Mapping the Ecosystem: Identifying and Validating Constructs for Drone Integration in Malaysian Education

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ABSTRACT

The integration of drone technology in Malaysian schools remains limited due to fragmented policies, limited training, and infrastructural constraints. To bridge this gap, this study aims to identify and validate the core constructs and key elements necessary to build an ecosystem that facilitates the optimal integration of drone technology by teachers and students within the school environment. Guided by an exploratory sequential mixed-methods approach, the qualitative phase employed Grounded Theory through expert focus group discussions and open-ended questionnaires to extract relevant construct. Six key constructs emerged: Drone Handling and Safety, Career Pathways, Structured Training, Collaborative Network Models, Competitions and Innovation Platforms, and School Governance. These constructs were then operationalized into a survey instrument for quantitative validation involving 305 respondents across the education and drone sectors. Data analysis using Partial Least Squares Structural Equation Modelling (PLS-SEM) confirmed the model's construct validity, with all constructs demonstrating acceptable levels of convergent and discriminant validity. The findings offer a validated ecosystem to support the structured and safe implementation of drone programs in schools, aligned with Malaysia's Digital Education Policy and STEM-TVET agenda. This study contributes to the development of evidence-based policy and practice by providing a reliable model that can inform future implementation and innovation in drone-based education.

Keywords: Drone education, construct validation, STEM-TVET, ecosystem, integration

INTRODUCTION

Despite national policy advancements in digital education, the integration of drone technology into Malaysian schools remains inadequate. The Ministry of Education's Digital Education Policy (DEP) emphasizes the importance of equipping students with digital competencies and exposure to emerging technologies, including drones, to align with the demands of Industrial Revolution 4.0 [13]. However, there is a noticeable gap between this policy aspiration and the actual implementation at the school level. Many schools lack clear procedures, structured training, and comprehensive support systems for deploying drone-based programs effectively. As a result, teachers and administrators are often left to navigate safety regulations, technological complexities, and pedagogical integration without a systematic framework.

Globally, drones have proven to be powerful tools in education by enhancing learning in physics, environmental science, geography, ICT, and even media studies [15]. Their hands-on nature promotes experiential and constructivist learning, which supports students in developing problem-solving, critical thinking, and spatial reasoning skills [23]. In countries like the United States, Australia, and South Korea, drones are already embedded in national STEM education agendas, often with industry collaboration and clear curricular integration [3], [19]. Malaysia, despite its aspiration, still lacks such coordinated and structured integration.

Locally, several barriers impede progress. First, there is a lack of teacher training and institutional readiness, with many educators unfamiliar with both the technical handling of drones and their instructional potential [9]. Second, compliance with Civil Aviation Authority of Malaysia (CAAM) regulations remains unclear at the school level, especially concerning permits, no-fly zones, safety documentation, and accountability. Third, there is no formal model or ecosystem that schools can follow to integrate drones meaningfully, safely, and sustainably into the learning environment.

Furthermore, current educational technology integration models in Malaysia's school such as STEM approach, 21st Century Learning (PAK 21), TPACK (Technological Pedagogical Content Knowledge) and SAMR (Substitution, Augmentation, Modification, Redefinition) are useful but insufficient for addressing the specific regulatory, safety, and collaboration-based aspects of drone implementation in Malaysian schools [16], [18]. These models focus largely on teaching and learning interactions but do not provide structural guidance for schools in managing drone-related resources, building partnerships with industry, or complying with aviation safety protocols.

Using the Knowledge–Attitudes–Practice (KAP) model, [21] found that Malaysian students are enthusiastic about drone technology and its diverse applications in STEM and TVET. However, the practice dimension remains weak because students rarely have sustained access to drone learning opportunities. This indicates that without a supportive ecosystem involving policy, pedagogy, training, and infrastructure, positive attitudes alone are insufficient to ensure long-term engagement or skills development.

From a theoretical perspective, the integration of drones into schools must be seen as an ecosystem involving multiple interdependent domains. Drawing on Bronfenbrenner's Ecological Systems Theory [2], this study frames the school as a microsystem influenced by external policies (macrosystem), inter-agency collaborations (exosystem), and teacher-student interactions (mesosystem). In parallel, constructivist learning theory supports the use of drones as active learning tools where students build knowledge through exploration, experimentation, and social interaction [20].

Given these complexities, this study seeks to address the central question: What are the constructs and elements required to establish an effective drone integration ecosystem in Malaysian schools? The aim is not merely to understand drone adoption, but to systematically determine and validate the critical components that should form the foundation of an ecosystem model. Through an exploratory sequential mixed-methods design, the study first explores expert and practitioner insights via qualitative methods (focus group discussions and open-ended questionnaires), then quantitatively validates the resulting constructs using Partial Least Squares Structural Equation Modelling (PLS-SEM).

By identifying and validating these core elements such as safety protocols, structured training, stakeholder collaboration, and institutional governance, the study contributes a validated, evidence-based framework. This model is expected to support school leaders, policymakers, and educators in implementing drone initiatives aligned with Malaysia's national educational goals, particularly in STEM and TVET. It also provides a practical tool to help close the implementation gap between policy and practice.

A. Drone Technology in Education: An Interdisciplinary Tool for STEM and TVET

Drone technology is emerging as a powerful interdisciplinary tool in education, particularly in supporting Science, Technology, Engineering, and Mathematics (STEM) and Technical and Vocational Education and Training (TVET). Drones combine multiple domains, such as mechanical engineering, electronics, computer programming, and geospatial analytics, making them ideal for holistic, project-based learning. In STEM education, drones can be used to teach real-world applications of physics (e.g., motion, force, aerodynamics), mathematics (e.g., coordinates, measurement, angles), and digital technologies (e.g., programming flight paths using coding platforms) [23], [1]. In TVET settings, drones support skills acquisition in areas such as surveying, precision agriculture, disaster management, logistics, and aerial photography, aligning well with current industry 4.0 skill demands [9].

As a hands-on technology, drones encourage students to engage in constructivist learning, where they build knowledge through active experimentation, inquiry, and real-time feedback. Students learn not only how to operate drones but also how to interpret data from sensors, analyze aerial imagery, and solve technical challenges [12], [22]. For instance, in agricultural TVET modules, students may use drones equipped with multispectral cameras to monitor crop health, bridging science concepts with vocational training [19].

B. Global and Local Perspectives on Drone Integration

In countries like Spain, South Korea, and the United States show that drones enhance students' cognitive and technical competencies when introduced through structured educational frameworks [3], [4]. In these contexts, drone curricular are often supported by national education authorities and integrated into STEM or CTE (Career and Technical Education) programs through partnerships with industry and regulatory bodies. For example, in South Korea, government-backed drone education initiatives focus on creating skilled drone operators and technicians, aligning with their national TVET agenda [19].

In Malaysia, while the Digital Education Policy (DEP) emphasizes the inclusion of emerging technologies such as drones, its implementation in STEM-TVET remains uneven. Schools face constraints such as limited equipment, untrained teachers, and uncertainty regarding CAAM regulations [11]. The lack of institutional readiness and systematic instructional models contributes to the inconsistent adoption of drones as a teaching and training tool.

C. Pedagogical Models and Drone-Specific Frameworks

Traditional technology integration models such as TPACK [16] and SAMR [18] help teachers align technological tools with content and pedagogy. However, they fall short in addressing the operational, safety, and regulatory aspects essential to drone usage. This gap has led to the emergence of new drone-specific pedagogical approaches, including "dronagogy", which emphasizes the instructional value of drones across transdisciplinary domains [4]. The Drone Technology Enabled STEM Curriculum (DTESC) model further provides a scalable, modular framework that integrates drones into learning progression stages from disciplinary learning to real-world application [4].

D. Theoretical Foundations for Ecosystem Development

To develop an integrated school-based drone model, the present study applies Bronfenbrenner's Ecological Systems Theory [2], which contextualizes educational change across microsystems (e.g., classroom practices), mesosystems (e.g., teacher-industry collaboration), and macrosystems (e.g., national policy, CAAM regulations). Complementing this is constructivist learning theory, which supports the role of drones in fostering inquiry-based, student-centered learning [12], [20].

While global examples highlight the potential of drones in skill development and technological literacy, a localized and validated model is needed to guide Malaysian schools in systematically integrating drone education. This study addresses that gap by identifying essential constructs such as training, safety, governance, collaboration, and innovation. Then identifying and validating them through a mixed-methods design. The result is the ecosystem model which provides a structural and pedagogical foundation for STEM-TVET implementation at the school level.

METHODOLOGY

This study employed an exploratory sequential mixed-methods design, which is suitable when qualitative findings are needed to inform the development of a quantitative instrument [5]. The primary aim was to determine and validate the constructs and elements necessary for developing an ecosystem model to integrating drone technology in Malaysian school. The research was conducted in two distinct but interconnected phases:

1. Qualitative Phase: To explore and identify relevant constructs and ecosystem elements

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2. Quantitative Phase: To empirically test and validate the constructs using Partial Least Squares Structural Equation Modelling (PLS-SEM)

The qualitative phase adopted Grounded Theory as the underlying strategy to explore emerging themes without being constrained by pre-existing frameworks [3],[8]. Data was collected through two main techniques:

TABLE I PLS-SEM Measurement Model Criteria [8], [6]

Techniques Data Collecting	
Focus Group Discussions (FGD)	a) MOE officials b) School administrators c) TVET educators d) Drone industry professionals e) Researchers in educational technology and aviation safety
Open-ended questionnaires distribution	Teachers and education officers with prior exposure to drone-related programs

A total of 21 participants were involved in the FGD sessions across three rounds, while 34 responses were received through open-ended instruments. The data was analysed thematically, using open, axial, and selective coding to generate emergent categories that were later refined into six major constructs.

Based on thematic analysis of qualitative data, six core constructs were identified as essential for the implementation of a school-based drone ecosystem:

1. Drone Handling and Safety
2. Career Pathways
3. Structured Training
4. Collaborative Network Models
5. Competitions and Innovation Platforms
6. School Governance

Each construct was elaborated into multiple measurable items, resulting in a 56-item draft instrument subjected to expert review and a pilot test.

The quantitative phase involved the development and validation of the measurement model using Partial Least Squares Structural Equation Modelling (PLS-SEM) via SmartPLS 4.0. This technique was selected due to its suitability for theory development, model testing with small to medium sample sizes, and its robustness in handling complex models with reflective constructs [8].

The final instrument consisted of close-ended items representing the six identified constructs, with statements measured on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The questionnaire undergoes content validation through five expert panels in educational technology, drone regulation, and psychometrics prior to administration of quantitative phase. The sample comprised 305 respondents from various stakeholder categories:

1. Secondary and primary school teachers involved in STEM or TVET
2. School administrators (principals, senior assistants)
3. Education officers from state and federal levels
4. Industry experts and certified drone trainers

Respondents were selected using purposive sampling to ensure relevance to the topic. Data was collected via online survey forms over a period of six weeks. Data analysis was conducted in two stages:

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TABLE 2 PLS-SEM Data Analysis Procedure [8], [6], [17]

Measurement Model Assessment	Evaluated using criteria such as: Composite Reliability (CR ≥ 0.70) Average Variance Extracted (AVE ≥ 0.50) Cronbach's Alpha (≥ 0.70) Outer loadings (≥ 0.60) Discriminant Validity via HTMT Ratio (≤ 0.90)

Based on Table 2, all constructs met the threshold values, indicating a reliable and valid measurement model, suitable for advancing to full model interpretation.

This study followed all ethical research standards, including obtaining informed consent from participants, ensuring data confidentiality, and acquiring institutional research ethics approval from the relevant university review board. Participation was voluntary, and respondents could withdraw at any stage without penalty.

RESULTS AND DISCUSSIONS

This section presents the empirical findings from the quantitative phase of the study, which aimed to validate the constructs and elements identified during the earlier qualitative phase. The purpose of this phase was to assess the reliability and validity of the proposed ecosystem model through Partial Least Squares Structural Equation Modelling (PLS-SEM). Using SmartPLS 4.0, the study evaluates the measurement model to confirm the robustness of the instrument, followed by a discussion of how each validated construct contributes to the conceptual and practical development of the drone ecosystem in Malaysian schools. The analysis provides empirical support for the multidimensional framework and offers insight into the interrelated factors that influence successful drone technology implementation within STEM and TVET education contexts.

A. Results

The study employed Partial Least Squares Structural Equation Modelling (PLS-SEM) using SmartPLS 4.0 to evaluate the reliability and validity of the six identified constructs. The measurement model was assessed using established criteria: internal consistency reliability (Composite Reliability and Cronbach's Alpha), convergent validity (Average Variance Extracted), and discriminant validity (HTMT ratio and cross-loadings), following guidelines by [8].

Internal Consistency Reliability: All constructs demonstrated strong internal consistency reliability. As shown in Table 3, Composite Reliability (CR) values ranged from 0.873 to 0.969, exceeding the minimum threshold of 0.70. Similarly, by referring to Table 4, Cronbach's Alpha values ranged from 0.785 to 0.952, indicating high reliability.

TABLE 3 Composite Reliability for All Constructs and Elements

Constructs	Elements	Composite Reliability
Drone Handling and Safety	Drone usage based on purpose	0.93
	Compliance with general regulations, control, and drone safety	0.947
	Guidelines for drone usage in schools	0.911
Career Pathway in Drone Field	Career pathway development through clubs and societies	0.887
	Technological advancement and innovation	0.936

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	enabling entrepreneurship in schools	
Structured Training	Structured training for teachers and students based on STEM	0.925
	Development of drone technology module for structured training	0.969
Collaborative Network Models	Strategic partnerships between MOE and stakeholders	0.936
	Collaboration on professional certification policies for teachers and students	0.95
Drone Competitions and Championships	Supervision of competition categories	0.873
	Drone sports championships	0.964
School Governance	School management readiness for drone-related programs	0.886
	Risk management in drone usage	0.889
	Implementation of co-curricular drone activities for curriculum enhancement	0.873

TABLE 4 Cronbach’s Alpha for All Constructs and Elements

Constructs	Elements	Cronbach's Alpha
Drone Handling and Safety	Drone usage based on purpose	0.904
	Compliance with general regulations, control, and drone safety	0.923
	Guidelines for drone usage in schools	0.867
Career Pathway in Drone Field	Career pathway development through clubs and societies	0.808
	Technological advancement and innovation enabling entrepreneurship in schools	0.866
Structured Training	Structured training for teachers and students based on STEM	0.877
	Development of drone technology module for structured training	0.952
Collaborative Network Models	Strategic partnerships between MOE and stakeholders	0.914
	Collaboration on professional certification policies for teachers and students	0.934
Drone Competitions and Championships	Supervision of competition categories	0.785
	Drone sports championships	0.95
School Governance	School management readiness for drone-related programs	0.828
	Risk management in drone usage	0.832
	Implementation of co-curricular drone activities for curriculum enhancement	0.805

Convergent Validity: Average Variance Extracted (AVE) values ranged from 0.660 to 0.912 in Table 5, exceeding the threshold of 0.50 [6], thus confirming convergent validity. As shown in Appendix A, all item loadings were greater than 0.60, with most exceeding 0.977, indicating acceptable item convergence. Detailed statistical outputs are provided in Appendix A.

TABLE 5 Average Variance Extracted for All Constructs and Elements

Constructs	Elements	Average Variance Extracted
Drone Handling and Safety	Drone usage based on purpose	0.731
	Compliance with general regulations, control, and drone safety	0.819
	Guidelines for drone usage in schools	0.719
Career Pathway in Drone Field	Career pathway development through clubs and societies	0.725
	Technological advancement and innovation enabling entrepreneurship in schools	0.880
Structured Training	Structured training for teachers and students based on STEM	0.806
	Development of drone technology module for structured training	0.912
Collaborative Network Models	Strategic partnerships between MOE and stakeholders	0.747
	Collaboration on professional certification policies for teachers and students	0.792
Drone Competitions and Championships	Supervision of competition categories	0.696
	Drone sports championships	0.871
School Governance	School management readiness for drone-related programs	0.660
	Risk management in drone usage	0.669
	Implementation of co-curricular drone activities for curriculum enhancement	0.633

Discriminant Validity: Discriminant validity in this study was assessed using the Heterotrait-Monotrait Ratio (HTMT), as recommended by [10], [7]. According to previous studies, an HTMT value of less than 0.90 [7] or 0.85 [14] indicates that the constructs within the model are sufficiently distinct and do not excessively overlap. HTMT values, which represent the ratio of between-construct correlations to within-construct correlations, confirm that discriminant validity has been achieved when the thresholds are met.

TABLE 6 Heterotrait-Monotrait Ratio (HTMT) for All Constructs

Constructs	Drone Competitions and Championships	Career Pathway in Drone Field	Structured Training	Collaborative Network Models	Drone Handling and Safety	School Governance
Drone Competitions and Championships	–					
Career Pathway in Drone Field	0.581	–				

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Structured Training	0.669	0.701	–			
Collaborative Network Models	0.698	0.636	0.672	–		
Drone Handling and Safety	0.792	0.598	0.652	0.587	–	
School Governance	0.686	0.591	0.594	0.562	0.796	–

Based on Table 6, the HTMT values for all construct pairs were found to be below the upper threshold of 0.90, as recommended by referring [10], [7]. This indicates that the constructs in the model meet the criteria for discriminant validity, thereby confirming that each construct measures a conceptually distinct dimension. However, several HTMT values were close to the more conservative threshold of 0.85, such as:

1. Drone Handling and Safety – School Governance (HTMT = 0.796),
2. Drone Handling and Safety – Drone Competitions and Innovation Platforms (HTMT = 0.792),
3. Structured Training – Career Pathways (HTMT = 0.701).

These values reflect moderately strong associations between the respective constructs yet remain within the acceptable range. The relatively high correlation between Drone Handling and Safety and School Governance may indicate that safety practices in school-based drone operations are closely tied to administrative systems and school-level regulations. Likewise, the relationship between Structured Training and Career Pathways highlights the importance of systematic and effective training in supporting students' career development in drone-related fields. These findings align with theoretical expectations and reinforce the multidimensional structure of the ecosystem model, where certain constructs are interrelated but still conceptually distinct.

Discriminant validity was further assessed using the Fornell-Larcker criterion, which compares the square root of the Average Variance Extracted (AVE) of each construct with the correlations between that construct and all others. According to [6], a construct demonstrates discriminant validity if the square root of its AVE is greater than its highest correlation with any other construct in the model.

As presented in Table 7, the square root of AVE values (bolded on the diagonal) for each construct were consistently higher than the inter-construct correlations:

TABLE 7 Fornell-Larcker criterion for All Constructs

Constructs	Drone Competitions and Championships	Career Pathway in Drone Field	Structured Training	Collaborative Network Models	Drone Handling and Safety	School Governance
Drone Competitions and Championships	**0.807**					
Career Pathway in Drone Field	0.539	**0.854**				
Structured Training	0.626	0.649	**0.904**			
Collaborative Network Models	0.648	0.567	0.628	**0.764**		
Drone Handling and Safety	0.760	0.559	0.631	0.544	**0.801**	
School Governance	0.662	0.536	0.570	0.516	0.746	**0.761**

These values were all greater than the respective correlations between constructs (ranging from 0.516 to 0.760), indicating that each construct shares more variance with its own indicators than with any other construct. This confirms that the constructs are statistically distinct from one another, thus fulfilling the requirement for discriminant validity under the Fornell-Larcker criterion. The findings affirm that each construct in the ecosystem model is conceptually and statistically independent, supporting the multidimensional structure of the ecosystem framework [8], [6].

DISCUSSION OF KEY FINDINGS

The validation of the six constructs provides strong empirical support for the proposed ecosystem model to integrating drone technology in Malaysian school. Each construct addresses a distinct yet interconnected domain necessary for successful drone integration in education.

This section discusses the findings based on the constructs and items involved, with emphasis on the internal consistency reliability of the model and its convergent validity. For discriminant validity, the findings are presented holistically, covering all constructs and items. In addition, several items are removed to ensure that the developed measurement model achieves acceptable levels of reliability and validity for the constructs and items examined.

1) Drone Handling and Safety: This construct had the highest reliability (CR = 0.948), underscoring its centrality in school-level drone implementation. Respondents consistently emphasized the need for clear Standard Operating Procedures (SOPs), teacher training on CAAM regulations, and physical space for safe operation. This reflects broader concerns in the literature regarding aviation compliance and school risk management [11], [22].

2) Career Pathways: The construct measuring career awareness and relevance of drone technology was also highly reliable (CR = 0.919). This aligns with TVET objectives, which seek to expose students to industry-relevant technologies. Drone applications in agriculture, logistics, and media were frequently cited by respondents as meaningful contexts for student learning [4], [19].

3) Structured Training: Teacher competency emerged as a major enabler of drone integration. Respondents highlighted the lack of formal certification or modular training. The findings support calls by [9] for teacher-specific training models, aligned with both pedagogy and technical handling.

4) Collaborative Network Models: This construct captured inter-institutional collaboration with industry, higher education, and aviation bodies. The model confirms the importance of ecosystem partnerships, echoing [2], where exosystem factors like institutional linkages shape classroom practice.

5) Competitions and Innovation Platforms: Respondents identified competitions, innovation showcases, and hackathons as effective ways to increase student motivation and real-world engagement. These co-curricular activities also help schools validate the outcomes of drone learning in non-exam-based formats [1].

6) School Governance: School leadership, budgeting, and strategic planning were captured under this construct. Though it had slightly lower AVE (still above 0.57), it remains crucial to sustaining drone programs. This reinforces the need for top-down commitment to complement bottom-up innovation.

Appendix B shown a structural model of the ecosystem model to integrating drone technology in Malaysian school developed using SmartPLS 4.0. The model demonstrates strong path relationships between the second-order construct and six key dimensions: Drone Handling and Safety, Career Pathways, Structured Training, Collaborative Network Models, Competitions and Innovation Platforms, and School Governance. All path coefficients indicate significant contributions to the overall ecosystem structure.

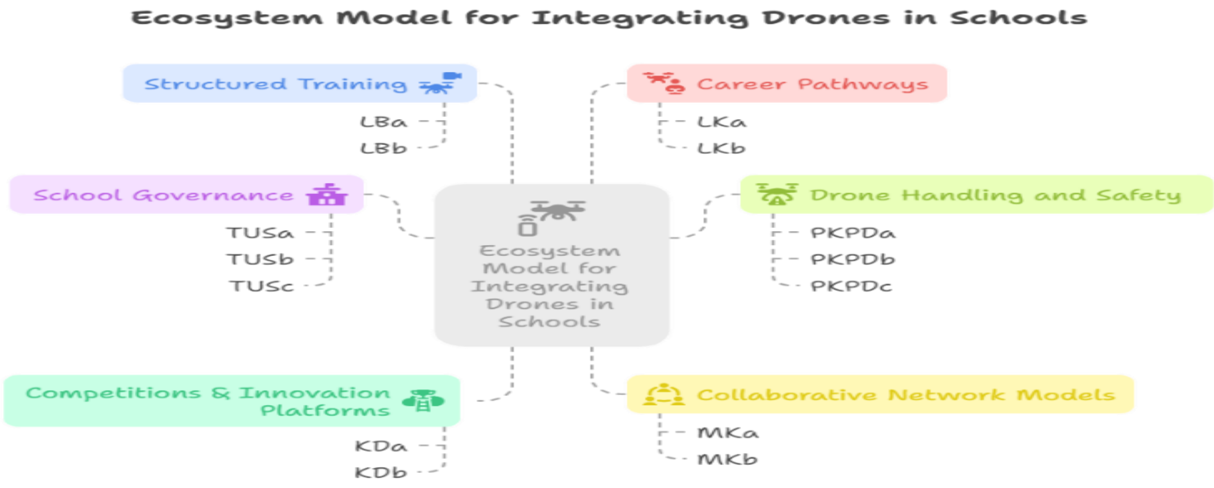

Fig. 1 Simplified Structural Model of the Ecosystem Model to Integrating Drone Technology in Malaysian School

Meanwhile, the model in Figure 1 represents a simplified structural model that is easier to interpret and understand.

This model specifically developed to support the integration of drone technology in Malaysian schools, its core components are not inherently limited to drones alone. The ecosystem-based approach comprising Structured Training, Career Pathways, Collaborative Network Models, School Governance, Competitions and Innovation Platforms, and Drone Handling and Safety offers a scalable and transferable framework for the integration of other emerging technologies within educational settings. Technologies such as robotics, artificial intelligence (AI), Internet of Things (IoT), and augmented/virtual reality (AR/VR) are increasingly becoming part of future-ready curriculum design, especially in STEM and TVET education.

For instance, the "Structured Training" construct emphasizes the need for teacher capacity building and student engagement through hands-on learning principles that are equally essential when introducing robotics or coding into the classroom. Similarly, the component on "Collaborative Network Models" encourages partnerships between schools, industry, and government bodies, a practice that aligns well with national strategies for AI or digital literacy rollouts. The "School Governance" construct, which includes policy, budgeting, and infrastructure considerations, also serves as a foundational requirement for any technology adoption in schools, regardless of the specific tool involved.

Thus, these ecosystem model holds potential as a blueprint for future educational technology frameworks, especially in systems where centralized curriculum planning and policy alignment are required. Adapting the model may involve contextualizing safety standards (e.g., from drone operation to data privacy in AI), or reconfiguring innovation platforms (e.g., robotics competitions instead of drone tournaments). Nevertheless, its modular and ecosystem-based design enables policymakers, educators, and stakeholders to reuse and modify the structure according to technological relevance and school readiness.

C. Limitation

Although this study provides a validated and empirically supported ecosystem model for integrating drone technology in schools, several limitations must be acknowledged that may affect the interpretation and generalizability of the findings. Firstly, the research employed a cross-sectional design, where data were collected at a single point in time. This limits and ability to assess the long-term impact, sustainability, and evolution of the model components when implementing in real school environments. Since educational ecosystems are dynamic and influence by policy shifts, technological advancement, and institutional changes, a longitudinal study would provide a more comprehensive understanding of the ecosystem model's effectiveness over time.

Secondly, the study relied primarily on self-reported data through questionnaires, which may be subject to response bias, including social desirability bias or overestimation of readiness or awareness among respondents. While the quantitative instrument was tested for reliability and validity, the absence of observational or implementation-based data limits the ability to confirm how the constructs operate in real-world school settings.

Thirdly, the sampling strategy, while involving various education stakeholders, may not fully represent the diversity of school contexts in Malaysia. For example, differences in infrastructure, access to technology, and teacher training across urban, rural, and remote schools could influence the feasibility and relevance of the ecosystem model's components. Additionally, the limited inclusion of certain stakeholder groups such as students or parents may mean some important perspectives were not captured.

Furthermore, the study was primarily conducted in the context of drone technology, and while the model shows potential to be adapted to other emerging technologies, this has not been empirically testing. The generalizability of the ecosystem model developed to other technologies (e.g., robotics, AI, AR/VR) in education requires further validation.

Lastly, although the model was evaluated statistically using advanced method such as PLS-SEM, its practical applicability has yet to be examine through pilot implementation or field testing. Without such trials, the study cannot conclusively demonstrate how the model influences teaching practices, student engagement, or educational outcomes in practice.

Considering these limitations, future research is encouraged to:

1. Conduct longitudinal or experimental studies to examine model effectiveness over time.
2. Implement pilot programs in schools to observe real-time adoption and outcomes.
3. Broaden stakeholder involvement, including students, parents, and policymakers, for a more holistic validation.
4. Explore the adaptation of the ecosystem model for other educational technologies or in different national contexts, especially in TVET/STEM integration programs.

Implications For Policy and Practice

The validated ecosystem model presents significant implications for educational policy, school management, teacher training, and cross-sector collaboration. As Malaysia continues to advance its Digital Education Policy and embrace Industry 4.0 through the integration of emerging technologies, the ecosystem model offers a structured and empirically tested framework to support the safe, systematic, and scalable adoption of drone-based programs, particularly within STEM and TVET education streams.

1) Operational Compliance: One of the most critical challenges in drone education is ensuring compliance with aviation regulations, particularly those outlined by the Civil Aviation Authority of Malaysia (CAAM). The ecosystem model’s inclusion of a specific construct on Drone Handling and Safety reflects the need for a dedicated operational framework that includes standard operating procedures (SOPs), flight safety checklists, emergency protocols, designated flying zones, and teacher certification mechanisms.

Policymakers and school authorities must collaborate with CAAM to develop drone operation guidelines tailored for educational contexts, ensuring that schools are not exposed to legal or safety risks. This could involve establishing a centralized digital platform for schools to apply for drone flight permits, access compliance templates, and report safety incidents. Embedding regulatory literacy into teacher training and school policies will also empower educators to manage drone activities responsibly and confidently.

2) Human Capital Development: The constructs related to Structured Training and Career Pathways underscore the importance of capacity building for both teachers and students. For teachers, this involves offering certified professional development programs that go beyond basic drone operation to include curriculum integration, safety instruction, and project-based learning strategies. Institutions such as the Institut Aminuddin Baki (IAB), or state education departments could play a central role in scaling such training.

For students, drone education opens diverse career opportunities in agriculture, geospatial technology, logistics, creative media, and drone maintenance. Aligning closely with TVET and IR4.0 skill demands. Thus, education policies should encourage modular learning pathways that link school-level drone competencies to certifications and micro-credentials, potentially in collaboration with drone industry partners. Integrating drone modules into existing STEM curricula or as part of co-curricular programs (e.g., robotics clubs, Young Innovators Challenge) could also promote equity in access and interest across urban and rural schools.

3) Organizational Readiness: The PDDS construct on School Governance emphasizes the need for institutional leadership and resource planning to ensure program sustainability. Schools require clear budgeting frameworks, procurement guidelines, and infrastructure planning tools (e.g., drone storage areas, flight zones, and maintenance kits). Leadership support is essential to allocate staff, time, and facilities for drone-related activities.

At the policy level, the Ministry of Education (MOE) can consider developing a national blueprint for drone education in schools, which outlines implementation milestones, infrastructure standards, funding options, and integration strategies for primary, secondary, and vocational institutions.

Moreover, the construct Collaborative Network Models reinforces the importance of forging multi-stakeholder partnerships, including ministries Ministry of Science and Technology (MOSTI), Ministry of Youth and Sports (KBS), universities, polytechnics, drone academies, and private drone service providers. These partnerships can facilitate resource sharing, mentorship programs, student internships, and collaborative innovation events such as hackathons or drone expos.

4) Bridging Policy and Practice: In summary, the ecosystem model acts as a translation mechanism between macro-level policies and ground-level practice. It provides policymakers, school leaders, and educators with a holistic and structured ecosystem that accounts for operational, pedagogical, and institutional dimensions of drone technology use in education.

By aligning national education goals with technical training, safety governance, and career relevance, the ecosystem model not only supports Malaysia’s Digital Education Policy and STEM-TVET aspirations but also contributes to producing a digitally skilled and future-ready generation.

CONCLUSION AND RECOMMENDATIONS

Conclusions

This study aimed to determine and validate the constructs and elements necessary for developing ecosystem model to integrating drone technology in Malaysian school. Through an exploratory sequential mixed-methods approach, the research identified six key constructs based on expert insights and validated them using Partial Least Squares Structural Equation Modelling (PLS-SEM).

The measurement model demonstrated strong internal consistency, convergent validity, and discriminant validity across all constructs. Notably, the constructs of Drone Handling and Safety, Career Pathways, Structured Training, Collaborative Network Models, Competitions and Innovation Platforms, and School Governance were shown to be statistically reliable and conceptually distinct. These constructs collectively reflect the multifaceted requirements for successful drone program implementation in Malaysian schools, particularly within STEM and TVET education contexts.

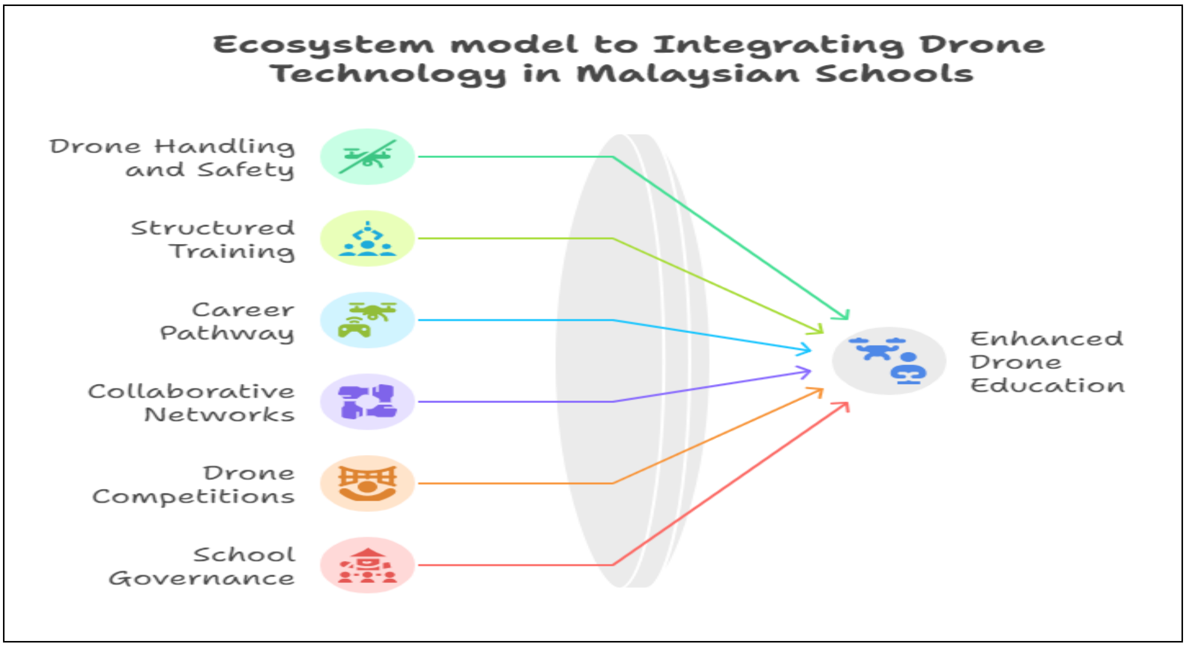

Fig. 2 The Ecosystem Model to Integrating Drone Technology in Malaysian School

The findings provide empirical evidence that a structured ecosystem model can bridge the gap between policy aspirations such as those articulated in the Ministry of Education's Digital Education Policy (DEP) and actual practice within schools. The validated ecosystem model offers a practical, scalable, and contextually grounded framework that can guide schools, policymakers, and industry partners in planning, implementing, and sustaining drone-based learning initiatives.

Recommendations

1) For Policymakers (MOE, CAAM, MOSTI):

1. Develop National Guidelines for drone usage in education, incorporating CAAM regulations, safety protocols, and educational outcomes.

2. Integrate drone technology into the Digital Education Policy implementation roadmap, with clear milestones for primary, secondary, and vocational institutions.

3. Collaborate with regulatory and training bodies to create a centralized platform for drone permit applications, SOP templates, and safety training modules for schools.

2) For School Leaders and Administrators:

1. Embed drone education into school development plans, including budgeting, infrastructure planning, and human resource allocation.

2. Establish dedicated teams or coordinators to manage drone programs, ensure SOP compliance, and liaise with external partners.

3. Support co-curricular integration through competitions, exhibitions, and cross-disciplinary projects that encourage innovation.

3) For Teacher Training Institutions and Educators:

1. Design and deliver modular training programs for teachers that cover drone operation, pedagogical integration, and regulatory literacy.

2. Align teacher training with TVET competencies and micro-credentials to ensure transferability of skills to students.

3. Encourage interdisciplinary teaching strategies, combining STEM, geography, ICT, and creative design through drone-based lessons.

4) For Industry and Higher Education Partners*:*

1. Establish mentorship and resource-sharing programs with schools, including internships, demo days, and guest lectures.

2. Support certification pathways for students and teachers that align with industry-recognized standards.

3. Contribute to research and development in drone education innovation, particularly in curriculum design and instructional technology.

In conclusion, the ecosystem model provides a comprehensive foundation for scaling drone technology integration in Malaysian schools. By aligning operational, pedagogical, and governance aspects within a unified framework, the model contributes to the broader national agenda of producing future-ready, digitally literate learners capable of thriving in a technology-driven society.

Contribution to Research

This study advances the academic discourse on drone pedagogy, especially in the under-researched Southeast Asian context. While global frameworks such as DTESC (Chung et al., 2025) and “dronagogy” have emerged, this study is among the first to empirically validate a localized, multi-dimensional drone ecosystem model using PLS-SEM.

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APPENDIX A

Item loadings for All Constructs and Elements

Constructs	Elements	Item Code	Outer Loading
Drone Handling and Safety	Drone usage based on purpose	PKPDa1	0.873
		PKPDa2	0.872
		PKPDa3	0.930
		PKPDa4	0.928
		PKPDa5	0.639
	Compliance with general regulations, control, and drone safety	PKPDb1	0.956
		PKPDb2	0.963
		PKPDb3	0.932
		PKPDb4	0.753
	Guidelines for drone usage in schools	PKPDc1	0.887
		PKPDc2	0.739
		PKPDc3	0.87
		PKPDc4	0.887
Career Pathway in Drone Field	Career pathway development through clubs and societies	LKa1	0.825
		LKa2	0.797
		LKa3	0.926
	Technological advancement and innovation enabling entrepreneurship in schools	LKb1	0.921
		LKb2	0.954
		LKb3	
Structured Training	Structured training for teachers and students based on STEM	LBa1	0.739
		LBa2	0.961
		LBa3	0.930
		LBa4	
	Development of drone technology module for structured training	LBb1	0.945
		LBb2	0.960
		LBb3	0.960
Collaborative Network Models	Strategic partnerships between MOE and stakeholders	MJKa1	0.908
		MJKa2	0.923
		MJKa3	0.914
		MJKa4	0.840
		MJKa5	0.779
	Collaboration on professional	MJKb1	0.797

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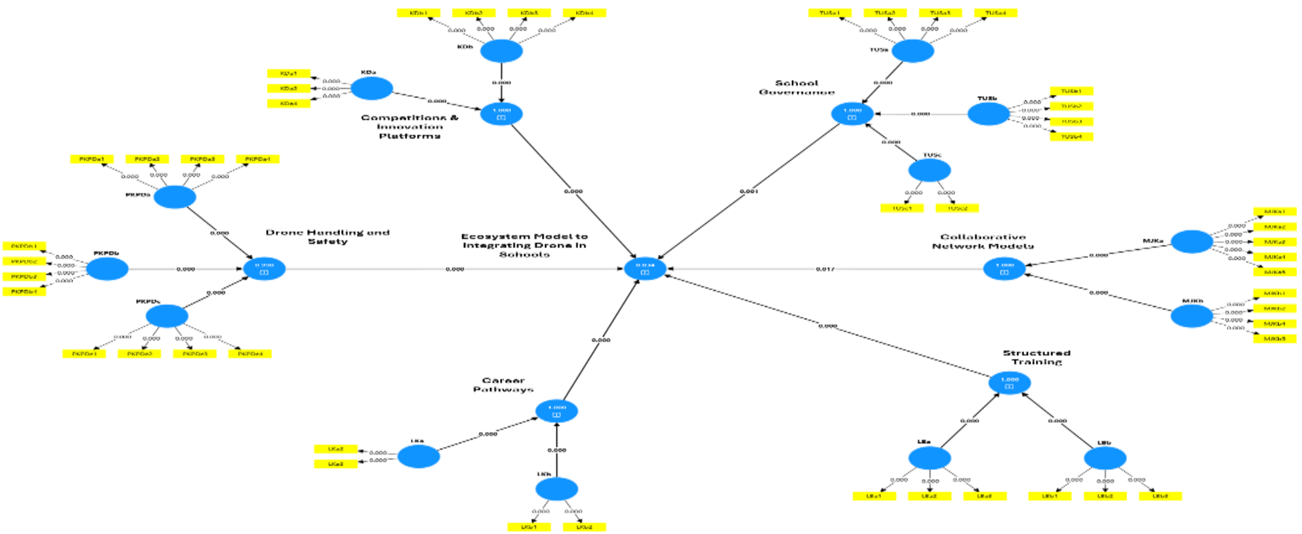
	certification policies for teachers and students	MJKb2	0.904
		MJKb3	
		MJKb4	0.636
		MJKb5	0.894
Drone Competitions and Championships	Supervision of competition categories	KDa1	0.799
		KDa2	0.850
		KDa3	
		KDa4	0.854
	Drone sports championships	KDb1	0.967
		KDb2	0.977
		KDb3	0.832
		KDb4	0.951
School Governance	School management readiness for drone-related programs	TUSa1	0.827
		TUSa2	0.824
		TUSa3	0.805
		TUSa4	0.792
	Risk management in drone usage	TUSb1	0.846
		TUSb2	0.674
		TUSb3	0.897
		TUSb4	0.837
	Implementation of co-curricular drone activities for curriculum enhancement	TUSc1	0.900
		TUSc2	0.829
		TUSc3	0.710
		TUSc4	0.729

APPENDIX B

Structural Model of the Ecosystem Model to Integrating Drone Technology in Malaysian School



APPENDIX C

Simplified Structural Model of the Ecosystem Model to Integrating Drone Technology in Malaysian School