

Validating Systemic Factors of STEM Integration in Early Childhood Education and Care Using Mixed Methods

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Abstract— The rapid global push toward STEM education and the increasing accessibility of robotics have prompted renewed attention to their integration in Early Childhood Education and Care (ECEC). While robotics in early learning has been shown to foster creativity, problem-solving, and socio-cognitive development, its adoption in Southeast Asia remains fragmented, hindered by uneven infrastructure, limited teacher readiness, and inconsistent curriculum alignment. This study aims to map the systemic factors shaping robotics integration in ECEC and to provide a strategic framework for policy and practice across the region. Employing a mixed-methods research design with 17 experts, including early childhood educators, curriculum specialists, and policymakers, the research combined the Nominal Group Technique (NGT) to identify and prioritize key factors, Interpretive Structural Modeling (ISM) to explore hierarchical interdependencies, and the Fuzzy Delphi Method (FDM) to validate expert consensus. Findings revealed five critical factors: teacher competency in STEM pedagogy, availability of age-appropriate robotics, curriculum integration, cost and infrastructure, and parental support and digital literacy. ISM analysis highlighted a dependency chain in which parental support and infrastructure form the foundational conditions, robotics availability and teacher competency act as drivers, and curriculum integration stands as the dependent, strategic goal. FDM validation confirmed strong consensus on teacher competency and curriculum reform, moderate consensus on infrastructure and robotics availability, and conditional consensus on parental engagement, with refinements emphasizing culturally relevant tools, innovative financing, and community-based digital literacy. The study concludes that sustainable integration requires a sequenced, systemic approach addressing foundational and enabling factors before curricular reform. These insights provide a roadmap for educational stakeholders to guide equitable and context-sensitive STEM transformation in early childhood education.

Keywords: *Early Childhood Education (ECEC), STEM Integration, Nominal Group Technique, Interpretive Structural Modeling (ISM), Fuzzy Delphi Method (FDM)*

I. INTRODUCTION

1.1 Global Landscape of Early STEM and Robotics

Globally, the rapid advancement of digital technologies and the rising emphasis on STEM (Science, Technology, Engineering, Mathematics) education are reshaping how learning is conceptualized from the earliest years of schooling. Robotics, once confined to higher levels of education, is increasingly being introduced to preschoolers through play-based approaches. This shift reflects a global recognition that early exposure to STEM concepts can nurture creativity, problem-solving, and critical thinking, laying the foundation for 21st-century competencies and future workforce readiness in the era of the Fourth Industrial Revolution (IR4.0) (Ceylan & Malçok, 2020; Keane & Garvis, 2024).

1.2 Regional Developments in Southeast Asia

In Southeast Asia, the push toward STEM integration in early childhood education and care (ECEC) is gathering momentum, but progress remains uneven across the region. Some countries have adopted innovative approaches that leverage technology for education, while others grapple with systemic challenges such as limited resources, inconsistent policy frameworks, and varying cultural

attitudes towards technology in early learning environments (Kaggwa et al., 2023; Mohtar et al., 2019). While some countries have begun experimenting with robotics and coding initiatives in preschool settings, others face systemic challenges such as limited resources, inconsistent policy support, and varying cultural perceptions of technology in early learning. These disparities underscore the urgent need for a contextualized framework to ensure equitable and effective adoption of STEM and robotics across diverse ECEC systems (Kaggwa et al., 2023).

Malaysia, as part of this regional landscape, has aligned its education policies with global STEM priorities, emphasizing early exposure to digital literacy and computational thinking. Initiatives under the Malaysia Education Blueprint and national STEM action plans highlight the importance of preparing children for a knowledge-driven economy. However, in practice, robotics and STEM integration in Malaysian preschools is still at an early stage. Implementation is often fragmented, heavily dependent on school leadership or individual teachers' initiatives (Mohtar et al., 2019; Dou et al., 2019), and hindered by constraints in infrastructure, teacher readiness, and parental engagement (DeJarnette, 2018; Amsbary, 2023).

1.3 Identified Gaps and Theoretical Anchors

Despite global momentum and national policy aspirations, the integration of robotics and STEM in Malaysian ECEC remains sporadic and under-theorized. There is a lack of systematic evidence mapping the interrelated factors, which are curriculum design, teacher capacity, leadership support, infrastructure availability, and socio-cultural acceptance, that shape successful implementation (Chedup et al., 2023). Without a structured framework, efforts risk being isolated, inequitable, and unsustainable, leaving many children without opportunities to benefit from early STEM and robotics education (Amsbary, 2023; Dou et al., 2019; DeJarnette, 2018).

While global research on early STEM and robotics education demonstrates strong cognitive benefits (Ceylan & Malçok, 2020; Keane & Garvis, 2024), studies in Southeast Asia are largely descriptive. Existing research in Malaysia and Indonesia has focused on isolated dimensions such as teacher readiness (Mohtar et al., 2019) or policy gaps (Chedup et al., 2023), without analyzing how these systemic factors interact. To address this gap, the present study introduces a hybrid methodological framework (NGT–ISM–FDM) that empirically maps the interdependencies among these factors across multiple Southeast Asian contexts, thereby advancing a systems-level understanding of robotics integration in ECEC. Therefore, this study aims to achieve the following objectives:

1. To prioritize the systemic factors influencing the integration of STEM in Early Childhood Education and Care (ECEC) through the Nominal Group Technique (NGT).
2. To examine the structural interdependence among the identified factors using Interpretive Structural Modeling (ISM).
3. To validate the systemic factors and hierarchical relationships through the Fuzzy Delphi Method (FDM).

II. METHODS

II.1 Research Design

This study employed a mixed-methods design to capture both the breadth of consensus and the depth of systemic understanding necessary for examining STEM and robotics integration in Early Childhood Education and Care (ECEC). The Nominal Group Technique (NGT) was employed to identify and prioritize the systemic factors influencing integration (Shoesmith et al., 2021). NGT was chosen because it minimizes power imbalances during group decision-making and ensures equitable contribution from all participants (Manera et al., 2019). Following this, Interpretive Structural Modeling (ISM) was applied to examine the interrelationships among the identified

factors (Wu et al., 2024). ISM was selected for its ability to map complex, multi-layered structures and provide policymakers with actionable hierarchies of influence (Shalamzari & Dodangeh, 2023). Finally, the Fuzzy Delphi Method (FDM) was applied to validate the findings (Mohamed Yusoff et al., 2021). FDM was chosen because it combines the systematic, iterative nature of the Delphi technique with fuzzy set theory, enabling researchers to quantify expert consensus while reducing ambiguity and subjectivity in responses. This hybrid design integrates structured prioritization (NGT), systemic modeling (ISM), and rigorous consensus validation (FDM) to bridge the gap between theory and practice, aligning with the study's aim to propose a robust framework for Early Childhood Education and Care (ECEC)'s implementation, especially in Southeast Asia.

II.2 Sample and Sampling Technique

The sample comprised 17 experts, who consisted of ECEC educators, curriculum specialists, and policymakers, with relevant expertise and experience in STEM- or robotics-based early childhood programs. Although small, this purposive sample aligns with methodological precedents emphasizing depth and structured consensus over statistical generalizability (Onwuegbuzie & Collins, 2007; Soares et al., 2024). Participants were selected purposively to ensure representation of micro-level (classroom), meso-level (curriculum), and macro-level (policy) perspectives.

Since the objective of this study was structured consensus and systems, the sample size ($n = 17$) was consistent with methodological recommendations for NGT, ISM, and FDM, which prioritize knowledge depth and structured consensus over large population generalizability. In the NGT, optimal group sizes typically range between 5–12 participants per session, ensuring balanced participation and idea saturation (McMillan et al., 2016). For ISM, recent methodological work affirms that conceptual coverage and triangulation of perspectives are more critical than panel size, with many studies using 7–15 experts effectively (Wu et al., 2024).

Similarly, FDM literature recommends a minimum of 10 experts to achieve stable consensus thresholds (Mohamed Yusoff et al., 2021). Therefore, the representative is achieved through geography triangulation and explicit consensus thresholds, which together support transferability to comparable ECEC systems.

II.3 Instrumentation

Instrumentation in this study involved structured protocols tailored to each methodological phase. For the NGT sessions, a hybrid approach was applied. A preliminary set of potential factors was identified through an extensive review of relevant literature and policy frameworks. These relevant literature and policy frameworks served as a reference point rather than a fixed framework. Experts were invited to critically refine the list by adding overlooked factors, removing irrelevant ones, and merging overlaps based on their expertise and lived experiences. The hybrid NGT approach was chosen over purely semi-structured or exploratory NGT because it ensured both academic rigor (evidence-based grounding) and contextual relevance (practice-informed validation).

For ISM, instruments included a Structured Self-Interaction Matrix (SSIM) and a reachability matrix, which enabled the hierarchical modeling of interrelationships. For the FDM, experts engaged with a structured expert consensus questionnaire based on the ISM-derived factors. Responses were captured on a triangular fuzzy scale to measure the degree of agreement, reducing linguistic uncertainty in expert judgments.

II.4 Data Collection Methods

Data collection proceeded in three stages. First, NGT sessions were conducted, where participants reviewed the reference list, proposed additional factors, and ranked them through iterative voting. This ensured that the final list reflected both evidence-based insights and practitioner realities.

Second, the prioritized factors were analyzed through the ISM modeling process, during which participants collaboratively constructed the SSIM to indicate directional relationships among variables. ISM computation was then performed using software to generate the final hierarchical model. Third, the ISM results were validated through the Fuzzy Delphi Method (FDM), in which experts independently rated the importance and relevance of each factor using fuzzy scales. Consensus was determined by using threshold values ($d \leq 0.2$) and percentage agreement ($\geq 75\%$), consistent with established FDM protocols (Mohamed Yusoff et al., 2021).

II.5 Data Analysis Methods

NGT data were analyzed quantitatively by aggregating experts' rankings and calculating weighted scores to determine the most critical factors. ISM analysis involved converting the SSIM into a reachability matrix, applying transitivity checks, and constructing a diagram to reveal the structural hierarchy of relationships. FDM results were analyzed by defuzzifying expert responses, calculating threshold values, and measuring consensus levels across items. Factors that did not reach consensus were either revised or excluded. The triangulation of NGT, ISM, and FDM strengthened the validity, reliability, and contextual relevance of the proposed framework.

II.6 Ethical Consideration

Ethical protocols were observed throughout the study to ensure integrity and protect participants' rights. Information consent was obtained from all participants before data collection, with assurances of confidentiality and voluntary participation. Anonymity was maintained in reporting findings by using coded identifiers instead of names or institutional affiliations. Given the cross-border nature of the study, additional care was taken to ensure that cultural sensitivities were respected, particularly during the consensus process. The research design and protocols adhered to the ethical standards of social science research, ensuring transparency, inclusivity, and respect for participant autonomy.

III. RESULTS AND DISCUSSION

The findings of this study were presented aligned with the research objectives: (i) to identify systemic factors influencing STEM integration in ECEC, (ii) to prioritize these factors using NGT, (iii) to map their interdependencies through ISM, and (iv) to validate and refine the findings through the Fuzzy Delphi Method (FDM). These findings provide a comprehensive understanding of the challenges and opportunities to shape STEM integration in ECEC.

III.1 Identification and Prioritization of Key Factors Through Nominal Group Technique

The first objective was to identify and prioritize key systemic factors influencing robotics integration in ECEC. Through the NGT sessions with 17 experts who were involved in this study, including educators, curriculum specialists, and policymakers, five critical factors emerged. These were ranked in order of importance in Table 1.

Table 2. Findings of Modified Nominal Group Technique: Ranking and Prioritization of Factors Influencing STEM Integration in Early Childhood Education and Care

Factors	Experts (1–17)																TV	R	
Teacher Competency in STEM Pedagogy	7	7	6	7	6	7	7	6	7	6	7	6	7	7	6	7	7	112	1

Factors	Experts (1–17)																TV	R	
Availability of / Appropriate Robotics	7	6	7	6	7	6	7	7	6	6	7	6	6	7	6	7	6	106	2
Integration into National ECEC Curriculum	6	6	7	6	6	7	6	6	6	6	7	5	6	6	6	6	7	98	3
Cost and Infrastructure	6	6	5	6	6	5	6	6	5	6	6	6	5	6	5	6	6	91	4
Parental Support Digital Literacy	5	6	5	6	5	6	5	5	6	5	6	5	6	5	5	6	5	87	5

Note: TV – Total Vote; R - Rank

Based on Table 2, the findings of the Nominal Group Technique (NGT) provided a clear prioritization of the systemic factors influencing the integration of STEM and robotics in early childhood education across Southeast Asia. As shown in Table 2, Teacher Competency in STEM Pedagogy emerged as the top-ranked factor (Total Vote = 112), reflecting strong consensus among experts that teacher capacity is the most critical enabler of robotics adoption in early learning. Without adequate pre-service and in-service training, educators are ill-equipped to design and facilitate developmentally appropriate robotics-based learning experiences, thus constraining systemic uptake. The second highest-ranked factor was the Availability of Age-Appropriate Robotics (Total Vote = 106), emphasizing that pedagogical innovation requires parallel access to developmentally suitable tools. This finding shows the link between resources and effective instructional design, particularly in play-based learning environments. The third rank, Integration into the National ECEC Curriculum (Total Vote = 98), highlights the recognition that sustainable reform requires systemic embedding of STEM objectives into early childhood policy and curriculum frameworks. However, experts stressed that curriculum changes cannot operate in isolation; they must be supported by teacher capacity and appropriate resources.

Furthermore, Cost and Infrastructure ranked fourth (Total Vote = 91), with experts acknowledging financial and logistical barriers, including affordability of robotics kits, connectivity, and classroom readiness. This was especially salient in rural areas, where digital divides risk exacerbating inequalities. Finally, Parental Support and Digital Literacy (Total Vote = 87) was ranked fifth, signaling that while family engagement remains an important dimension, it is often mediated by socio-economic conditions and cultural perceptions of technology in early learning. In summary, the NGT findings show that STEM and robotics integration is perceived not as a single-variable challenge but as an interconnected system, where teacher readiness and access to developmentally appropriate tools form the immediate priorities. These priorities, in turn, must be reinforced through curriculum reform, infrastructural investment, and parental engagement to ensure long-term, equitable adoption across diverse ECEC contexts in Southeast Asia, especially in the Malaysian context.

III.2 Mapping Structural Relationships through Interpretative Structural Modelling

The Interpretive Structural Modeling (ISM) analysis provided a clear understanding of the hierarchical relationships among the five prioritized factors influencing the integration of STEM and robotics in ECEC (see Figure 1). The generated model revealed a layered dependency structure in which Parental Support and Digital Literacy occupied the base layer, highlighting the foundational role in reinforcing early STEM learning. However, without parental acceptance and digital readiness,

efforts within schools are unlikely to be sustained or extended into the home environment. Building upon this, Cost and Infrastructure emerged as the second layer, highlighting the enabling conditions required to ensure equitable access to robotics resources and reliable connectivity, particularly in rural and underserved contexts.

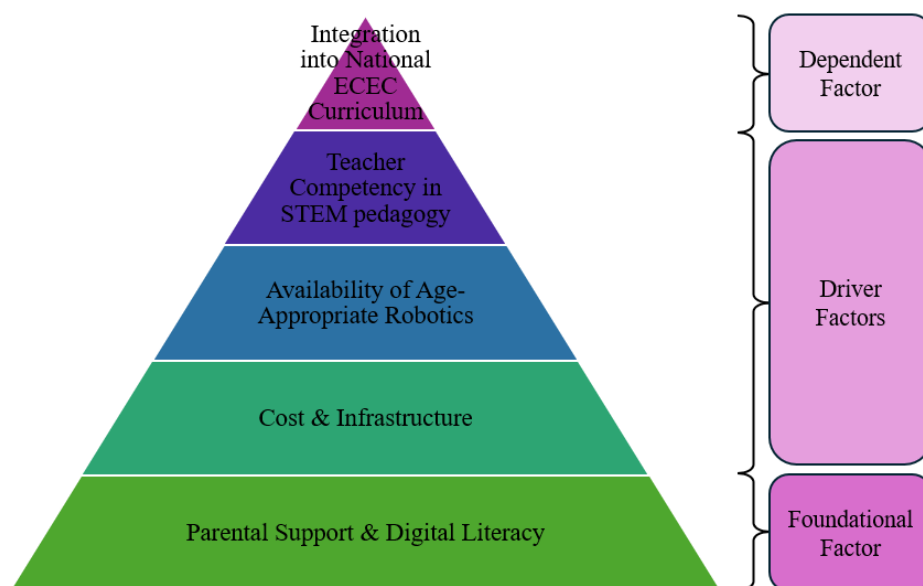


Figure 1. The Hierarchy Model of STEM integration in Early Childhood Education Care (ECEC)

The third layer, Availability of Age-Appropriate Robotics, was positioned as contingent upon infrastructural and financial support, reinforcing the view that pedagogical innovation cannot occur without access to developmentally suitable tools. At the fourth level, Teacher Competency in STEM Pedagogy was identified as a critical determinant of effective implementation, but its development is dependent on the prior availability of tools and training resources. Finally, at the top of the hierarchy, Integration into the National ECEC Curriculum was recognized as the ultimate strategic goal, yet one that is heavily reliant on the successful alignment of the preceding layers. In summary, the ISM findings demonstrate that curriculum reform cannot be pursued in isolation; rather, it requires a bottom-up strategy in which parental engagement, infrastructure, resource availability, and teacher training are systematically addressed to create the enabling ecosystem necessary for large-scale and sustainable adoption of robotics in early childhood education.

III.3 Validation of Consensus Through the Fuzzy Delphi Method

In this study, the Fuzzy Delphi Method (FDM) was employed to validate and refine the structural model generated through ISM, ensuring consensus across diverse expert perspectives. Across two iterative rounds, a group of thirteen experts, which included ECEC educators, curriculum specialists, and policymakers, evaluated the importance and relevance of the five prioritized factors on a fuzzy scale, with consensus determined by a threshold value of $d \leq 0.2$ and an agreement level of $\geq 75\%$. The FDM findings demonstrated strong consensus for Teacher Competency in STEM Pedagogy and Integration into the National ECEC Curriculum, both of which exceeded 90% agreement with low threshold values ($d = 0.12$ and $d = 0.15$, respectively). Experts highlighted that without systematic teacher training and explicit curriculum embedding, robotics integration would remain fragmented and unsustainable. Cost and Infrastructure achieved 82% agreement ($d = 0.18$), reflecting recognition of its critical role while acknowledging that innovative financing, such as public-private partnerships, could mitigate barriers. Similarly, the Availability of Age-Appropriate Robotics achieved 78% consensus ($d = 0.19$), though experts refined the definition to emphasize the need for culturally relevant and developmentally appropriate robotics tools. Finally, Parental Support and Digital

Literacy reached conditional consensus at 76% ($d = 0.20$), with experts noting significant variability across socio-economic contexts and recommending community-level digital literacy initiatives to enhance parental engagement. In summary, the FDM findings confirm that all five factors are indispensable for STEM integration in ECEC, while the refinements illustrate the importance of contextual adaptability in policy and practice of different contexts. Table 2 shows the FDM findings for the factors influencing STEM integration in ECEC.

Table 2. Fuzzy Delphi Method Findings for Factors Influencing STEM Integration in Early Childhood Education and Care

Factors	Experts in Agreement	Experts Agreement	Threshold Value (d)	Consensus Status	Refinement Notes
Teacher Competency in STEM Pedagogy	12 / 13	92%	0.12	Strong Consensus	Emphasized structured pre-service and in-service training for STEM pedagogy
Integration into National ECEC Curriculum	12 / 13	92%	0.15	Strong Consensus	Curriculum embedding must align STEM and robotics activities with developmental milestones
Cost and Infrastructure	11 / 13	85%	0.18	Consensus	Experts suggested innovative financing models to mitigate barriers
Availability of Age-Appropriate Robotics	10 / 13	77%	0.19	Consensus	Refined to specify culturally relevant and appropriate robotics kits
Parental Support and Digital Literacy	10 / 13	77%	0.20	Conditional Consensus	Recommended framing parental engagement as part of broader community digital literacy initiatives

The findings of this study reaffirm and extend the literature on STEM integration in early childhood education and care by highlighting the systemic interdependencies that condition successful implementation. The prioritization of teacher competency in STEM pedagogy as the most critical factor aligns with previous Malaysian studies that identified limited teacher readiness and digital confidence as significant barriers to educational innovation (Rahman et al., 2021; MacDonald et al., 2021). Consistent with Vygotsky's (1978) Sociocultural Theory, the findings highlight that teachers are not merely transmitters of knowledge but act as mediators of learning, scaffolding children's engagement with robotics in ways that expand their Zone of Proximal Development (Vygotsky, 1978). The ISM model further validated this relationship by situating teacher competency as dependent upon access to tools and infrastructure, reinforcing constructivist perspectives that learning

cannot occur without meaningful, hands-on interaction with developmentally appropriate materials (Kalogiannidou et al., 2021).

Equally significant is the positioning of parental support and digital literacy at the foundational level, which resonates with Bronfenbrenner's Ecological Systems Theory. The family microsystem plays a decisive role in reinforcing learning experiences, and our findings confirm that without parental acceptance and engagement, home reinforcement of robotics activities remains weak. This supports earlier Southeast Asian research showing that cultural attitudes toward technology and socio-economic disparities strongly shape parental involvement in STEM initiatives (White et al., 2022; Salvatierra & Cabello, 2022). The FDM results indicated conditional consensus on this factor, reflecting variability across contexts, which echoes Epstein's (2002) framework of parental involvement that stresses differentiated strategies for engaging families across diverse social strata and aligns with Salvatierra and Cabello's (2022) findings where parents shape children's interests and self-efficacy about STEM and content application that can favor their children's approach to STEM. From a policy perspective, this finding mirrors UNESCO's (2017) and UNESCO's (2021) call for holistic approaches to digital inclusion, where community-driven literacy programs complement formal education systems.

At the structural level, the recognition of cost and infrastructure as an enabling driver corroborates the Malaysia Education Blueprint (2013–2025) (MOE, 2012), which identifies equitable access to digital tools as a prerequisite for systemic reform. Similar challenges have been reported in Indonesia, where rural schools face persistent resource constraints that undermine the scalability of robotics programs (Rahmi et al., 2025). The FDM consensus on infrastructure, coupled with recommendations for public–private partnerships, aligns with OECD's (2019) framework on future-ready education systems, which advocates leveraging cross-sector collaboration to mitigate funding disparities. Moreover, the emphasis on the availability of age-appropriate robotics kits reflects global findings that early exposure must be developmentally appropriate to be effective (Kalogiannidou et al., 2021), yet the experts of this study refined this to stress cultural adaptability, pointing to the necessity of contextualized interventions (Mansouri & Taylor, 2024).

Furthermore, the identification of curriculum integration as the dependent, top-level factor confirms that systemic reform cannot be achieved through policy mandates alone. This finding is congruent with the Malaysia Education Blueprint (2013–2025) (MOE, 2013) and SEAMEO CECCEP's (2025) regional agenda, both of which highlight the need to embed robotics into early childhood curricula as part of long-term digital transformation strategies. However, as our ISM hierarchy and FDM validation demonstrate, curriculum reform is only effective when foundational conditions, which are parental engagement, infrastructure, and teacher readiness, are already in place. This aligns with international policy evidence, such as UNESCO's Global Education Monitoring Report (2021), which warns against “policy-first” reforms that ignore enabling conditions at the local level.

The findings also found meaningful urban–rural contrasts in the readiness and implementation of STEM and robotics in early childhood settings. In urban preschools, where infrastructure, internet connectivity, and teacher exposure to digital tools are more advanced, the integration process tends to focus on curriculum design and pedagogical innovation. Teachers in these environments are often early adopters of robotics kits and STEM pedagogies, aligning well with national digital education goals. In contrast, rural preschools face structural barriers, including unreliable electricity supplies, limited access to robotics materials, and insufficient teacher training opportunities.

For these contexts, foundational investments in infrastructure, community digital literacy, and mobile STEM outreach are prerequisites before curriculum integration can occur. This contextual sensitivity confirms the sequenced nature of systemic reform suggested by the ISM hierarchy, that without addressing infrastructural and parental engagement layers, top-level reforms like curriculum revision risk being unsustainable. Therefore, policies must be differentiated, particularly with an infrastructure-first approach for rural areas and a pedagogy-first approach for urban areas, to ensure equitable STEM access and genuine early learning impact. Figure 2 shows the comparative

sequencing relationships among systemic factors for STEM robotics integration for the urban-rural context.

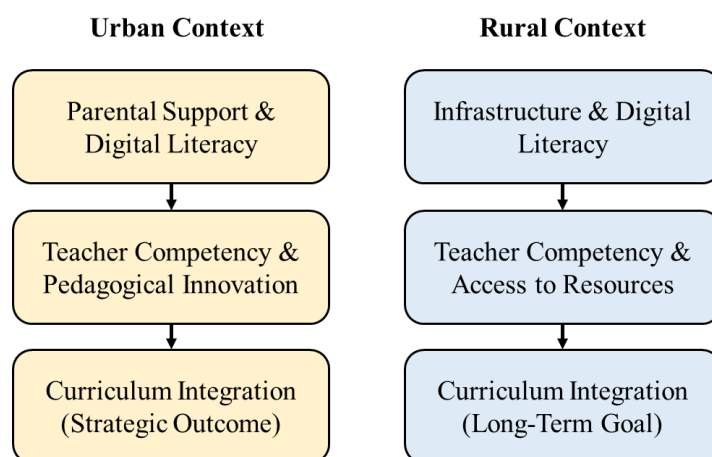


Figure 2. Comparative Sequencing of STEM–Robotics Integration in Urban and Rural ECEC Contexts

III.4 Theoretical Implications

Theoretical implications of this study include the validation of systems theory as an analytical lens for examining STEM integration in ECEC. By employing ISM and FDM, the study extends Bronfenbrenner’s ecological model into a practical framework that illustrates hierarchical dependencies among systemic factors (Fuller et al., 2021). Furthermore, this study extends existing theories of learning and system design by empirically demonstrating how systems theory can model the interdependence of enabling conditions in early STEM education. Through the integrated use of NGT, ISM, and FDM, the research operationalizes Bronfenbrenner’s (1979) ecological model into a structured hierarchy that captures micro- (parental and teacher), meso- (school and curriculum), and macro-level (policy and infrastructure) dynamics. The hierarchical relationships observed, where parental support and infrastructure form foundational layers and curriculum integration sits as a dependent outcome, illustrate the nested interactions described in ecological and sociocultural frameworks (Vygotsky, 1978). Furthermore, by linking teacher competency to both resource availability and curriculum reform, the study advances constructionist perspectives on how material tools and social mediation jointly enable young children’s learning through robotics. These theoretical insights contribute to a systems-based understanding of STEM integration in ECEC, bridging conceptual work in developmental psychology with emerging scholarship on educational technology and early childhood innovation.

III.5 Practical Implications

The validated model offers clear, actionable pathways for stakeholders in early childhood STEM education. For policymakers, the results highlight the need to sequence reforms by addressing foundational conditions, starting with equitable infrastructure development and community digital-literacy programs before mandating curriculum change. Ministries of education and SEAMEO CECCEP can utilize the hierarchy of factors as a regional roadmap to coordinate multi-country initiatives and funding mechanisms, such as public–private partnerships for robotics kits and mobile STEM laboratories for rural schools (Marangu & Chahira, 2024; Su et al., 2022).

For teachers and school leaders, the findings emphasize that sustainable robotics integration requires targeted professional learning, including micro-credentialing in STEM pedagogy, peer mentoring, and localized communities of practice. For example, teacher training could be redesigned around micro-credentialing and regional peer mentoring, consistent with recent calls for scalable professional

development in low-resource contexts (Tooley & Hood, 2021). Curriculum developers can embed robotics and computational thinking within play-based modules aligned to early learning standards. Finally, for parents and communities, the model underscores the importance of family engagement and digital readiness. Community-based digital-literacy workshops and parent–child robotics activities can strengthen the home–school connection, reinforcing early STEM learning. Together, these measures operate a sequenced and context-sensitive approach to implementing robotics in ECEC across Southeast Asia.

III.6 Limitations

This study has several limitations to be noted. First, the sample size, though adequate for NGT, ISM, and FDM, was relatively small and may not fully represent the diversity of stakeholders across Southeast Asia (Onwuegbuzie & Collins, 2007; Soares et al., 2024). Second, the study relied on expert consensus rather than direct classroom observations or longitudinal data, which may limit the ecological validity of the findings. Third, while cross-country representation was included, the analysis did not disaggregate results by national context, potentially overlooking intra-regional variations (Barrot, 2023). Finally, the reliance on virtual data collection may have constrained participation from educators in regions with limited internet access (Risser et al., 2024).

III.7 Future Research Directions

Future research should address these limitations by expanding the sample size to include a broader spectrum of stakeholders, such as parents, community leaders, and technology developers, whose perspectives are crucial for holistic policy design. Mixed-methods longitudinal studies should be conducted to track the actual impact of robotics integration on children’s cognitive and socio-emotional development across diverse contexts (Amsbary et al., 2023). Comparative case studies across Southeast Asian countries could provide richer insights into cultural and infrastructural variations (Tan, 2016; Barrot, 2023). At a practical level, pilot programs for mobile STEM labs and micro-credentialing for teacher training should be implemented and evaluated to inform scalable models (Doss et al., 2024). At the policy level, SEAMEO CECCEP and national ministries of education should jointly develop regional guidelines that integrate equity safeguards, ensuring that rural and marginalized populations are not excluded from robotics-based STEM opportunities (UNESCO Bangkok & SEAMEO CECCEP, 2019).

IV. CONCLUSION AND RECOMMENDATION

This study identified and validated five systemic factors that shape the integration of STEM and robotics in Early Childhood Education and Care (ECEC): teacher competency, availability of age-appropriate robotics, curriculum integration, cost and infrastructure, and parental support and digital literacy. Using a combined methodology of NGT–ISM–FDM approaches, the findings revealed a hierarchical model in which parental support and infrastructure act as foundational enablers, teacher competency and resource availability serve as mediators, and curriculum integration functions as the strategic outcome.

The study contributes new knowledge by extending systems theory into early STEM education, demonstrating how interdependent factors collectively determine sustainable integration across Southeast Asian contexts. It advances methodological innovation through the triangulated use of NGT, ISM, and FDM, providing a replicable framework for cross-national educational research. Practically, the model offers policymakers and practitioners a sequenced roadmap for regional STEM transformation, which begins with community digital-literacy initiatives and infrastructure investment, followed by teacher professional development and curriculum reform.

While limited by a small, expert-based sample, the findings remain transferable across comparable contexts and highlight the need for longitudinal, multi-country studies that examine children's actual learning outcomes. In conclusion, this study provides both a conceptual contribution to systems-based ECEC research and a practical guide for equitable STEM policy and practice in Southeast Asia.

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