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Simulation Approaches To Thermal Comfort In Tvet Workshops: A Review

Norarziana Sasudian¹, Asmat Ismail², Iryani Abdul Halim Choo³

^{1, 2, 3} *University Teknologi Mara (UiTM), Department of Built Environment and Technology, Perak Branch, Malaysia*

SUBMISSION TRACK

Received: 12, 25, 2026

Final Revision: 01, 07, 2026

Available Online: 02, 02, 2026

KEYWORD

Thermal Comfort, Simulation, Computational Fluid Dynamics (CFD), TVET Workshops, Education 5.0

CORRESPONDENCE

E-mail:

norarziana@kkmen.edu.my

asmat926@uitm.edu.my

iryan542@uitm.edu.my

A B S T R A C T

Thermal comfort is a crucial element of indoor environmental quality (IEQ), affecting health, cognitive performance, and educational results. Technical and Vocational Education and Training (TVET) workshops exhibit unique thermal issues owing to heat-producing equipment, elevated occupant activity, and intricate ventilation systems. This study consolidates simulation-based studies published from 2016 to 2025 regarding thermal comfort in educational and vocational settings. This narrative review examines the uses of Computational Fluid Dynamics (CFD), EnergyPlus, DesignBuilder, and TRNSYS. The findings indicate that while simulation tools are extensively utilized in classrooms and laboratories, their application in TVET workshops is still constrained. Some of the most important shortcomings are that equipment heat loads are too accessible, occupant activity is not extensively represented, field validation is not effective enough, and hot and humid climates are not given enough attention. The paper supports representative TVET workshop models, hybrid simulation–measurement workflows, and Education 5.0-aligned simulation technologies in vocational education.

I. INTRODUCTION

Thermal comfort has been defined as “that condition of mind which expresses satisfaction with the thermal environment” [1], is an important component of indoor environmental quality (IEQ). Its determinants include air temperature, mean radiant temperature, humidity, air velocity, clothing insulation, and metabolic rate [2], [3]. Standards such as ISO 7726 and ASHRAE Standard 55 provide widely accepted frameworks for assessing comfort, primarily through indices such as Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). However, there are increasing concerns with the predictive validity of these models in hot and humid climates and for buildings with occupant activities that are not sedentary office work [4].

In schools and universities, the thermal comfort conditions have been linked to health, attendance and learning performance of students. Research in these environments has indicated that lower learning performance and concentration levels occur in unsatisfactory thermal environments [5]. However, the majority of these studies have been on classrooms and lecture halls where occupant activity levels are low and the thermal environments are reasonably homogenous. Thermal environments in TVET workshops, such as welding bays, automotive labs and machining rooms, are affected by extreme local heat and the high metabolic rates of students engaged in manual work [6], [7], [8]. These factors create strong spatial heterogeneity in comfort conditions, which are poorly captured by conventional assessment tools.

Airflow, thermal comfort, and energy performance in classrooms and laboratories were analysed by different simulation methods such as CFD, EnergyPlus, DesignBuilder, and TRNSYS [9], [10], [11], [12]. Hybrid approaches that integrate simulation with IoT-based monitoring and machine learning are emerging as promising methods for predictive control of thermal comfort [13], [14], [15]. On the other hand, while the application of such approaches to conventional school buildings has grown, their straightforward application to TVET workshops remains uncommon. Therefore, this paper reviews the literature with a focus on the simulation of thermal comfort in learning and vocational spaces, to synthesize a view of the methodological gaps and practical implications, as well as propose an agenda for future research that is pertinent to TVET.

II. LITERATURES REVIEW

The assessment of thermal comfort has traditionally been based on PMV and PPD models developed [16]. These models assume steady-state conditions and are most accurate for sedentary activities in temperate climates. However, in hot–humid environments, as well as in contexts where occupants are engaged in active tasks, the PMV/PPD framework often underpredicts dissatisfaction [17], [18], [19]. While adaptive models are increasingly used in naturally ventilated classrooms [20], their relevance to mechanically ventilated TVET workshops has yet to be tested.

Simulation tools provide a powerful means to extend thermal comfort assessment beyond static indices. CFD is widely used to analyze local air velocity, temperature gradients, and turbulence at high spatial resolution. Studies in classrooms and laboratories show that CFD can identify draft risks, hot spots, and poor mixing zones [21], [22]. Whole-building energy models, such as EnergyPlus, DesignBuilder, TRNSYS, and IES-VE, are commonly applied for long-term performance simulations, HVAC sizing, and energy–comfort trade-off analysis [23], [24], [25]. Hybrid approaches that combine CFD with energy models or integrate simulation with IoT-based monitoring and machine learning have demonstrated improved predictive accuracy and greater potential for adaptive control [26].

Simulation tools of each category have their own pros and cons. For instance, CFDs provide better results but are more expensive and sensitive to boundary conditions. Energy plus and similar tools can evaluate the performance of a few connected zones, over an entire year and continuously, but they cannot account for the localized microclimates. Hybrid methods represent a trade-off between accuracy and scalability. The methods are more data and computationally intensive, and the evaluation itself is more complex. The trade-offs are more critical in the case of TVET

workshops when it comes to localized machine-generated heat and whole building HVAC performance.

III. METHODS

This study employed a narrative review method because the objective was to synthesize and offer a critical discussion of simulation-based studies that are related to the thermal comfort research on TVET workshops and similar contexts instead of undertaking statistical meta-analysis. For the literature review, searches were conducted across three main databases, namely Scopus, Web of Science, and Google Scholar. The terms used for the search were “thermal comfort,” “indoor environmental quality,” “simulation,” “CFD,” “EnergyPlus,” “DesignBuilder,” “TRNSYS,” “educational,” “school,” “classroom,” “laboratory,” “workshop,” and “TVET” in different combinations. Studies were included if they met the following criteria: (a) peer-reviewed journal articles or high-quality conference proceedings published between 2016 and 2025; (b) studies employing one or more simulation tools to assess thermal comfort or indoor environmental conditions in educational or workshop type settings; and (c) discussed aspects of validation, hybrid modelling, or adaptive comfort frameworks.

Technical reports were selectively considered where they offered unique methodological contributions or practical insights. Where direct TVET studies were not available, adjacent contexts such as university laboratories, engineering workshops, and small industrial halls were included for comparative evaluation of transferability. The literature screening process followed the PRISMA 2020 flow framework, encompassing identification, screening, eligibility, and inclusion stages. Out of 112 records initially identified, 87 remained after duplicate removal. After abstract and title screening, 54 studies were assessed for eligibility, of which 36 met the inclusion criteria and were included in the final synthesis.

The PRISMA flow diagram (Figure 1) outlines the systematic process of literature identification and screening adopted in this review. The final dataset represents a focused synthesis of simulation-based thermal comfort studies relevant to educational and vocational contexts, forming the empirical base of this paper.

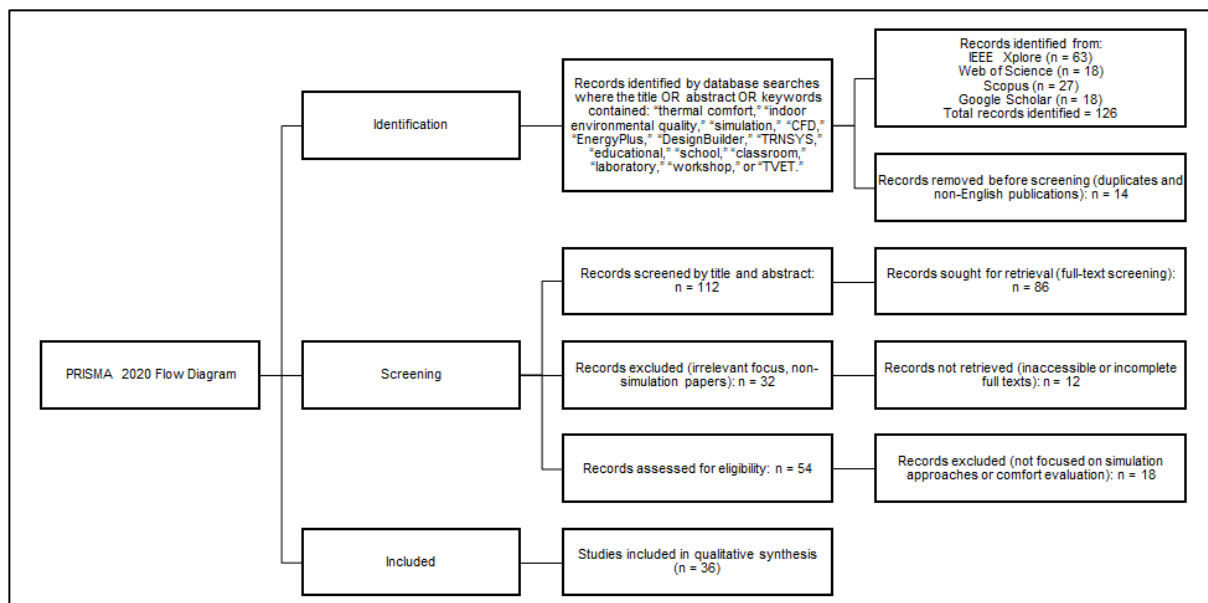


Figure 1. PRISMA 2020 Flow of Literature Selection

These selected studies comprised three major groups of simulation-based approaches. These included CFD based case studies [9], [10], [18], [21], [27], [45], whole-building energy simulation studies employing tools such as EnergyPlus, DesignBuilder, and TRNSYS for long term comfort

and energy assessment [20], [33], and hybrid or validation oriented approaches integrating IoT, AI, or field data for adaptive model calibration and predictive comfort evaluation [36].

IV. RESULTS

The analysis of thirty-six studies selected via the PRISMA methodology established four predominant categories of simulation methodologies utilized in thermal comfort research within educational and vocational settings: Computational Fluid Dynamics (CFD), comprehensive building energy simulation tools (including EnergyPlus, DesignBuilder, and TRNSYS), hybrid or data-driven models, and supplementary field, pedagogical, or review-oriented studies.

Table 1 illustrates the different types of simulation tools that were found in the thirty-six studies that explored thermal comfort in educational and vocational settings. The research studies were classified into four primary categories: CFD-based methods, whole-building energy simulation tools, hybrid or data-driven frameworks, and field, educational, or review studies that support simulation approaches.

The analysis of evaluated research reveals that Computational Fluid Dynamics (CFD) is the predominant approach, including almost 39% of all examined works. Whole-building energy simulation tools, such as EnergyPlus, DesignBuilder, and TRNSYS, accounted for 33%, but hybrid and data-driven approaches using IoT, AI, or multi-scale modeling constituted 14%. The remaining 14% comprised field, pedagogical, and conceptual investigations that enable empirical validation and learning through simulations. In educational contexts, CFD and energy-based models are preferred, but hybrid, adaptive, and validation-oriented frameworks are gaining popularity, indicating a shift toward more integrated and intelligent simulation practices relevant to TVET workshop environments.

These findings collectively highlight a significant transition in simulation analysis, shifting from conventional, static comfort evaluations to hybrid, performance-oriented frameworks that are consistent with Education 5.0 concepts. Those approaches make predictions more accurate and save energy, while additionally contributing to bring information regarding a digital revolution in vocational learning environments.

Table 1. Distribution of Simulation Tools in Reviewed Studies (2016–2025)

Category	Representative Studies	Tools / Methods	No. of Studies	Description / Relevance
Computational Fluid Dynamics (CFD)	[6], [9], [10], [19], [21], [27], [28], [29], [30], [31], [32]	ANSYS Fluent, OpenFOAM, COMSOL Multiphysics	14	CFD-based studies dominate the reviewed literature, focusing on airflow behaviour, temperature gradients, and local turbulence effects. These methods are especially relevant for assessing non-uniform heat zones and airflow patterns generated by equipment in TVET workshops.
Whole-Building Energy Simulation	[1], [3], [5], [17], [20], [23], [24], [25], [33], [34], [35]	EnergyPlus, DesignBuilder, IES-VE	12	Energy-based simulations provide annual and seasonal assessments of thermal comfort and HVAC performance. They are effective for evaluating passive design strategies and overall comfort in educational buildings, though less suited to capturing localised variations typical of

<p>Hybrid / AI / IoT-Integrated Approaches</p>	<p>[6], [7], [26], [36], [37], [38]</p>	<p>IoT Sensor Networks, AI Calibration, Multi-Scale CFD–Energy Modelling</p>	<p>5</p> <p>workshop environments. Hybrid approaches combine CFD and energy models with IoT-based monitoring and AI-driven calibration. These frameworks support adaptive comfort control and real-time performance optimisation, marking a shift toward data-driven simulation ecosystems.</p>
<p>Field Validation Pedagogical Review Studies (Supporting Works)</p>	<p>[39], [40], [41], [42]</p>	<p>TRNSYS, Adaptive Comfort Models, Field/Review Studies</p>	<p>5</p> <p>Supporting studies provided empirical validation, educational integration, and conceptual grounding for simulation-based thermal comfort research in TVET contexts. They highlight the pedagogical and methodological potential of simulation in vocational education.</p>

CFD-Based Approaches

Computational Fluid Dynamics (CFD) has emerged as a primary analytical technique for examining airflow patterns and thermal fluctuations in educational settings. Recent studies have demonstrated its capacity to detect irregular air distribution, drafts, and micro-level variations that conventional measurement techniques often fail to capture [9], [21], [27]. In technical and vocational education and training (TVET) environments where heat-emitting machinery and high levels of human activity intensify microclimatic dynamics CFD serves as an effective diagnostic tool for identifying environmental deficiencies. Prior investigations have also shown that CFD-based visualization can be used to optimize exhaust configurations in welding laboratories [29], and to refine forced-ventilation strategies in engineering laboratory settings to mitigate heat accumulation and airborne contaminants [22]. Although CFD has such benefits, its computational complexity and sensitivity to input factors make it better for robust, localized analysis than for enormous, long-term simulations.

Whole-Building Energy Simulation Approaches

Approximately one-third of the reviewed studies employed energy-related simulation tools such as EnergyPlus, DesignBuilder, and TRNSYS. These platforms facilitate comprehensive evaluations of indoor comfort and energy use across various building components. Evidence suggests that adaptive comfort models can significantly reduce cooling demand in tropical educational settings [20], [43], while other investigations have focused on determining optimal energy–comfort trade-offs within university environments [24], [25]. These technologies provide substantial insight about exactly how HVAC systems work annually in order to improve them for educational TVET implementation. They typically assume that thermal zones are seamless, which makes it further for them to find regional discomfort caused by machinery heat and fluctuating levels of activity. So, to enhance realism, it's vital to combine CFD or sensor data.

Hybrid and Data-Driven Approaches

Recent studies increasingly integrate simulation methods with data-driven approaches. Some investigations have combined EnergyPlus with CFD to enable more comprehensive multiscale analyses [33], while others have utilized IoT sensor networks to support dynamic model calibration and real-time environmental updates [36]. Additional research has applied artificial intelligence techniques to predict adaptive comfort conditions [26], [38], and subsequent field measurements have been used to validate these predictive models [6]. These hybrid frameworks possess an

immense amount of enthusiasm for making the environment more comfortable continually, especially since TVET workshops utilize various settings all the time. Even if they are still evolving, these approaches offer the best prospect of combining digital monitoring and predictive analytics into the oversight of workshop settings.

Critical Evaluation and Scientific Insight

Overall, CFD provides high spatial detail but limited versatility; energy simulation models deliver temporal depth but less local accuracy. Hybrid approaches integrate these complementary strengths, particularly when calibrated with empirical field data. Recent studies underscore the need to validate simulation assumptions related to occupancy patterns and heat emission profiles [6], [30]. Furthermore, methodological deficiencies endure. People often make machinery heat loads excessively straightforward, insufficiently exhibit how an individual's metabolism affects them, and there is insufficient field validation. Most research comes from temperate regions, so there is a need for climate-specific models that work in hot, humid regions including Malaysia. In conclusion, hybrid, sensor-calibrated workflows signify the most optimal trend for forthcoming TVET research. They not only contribute to constructs more comfortable and save energy, but they also fit with the ideas of Education 5.0 by using simulation technologies in both building operation and student learning.

Simulation Approaches in Educational and Vocational Contexts

Utilization of CFD-based studies has been done in classrooms, laboratories, and small workshop environments. Prior studies have demonstrated that CFD is capable of identifying airflow stratification and localized thermal discomfort within classroom settings [26], [27]. In vocational training laboratories, CFD analysis has also been employed to detect stagnation zones around heat-generating equipment and to optimize the placement of exhaust systems for improved ventilation efficiency [29]. These findings highlight the value of CFD for analyzing non-uniform comfort conditions typical of TVET workshops.

On the other hand, whole-building energy simulation studies can provide information on long-term comfort and energy consumption. Recent work has employed EnergyPlus to evaluate classroom comfort under varying HVAC control strategies [33], while other simulation-based analyses have explored the applicability of adaptive comfort models in school settings [20]. These approaches prove helpful for determine out the typical cooling load for a workshop or examining how passive design measures perform, but they disregard into account the way uncomfortable equipment can make individuals uncomfortable.

Hybrid approaches are gaining traction. Recent studies have demonstrated that combining EnergyPlus with CFD enables multi-scale analyses capable of capturing both annual energy performance and localized comfort conditions [33]. Other research has integrated IoT-based environmental monitoring with simulation models to support adaptive comfort control [36], while additional work has shown the potential of machine learning techniques for predictive thermal comfort modeling [37]. Such hybrid frameworks could be particularly valuable for TVET workshops, where dynamic machine schedules and variable occupancy make simple models unreliable.

Validation remains a persistent challenge. Empirical evidence shows that incorporating field data is essential for enhancing the accuracy of classroom-level simulation predictions [44], and machine learning-assisted calibration has been identified as a promising direction for improving model reliability [38]. However, the absence of validation in workshop or vocational settings makes it harder to apply the concepts learned in a simulation to those circumstances. A comprehensive glance at the research demonstrates that CFD aims to capture local spatial aspects, EnergyPlus scales over time and space across building zones, and the hybrid techniques cleverly combine the two. Hybrid approaches appear as the optimal choice for TVET workshops as it accommodates with both regional specificity on a micro scale and overall efficiency on a global basis.

V. DISCUSSION

This overview shows significant gaps in simulation-based thermal comfort research findings in educational and vocational settings. The oversimplification of equipment heat loads as uniform internal gains instead of dynamic, source-specific emissions persist [26].

Simulations of actual working conditions are limited by this. In dynamic, high-activity environments, occupant activity and metabolic rates affect heat perception, but models rarely include them [30], [32]. The majority of current research is in temperate climates, with inadequate representation from hot-humid regions like Malaysia and Southeast Asia [35], [39]. Field data validation remains limited, diminishing simulation validity.

More representative TVET workshop models with realistic dimensions, dynamic machine heat fluxes, and transient occupancy schedules are required to address these challenges. Hybrid simulation–measurement workflows using CFD, energy models, and IoT-based sensor networks might boost calibration accuracy and adaptive comfort prediction [38]. Short-term field campaigns in TVET institutions would also offer empirical data on real-world comfort dynamics and model validation in various climatic and operational contexts.

Besides research, practice, policy, and education are engaged. Simulating ventilation, diffuser design, and concentrated heat mitigation conserves architects and facility managers cost [28]. The results indicate that officials ought to revise ISO 7726 and ASHRAE to more accurately represent the dynamic and active environments of TVET workshops. Customized comfort standards for work settings make sure that thermal performance standards are good for health and energy efficiency. Project prototype workshop models that represent occupant activities and machine operation cycles in TVET typologies such welding bays, automotive laboratories, and electronics workshops should be developed. In hybrid processes, real-time monitoring, IoT sensors, and machine learning can help with data-driven calibration and predictive control. Many educational institutions may be able to use simplified CFD approaches, surrogate models, and cheap sensor networks because they don't have a lot of money.

The educational part is equally important. Simulation tools in TVET programs allow students evaluate and improve workshop settings while learning digital and sustainability skills. This integration aligns with the Education 5.0 paradigm, which promotes problem-based and technology-enhanced learning. TVET institutions can enhance environmental performance and student learning outcomes by integrating simulation research, institutional practices, and instructional innovations.

VI. CONCLUSION

CFD, EnergyPlus, and TRNSYS are widely used simulation tools for assessing thermal comfort in educational environments, yet their application within TVET workshops remains limited. Each method presents inherent methodological trade-offs: CFD offers fine-grained spatial detail but demands significant computational resources, while whole-building energy models such as EnergyPlus provide broader temporal and zonal analyses but often oversimplify localized thermal variations. These constraints highlight the need for more context-sensitive modeling strategies capable of addressing the unique microclimatic characteristics of vocational training spaces.

Hybrid simulation approaches, which combine the strengths of different modeling techniques, offer considerable potential but pose challenges in development and verification. To enhance predictive accuracy, future research must incorporate realistic representations of machinery-generated heat loads, dynamic occupant activity, and climate-specific variables. Doing so will support the optimization of ventilation configurations, workshop retrofits, and passive cooling measures, while also offering evidence to inform policymakers about comfort standards tailored to vocational settings.

Addressing these gaps will require coordinated efforts among researchers, practitioners, and policymakers. By developing sensor-informed simulation frameworks and embedding them within

TVET curricula, institutions can more effectively design, operate, and teach within workshop environments. Such integrated approaches promise improvements in energy efficiency and thermal comfort while advancing the broader aims of Education 5.0, particularly the promotion of technologically enhanced, learner-centered vocational training ecosystems.

VII. ACKNOWLEDGEMENT

This research forms part of an ongoing Master's study at the Faculty of Built Environment, Universiti Teknologi MARA (UiTM). For this paper, the authors responsibly used AI-based tools and platforms like ChatGPT for text structure and clarity, Semantic Scholar for literature review assistance, Google Scholar for academic sourcing, and Mendeley for citation management. All tools were used legitimately and according to academic honesty. The authors further extend appreciation to the organizing committee of the International Conference on ICT in Education (ICTE 2025) for providing a valuable platform for researchers to exchange knowledge and foster academic networking. Conflict of Interest Statement, authors declare that there is no conflict of interest related to this publication.

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BIOGRAPHY

Norarziana Binti Sasudian, is currently pursuing a Master's degree in Green Architecture at the Faculty of Built Environment, Universiti Teknologi MARA (UiTM) Perak Branch. She holds a Certificate in Architecture from Port Dickson Polytechnic, a Diploma in Building from UiTM Perak Branch, and a Bachelor of Science (Hons.) in Construction Management from UiTM Shah Alam. Her research focuses on thermal comfort, indoor environmental quality, and building performance simulation, with particular emphasis on educational buildings and TVET workshop environments. Her research interests include whole-building energy simulation tools and adaptive thermal comfort assessment in hot-humid climates. This work forms part of her ongoing postgraduate research conducted under academic supervision.

Ts. Sr. Dr. Asmat Binti Ismail, is a Senior Lecturer (DS13) at the Faculty of Architecture, Planning and Surveying, Universiti Teknologi MARA (UiTM) Perak Branch. She holds a PhD in Housing Design, an MSc in Building Technology, and a BSc (Hons.) in Housing, Building and Planning from Universiti Sains Malaysia. Her academic and professional work focuses on building environmental performance, passive design strategies, thermal comfort, daylighting, and green roof technology in tropical climates. She has extensive experience in supervising postgraduate research, reviewing journal and conference papers, and serving as an examiner and expert panel member. She is actively involved in nationally and institutionally funded research projects and has published widely in journals and conference proceedings related to sustainable built environment studies. She is a registered Professional Technologist with the Malaysia Board of Technologists (MBOT) and a member of the Royal Institution of Surveyors Malaysia and the Malaysia Green Building Confederation.

Dr. Iryani Binti Abdul Halim Choo, holds a Bachelor of Architecture (LAM Part II) from Universiti Teknologi MARA (UiTM), Shah Alam, an MSc in Architectural Conservation from the University of Edinburgh, Scotland, and a PhD in Design and Built Environment from UiTM Perak. She served as an Architect at ZONE Architect, Kuala Lumpur (2013–2015), and is currently a Senior Lecturer in the Architecture Programme, College of Built Environment, Faculty of Architecture, Planning and Surveying, Universiti Teknologi MARA (UiTM) Perak Branch. She has contributed as a speaker and moderator at international and regional conferences & lectures, including Simposium Nusantara 2026 and the International Virtual Go Green Conference 2026. Her academic achievements include securing competitive research grants such as the Endangered Wooden Architecture Programme (EWAP). She has published extensively on traditional Malay architecture, architectural heritage, and conservation. Her current research interests encompass traditional Malay architecture, architectural heritage, and conservation, and she is a Graduate Architect registered with the Board of Architects Malaysia (LAM).