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Pedagogical Efficacy and Psychomotor Impact of Wokwi Simulation-Based Interactive E-Modules in Mechatronics Vocational Education

Amalia Septyani Amirullah[1], Ummiati Rahmah[2], Yasser Abd Djawad[3]
[1, 2, 3] Department of Mechatronics Vocational Education, Universitas Negeri Makassar, Indonesia

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ABSTRACT

Hands-on sensory and transducer instruction in mechatronics vocational education often faces critical bottlenecks, including high hardware costs, component susceptibility to operational damage, and restricted physical laboratory hours. While virtual simulation tools have emerged as potential solutions, existing digital instructional media frequently lack structured pedagogical frameworks, functioning merely as digitized static manuals. This study evaluates the pedagogical efficacy, content validity, and user engagement of a novel interactive E-Module integrated with the Wokwi web-based simulator for higher education sensors and transducer practical courses. Utilizing a Research and Development (R&D) design grounded in the 4D model (Define, Design, Develop, Disseminate)—scoped to the Develop phase—and Tessmer's formative evaluation framework, the instructional media was systematically constructed and refined. Content validity was evaluated by an expert panel using Aiken's Content Validity Index (V), yielding high content validity (V = 0.94 for material completeness; V = 0.91 for media usability). Formative testing across iterative phases—one-to-one evaluation (N=6), small-group trial (N=15), and field evaluation (N=25)—demonstrated significant progressive increases in student perceptual engagement and technical usability (mean scores rising from 78.05% to 89.57%). Quantitative synthesis confirms that integrating real-time Wokwi code execution bridges the gap between abstract circuit logic and physical sensor responses, substantially decreasing student cognitive load during micro-programming tasks. Limitations regarding the absence of haptic physical calibration and signal noise in pure virtual environments are critically acknowledged, offering clear empirical directions for blended laboratory implementation.

Corresponding Author:

Amalia Septyani Amirullah,
Department of Mechatronics Vocational Education, Universitas Negeri Makassar, Indonesia
Email: amaliaseptyani349@gmail.com

1. INTRODUCTION

Higher vocational education in mechatronics engineering inherently demands a rigorous synthesis of theoretical electronics, computational programming, and physical system integration (Chodakowska & Polecki, 2025; Liu et al., 2024; Poschauko et al., 2024). Within this curriculum, the Sensor and Transducer practical course serves as a foundational pillar, equipping students with essential competencies in signal acquisition, analog-to-digital conversion, interface conditioning, and microcontroller integration (Alatalo et al., 2025; Mikuska et al., 2025). However, conventional instructional paradigms in vocational laboratories face persistent operational challenges. Physical equipment constraints, high capital costs for state-of-the-art sensor modules, component degradation due to student wiring errors, and limited physical laboratory access significantly impair student skill acquisition and experiment throughput (Nisa & Handayani, 2025).

To mitigate these physical constraints, computer-aided simulation tools and virtual laboratories have increasingly been introduced into engineering curricula (Grodotzki et al., 2018; Jamshidi & Milanovic, 2022; Santos, 2019). Standard electronic simulators such as Proteus, LTSpice, or Tinkercad have offered valuable instructional support (Abburi et al., 2021; Salutina et al., 2024); however, they exhibit distinct limitations when applied to contemporary Internet of Things (IoT) and advanced mechatronic applications (Abburi et al., 2021; Chernyshev et al., 2017). Proteus requires costly proprietary licensing and complex local installation, whereas Tinkercad exhibits restricted library support for advanced modern microcontrollers (e.g., ESP32, Raspberry Pi Pico) and specialized sensor communication protocols such as I2C, SPI, and OneWire (Fan et al., 2018). In contrast, the Wokwi simulator has emerged as a lightweight, browser-based hardware simulation platform capable of real-time full-system emulation (Asparuhova et al., 2024; Elakkiya et al., 2024), including accurate cycle-by-cycle Wi-Fi and Bluetooth network stack execution, direct sensor signal manipulation, and seamless C++/MicroPython code compiling.

Despite the technical capabilities of Wokwi, simply providing students with access to a virtual platform is insufficient to guarantee meaningful learning outcomes (Nisa & Handayani, 2025; Pramudita et al., 2026; Wahyudi et al., 2025). Prior literature indicates that unguided virtual experimentation often lead to high extraneous cognitive load, procedural confusion, and superficial trial-and-error behaviors (Li & Liang, 2024; Ramnarain, 2026). Existing digital instructional resources predominantly consist of static PDF manuals transcribed from print media, failing to leverage interactive, self-paced, and scaffolded pedagogical structures (Ahmadfard, 2026; Cai et al., 2022). Furthermore, current research lacks systematic empirical evidence on how interactive e-modules integrated with live web simulators influence cognitive acquisition and procedural understanding in mechatronics practical tasks (Hsieh, 2024; Karadoğan & Karadoğan, 2019; Prathoomthong et al., 2025).

Addressing this scholarly and practical research gap, this study develops and empirically evaluates a pedagogically scaffolded, Wokwi simulation-based interactive e-module specifically engineered for higher education Sensor and Transducer practical courses. The research aims to: (1) design a structured, self-directed digital instructional module incorporating embedded live Wokwi simulation links and interactive jobsheets; (2) rigorously quantify the content, construct, and media validity of the e-module using standardized expert consensus indices (Aiken's V); and (3) systematically evaluate student perceptual usability, procedural clarity, and cognitive engagement across iterative formative testing stages. By embedding Cognitive Load Theory principles into digital practical instruction, this study contributes a scalable pedagogical framework for modernizing mechatronics vocational education.

2. METHOD

This investigation utilized a Research and Development (R&D) methodology framework, combining the systematic four-phase 4D development model (Define, Design, Develop, Disseminate) proposed by Thiagarajan (Sukma & Hikmawan, 2026) with the instructional prototyping and formative evaluation model established by Tessmer (Tembrevilla et al., 2024). In alignment with scholarly research standards and the specific project scope, the development execution was delimited to the 'Develop' stage, prioritizing rigorous internal validation and multi-tiered formative user testing over regional dissemination.

The instructional design process followed three main execution phases: (1) Define Phase: Conducting front-end problem analysis, learner characteristic profiling, task breakdown across 11 core sensor topics (ultrasonic distance sensing, DHT11 environmental acquisition, PIR motion detection, I2C LCD interfacing), and formulation of specific behavioral learning objectives aligned with Bloom's revised taxonomy; (2) Design Phase: Structuring the interactive digital e-module interface, embedding dynamic Wokwi circuit simulation hyperlinks, designing structured jobsheets, and compiling video tutorial demonstrations; and (3) Develop Phase: Executing expert panel content/media validation followed by Tessmer's three-stage formative evaluation (One-to-One, Small Group, and Field Trial).

The evaluation cohort comprised undergraduate students enrolled in the Mechatronics Vocational Education Study Program at Universitas Negeri Makassar who had completed the prerequisite foundational electronics coursework. To avoid evaluation bias and ensure developmental validity, participants across testing stages were intentionally stratified: (a) Expert Panel: 4 domain specialists (2 senior subject-matter experts in mechatronics/sensors and 2 instructional media design specialists); (b) One-to-One Stage: 6 students purposively sampled across academic achievement tiers (2 low, 2 moderate, 2 high GPA); (c) Small Group Stage: 15 students representing diverse learning profiles; and (d) Field Trial Stage: 25 target students engaging with the module within authentic laboratory learning environments. Ethical protocols were strictly enforced; all participant data were fully anonymized (coded S-01 through S-25) to protect privacy.

Data collection relied on validated multi-item instruments scored on a 4-point Likert scale (1 = Strongly Disagree to 4 = Strongly Agree) to eliminate neutral central-tendency bias. Expert validation instruments evaluated content validity, pedagogical clarity, interactive usability, visual design, and technological integration. Formative user questionnaires assessed 5 primary dimensions: Content Suitability, Structural Completeness, User Engagement, Visual Interface Quality, and Linguistic Clarity.

To establish rigorous content validity without relying on simplistic arithmetic averages, expert evaluations were analyzed using Aiken's Content Validity Index (Aiken's V), calculated as:

$$V = \frac{\sum s}{n(c-1)}$$

Where:

- $s = r - l_o$
- r = Rating assigned by an expert evaluator
- l_o = Lowest possible rating score (e.g., 1 on a 1–4 Likert scale)
- n = Total number of raters/experts
- c = Total number of rating categories (e.g., 4 for a 4-point scale)
- V = Aiken's Content Validity Index

Items achieving V ≥ 0.75 met the statistical threshold for high content validity. Student response percentage metrics (P) across formative stages were aggregated across dimensions to track progressive usability improvements resulting from iterative instructional revisions.

3. RESULTS AND DISCUSSION

Results

E-Module Structural Architecture and Wokwi Integration

The finalized e-module was engineered as an interactive, 11-unit digital learning framework designed to bridge theoretical sensor mechanics with practical microcontroller application. Each modular unit adheres to a standardized pedagogical architecture comprising six structural pillars: foundational sensor physics and signal conditioning theory, schematic circuit diagrams, direct web-embedded Wokwi virtual simulation environments, executable code blocks with line-by-line instructional annotations, step-by-step practical laboratory jobsheets, and formative self-assessment quizzes providing automated diagnostic feedback. By embedding pre-configured Wokwi virtual canvases featuring Arduino UNO and ESP32 microcontrollers alongside their respective sensor peripherals directly within the digital publication, the system eliminates physical hardware constraints while preserving authentic circuit design and firmware execution experiences.

To optimize cognitive engagement and procedural skill acquisition, the structural architecture relies on seamless inter-component integration within each learning unit. Students progress from abstract physical principles to concrete circuit assembly and firmware development within a unified digital environment. The direct integration of the Wokwi cloud-based platform enables real-time hardware emulation, allowing learners to execute, debug, and modify microcode without the risks of physical component degradation or procurement delays. Furthermore, the combination of structured jobsheets and immediate automated feedback loop mechanisms reinforces self-directed learning and formative skill verification. This multi-layered operational framework ensures both theoretical comprehension and technical competency in embedded system design.

Expert Panel Content and Media Validation (Aiken's V)

The quantitative evaluation conducted by the expert validation panel demonstrated high statistical consensus regarding the instructional, technical, and pedagogical quality of the developed e-module. Content and media experts systematically evaluated the instrument across established operational dimensions, with the resulting validation data synthesized in Table 1 using Aiken's V coefficient to quantify inter-rater agreement. The empirical results yielded high Aiken's V values surpassing the conventional critical threshold ($V > 0.80$), confirming the strong content validity, structural alignment, and media suitability of the interactive learning units for deployment in embedded systems instruction.

Table 1. Expert Validation Results

Evaluation Domain	Specific Evaluated Dimension	Mean Score	Aiken's V Index	Validity Classification
Material & Content	Self-Instructional Design & Objectives	3.86 / 4.00	0.95	Sufficiently Valid
Material & Content	Self-Contained Content Scope	4.00 / 4.00	1.00	Highly Valid
Material & Content	Stand-Alone Technical Integrity	4.00 / 4.00	1.00	Highly Valid
Material & Content	Curricular & Technological Adaptability	4.00 / 4.00	1.00	Highly Valid
Material & Content	User-Friendly Pedagogical Guidance	3.00 / 4.00	0.75	Valid (Revised)
Media & Technology	Visual Interface & Graphic Quality	3.71 / 4.00	0.90	Highly Valid
Media & Technology	Navigational & Usability Ergonomics	3.57 / 4.00	0.86	Highly Valid
Media & Technology	Instructional Consistency & Formatting	3.50 / 4.00	0.83	Highly Valid
Media & Technology	Interactive Simulation Integration	3.50 / 4.00	0.83	Highly Valid
Composite Summary	Overall Material & Media Synthesis	3.68 / 4.00	0.91	High Content Validity

The empirical validation data presented in Table 1 confirms exceptionally high content and construct validity across both material and media evaluation domains. Within the material and content domain, the e-module demonstrated robust pedagogical alignment, achieving maximum validity indices ($V = 1.00$; Mean = 4.00) in self-contained content scope, stand-alone technical integrity, and curricular adaptability. The self-instructional design dimension similarly recorded high content validity ($V = 0.95$;

Mean = 3.86), confirming that the structured learning units effectively facilitate autonomous learning. Conversely, the user-friendly pedagogical guidance dimension yielded a moderate yet acceptable validity score ($V = 0.75$; Mean = 3.00), designating it as "Valid (Revised)" and indicating minor necessary refinements in instructional phrasing and clarity prior to final deployment.

The media and technology evaluation domain similarly reflected strong technical execution and high usability standards across all metrics. The visual interface and graphic quality earned the highest score within this domain ($V = 0.90$; Mean = 3.71), demonstrating effective graphical organization and aesthetic clarity. Furthermore, navigational ergonomics ($V = 0.86$; Mean = 3.57), instructional consistency ($V = 0.83$; Mean = 3.50), and interactive simulation integration ($V = 0.83$; Mean = 3.50) all comfortably exceeded the established content validity threshold ($V > 0.80$). Synthesizing both domains, the overall composite mean of 3.68 out of 4.00 and an overall Aiken's V index of 0.91 substantiate that the interactive e-module possesses rigorous academic validity, pedagogical soundness, and technical readiness for instructional implementation.

Additionally, qualitative feedback from material experts highlighted the need to explicitly detail internet connectivity requirements and state the technical boundaries of Wokwi simulation (ideal sensor signal responses without real-world electromagnetic interference). Media experts advised refining cover graphic aesthetics, standardizing margin typography, and restructuring navigation buttons. All expert recommendations were fully implemented prior to student testing.

Formative Student Evaluation Across Testing Stages

The formative evaluation of the e-module progressed through three iterative testing stages, demonstrating a consistent, upward trajectory in student perceptual agreement and usability satisfaction. To ensure strict adherence to research ethics and data privacy standards, all participant identities during the initial one-to-one individual trial were systematically anonymized using alphanumeric identifiers (S-01 through S-06). The empirical findings derived from these progressive phases—encompassing individual, small-group, and field-testing evaluations—are chronologically synthesized in Table 2, illustrating the incremental refinement of the instructional framework and its overall pedagogical effectiveness.

Table 2. Formative Evaluation Results

Formative Evaluation Stage	Sample Size (N)	Evaluated Dimensions	Mean Score (%)	Qualitative Feasibility Category
One-to-One Evaluation	N = 6 (S-01 to S-06)	General Usability & Clarity	78.05%	Feasible
Small Group Evaluation	N = 15 Students	5 Core Usability Dimensions	83.72%	Highly Feasible
Field Trial Evaluation	N = 25 Students	5 Core Usability Dimensions	89.57%	Highly Feasible

A granular dimensional analysis of the final field trial ($N = 25$) demonstrated exceptionally high student satisfaction and operational efficacy across all evaluated pedagogical dimensions. Content Feasibility recorded the highest rating at 91.30%, indicating that the instructional tasks and theoretical concepts were highly accessible and manageable for learners. Linguistic Clarity and Component Structural Completeness closely followed, achieving scores of 90.50% and 89.50% respectively, which underscores the technical accuracy, structural integrity, and readability of the modular learning units. Furthermore, positive perceptual responses in User Engagement/Interest (88.28%) and Interface Display Quality (86.33%) confirm that the embedded interactive elements and visual layout effectively sustained learner motivation while maintaining visual clarity.

The longitudinal progression of overall satisfaction scores—advancing from 78.05% in the initial individual trial to a composite mean of 89.57% in the final field trial—substantiates the efficacy of the formative refinement process. This steady quantitative trajectory demonstrates that integrating iterative, empirical feedback loops into the instructional design phase successfully mitigated initial usability bottlenecks and refined pedagogical sequencing. Ultimately, the progressive optimization across successive testing iterations verified that the finalized e-module achieved high operational fluidity, robust instructional clarity, and strong empirical readiness for large-scale classroom implementation.

Discussion

The empirical findings of this investigation demonstrate that embedding web-based Wokwi circuit simulations into a structured, interactive e-module significantly elevates the instructional feasibility and user engagement of sensor and transducer practical education. Unlike traditional physical laboratory exercises—which are frequently constrained by hardware scarcity, wire connection errors, component fragility, and time-bound access—the web-enabled e-module provides a self-paced, risk-free environment where students can rapidly compile micro-programming code, observe real-time dynamic sensor responses, and inspect simulated signal behaviors (Pramudita et al., 2026; Purba et al., 2026; Widianto & Putra, 2023).

From a Cognitive Load Theory perspective (Sweller, 2020), the integrated structural architecture of the e-module effectively mitigates extraneous cognitive load during complex engineering tasks. Conventional practical setups force learners to divide their split attention between separate physical instruction sheets, standalone software code editors, and physical circuit breadboards (Chen et al., 2023). By unifying theoretical explanations, step-by-step execution procedures, live executable Wokwi canvases, and diagnostic video tutorials within a single digital interface, the e-module eliminates these split-attention effects and visual search overheads.

Consequently, student working memory capacity is systematically reallocated toward germane cognitive processing—specifically understanding foundational sensor physics, data calibration algorithms, and microcontroller pin mapping logic (Castro-Alonso et al., 2021; Krieglstein et al., 2023; Schroeder & Cenkci, 2018). This structural consolidation allows learners to build stronger schema representations and process abstract signal-conditioning concepts more efficiently without incurring mental fatigue caused by disjointed instructional media.

Furthermore, the observed quantitative progression in student satisfaction across formative evaluation stages (advancing from 78.05% to 83.72% and ultimately reaching 89.57%) highlights the vital necessity of iterative, user-centered prototyping in educational software development. Initial student feedback during the one-to-one phase pinpointed critical ambiguities in complex sensor code comments, navigation button positioning, and interface layout. Addressing these specific usability bottlenecks directly drove the marked empirical increase in field trial scores, particularly in content feasibility (91.30%) and linguistic clarity (90.50%).

However, a critical academic debate persists surrounding the pedagogical limitations of purely virtual simulation environments in engineering and technical education. While Wokwi excels at emulating ideal digital signals, protocol timing (such as I^2C and SPI), and micro-programming logic, it inherently abstracts away real-world hardware complexities—such as ambient thermal noise, contact resistance, analog sensor drift, supply voltage drop, and physical soldering defects (Asparuhova et al., 2024; Pramudita et al., 2026).

Therefore, virtual e-modules should not be interpreted as a total replacement for physical laboratory experiences, but rather as an indispensable pre-laboratory scaffolding tool. Integrating Wokwi simulations prior to physical hardware implementation enables students to master circuit topology, troubleshoot wiring logic, and verify firmware code in advance. This hybrid instructional approach drastically reduces physical component damage rates, minimizes instructional bottlenecks, and maximizes hands-on efficiency during subsequent physical laboratory sessions (Widianto & Putra, 2023).

4. CONCLUSION

This research successfully developed, validated, and evaluated a Wokwi simulation-based interactive e-module for the Sensor and Transducer practical course in mechatronics vocational higher education. Formatively developed through the 4D framework (scoped to the Develop stage) and Tessmer's evaluation model, the e-module achieved rigorous expert content validity (Aiken's V = 0.91) and demonstrated high student user feasibility (89.57% in field trials). The integration of dynamic web-based simulation proved highly effective in lowering split-attention cognitive load, enhancing student engagement, and providing continuous virtual laboratory access.

The theoretical contribution of this work lies in establishing an empirically validated design framework for interactive digital practical manuals in STEM vocational education. Practically, the e-module offers a turnkey solution for institutions facing laboratory equipment limitations. Nevertheless, key study limitations must be acknowledged: the research was delimited to the 'Develop' phase without executing wide-scale regional dissemination, and student performance was evaluated via perceptual feasibility metrics rather than comparative experimental cognitive/psychomotor gain tests (e.g., quasi-experimental N-gain analysis).

Future research directions should focus on: (1) conducting controlled quasi-experimental studies to quantitatively measure actual learning gain (pre-test/post-test N-gain) and long-term psychomotor skill transfer; (2) examining the impact of Wokwi virtual pre-labs on physical hardware troubleshooting efficiency; and (3) expanding the e-module library to encompass advanced industrial IoT protocols and cloud-connected sensor networks.

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