Linking Industry 4.0-Enabled Interactive TVET Instructional Management to Perceived Competency Readiness: The Mediating Role of Student Engagement in Malaysian Accredited Skills Programmes

Mohd Nor Azlan Mohamed Sidek[1*], Zulkifflee Mohamed[2], Mohammed Reyasudin Basir Khan[3],Mohd Muslim Md Zalli[4], Zainisah Abdullah[5], Thanapauge Chamaratana[6]

[1,2,3]Tun Razak Graduate School, Universiti Tun Abdul Razak, Kuala Lumpur, Malaysia

[4]Faculty of Human Development, Universiti Pendidikan Sultan Idris, Perak, Malaysia

[5]Humex Malaysia Skills Development Sdn. Bhd., Pulau Pinang, Malaysia

[6] Faculty of Humanities and Social Sciences, Khon Kaen University, Khon Kaen, Thailand

***Corresponding Author**

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ABSTRACT

Industry 4.0 has widened the competency expectations placed on technical and vocational education and training (TVET), yet technology acquisition alone does not explain how digitally supported learning is associated with students' readiness for occupational competence. This study examined the relationships among Industry 4.0-enabled interactive TVET instructional management, student engagement, and perceived TVET competency readiness, with particular attention to the mediating role of engagement. A quantitative cross-sectional survey was completed by 1,025 students enrolled in Malaysia's Accredited Programme Training System (Sistem Latihan Program Bertauliah; SLaPB) under the Malaysian Skills Certification System. The constructs were measured using a bilingual seven-point questionnaire and analysed with partial least squares structural equation modelling. Interactive instructional management was positively associated with student engagement ($\beta = .496$, $p < .001$) and perceived competency readiness ($\beta = .452$, $p < .001$). Student engagement was also positively associated with perceived readiness ($\beta = .261$, $p < .001$). The bootstrapped indirect association from instructional management to readiness through engagement was significant ($\beta = .129$, 95% bias-corrected confidence interval [.098, .163]), while the direct path remained significant, indicating complementary partial mediation. The complete structural model explained 36.4% of the variance in engagement and 38.8% of the variance in perceived readiness. These findings position Industry 4.0 transformation in TVET as an instructional-management and learner-engagement challenge, not only an infrastructure challenge. Because the data are cross-sectional and self-reported, the results concern perceived readiness and statistical mediation rather than demonstrated competence or causal change. The study therefore supports competency-centred digital pedagogy, authentic practice, feedback, and active learner participation across accredited skills programmes.

Keywords: Industry 4.0, TVET, instructional management, student engagement, competency readiness

INTRODUCTION

Industry 4.0 is reshaping occupational work through connected production, automation, intelligent systems, data-rich processes, and digitally mediated collaboration. These changes do not remove the need for occupation-specific practical competence; instead, they combine it with technological literacy, problem-solving, adaptability, communication, and continuous learning (Benešová & Tupa, 2017; Chaka, 2020; van Laar et al., 2020). Recent international and Malaysian discussions continue to identify digital transformation and future-fit talent as priorities for technical and vocational education and training (TVET) (Majlis TVET Negara, 2024; Paryono & Mashod, 2025; World Economic Forum, 2025). Malaysian research likewise treats Industry 4.0 talent and job readiness as active concerns for TVET students (Mazlan et al., 2026; Wong & Abdullah, 2025).

The educational challenge is not simply to place more technologies in classrooms and workshops. Digital transformation becomes instructionally consequential only when tools are connected with occupational content, purposeful practice, feedback, assessment, collaboration, and authentic work problems. Reviews of Education 4.0 and technology-supported engagement show that educational technology can widen learning opportunities, but its value depends heavily on learning design and the activities students are asked to undertake (Bedenlier et al., 2020; Bond et al., 2020; Bonfield et al., 2020; Mukul & Büyüközkan, 2023). Recent TVET work similarly emphasises whole-institution capability, industry-provider partnership, and pedagogical integration rather than treating digitalisation as an equipment project (Niwamanya et al., 2025; Paryono & Mashod, 2025; Zhong & Juwaheer, 2024).

This distinction is especially relevant in competency-based TVET. Competence involves the integrated use of knowledge, skills, attitudes, and judgement in occupational contexts (Mulder et al., 2007). Students may encounter simulations, learning-management systems, virtual demonstrations, smart equipment, digital assessments, and collaborative platforms, yet exposure alone does not establish that they understand occupational requirements or feel ready to perform them. Instructional management must organise these resources into coherent experiences that allow learners to practise, receive feedback, solve relevant problems, and connect training with workplace standards. Accordingly, the present study defines Industry 4.0-enabled interactive TVET instructional management as students' perception of a coherent learning environment in which digital and Industry 4.0-related resources are integrated with guided occupational practice, simulation, feedback, collaboration, authentic problem-solving, reflection, and workplace relevance.

A second issue concerns the learner process through which such an environment may be associated with readiness. Student engagement captures the quality of learners' participation, interest, cognitive investment, and contribution to learning activities (Fredricks et al., 2004; Kahu, 2013; Reeve & Tseng, 2011). Technology-supported activities may remain passive, or they may invite students to manipulate information, explain decisions, collaborate, ask questions, and propose improvements. The ICAP framework predicts qualitatively stronger learning when activity moves from passive reception toward active, constructive, and interactive participation (Chi & Wylie, 2014). Engagement may therefore provide a theoretically plausible link between the instructional environment and perceived competency readiness.

Despite growing literature on Industry 4.0 skills, digital competence, institutional readiness, and educational technology, three limitations remain relevant. First, much TVET 4.0 work identifies required skills or implementation barriers but provides less student-level evidence about the instructional processes associated with readiness. Second, technology use is often treated as adoption or access rather than as an integrated instructional-management construct. Third, engagement is frequently examined as an outcome of educational technology, but less often as an explanatory process connecting technology-integrated TVET instruction with perceived occupational readiness. The present study addresses these limitations in Malaysia's Accredited Programme Training System (Sistem Latihan Program Bertauliah; SLaPB), a structured route under the Malaysian Skills Certification System (MSCS) in which training is aligned with National Occupational Skills Standards.

The study asks two questions: (1) How is Industry 4.0-enabled interactive TVET instructional management associated with student engagement and perceived TVET competency readiness among SLaPB students? and (2) Does student engagement statistically mediate the association between instructional management and perceived readiness? Four hypotheses test the direct and indirect relationships. The study contributes by integrating technology-pedagogy-content alignment, active and interactive learning, student engagement, and competence-based vocational education within one student-level model. It also provides evidence from a large multi-institutional sample while maintaining an important boundary: the outcome is perceived readiness, not objectively assessed competence, certification performance, or employment success.

THEORETICAL FRAMEWORK AND HYPOTHESES

Perceived TVET competency readiness

Perceived TVET competency readiness refers to a student's self-assessed preparedness to meet occupationally relevant competency requirements. It is related to, but distinct from, actual competence, employability, satisfaction, or technology acceptance. Actual competence requires performance evidence against standards, whereas perceived readiness captures the learner's judgement that they can demonstrate practical skills, apply technical knowledge, solve workplace problems, complete competency-based assessments, and meet occupational expectations. Work-readiness research treats such perceptions as relevant to transition and professional preparation, but it also cautions that self-reports should not substitute for performance assessment (Caballero et al., 2011).

Competence-based vocational education provides the principal conceptual anchor. Mulder et al. (2007) describe competence as an integrated capacity expressed in professional practice rather than a collection of isolated knowledge statements. Mulder (2017) further emphasises the need to bridge education and work. Under Industry 4.0, this bridge includes not only conventional practical performance but also digitally mediated problem-solving, adaptation to changing tools, and participation in connected work processes (Chaka, 2020; van Laar et al., 2020). Perceived readiness is therefore useful as a proximal learner outcome: it indicates whether students recognise themselves as prepared for the competencies they expect to encounter, while remaining conceptually narrower than verified occupational competence.

Industry 4.0-enabled interactive TVET instructional management

The construct of Industry 4.0-enabled interactive TVET instructional management combines several complementary traditions. The technological pedagogical content knowledge framework (TPACK) argues that effective technology integration requires alignment among technological possibilities, pedagogy, and subject matter rather than the independent possession of technical knowledge (Mishra & Koehler, 2006). In TVET, the relevant content is occupational and competency-based; technology should therefore be selected and sequenced in ways that improve understanding and performance of occupational tasks.

Multimedia learning theory adds a cognitive-design perspective. Digital visualisations, demonstrations, and simulations can support learning when they direct attention to relevant information and help learners organise and integrate representations; poorly designed multimedia can instead impose unnecessary processing demands (Mayer, 2020). Authentic learning and learning-factory research add contextual fidelity. Activities become occupationally meaningful when they approximate workplace problems, tools, constraints, and decisions (Abele et al., 2015; Baena et al., 2017; Herrington & Oliver, 2000). Simulation-based learning is particularly relevant where real equipment is expensive, hazardous, scarce, or difficult to pause and repeat. A meta-analysis by Chernikova et al. (2020) found that simulation can support complex skills when it is embedded in appropriate instructional support.

Interactive instructional management also includes feedback and reflection. Feedback is most useful when it clarifies goals, current performance, and actionable next steps (Hattie & Timperley, 2007). Within competency-based training, feedback connects performance evidence with occupational standards and provides a basis for repeated practice. The construct examined here therefore does not denote an inventory of devices. It denotes students' perception that instructors and programmes consistently integrate Industry 4.0-related tools with practical learning, demonstrations, guided practice, feedback, digital collaboration, authentic workplace problems, reflection, and occupational relevance.

Instructional management and perceived competency readiness

Interactive instructional management should be positively associated with perceived readiness for several reasons. First, authentic digital and simulated tasks can make future work demands visible and allow students to rehearse procedures before workplace performance. Second, guided practice and feedback help students compare current performance with competency expectations. Third, consistent integration allows learners to connect digital tools with occupational content rather than encounter technology as an isolated demonstration. Learning-factory and simulation literature supports the value of learning environments that connect educational tasks with realistic production or professional processes (Abele et al., 2015; Baena et al., 2017; Chernikova et al., 2020). Recent Malaysian TVET work also continues to frame Industry 4.0 readiness as a combination of technical, digital, and work-based talent development (Mazlan et al., 2026; Wong & Abdullah, 2025). Accordingly:

H1. Industry 4.0-enabled interactive TVET instructional management is positively associated with perceived TVET competency readiness.

Instructional management and student engagement

Student engagement is commonly understood as a multidimensional relationship between a learner and educational activity. Fredricks et al. (2004) distinguish behavioural, emotional, and cognitive engagement, while later work emphasises social participation and learner agency (Kahu, 2013; Kahu & Nelson, 2018; Reeve & Tseng, 2011). In technology-supported learning, engagement is not equivalent to logging in or using a device. It is expressed when students attend to tasks, invest effort, perceive relevance, think through problems, collaborate, ask questions, and influence the learning process. Systematic reviews indicate that educational technology can facilitate these forms of engagement when it supports communication, feedback, active learning, and learner control, although technology does not guarantee engagement by itself (Bedenlier et al., 2020; Bond & Bedenlier, 2019; Bond et al., 2020).

The ICAP framework offers a process explanation. Passive exposure requires learners mainly to receive information; active engagement involves physical manipulation or selection; constructive engagement requires the generation of new inferences or explanations; and interactive engagement involves mutually responsive dialogue or collaboration (Chi & Wylie, 2014). The instructional-management features examined in this study - simulations, guided practice, authentic problems, feedback, collaboration, and reflection - are designed to move students toward active, constructive, or interactive participation. Digital learning research also suggests that learners' attitudes, literacy, and self-efficacy are associated with online engagement, reinforcing the view that engagement reflects an active response to a designed environment rather than simple access (Getenet et al., 2024). Therefore:

H2. Industry 4.0-enabled interactive TVET instructional management is positively associated with student engagement.

Student engagement and perceived competency readiness

Engagement should also be associated with perceived readiness. Competence is developed and recognised through purposeful activity: practising, integrating knowledge with action, responding to feedback, and transferring learning to work-like situations. Engaged students are more likely to examine the occupational meaning of a task, persist through difficulty, ask for clarification, test alternatives, and reflect on performance. The educational-interface perspective similarly proposes that engagement is a mechanism through which institutional and learner factors become connected with educational outcomes (Kahu & Nelson, 2018).

In the present context, the retained engagement indicators focus particularly on interest in digitally supported practical learning, perceived occupational relevance, careful thinking about how digital tools improve practical skills, questioning, and proposing improvements. These cognitive, relevance-oriented, and agentic behaviours are theoretically close to the reflective and adaptive activity needed for competency development. They should support students' judgement that they can meet practical, problem-solving, assessment, and occupational-performance requirements. Therefore:

H3. Student engagement is positively associated with perceived TVET competency readiness.

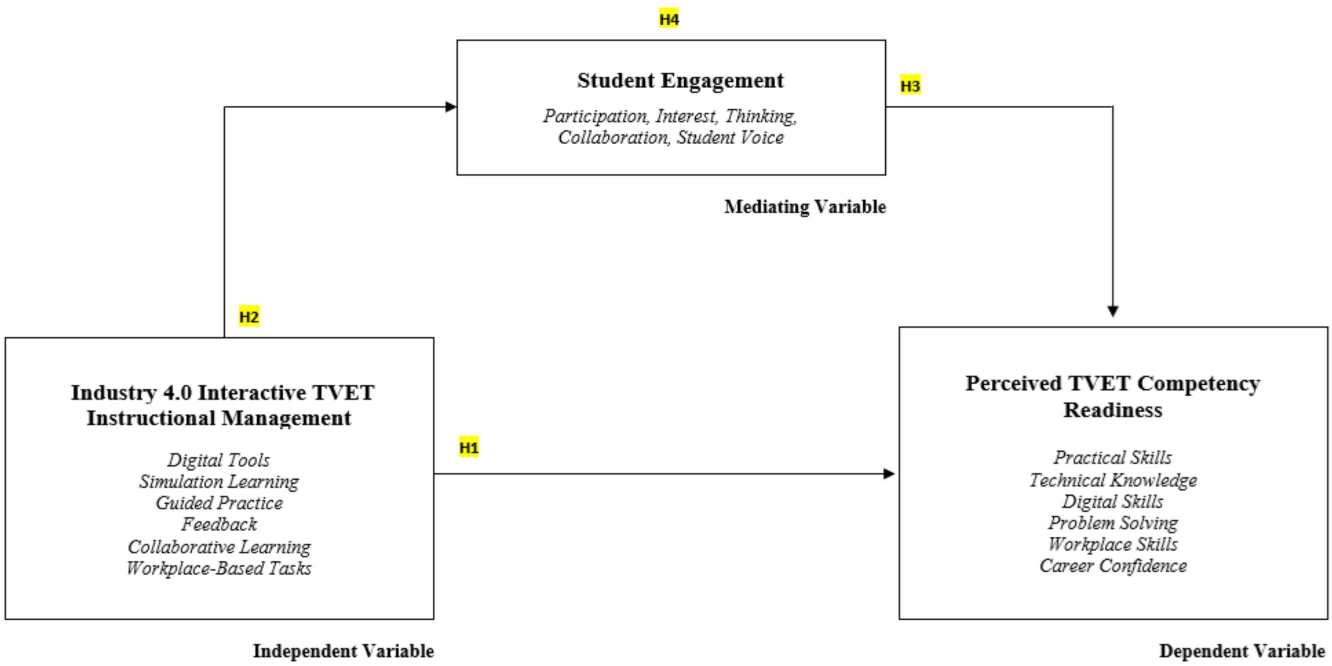
The mediating role of student engagement

The preceding relationships imply an indirect pathway. Interactive instructional management may be associated with readiness because it creates conditions that invite deeper student participation; engagement then helps students convert those opportunities into personally meaningful preparation. The mechanism is consistent with TPACK, which explains the integration of technology, pedagogy, and content; ICAP, which explains differences in learner activity; and competence-based vocational education, which locates learning in purposeful occupational performance.

Engagement is not expected to explain the entire association. Instructional management may also relate directly to perceived readiness through access to authentic tasks, explicit competency alignment, repeated practice, and performance feedback. A pattern in which both direct and indirect coefficients are positive and significant is described as complementary mediation (Zhao et al., 2010). The indirect coefficient should be tested through bootstrapping because the sampling distribution of a product term is not normally distributed (Nitzl et al., 2016). Because the present design is cross-sectional, a significant indirect association can support the hypothesised statistical mechanism but cannot establish temporal causation (Maxwell & Cole, 2007). Therefore:

H4. Student engagement statistically mediates the positive association between Industry 4.0-enabled interactive TVET instructional management and perceived TVET competency readiness.

Figure 1. Conceptual model and focal hypotheses



Note. H4 represents the specific indirect association from instructional management to perceived readiness through student engagement.

METHODOLOGY

Research design and study context

A quantitative, cross-sectional, correlational survey design was used. The design was appropriate for estimating associations among latent constructs measured through multiple questionnaire indicators, but it does not establish temporal order or causal change. The empirical context was the Accredited Programme Training System (Sistem Latihan Program Bertauliah; SLaPB), a structured training route within the Malaysian Skills Certification System. SLaPB providers deliver programmes aligned with National Occupational Skills Standards and lead to Malaysian Skills Certificate (SKM), Malaysian Skills Diploma (DKM), or Malaysian Skills Advanced Diploma (DLKM) credentials. Recognition of Prior Achievement and industry-based routes were outside the empirical scope (Department of Skills Development Malaysia, n.d.-a, n.d.-b).

The target population recorded in the thesis sampling frame comprised 39,977 current SLaPB students. The unit of analysis was the individual student because the model concerns learners' perceptions of instructional management, their own engagement, and their perceived readiness. Eligible respondents were currently enrolled in selected SLaPB programme and certification-level categories and had experienced digitally supported or Industry 4.0-related learning, such as simulation, virtual laboratories, augmented or virtual reality, smart equipment, learning-management systems, digital assessment, or online learning applications.

Participants and sampling

Sampling combined multistage stratified cluster procedures for the accessible public and agency-based component with criterion-based purposive inclusion of selected private providers. Institutions and classes were organised across certification levels, ministries or agencies, programme clusters, and locations. Private institutions were included when they offered relevant accredited programmes, had an active eligible class, contributed field diversity, provided institutional permission, and had students with relevant digital-learning exposure. This design increased coverage across a geographically and institutionally dispersed population, but it was not a fully national probability sample. The findings should therefore be generalised to the selected SLaPB sampling frame with appropriate caution.

The final dataset contained 1,025 eligible and complete responses. The sample exceeded the thesis's conservative power benchmarks for the wider PLS-SEM model, which included direct, indirect, and interaction paths. Respondents represented SKM Level 2 (n = 164, 16.0%), SKM Level 3 (n = 562, 54.8%), DKM Level 4 (n = 246, 24.0%), and DLKM Level 5 (n = 53, 5.2%). The sample covered public and private institutions, urban, semi-urban, and rural settings, and multiple occupational clusters. Because 93.5% of respondents were enrolled in government institutions and 92.0% were aged 19-22 years, these characteristics are important interpretation boundaries.

Table 1. Participant and learning-context profile (N = 1,025)

Characteristic	Category	n	%
Gender	Male	697	68.0
	Female	328	32.0
Age	19–22 years	943	92.0
	23–26 years	82	8.0
Certification level	SKM Level 2	164	16.0
	SKM Level 3	562	54.8
	DKM Level 4	246	24.0
	DLKM Level 5	53	5.2
Institution location	Urban	542	52.9
	Semi-urban	277	27.0

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	Rural	206	20.1
Industrial training	Completed	861	84.0
	Not started	164	16.0
Institution type	Government/public agency	958	93.5
	Private	67	6.5
Previous digital/Industry 4.0 experience	None	107	10.4
	Basic	333	32.5
	Moderate	432	42.1
	High	153	14.9
Digital/Industry 4.0 activity frequency	Rarely	107	10.4
	Sometimes	267	26.0
	Often	401	39.1
	Very often	250	24.4
Main learning mode	Face-to-face	569	55.5
	Blended/hybrid	344	33.6
	Mostly online	112	10.9

Note. SKM = Malaysian Skills Certificate; DKM = Malaysian Skills Diploma; DLKM = Malaysian Skills Advanced Diploma. Percentages may not total 100 because of rounding.

Measures

Data were collected using a structured bilingual English-Malay questionnaire. Two screening items established eligibility; 20 profile items described demographic, programme, institutional, access, and digital-exposure characteristics; and four ten-item scales measured the constructs in the wider thesis model. The present article focuses on three scales. All latent-variable items were positively worded and answered on a seven-point agreement scale ranging from 1 (strongly disagree) to 7 (strongly agree).

Industry 4.0-enabled interactive TVET instructional management was initially represented by 10 items. The items assessed whether Industry 4.0-related tools were used in teaching, integrated into practical learning, used for simulation or visualisation, connected with guided occupational practice, used to provide feedback, and embedded in collaboration, authentic workplace problem-solving, reflection, and sustained programme delivery. All 10 items were retained. Their development drew on TPACK, multimedia learning, authentic learning, feedback, ICAP, simulation-based learning, and competence-based vocational education (Chernikova et al., 2020; Chi & Wylie, 2014; Hattie & Timperley, 2007; Herrington & Oliver, 2000; Mayer, 2020; Mishra & Koehler, 2006; Mulder et al., 2007).

Student engagement was initially measured with 10 items covering behavioural participation, effort, enjoyment, interest, occupational relevance, cognitive processing, collaboration, idea sharing, questioning, and suggestions for improvement (Fredricks et al., 2004; Kahu, 2013; Reeve & Tseng, 2011). Five indicators were retained after measurement-model refinement: interest in digitally supported practical learning (C4), understanding the relevance of Industry 4.0-enabled activities to a future occupation (C5), careful consideration of how digital tools can improve practical skills (C6), asking questions when using Industry 4.0-related technologies (C9), and suggesting improvements during digitally supported activities (C10). Consequently, the final operational measure principally represents interest, cognitive-occupational relevance, and agentic engagement rather than the full behavioural-emotional-cognitive-social breadth of the original scale.

Perceived TVET competency readiness was initially measured with 10 items adapted from competence-based vocational education and work-readiness literature (Caballero et al., 2011; Mulder, 2017; Mulder et al., 2007). Six indicators were retained: readiness to demonstrate practical skills (E1), apply technical knowledge to work-related problems (E2), solve workplace problems (E4), complete competency-based practical assessments (E5), perform successfully in a future occupation (E9), and meet overall professional competency requirements (E10). The construct is explicitly perceptual. It does not represent certification results or independently observed performance.

Table 2. Conceptual coverage of the focal measures

Construct	Initial items	Retained items	Retained content	Principal conceptual sources
Industry 4.0-enabled interactive TVET instructional management	10	10	Technology integration, practical learning, simulation/visualisation, guided practice, feedback, collaboration, authentic problems, workplace connection, reflection, sustained integration	Mishra & Koehler (2006); Chi & Wylie (2014); Chernikova et al. (2020); Mulder (2017)
Student engagement	10	5	Interest, occupational relevance, cognitive processing, questioning, and learner suggestions/agency	Fredricks et al. (2004); Reeve & Tseng (2011); Bond et al. (2020)
Perceived TVET competency readiness	10	6	Practical-skill demonstration, technical application, workplace problem-solving, competency-based assessment, occupational confidence, and readiness to meet competency requirements	Caballero et al. (2011); Mulder et al. (2007); Department of Skills Development Malaysia (n.d.-a)

Note. The retained engagement and readiness indicators provide narrower empirical coverage than the original multidimensional construct definitions; this limitation is addressed explicitly in the discussion.

Instrument review and pilot study

Face and content validity were examined before the main survey. Students and experts reviewed clarity, bilingual wording, relevance to SLaPB, and distinctions among the constructs. Experts with backgrounds in TVET, educational technology, measurement, and methodology examined whether the indicators adequately covered each conceptual domain and whether wording inadvertently overlapped across constructs. A pilot study was then conducted with 60 students from four Selangor-based skills-training institutions; these respondents were excluded from the main dataset. Pilot Cronbach's alpha values were .884 for instructional management, .804 for engagement, and .843 for perceived readiness, supporting progression to the main survey after wording and sequencing refinements.

Data-collection procedure and research ethics

The online questionnaire was distributed through authorised institutional administrators or coordinators after institutional permission had been obtained. The scheduled main data-collection window was 23 February to 1 March 2026. Before proceeding, students received information about the purpose of the study, eligibility criteria, expected completion time, voluntary participation, confidentiality, the right to stop before submission, and the absence of any effect on grades, assessment, certification, or access to training. Electronic informed consent was required. Responses were reported in aggregate, and individual students and institutions were not identified.

Procedural safeguards against common-method bias included construct-specific wording, separated questionnaire sections, neutral instructions, anonymity or confidentiality assurances, and screening for careless response patterns (Podsakoff et al., 2003). A post hoc single-factor diagnostic indicated that the first unrotated factor accounted for 25.94% of the variance. This diagnostic is reported only as supplementary evidence; it cannot demonstrate that common-method bias is absent. The shared source, response format, and collection occasion remain limitations.

Data analysis

SPSS was used for screening, descriptive statistics, and preliminary reliability analysis. SmartPLS 4 was used for partial least squares structural equation modelling (PLS-SEM). The measurement model was evaluated before the structural paths. Indicator loadings, Cronbach's alpha, rho_A, composite reliability (rho_C), and average variance extracted (AVE) were examined. AVE values of at least .50 supported convergent validity, while the heterotrait-monotrait ratio (HTMT) was used as the principal discriminant-validity criterion (Fornell & Larcker, 1981; Hair et al., 2019; Hair & Alamer, 2022; Henseler et al., 2015). Item removal was conservative and considered both statistical performance and conceptual coverage.

Structural assessment examined predictor collinearity, path coefficients, explained variance, effect sizes, and predictive indicators. Bootstrapping with 5,000 resamples generated standard errors, t values, p values, and confidence intervals. The indirect association for H4 was evaluated using its bootstrapped confidence interval; mediation was supported when the interval excluded zero (Nitzl et al., 2016). Cohen's conventional f2 benchmarks of .02, .15, and .35 were used as approximate small, medium, and large reference points.

The estimates reported in this article come from the complete thesis model rather than a newly estimated three-construct model. That wider model retained digital learning self-efficacy, its constituent main paths, and three interaction terms. This decision preserves exact correspondence with the available SmartPLS output and avoids presenting coefficients from a reduced model that was not rerun. The focal hypotheses concern only instructional management, engagement, and readiness; all non-focal structural coefficients are disclosed in Supplementary Table S1. Accordingly, the R2 and Q^2predict values reported below describe the complete thesis model. Positive Q^2predict values are treated as preliminary predictive evidence because no linear-model benchmark comparison was available (Shmueli et al., 2019).

RESULTS

Data screening and respondent profile

All 1,025 retained cases contained complete responses for the 40 main scale items. No values fell outside the one-to-seven response range, and no respondent selected the same category for all 40 items. Construct-level skewness ranged from -.327 to -.087 and excess kurtosis from -.400 to -.191, indicating no extreme distributional departures. Table 1 summarises the principal sample characteristics. Men represented 68.0% of the sample, and 92.0% of respondents were aged 19-22 years. Most students were enrolled at SKM Level 3 (54.8%), 84.0% had completed industrial training, and 63.5% reported that digital or Industry 4.0-supported activities occurred often or very often. Face-to-face learning remained the main mode for 55.5%, while 33.6% reported blended or hybrid learning and 10.9% reported mostly online learning.

Measurement model

Mean scores were above the midpoint of the seven-point scale: 5.37 (SD = .80) for interactive instructional management, 5.35 (SD = .65) for the retained engagement measure, and 5.21 (SD = .67) for perceived readiness. These descriptive levels indicate generally favourable perceptions, but they are not evidence that all students experienced equivalent provision or achieved objective competence.

The initial model contained 10 indicators for each construct. All instructional-management items were retained. Five engagement items and six readiness items were retained after conservative refinement because the initial

AVE values for those constructs were below .50. As shown in Table 3, final loadings ranged from .741 to .774 for instructional management, .703 to .719 for engagement, and .698 to .723 for perceived readiness. Cronbach's alpha values were .916, .753, and .804, respectively; composite reliabilities were .930, .835, and .859; and AVE values were .569, .503, and .505. These values supported internal consistency and convergent validity, although the narrowing of engagement and readiness content is considered in the limitations.

Table 3. Descriptive statistics, indicator loadings, reliability, and convergent validity

Construct	Items	Mean	SD	Loading range	α	ρA	ρC	AVE
Interactive instructional management	10	5.37	.80	.741–.774	.916	.917	.930	.569
Student engagement	5	5.35	.65	.703–.719	.753	.753	.835	.503
Digital learning self-efficacy	10	5.49	.72	.702–.746	.898	.900	.916	.522
Perceived competency readiness	6	5.21	.67	.698–.723	.804	.805	.859	.505

Note. α = Cronbach's alpha; ρA = Dijkstra–Henseler's reliability; ρC = composite reliability; AVE = average variance extracted. Digital learning self-efficacy is reported because it was included in the complete thesis model from which the focal coefficients were obtained.

Discriminant validity and collinearity

Each retained indicator loaded most strongly on its intended construct. The HTMT coefficients for the focal pairs were .582 for instructional management and engagement, .671 for instructional management and readiness, and .618 for engagement and readiness; all were below the conservative .85 guideline. Table 4 also reports the low HTMT associations involving digital learning self-efficacy because it remained in the complete thesis model. Structural predictor VIF values ranged from 1.001 to 1.565, providing no indication of problematic collinearity. The standardised root mean square residual was .040 for both the saturated and estimated model; in keeping with PLS-SEM guidance, this value was treated as supplementary rather than as the principal basis for model evaluation.

Table 4. Heterotrait–monotrait ratios

Construct	1	2	3	4
1. Interactive instructional management	—			
2. Student engagement	.582	—		
3. Digital learning self-efficacy	.048	.416	—	
4. Perceived competency readiness	.671	.618	.100	—

Note. All reported HTMT values were below .85. Digital learning self-efficacy is included to document the complete measurement model.

Direct associations

Table 5 presents the focal direct paths. Interactive instructional management was positively associated with perceived readiness ($\beta = .452$, SE = .027, $t = 16.492$, $p < .001$), supporting H1. It was also positively associated with student engagement ($\beta = .496$, SE = .023, $t = 21.775$, $p < .001$), supporting H2. Student engagement was positively associated with perceived readiness ($\beta = .261$, SE = .031, $t = 8.502$, $p < .001$), supporting H3.

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The practical contribution of instructional management was largest for engagement ($f^2 = .386$) and medium for perceived readiness ($f^2 = .241$). Engagement made a smaller but non-trivial contribution to readiness ($f^2 = .071$). These effect-size patterns indicate that instructional management was the dominant focal predictor in the estimated model, particularly for students' engagement.

Table 5. Focal direct-path results

Hypothesis	Path	β	SE	t	p	f^2	Decision
H1	Instructional management → perceived readiness	.452	.027	16.492	< .001	.241	Supported
H2	Instructional management → student engagement	.496	.023	21.775	< .001	.386	Supported
H3	Student engagement → perceived readiness	.261	.031	8.502	< .001	.071	Supported

Note. Coefficients were estimated in the complete thesis model using 5,000 bootstrap resamples. β = standardised path coefficient; SE = bootstrap standard error; f^2 = local effect size.

Indirect association through student engagement

The SmartPLS bootstrapping results showed that the bootstrapped specific indirect association from instructional management to perceived readiness through engagement was positive and significant (β = .129, SE = .017, t = 7.784, $p < .001$). The percentile 95% confidence interval [.099, .163] and bias-corrected interval [.098, .163] both excluded zero. H4 was therefore supported. Because the direct path from instructional management to readiness remained positive and significant, and the direct and indirect coefficients pointed in the same direction, the pattern is consistent with complementary partial mediation (Zhao et al., 2010). The result indicates that engagement statistically carries part, but not all, of the association between interactive instructional management and perceived readiness. It does not establish a longitudinal causal sequence.

Table 6. Bootstrapped indirect association

Hypothesis	**Specific indirect path**	**β**	**SE**	**t**	**p**	**95% percentile CI**	**95% BC CI**	**Decision**
H4	Instructional management → engagement → perceived readiness	.129	.017	7.784	< .001	[.099, .163]	[.098, .163]	Supported

Note. BC CI = bias-corrected confidence interval. The concurrent positive direct coefficient (β = .452, $p < .001$) and indirect coefficient are consistent with complementary partial mediation.

Explanatory and predictive indicators

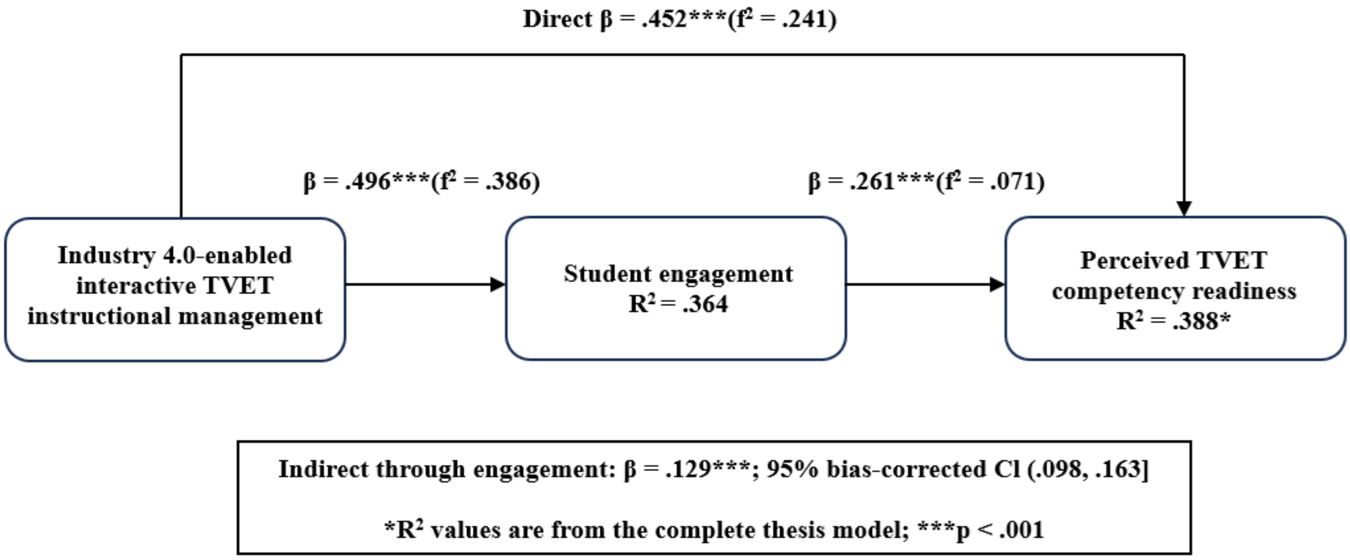
The complete thesis model explained 36.4% of the variance in student engagement (adjusted $R^2 = .363$) and 38.8% of the variance in perceived readiness (adjusted $R^2 = .386$). Q^2predict values were positive for engagement (.358; RMSE = .803; MAE = .644) and readiness (.339; RMSE = .815; MAE = .656). These values indicate that the model generated out-of-sample predictive relevance relative to a naive benchmark in the SmartPLS procedure, but the absence of a reported linear-model comparison limits stronger predictive claims. Figure 2 displays the focal coefficients and notes that the R2 values derive from the complete model.

Table 7. Explanatory and predictive indicators from the complete thesis model

Endogenous construct	R^2	Adjusted R^2	Q^2predict	RMSE	MAE	Interpretive boundary
Student engagement	.364	.363	.358	.803	.644	Full model; no reported linear-model benchmark comparison
Perceived competency readiness	.388	.386	.339	.815	.656	Full model; no reported linear-model benchmark comparison

Note. Q^2predict, RMSE, and MAE were generated in the SmartPLS predictive-assessment procedure. Positive Q^2predict values alone should not be described as strong predictive superiority without an appropriate benchmark comparison (Shmueli et al., 2019).

Figure 2. Focal structural results



Note. Standardised coefficients are from the complete thesis model. R^2 values likewise reflect that full specification. The figure does not imply temporal causality.

DISCUSSION

Overview of findings

This study examined whether Industry 4.0-enabled interactive TVET instructional management was associated with perceived competency readiness and whether student engagement helped explain that association. All four focal hypotheses were supported. Instructional management had positive paths to both engagement and perceived readiness, engagement had a positive path to readiness, and the bootstrapped indirect association through engagement was significant. The direct path remained significant, producing a complementary partial mediation pattern. Taken together, the results suggest that technology-integrated TVET learning is most meaningfully understood as a combination of instructional design, learner activity, and competency orientation rather than as technology availability alone.

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Interactive instructional management and perceived readiness

The positive instructional management-readiness path supports H1 and is consistent with competence-based vocational education. Students reported greater readiness when they perceived that digital and Industry 4.0-related resources were integrated with practical learning, guided occupational practice, feedback, authentic problems, and workplace relevance. This result does not show that the technologies themselves increased competence. Instead, it indicates that a coherent instructional environment was associated with students' judgement that they could demonstrate practical skills, apply technical knowledge, solve work-related problems, complete competency-based assessments, and meet occupational expectations.

This distinction matters because digitalisation can otherwise become detached from occupational purpose. TPACK predicts that technology contributes to learning when it is aligned with pedagogy and content (Mishra & Koehler, 2006). Authentic-learning and learning-factory perspectives similarly stress the value of work-like tasks and systems rather than decontextualised demonstrations (Abele et al., 2015; Baena et al., 2017; Herrington & Oliver, 2000). The present finding extends those arguments to students' perceived readiness across a broad SLaPB sample. It is also compatible with recent Malaysian work identifying work-based learning, applied research, and integrated Industry 4.0 talent domains as components of future-fit TVET development (Mazlan et al., 2026).

The direct path remained substantial after engagement was included. This may reflect instructional features that relate to readiness more immediately, such as explicit alignment with occupational standards, opportunities to rehearse assessments, repeated exposure to work-relevant procedures, and feedback about performance. The study did not measure these additional mechanisms separately, so this interpretation should be tested rather than assumed.

Interactive instructional management and student engagement

The instructional management-engagement path was the strongest focal relationship, supporting H2. Students were more engaged when they perceived digital tools as part of guided, interactive, feedback-rich, and occupationally relevant learning. The result aligns with evidence that educational technology facilitates engagement when it enables active participation, communication, collaboration, feedback, and learner agency (Bedenlier et al., 2020; Bond & Bedenlier, 2019; Bond et al., 2020). It also reinforces the ICAP proposition that the cognitive quality of learner activity matters more than the mere presence of a technological medium (Chi & Wylie, 2014).

The final engagement measure emphasised interest, occupational relevance, careful thinking, questioning, and suggestions for improvement. The strong coefficient therefore indicates that interactive instructional management was particularly associated with cognitive-relevance and agentic responses. When students can see how a digital activity relates to a future occupation, think about how tools improve practical performance, ask questions, and propose improvements, technology-supported learning is less likely to remain passive. This interpretation is also consistent with current digital-learning evidence linking learner capability and attitudes with active engagement (Getenet et al., 2024).

For SLaPB providers, the finding shifts attention from how many tools are available to what students actually do with them. A simulation that students merely watch may be technologically advanced but instructionally passive. The same simulation can become more engaging when students predict outcomes, make decisions, diagnose errors, explain procedures, compare solutions, and receive feedback. This difference is central to the argument that TVET digital transformation requires pedagogical and organisational capacity alongside infrastructure (Niwamanya et al., 2025; Paryono & Mashod, 2025; Zhong & Juwaheer, 2024).

Student engagement and perceived readiness

H3 was also supported: engagement was positively associated with perceived readiness. The coefficient was smaller than the instructional-management paths but remained statistically and practically relevant. Competency-based learning requires more than attendance or exposure. Learners must connect knowledge with practical decisions, monitor performance, seek clarification, and adapt action. Interest, occupational relevance, cognitive investment, and agency can help students interpret learning experiences as preparation for future work.

The result supports the educational-interface view of engagement as a process through which institutional conditions and learner activity connect with outcomes (Kahu & Nelson, 2018). It also fits the competence perspective that integrated capability is developed in meaningful professional contexts (Mulder, 2017; Mulder et al., 2007). However, the outcome remains perceived readiness. Students who are engaged may form better calibrated and more positive judgements about their preparation, but this study cannot determine whether those judgements correspond to independent competency assessments. The association should therefore motivate, not replace, validation against practical performance.

Engagement as an explanatory pathway

The mediation result provides the study's central explanatory contribution. Engagement carried a significant portion of the association between instructional management and perceived readiness, supporting H4. In substantive terms, students who experienced more coherent interactive instruction also reported stronger interest, occupational connection, cognitive processing, questioning, and contribution; those responses were in turn associated with greater perceived readiness. The pattern connects an environmental construct with a learner-process construct and then with a proximal readiness outcome.

The mediation was partial rather than complete. Engagement is therefore an important pathway, but not the only one. Other plausible mechanisms include feedback use, self-regulation, reflective practice, perceived task authenticity, transfer motivation, and clarity of competency standards. Future research should compare these mechanisms rather than treating engagement as an exhaustive explanation.

The statistical pattern also requires careful temporal interpretation. The cross-sectional questionnaire measured instructional perceptions, engagement, and readiness at the same time. As Maxwell and Cole (2007) show, cross-sectional mediation estimates can differ from longitudinal processes and cannot establish that the proposed sequence unfolded over time. Reverse or reciprocal relationships are plausible: students who already feel ready may engage more actively or evaluate instruction more favourably. The present evidence is therefore consistent with the hypothesised mechanism, not proof of causation.

Theoretical Contributions

The study makes four theoretical contributions. First, it reframes Industry 4.0 implementation in TVET as an instructional-management construct. The focal environment is not defined by isolated technology use but by the integration of technology with occupational content, guided practice, feedback, collaboration, authentic problems, reflection, and sustained programme delivery. This formulation connects TPACK with competence-based vocational education and responds to Education 4.0 literature that calls for pedagogical transformation rather than simple digitisation (Bonfield et al., 2020; Mishra & Koehler, 2006; Mukul & Büyüközkan, 2023).

Second, the study links learning-environment design with the quality of learner activity. ICAP explains why technology-supported instruction should differ according to whether students receive, manipulate, generate, or jointly construct knowledge (Chi & Wylie, 2014). The strong instructional management-engagement coefficient provides context-specific evidence that these learner processes are relevant in competency-oriented TVET.

Third, the mediation model places engagement between instructional management and perceived readiness. Prior literature has extensively conceptualised engagement and documented technology-engagement associations, but the present model specifies engagement as a learning-process link to a TVET readiness outcome. The complementary partial pattern indicates that engagement adds explanatory value without reducing instructional management to an indirect-only influence.

Fourth, the study sharpens the boundary around readiness. By explicitly measuring perceived competency readiness rather than actual competence or employability, it avoids equating confidence with certified performance. This distinction is theoretically useful because perceived readiness can influence participation and transition while still requiring external validation. Recent research on Industry 4.0 job readiness reinforces the importance of examining readiness directly, but future models should combine perception with performance evidence (Wong & Abdullah, 2025).

Practical And Policy Implications

For instructors, the findings support an activity-first approach to Industry 4.0 tools. Learning sessions should begin with a competency or occupational problem and then select technology that helps students observe, practise, diagnose, decide, collaborate, or reflect. Simulations and digital demonstrations should include prompts that require prediction and explanation; guided practice should include repeated attempts; digital feedback should identify the gap between current performance and competency criteria; and collaborative tasks should require learners to justify decisions rather than divide work mechanically. These principles are consistent with evidence on simulation, authentic learning, and feedback (Chernikova et al., 2020; Hattie & Timperley, 2007; Herrington & Oliver, 2000).

For SLaPB institutions, procurement and instructional capacity should be planned together. Equipment, connectivity, platforms, and smart systems require instructor development in lesson design, assessment alignment, facilitation, and troubleshooting. Institutions can evaluate implementation with learner-process indicators: Do students ask questions, connect tasks with occupational practice, use feedback, and propose improvements? Low engagement may signal a design or support problem even where technology is available. Whole-institution and enterprise-provider approaches are particularly relevant because digital TVET depends on leadership, instructor capability, industry relevance, infrastructure, and learner support (Niwamanya et al., 2025; Zhong & Juwaheer, 2024).

For programme and certification quality, Industry 4.0 activities should be mapped explicitly to National Occupational Skills Standards and the relevant certification level. Students should understand which competency is being practised, what evidence demonstrates acceptable performance, and how digital work processes relate to occupational requirements. Assessment preparation should be integrated with learning rather than treated as a separate end-stage exercise.

For policy makers, the findings suggest that investment indicators should extend beyond numbers of devices or laboratories. Policy evaluation can include the extent of authentic use, frequency and quality of feedback, opportunities for interactive practice, student engagement, and alignment with occupational standards. Malaysia's National TVET Policy 2030 provides a relevant strategic context for combining quality, industry responsiveness, and future skills (Majlis TVET Negara, 2024). Regional evidence also indicates that TVET responses to digital transformation require coordinated institutional and industry action (Paryono & Mashod, 2025).

Limitations And Future Research

Several limitations define the interpretation of the results. First, the cross-sectional design does not establish temporal order or causality. Longitudinal studies should measure instructional experiences before engagement and readiness, while intervention studies could compare structured interactive designs with conventional delivery. Cross-lagged or latent-change models would provide stronger evidence about direction and reciprocal relationships.

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Second, all focal variables were reported by the same students in one questionnaire. Procedural safeguards and diagnostic checks reduce some concerns but cannot eliminate common-method variance, consistency motives, or favourable response tendencies. Future research should combine student reports with instructor observations, platform traces, digital portfolios, practical-assessment scores, and workplace-supervisor ratings.

Third, the outcome was perceived competency readiness. It should be validated against actual practical performance, certification evidence, safety and quality behaviour, and workplace transfer. Such comparisons would show whether confidence is accurate, overestimated, or underestimated across students and programme levels.

Fourth, measurement-model refinement narrowed content. The final engagement construct retained five items centred on interest, occupational relevance, cognitive processing, questioning, and agentic contribution; behavioural completion, enjoyment, and social-collaboration indicators were removed. The final readiness scale omitted several digital, safety, adaptation, and communication indicators. Although reliability and AVE improved, the constructs no longer represented every dimension in the original definitions. Future studies should validate multidimensional, higher-order, or composite specifications and avoid deleting theoretically important content solely to reach numerical thresholds.

Fifth, the sample was large and institutionally diverse but not a fully national probability sample. It was dominated by young students and government institutions, and all participants had some relevant digital-learning exposure. Generalisation to private providers, adult learners, other Malaysian certification routes, or TVET systems outside Malaysia requires replication. Multigroup analyses across certification levels, occupational clusters, institution types, and access conditions may reveal important heterogeneity.

Sixth, the focal estimates were obtained from the complete structural model reported in the thesis. Future robustness analyses should re-estimate the reduced three-construct mediation model and compare its coefficients, explanatory power, and predictive performance with the complete model. Predictive assessment should also include an explicit linear-model benchmark and indicator-level error comparison in line with PLSpredict guidance (Shmueli et al., 2019).

CONCLUSION

Industry 4.0-enabled interactive TVET instructional management was positively associated with both student engagement and perceived competency readiness among 1,025 Malaysian SLaPB students. Engagement was also positively associated with readiness and carried a significant part of the instructional management-readiness relationship. The strongest focal path linked instructional management with engagement, indicating that the educational value of Industry 4.0 resources is closely connected with the participation, thinking, relevance, and agency they elicit.

The findings support a shift from technology-centred implementation to competency-centred instructional design. Digital tools, simulations, platforms, and smart systems should be organised around authentic occupational tasks, guided practice, formative feedback, collaboration, reflection, and transparent competency standards. Engagement can serve as an intermediate indicator of whether that design is functioning as intended.

The conclusions remain bounded by the cross-sectional, self-report design and by the use of perceived rather than demonstrated readiness. Even so, the study provides a coherent basis for longitudinal, intervention, and performance-validated research. For SLaPB institutions and the wider TVET sector, the practical message is that infrastructure becomes educational transformation only when students are enabled to use it in purposeful, interactive, and occupationally meaningful ways.

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Declarations

Ethical approval and consent to participate. The study followed the ethical requirements of Universiti Tun Abdul Razak and the participating institutions. Institutional permission was obtained before data collection, and electronic informed consent was obtained from all participants.

Data availability. De-identified data and analysis documentation may be available from the corresponding author upon reasonable request, subject to institutional, ethical, and confidentiality requirements.

Conflict of interest. The author declares that there is no conflict of interest regarding the publication of this paper.

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