexible sheet-metal parts (Goetz et al., 2025; Sawant & Kadam, 2024). Furthermore, laboratory practicals rarely incorporate Measurement System Analysis (MSA) or Gage Repeatability and Reproducibility (GRR) studies (McPherson & Reiter, 2019; Sumasto et al., 2025). Lacking MSA exposure, future technicians and engineers cannot differentiate true workpiece variation from gauge or operator error, leading to flawed quality decisions on the factory floor (McPherson & Reiter, 2019; Sumasto et al., 2025).

Synthesizing current TVET and engineering literature reveals three core structural gaps in quality control education:

- The CAD & GD&T Pedagogy Gap: While conventional CAD courses excel at teaching software navigation and geometry creation, they routinely fail to demonstrate how digital tolerance callouts translate into physical manufacturing constraints, realistic datum selection, or 3D tolerance stack-ups (Sarıkaya et al., 2026; Zhang et al., 2025).
- The Workholding & Locating Mechanics Gap: Standard machining modules focus heavily on producing part geometry on screen while neglecting workholding mechanics. Consequently, students rarely master kinematic 3-2-1 locating, datum targeting, or clamp-induced deflection in thin-walled or flexible components (Goetz et al., 2025; Sawant & Kadam, 2024).
- The MSA & Verification Gap: Metrology instruction remains overwhelmingly abstract and lecture-driven. By omitting Measurement System Analysis (MSA) and Gage R&R protocols from laboratory practicals, academic institutions reinforce a low-stakes culture that tolerates measurement inaccuracy and lacks accountability (ASEE, 2019; Sumasto et al., 2025).

Active Pedagogies, CDIO Educational Framework, and Closed-Loop Metrology

To bridge these competency gaps, technical programs increasingly adopt active learning paradigms, notably Project-Based Learning (PBL), Teaching Factory (TF) models, and the Conceive-Design-Implement-Operate (CDIO) educational framework (Agordah, 2026; Khan et al., 2021; Peasura et al., 2025; Zhang et al., 2026). PBL replaces passive lecturing with student-driven problem solving, strengthening spatial reasoning and core analytical capabilities (Khan et al., 2021; Niknam et al., 2021; Sawant & Kadam, 2024). For instance, hands-on instructional modules focused on jig and fixture design boosted Course Outcome attainment by 10.37% over traditional lecture methods (Sawant & Kadam, 2024).

However, most CDIO and PBL initiatives in TVET short-circuit at the finish line. Instructional lifecycles typically terminate at fabrication ('Implement') or rely on subjective visual scoring during 'Operate' (ASEE, 2019; Blacklock & Vanderbeek, 2022; Gani et al., 2024). Rather than holding student prototypes to industrial quality protocols, conventional courses evaluate work based on superficial assembly or visual finish alone (ASEE, 2019; McPherson & Reiter, 2019; Sarıkaya et al., 2026; Sumasto et al., 2025).

To elevate CDIO into a zero-defect engineering discipline, active learning frameworks must incorporate a closed-loop metrological validation pipeline into the 'Operate' phase (Crawley et al., 2014; Goetz et al., 2025; Zheng et al., 2025). Adopting physical checking fixtures as unifying instructional artifacts directly binds digital CAD modeling and physical manufacturing to quantitative metrology. Requiring student-fabricated fixtures to satisfy empirical Measurement System Analysis benchmarks, specifically achieving a Gage Repeatability and Reproducibility score of GRR < 30% and a Number of Distinct Categories of Ndc ≥ 5 (McPherson & Reiter, 2019; Sumasto et al., 2025), closes the loop between theoretical design and shop-floor quality. Furthermore, this integrated model ensures student learning is evaluated holistically across all five core TVET vocational competency domains: Task Skill (TS), Task Management Skill (TMS), Contingency Management Skill (CMS), Environment Management Skill (EMS), and Job Role Environment Skill (JRES) (Nurtanto et al., 2020).

Conceptual Framework for Industrial Checking Fixture Integration

Checking fixtures serve as the ideal physical and pedagogical bridge connecting digital CAD models, theoretical GD&T callouts, physical tool fabrication, and empirical shop-floor metrology (Culler, 2025; Goetz et al., 2025;

McPherson & Reiter, 2019; Sawant & Kadam, 2024; Sumasto et al., 2025). The proposed conceptual framework links four sequential operational stages across the CDIO lifecycle:

1. 3D CAD & Digital Thread Modeling: Students interpret Product Manufacturing Information (PMI) and apply ASME Y14.5/ISO GPS standards to design checking fixtures within parametric CAD environments (Culler, 2025; Schuldt et al., 2026; Zhang et al., 2025).
2. Kinematic Locating & Clamping Selection: Students apply workholding mechanics, implementing 3-2-1 kinematic locating pins, datum targeting, and toggle clamps for deterministic workpiece orientation (Goetz et al., 2025; Sawant & Kadam, 2024).
3. Additive & Subtractive Tool Fabrication: Students fabricate fixture baseplates and locating pins using CNC milling, precision turning, and FDM 3D printing in a Teaching Factory setting, experiencing manufacturability constraints firsthand (ASEE, 2019; Gani et al., 2024; Niknam et al., 2021).
4. Empirical MSA & GRR Verification: Students use Coordinate Measuring Machines (CMMs), dial indicators, and flush-pin gages to execute structured Gage R&R trials on student-fabricated hardware (McPherson & Reiter, 2019; Sumasto et al., 2025).

Empirical evidence demonstrates that implementing checking fixtures within a Teaching Factory environment can reduce Gage R&R variation from an unviable 100% down to an acceptable 26.27% while increasing measurement resolution (Ndc) from 1 to 5 (Sumasto et al., 2025). Embedding this physical pipeline into TVET curricula establishes a high-stakes, industry-aligned learning environment that replaces passive academic grading with zero-defect industrial quality standards (ASEE, 2019; McPherson & Reiter, 2019; Sumasto et al., 2025).

METHODOLOGY

Research and Curriculum Development Design

We combined Design-Based Research (DBR) with the Conceive-Design-Implement-Operate (CDIO) educational model to build an industry-aligned TVET curriculum framework for checking fixture fabrication. DBR provides a practical research structure that connects theoretical instructional design with real classroom practice through iterative cycles of needs analysis, framework design, structural refinement, and expert evaluation. Grounded in national "Link-and-Match" vocational policies, the CDIO framework structures the learning workflow across four clear stages: Conceive (requirements analysis and GD&T specification), Design (3D CAD modeling and tolerance allocation), Implement (additive/subtractive fabrication), and Operate (metrological verification and MSA).

A socio-technical, practice-integrated development approach is essential to align TVET instruction with modern industrial assembly standards (Agordah, 2026; Bondin & Zammit, 2025; Metavia et al., 2026; Niknam et al., 2021; Sarıkaya et al., 2026). Traditional vocational programs often suffer from institutional silos, teaching drafting, machining, and metrology as isolated topics without a unifying physical product (American Society for Engineering Education [ASEE], 2019; Culler, 2025; McPherson & Phillips, 2019). By integrating checking fixture mechanics with standard quality protocols, our design transforms classroom instruction into an authentic production environment (Agordah & Akrofi, 2026; Metavia et al., 2026; Sumasto et al., 2025; Yoto et al., 2024).

In accordance with Design-Based Research (DBR) iteration protocols, the current research phase encapsulates the initial iterative cycle specifically focusing on baseline competency mapping, structural curriculum modeling, and formal expert validation. Empirical measurement of student learning effectiveness across active academic cohorts is positioned as the subsequent operational cycle within this broader DBR roadmap.

Industry-Driven Needs Analysis, Expert Selection, and Competency Mapping

To systematically establish baseline competency requirements for automotive quality control, a multi-stage needs assessment was conducted using structured Focus Group Discussions (FGDs) and job task analyses1. Participant selection for the FGD panel followed a purposive sampling strategy to ensure rigorous domain

expertise across both industrial manufacturing operations and vocational pedagogy12. The panel comprised twenty experts (n = 20) divided into two equal, representative cohorts:

- Industrial Quality Experts (n = 10): Comprising senior quality managers, metrology engineers, and tooling design specialists from Tier-1 automotive manufacturing suppliers. Each industrial panelist possessed a minimum of 10 years of professional experience in checking fixture design, GD&T implementation, and Measurement System Analysis (MSA) protocols.
- TVET Academic Experts (n = 10): Comprising senior vocational educators, curriculum developers, and mechanical engineering department heads specializing in manufacturing technology, precision machining, and quality control from accredited technical institutions.

The qualitative FGD protocol was executed across three iterative sessions (each lasting 120–180 minutes). Discussions focused on identifying shop-floor technical deficiencies, evaluating current TVET curriculum gaps, and mapping required job tasks against National Occupational Standards (NOS). Qualitative discussion transcripts were coded thematically, while quantitative skill gap prioritization was performed using Importance-Performance Analysis (IPA) and the Competency Gap Index (CGI) methodology.

The resulting competency mapping was structured into five core technical domains:

1. Geometric Dimensioning & Tolerancing (GD&T): Interpreting ASME Y14.5 and ISO GPS standards, establishing functional Datum Reference Frames (DRFs), and assigning geometric tolerance callouts.
2. Kinematic Locating & Workholding Mechanics: Applying 3-2-1 locating principles, determining datum targets, and calculating clamping forces to prevent workpiece deflection.
3. Tolerance Stack-Up & DFM Analysis: Conducting 1D/2D worst-case and Root-Sum-Square (RSS) tolerance stack-up calculations, selecting limits and fits, and applying Design for Manufacturability (DFM) constraints.
4. Physical Fixture Fabrication & Tooling: Generating CAM toolpaths, optimizing FDM 3D printing parameters, operating CNC mills/lathes, and executing precision mechanical assembly.
5. Measurement System Analysis (MSA) & Verification: Operating Coordinate Measuring Machines (CMMs), executing Gage Repeatability and Reproducibility (GRR) trials, and compiling Production Part Approval Process (PPAP) documentation.

Practical Curriculum Framework Structure & Pedagogical Delivery

We structured the curriculum as a 14-week project-based learning (PBL) module with 90 contact hours split between theoretical lectures, CAD laboratory sessions, and hands-on manufacturing/metrology workshops. Operationalized through the four CDIO stages, the module guides students through the full lifecycle of automotive checking fixtures:

- Conceive Phase (Weeks 1–3, 18 Hours): Students interpret ASME Y14.5 and ISO GPS drawings to identify Key Product Characteristics (KPCs). From there, they establish Datum Reference Frames (DRFs) around 3-2-1 locating principles for sheet-metal and molded plastic components.
- Design Phase (Weeks 4–7, 24 Hours): Teams develop parametric 3D CAD models of checking fixtures in industrial software. Core tasks include designing baseplates, toggle clamps, Go/No-Go plug gages, and spring-loaded flush-pin indicators. Before physical fabrication, students run tolerance stack-ups and kinematic simulations to verify clearances.
- Implement Phase (Weeks 8–11, 27 Hours): Fabrication takes place in a Teaching Factory environment. Baseplates and locating pins are machined via CNC milling and turning, while complex nests and handles are 3D printed with FDM equipment. Final assembly relies on dowel pins, shims, and precise mechanical alignment.
- Operate Phase (Weeks 12–14, 21 Hours): Student teams validate production sample parts on their completed fixtures. Combining Coordinate Measuring Machines (CMMs) with manual gages, they conduct full Measurement System Analysis (MSA) and Gage R&R trials against target industrial benchmarks (GRR < 30%, Ndc ≥ 5).

Our instructional approach blends three active learning strategies:

1. Project-Based Learning (PBL): By grounding assignments in real client specifications, student teams build self-directed problem-solving and collaboration skills (Gani et al., 2024; Khan et al., 2021; Niknam et al., 2021).
2. Teaching Factory (TF) Model: Workshops mirror true industrial shop floors, requiring students to strictly adhere to Occupational Safety and Health (OSH) and Quality Management System (QMS) protocols (Bondin & Zammit, 2025; Hamdani et al., 2021; Sumasto et al., 2025).
3. Experiential Learning & Scaffolding: Instructors supply initial templates and direct guidance, then systematically step back as students gain independence (Blacklock & Vanderbeek, 2022; Sawant & Kadam, 2024; Zhang et al., 2026).

Focus Group Discussion (FGD) Protocols and IOC Expert Validation

To evaluate content and construct validity for the proposed 14-week curriculum framework and authentic assessment blueprint, a formal two-stage review protocol was deployed using the Item-Objective Congruence (IOC) Index methodology. The validation process engaged the panel of 20 industrial and academic experts (n = 20) across structured evaluation rounds coupled with consensus-building FGD sessions.

In Stage 1, experts evaluated each framework component, module schedule, and assessment rubric item using a standardized three-point congruence scale: +1 (clearly congruent with industrial objectives), 0 (uncertain / requires minor editorial revision), and -1 (non-congruent / irrelevant). Item-level congruence was calculated using Equation (1):

$$IOC = \sum R / N \quad (1)$$

where $\sum R$ represents the sum of expert ratings for a specific item, and N is the total number of evaluating experts (N = 20). In accordance with established psychometric validation standards, items achieving an IOC ≥ 0.60 were retained, while components scoring below 0.60 were revised or eliminated based on qualitative expert recommendations obtained through follow-up Focus Group Discussions (FGDs). Overall dimension scores achieving an IOC ≥ 0.80 established high content validity, structural coherence, and practical applicability for TVET adoption.

In Stage 2, flagged items and qualitative recommendations were addressed during a follow-up consensus FGD session. Experts provided specific qualitative guidance to refine rubric weighting, specifically approving the allocation of 70% of module marks to physical fabrication and metrological accuracy, and adjust contact-hour distributions. Framework dimensions achieving an aggregate IOC ≥ 0.80 established high content validity, structural coherence, and practical applicability for TVET adoption.

Assessment Protocol and Statistical Threshold Justification

To eliminate subjective academic grading and mirror shop-floor quality accountability, an authentic assessment blueprint was established across five vocational competency domains (Nurtanto et al., 2020): Task Skill (TS), Task Management Skill (TMS), Contingency Management Skill (CMS), Environment Management Skill (EMS), and Job Role Environment Skill (JRES).

A core methodological feature of this blueprint is the deliberate 70:30 weighting split between hands-on physical execution (70%) and digital design/technical documentation (30%). Specifically, the module mark is allocated across five evaluated dimensions:

- CAD Design & GD&T Compliance (20% – Task Skill)
- Physical Fabrication Precision (25% – Task Management Skill)
- Mechanical Assembly & Functionality (20% – Contingency Management Skill)
- Metrological Verification & MSA Performance (25% – Environment Management Skill)
- Technical Documentation & Defense (10% – Job Role Environment Skill)

This 70% concentration on physical tool fabrication, mechanical assembly, and CMM metrology is grounded in authentic vocational assessment theory (ASEE, 2019; McPherson & Reiter, 2019). Traditional TVET grading frequently awards passing marks to non-conforming or out-of-tolerance physical components based on partial student effort, attendance, or theoretical understanding. In contrast, automotive manufacturing operates under a strict binary compliance model where out-of-spec inspection tooling compromises entire assembly lines. Weighting physical precision and empirical metrology at 70% enforces real-world quality accountability, preventing students from passing the module through CAD modeling prowess alone while producing non-functional hardware.

Furthermore, the empirical metrological thresholds for checking fixture qualification are directly benchmarked against the Measurement System Analysis (MSA) guidelines (Automotive Industry Action Group [AIAG], 2010; McPherson & Reiter, 2019; Sumasto et al., 2025):

- Gage Repeatability and Reproducibility (GRR): A GRR < 10% yields a Grade A designation, indicating an optimal measurement system suitable for high-precision production. A GRR between 10% and 30% yields a Grade B designation, classified as marginal but acceptable depending on application criticality and fixture complexity. Any student-fabricated checking fixture exhibiting GRR ≥ 30% fails calibration outright, requiring immediate structural redesign, clamp re-alignment, or remachining.
- Number of Distinct Categories (Ndc): The measurement setup must achieve Ndc ≥ 5. Mathematically derived from the ratio of process variation to measurement system variation ($Ndc = 1.41 \times (\delta_{part}/\delta_{msa})$), a Ndc ≥ 5 guarantees that the checking fixture possesses adequate data resolution to discriminate product process variability across production batches without being masked by measurement noise.

By anchoring student evaluation to AIAG GRR < 30% and Ndc ≥ 5 criteria, the assessment blueprint replaces passive academic evaluation with standardized, industry-accepted metrological verification.

RESULTS AND FRAMEWORK PRESENTATION

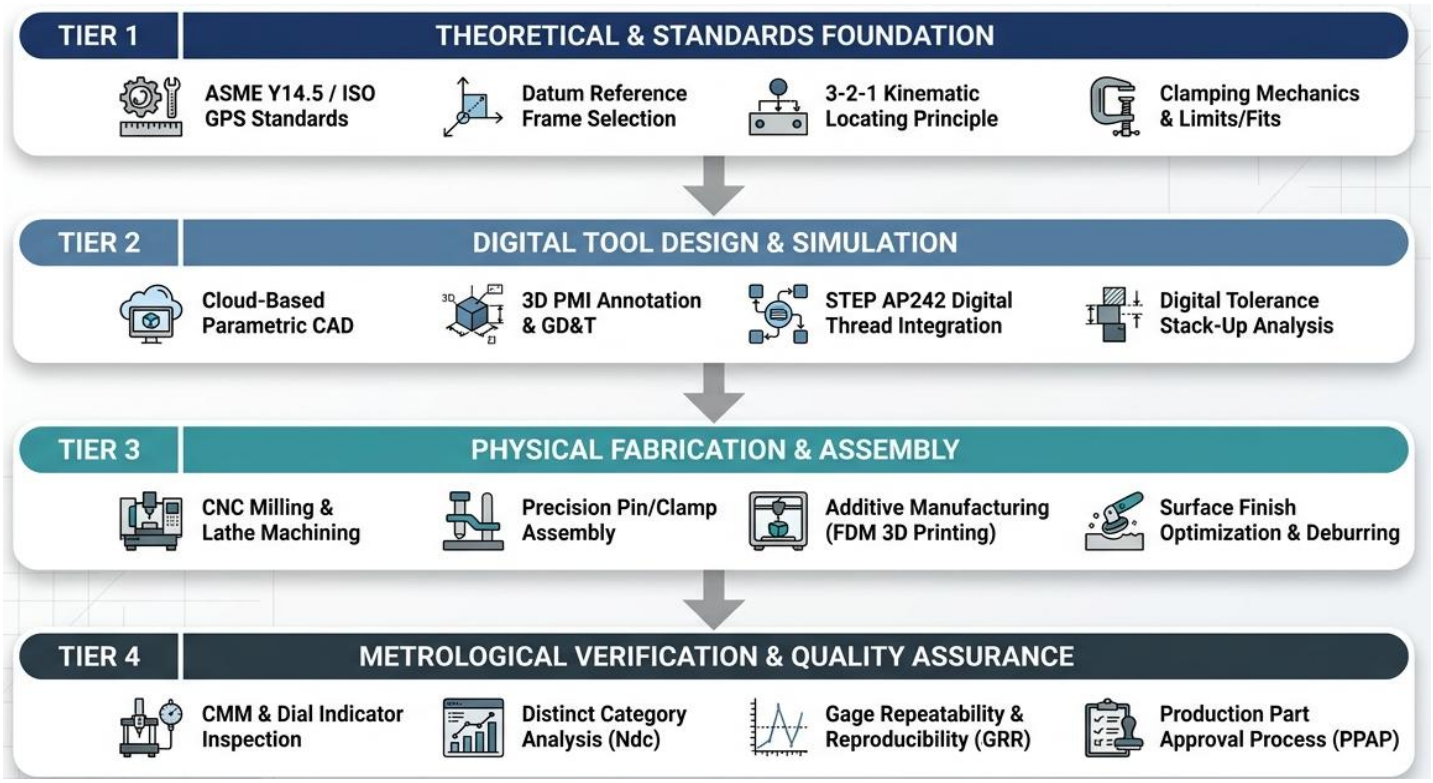
Curriculum Framework Architecture and 14-Week Instructional Blueprint

We developed a multi-tiered TVET curriculum framework that connects digital CAD design, physical tool fabrication, and shop-floor metrology. Conventional TVET programs typically teach drafting, machining, and quality verification in isolation. As a result, students frequently generate CAD models without considering physical workholding constraints or measurement feasibility. Our framework resolves this disconnect by placing the automotive checking fixture at the center of both conceptual instruction and practical shop-floor execution.

Figure 1 outlines the core framework, structuring four progressive tiers around the Conceive-Design-Implement-Operate (CDIO) lifecycle (Goetz et al., 2025; McPherson & Reiter, 2019; Sawant & Kadam, 2024):

- Conceive Tier (GD&T & Digital Thread Specification): Students analyze ASME Y14.5 and ISO GPS drawings to establish functional Datum Reference Frames (DRFs) and Key Product Characteristics (KPCs). From there, they map out 3-2-1 kinematic locating schemes for sheet-metal automotive components.
- Design Tier (Kinematic Workholding & Parametric CAD): Working in industrial CAD software, student teams develop parametric 3D fixture assemblies incorporating baseplates, toggle clamps, Go/No-Go plug gages, and spring-loaded flush pins. Before finalizing designs, they run tolerance stack-up analyses to prevent physical interference.
- Implement Tier (Additive & Subtractive Tool Fabrication): Hardware fabrication occurs in a Teaching Factory setting. Baseplates and locating pins are machined from aluminum and steel via CNC milling and turning, while complex nests and handles are produced through FDM 3D printing.
- Operate Tier (Closed-Loop Metrological Verification): Teams use their completed checking fixtures to evaluate sample production parts. Combining Coordinate Measuring Machines (CMMs) with manual metrology instruments, they conduct full Measurement System Analysis (MSA) trials to satisfy industry Gage R&R benchmarks (GRR < 30%, Ndc ≥ 5).

Figure 1. The Multi-tiered Checking Fixture Curriculum Framework Architecture



The operational weekly breakdown, contact hour allocations (30% theory, 70% practical workshop), learning outcomes, and tangible student deliverables across the 14-week instructional schedule are codified in Table 1.

Table 1. Consolidated 14-Week Pedagogical Module & Fabrication Workflow

Module & Week(s)	Core Technical Focus & Content	Hands-On Laboratory Activities	Core Student Deliverables
Module 1: Metrology, GD&T & Datum Targeting (Weeks 1–3, 18 Hours)	• Quality assurance & checking fixture roles in automotive assembly • ASME Y14.5 / ISO 1101 GD&T, MMC/LMC, DRF • 3-2-1 locating principles, pin selection & clamping	• Baseline inspection of automotive sheet metal/castings using micrometers & height gages • Physical setup of locating pins & toggle clamps on modular fixture plates	• Datum reference frame mapping report • Fully dimensioned part drawing package with GD&T callouts
Module 2: CAD Design, 3D Modeling & Tolerance Stack-Up (Weeks 4–7, 24 Hours)	• 1D/2D worst-case & RSS tolerance stack-up analysis. • Parametric 3D CAD modeling of baseplates, pins, clamps, & flush pin gages. • 3D PMI embedding (STEP AP242) & 2D shop drawings	• Spreadsheet-based tolerance stack-up calculations. • 3D CAD modeling & kinematic workholding simulation in Fusion 360 / SolidWorks. • Digital interference checking & BOM compilation	• Tolerance stack-up dossier & spreadsheet. • Complete 3D fixture assembly model, BOM, & 2D production drawings
Module 3: Physical Fabrication, Machining & Assembly (Weeks 8–11, 24 Hours)	• CNC CAM toolpath & G-code. • Precision turning, grinding & pin/bushing hardening	• CNC/manual milling of aluminum baseplates & mounting blocks • FDM 3D printing of custom locating nests.	• Fully assembled physical checking fixture. • CAM programs & shop floor execution log

	• Additive manufacturing parameters (FDM carbon fiber/PLA)	• Mechanical assembly, dowel pinning, shim adjustment, & CMM alignment	• CMM dimensional verification report
Module 4: Metrology Verification, CMM & MSA (Weeks 12–14, 24 Hours)	• Measurement System Analysis (MSA) & Gage R&R ANOVA principles. • GRR variation & Number of Distinct Categories calculation. • Root cause error analysis & PPAP documentation.	• 10-part / 3-operator Gage R&R trials using dial indicators & CMM probing. • Statistical variance evaluation in Minitab & clamp tuning. • Capstone live part inspection defense.	• Formal MSA / Gage R&R statistical evaluation report. • Standard Operating Procedure (SOP) instructions & PPAP dossier • Capstone portfolio & presentation defense.

Authentic Assessment Blueprint and Performance Criteria

To match industrial quality expectations, we developed an authentic assessment blueprint (Table 2). Traditional TVET grading often passes non-functional or out-of-tolerance parts based on partial effort, reinforcing a low-stakes academic culture.

Table 2. Authentic Assessment Rubric for Industrial Checking Fixture Student Capstone Project

Assessment Domain	Weight	Exemplary (85–100%)	Proficient (70–84%)	Developing (50–69%)	Unacceptable (<50%)
1. CAD Design & GD&T Compliance	20%	Flawless 3D CAD model; precise 3-2-1 datum scheme; correct ASME Y14.5 GD&T callouts; zero assembly interference, complete production drawing package with BOM.	Minor GD&T callout errors; correct datum scheme; fully functional CAD model with negligible tolerance stack-up oversights.	Incorrect datum targeting; incomplete 2D drawings; minor component interferences; incomplete BOM.	Critical errors in datum selection; missing GD&T callouts; non-functional CAD assembly.
2. Physical Fabrication & Machining Precision	25%	Baseplate and locating elements machined strictly within specified drawing tolerances; superior surface finish; correct pin hardening/grinding.	Components machined within acceptable shop tolerances; adequate surface finish; functional fit of pins and bushes.	Out-of-tolerance dimensions requiring excessive shimming; rough surface finish; loose pin fits.	Critical machining errors preventing assembly; severe dimensional deviations; damaged stock.
3. Mechanical Assembly & Functionality	20%	Smooth operation of toggle clamps and flush pins; exact part seating without deflection; robust structural rigidity; precise dowel pin alignment.	Functional clamping and part loading; minor stiffness in sliding flush pins; stable baseplate alignment.	Part deflection occurs during clamping; sticky flush pin movement; loose mechanical joints.	Part cannot be loaded or clamped; structural instability; misaligned locating pins causing part distortion.
4. Metrological Verification & MSA Performance	25%	CMM verification confirms fixture pin locations; Gauge R&R study yields GRR < 10% and Ndc ≥ 5 (Industry Grade A).	CMM verification within 0.03; Gauge R&R study yields 10%< GRR < 30% and Ndc ≥ 5 (Acceptable for industrial use).	CMM shows location errors up to 0.08mm, Gauge R&R yields GRR > 30% corrective actions.	Fixture fails CMM verification; MSA study indicates unrepeatable measurements invalid data.

5. Technical Documentation & Defense	10%	Comprehensive engineering dossier (CMM log, MSA report, cost analysis); clear professional oral defense demonstrating mastery of quality assurance principles.	Well-structured dossier with minor formatting errors; clear oral defense with basic understanding of metrology principles.	Incomplete dossier (missing CMM or MSA logs); weak oral defense; limited technical justification of design choices.	Disorganized or missing documentation; inability to explain fixture design or measurement variance during defense.

The assessment framework allocates 70% of total module marks to hands-on execution fabrication, mechanical assembly, and metrological validation and reserves the remaining 30% for design rigor and technical documentation:

- CAD Design & GD&T Compliance (20% Weight – Task Skill): Assesses 3-2-1 locating logic, 3D PMI annotations, drawing completeness, and tolerance stack-up validity.
- Physical Fabrication Precision (25% Weight – Task Management Skill): Verifies that CNC-machined baseplates and FDM-printed nests meet specified dimensional tolerances and surface finish standards.
- Mechanical Assembly & Functionality (20% Weight – Contingency Management Skill): Examines structural rigidity, toggle clamp operation, flush-pin alignment, dowel-pin engagement, and overall workholding stability.
- Metrological Verification & MSA Performance (25% Weight – Environment Management Skill): Focuses on CMM probing accuracy, execution of Gage R&R trials (GRR < 30%, Ndc ≥ 5), and strict adherence to lab safety protocols.
- Technical Documentation & Defense (10% Weight – Job Role Environment Skill): Evaluates the engineering depth of the final PPAP dossier, standard work instructions, and the team's oral defense before a joint industry-academic panel.

Industry-Aligned Design Principles

Grounded in automotive quality standards and industry focus group insights, four core design principles establish industrial authenticity in TVET checking fixture instruction:

1. Kinematic Determinism (3-2-1 Principle): Checking fixtures must enforce deterministic workholding without over-constraining the component. Under this framework, the primary datum plane rests on three pins (A1, A2, A3), the secondary datum engages two locating pins (B1, B2), and the tertiary datum relies on a single pin (C1). Students calculate and machine pin heights directly from surface CAD data.
2. Clamping Force Mechanics & Deflection Control: Clamps must align directly opposite locating supports to prevent bending moments and elastic deformation during inspection. Toggle clamp holding forces are sized mathematically based on sheet-metal thickness and clamp-induced deflection limits.
3. Dual Physical Verification Mechanics: Fixtures integrate complementary checking elements: Go/No-Go step pins evaluate hole size tolerances, while spring-loaded flush-pin indicators with +0.5 mm steps provide immediate visual and tactile verification for surface profile tolerances.
4. Model-Based Enterprise (MBE) & Digital Thread Integration: Reflecting modern smart manufacturing practices, CAD instruction transitions from static 2D drawings to Model-Based Definition (MBD). By utilizing STEP AP242 files with embedded 3D PMI, digital data flows seamlessly from CAD models directly into CNC CAM post-processing and CMM inspection routines.

Discussion and Comparative Analysis of Instructional Models

The framework redefines traditional TVET instruction across four core operational areas:

- Focus & Media: Transitions from isolated CAD exercises and lecture-based metrology to a hands-on CDIO project lifecycle that yields functional inspection hardware.
- Workholding Mechanics: Moves past abstract drawing callouts by embedding 3-2-1 kinematic locating, workholding clamp mechanics, and flush-pin verification into applied assignments.

- Shop-Floor Fabrication: Replaces purely digital assignments (where CAD models are unrealistically assumed perfect) with physical CNC milling and FDM 3D printing in a Teaching Factory setting.
- Assessment Criteria: Replaces subjective visual scoring and written exams with an empirical evaluation scheme that ties 70% of the mark directly to physical CMM probing and Gage R&R benchmarks (GRR < 30%).

By requiring students to fabricate physical hardware and run empirical Measurement System Analysis (MSA), our curriculum addresses the "CAD black box" problem. Students observe directly how thermal expansion, machining errors, and clamping forces impact measurement accuracy. Furthermore, grounding assessment in objective metrological targets (GRR < 30%) builds industrial accountability and improves graduate readiness for quality engineering roles.

Critical Literature Synthesis and Theoretical Contribution

A critical evaluation of recent literature in TVET and engineering education reveals that while active learning methodologies have gained widespread adoption, existing paradigms exhibit distinct structural limitations when applied to precision manufacturing and metrology education.

- First, while Project-Based Learning (PBL) frameworks (e.g., Khan et al., 2021; Sawant & Kadam, 2024) demonstrably enhance student engagement and spatial visualization capabilities, conventional PBL implementations remain predominantly "open-loop." In standard PBL modules, project success is typically evaluated through qualitative rubric criteria, subjective aesthetic finish, or basic functional fitting. Consequently, PBL frequently lacks the high-stakes quality accountability required in automotive mass production, where components must conform strictly to Geometric Dimensioning and Tolerancing (GD&T) callouts under ASME Y14.5 and ISO GPS standards (Sarıkaya et al., 2026; Schuldt et al., 2026).
- Second, while Teaching Factory (TF) environments (Agordah, 2026; Nurtanto et al., 2020) successfully replicate shop-floor organizational structures and physical machinery exposure, traditional TF coursework tends to prioritize production volume and machining operations over statistical quality verification. As highlighted by Sūtoová et al. (2026) and Farber et al. (2026), exposing students to modern machine tools without integrating Measurement System Analysis (MSA) fails to resolve the graduate competency gap in quality engineering. Without formal Gage Repeatability and Reproducibility (GRR) training, students in standard TF settings cannot systematically differentiate workpiece machining variation from operator or gauge bias (McPherson & Reiter, 2019; Sumasto et al., 2025).
- Third, conventional implementations of the Conceive-Design-Implement-Operate (CDIO) educational framework (Peasura et al., 2025; Zhang et al., 2026) frequently "short-circuit" during the transition from 'Implement' to 'Operate.' In traditional CDIO engineering project courses, student learning lifecycles terminate once a functional prototype is fabricated, treating operational testing as an informal postscript rather than a rigorous metrological audit (ASEE, 2019; Blacklock & Vanderbeek, 2022).

The framework developed in this study advances vocational education theory by establishing a novel "Closed-Loop Metrology Pipeline" that directly synthesizes CDIO architecture, Teaching Factory realism, and AIAG MSA metrological protocols. By utilizing physical checking fixtures as integrating instructional artifacts, the framework bridges the "CAD Black Box" phenomenon (Zhang et al., 2025). Digital CAD designs and 3-2-1 kinematic locating decisions are mathematically validated against empirical CMM measurement data and statistical GRR thresholds (%GRR < 30%, Ndc ≥ 5). This closed-loop integration transforms passive, subjective academic grading into an industry-aligned zero-defect discipline, establishing a replicable pedagogical blueprint for TVET institutions operating under Quality 4.0 requirements.

CONCLUSION AND FUTURE WORK

Conclusion

To bridge the persistent competency gap in TVET automotive education, this study introduces an industry-aligned, 14-week curriculum framework and assessment blueprint centered on checking fixture fabrication. Traditional instruction frequently separates 3D CAD design from physical production and metrology. This divide

creates a "CAD black box," leaving graduates ill-equipped to apply Geometric Dimensioning and Tolerancing (GD&T), workholding mechanics, or Measurement System Analysis (MSA) on the shop floor.

Grounded in Design-Based Research (DBR) and the CDIO lifecycle, our framework links parametric CAD, CNC machining, FDM 3D printing, and closed-loop CMM verification into a single instructional thread. Its primary contribution is a 90-contact-hour blueprint paired with an authentic grading scheme. By shifting 70% of module marks to physical precision and empirical metrology (GRR < 30%, Ndc ≥ 5), the model replaces passive academic grading with zero-defect industrial standards. Ultimately, this provides TVET institutions with a scalable roadmap to boost graduate employability and directly align coursework with modern automotive assembly.

Limitations and Future Research

A primary limitation of this study is its foundational emphasis on structural design, curricular synthesis, and expert-based psychometric validation. Due to academic scheduling constraints and institutional approval cycles, empirical pilot implementation across active student cohorts was not conducted in this phase. Consequently, while the framework demonstrates robust content validity and industrial alignment based on expert evaluation (IOC > 0.80), empirical metrics regarding direct student skill acquisition, workplace performance improvements, and learning efficacy remain to be validated in real classroom environments.

To address these limitations, future research will progress through two distinct operational phases:

1. Empirical Field Implementation and Learning Analytics: Deploying the 14-week checking fixture module across active TVET student cohorts to quantify learning gains through pre- and post-test assessments across the five vocational domains: Task Skill (TS), Task Management Skill (TMS), Contingency Management Skill (CMS), Environment Management Skill (EMS), and Job Role Environment Skill (JRES).
2. Longitudinal Gage R&R Metrological Audits: Conducting systematic Gage Repeatability and Reproducibility (GRR) audits on physical checking fixtures fabricated by students. This will empirically test whether student hardware consistently achieves production-grade metrological accuracy (GRR < 30%, Ndc ≥ 5) across multiple cohort cycles, thereby verifying the long-term efficacy of the authentic assessment blueprint in factory settings.

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