

Engineering-based Educational Technology for Integrated STEM Learning: A Five-component Model from Resource Constrained Contexts

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Abstract—This paper contributes to educational technology research by presenting a five-component offline-first framework for implementing integrated STEM education in resource constrained contexts. Drawing from five years of implementation research (2018–2023) with 157 students in Aba, Nigeria, we demonstrate that strategic educational technology design, not infrastructure abundance determines, effective STEM integration. Our context presented typical barriers: intermittent electricity (outages 2–3 times daily), limited internet connectivity, and minimal computing resources. The intervention model integrates STEM disciplines through engineering-based computational thinking activities employing carefully selected educational technologies: Scratch for algorithm design, Python for authentic problem solving, and IoT sensors for scientific inquiry. The five components comprise: (1) structured computing camps emphasizing integrated problem solving, (2) continuous after-school engagement, (3) school partnerships introducing offline capable educational technologies, (4) teacher capacity building in integrated STEM pedagogy and educational technology facilitation, and (5) community engagement demonstrating engineering thinking. Outcomes measured through 2024 include sustainable digital learning infrastructure in three partner schools operating independently 12–18 months post intervention, measurable gender equity improvement (30% to 50% female participation), and two program alumni selected for the competitive U.S. State Department TechGirls International Exchange Programme (111 participants selected globally from 37 countries). Analysis reveals five critical instructional design principles: integration occurs through engineering pedagogy not expensive technology, context specific challenges enhance relevance, sustained mentorship develops integrated thinking, representation transforms participation, and pedagogical capacity ensures sustainability. This implementation research demonstrates that authentic STEM integration through engineering-based educational technology is achievable without infrastructure parity, offering a replicable framework with transferable design principles for educational technology practitioners globally.

Keywords—educational technology, engineering education, implementation research, instructional design, integrated

STEM, offline-first design, resource-constrained environments

I. INTRODUCTION

The global digital divide in STEM education represents not merely a gap in access to devices, but fundamentally a disparity in access to effective educational technology for integrated STEM learning where students engage with science, mathematics, and technology through authentic engineering challenges supported by strategically designed educational technologies [1]. Integrated STEM education, where students apply mathematical reasoning, scientific inquiry, and technological tools through engineering design activities, has proven more effective than teaching subjects in isolation for developing problem solving skills and STEM identity [2]. Educational technology plays a critical role in facilitating this integration, providing tools for computational thinking, data analysis, simulation, and collaborative design [3]. However, existing educational technology for integrated STEM often assumes infrastructure abundance, reliable electricity, high bandwidth internet, modern computing equipment, and sophisticated software platforms [4]. This technology deterministic approach limits integrated STEM education's global democratization, excluding contexts where such infrastructure remains unavailable or unreliable.

This paper presents implementation research examining how educational technology for integrated STEM can be effectively designed and implemented in resource constrained environments through offline first, minimal infrastructure approaches grounded in engineering-based pedagogy. We document the Credoville initiative in Aba, Abia State, Nigeria (2018–2023), which developed and deployed a five-component educational technology model enabling authentic integrated STEM learning despite severe infrastructure constraints: intermittent electricity (outages 2–3 times daily), limited internet connectivity, constrained budgets, minimal computing infrastructure, and few visible STEM role models, particularly for

girls [5]. Traditional educational technology approaches designed for well-resourced Western environments proved incompatible with these realities [6], necessitating fundamental reconceptualization of educational technology for integrated STEM.

This implementation research contributes empirical evidence from 157 students across multiple cohorts (2018–2023), demonstrating that authentic STEM integration through engineering-based educational technology is achievable without expensive infrastructure. Outcomes include sustainable digital learning labs in three partner schools operating independently, measurable gender equity improvement (30% to 50% female participation), and two students' selection for the competitive U.S. State Department TechGirls International Exchange Programme (111 participants selected globally from 37 countries) in subsequent cohorts (2024, 2025). This paper documents the five-component intervention model, demonstrates how engineering-based educational technology activities integrate multiple disciplines even under severe constraints, presents implementation outcomes with evidence of sustainability, and distills five instructional design lessons for educational technology practitioners working to democratize integrated STEM access in similar contexts globally.

- *Theoretical Framework*

This implementation research draws on and extends multiple theoretical traditions in educational technology, learning sciences, and engineering education, synthesizing them into a unified framework addressing STEM integration in resource-constrained contexts.

Technological Pedagogical Content Knowledge (TPACK): Our model operationalizes Mishra and Koehler's TPACK framework [7], recognizing that effective educational technology integration requires an intersection of technological knowledge, pedagogical knowledge, and content knowledge. However, we extend TPACK by demonstrating that this integration can occur effectively with minimal technological sophistication when pedagogical knowledge and content expertise are strong. We propose 'Context-Aware TPACK', recognizing that the technological dimension must account for infrastructure realities, cultural contexts, and sustainability requirements not merely technological features.

Constructionism and Engineering Design: Building on Papert's constructionism [8], our approach positions students as designers who learn by constructing meaningful artifacts. Engineering design thinking provides the pedagogical framework: students define problems, ideate solutions, prototype implementations, test and evaluate, then iterate. This design cycle naturally integrates STEM disciplines. We demonstrate that constructionism's effectiveness extends beyond technology-rich 'maker spaces' to resource-constrained contexts.

Situated Learning: Drawing on Lave and Wenger's situated learning theory [9], our sustained mentorship model enables legitimate peripheral participation.

Students' progress from observing mentors model integrated problem-solving, to participating in guided projects, to independently facilitating subsequent cohorts' learning. This addresses not merely knowledge acquisition, but identity development: students see themselves as people who solve problems by integrating STEM disciplines.

Engineering Integrated STEM: Contemporary integrated STEM frameworks [10] position engineering as the integrating discipline. Our model operationalizes this principle but challenges the assumption that engineering education requires expensive infrastructure. We demonstrate engineering thinking can be cultivated through activities requiring minimal technology but substantial integrated reasoning.

II. CONTEXTUAL CHALLENGES

A. Infrastructural Barriers

Schools in Aba, Abia State faced multiple systemic barriers to integrated STEM implementation:

Limited IT Infrastructure: Most schools possessed minimal computing equipment. The average school had 5–8 functioning computers for 500+ students, with equipment dating from 2005–2010 running outdated operating systems.

Power Instability: Electricity availability remained unreliable, with outages occurring 2–3 times daily for extended periods (30 min to 4+ h), disrupting typical technology-dependent integrated STEM lessons. This unpredictability made cloud-based educational technology platforms and synchronous online activities impossible.

Internet Connectivity: Internet access proved sporadic, expensive, and insufficient for cloud based educational technology platforms. Average connection speeds of 1–2 Mbps (when available) precluded video streaming, large file downloads, or simultaneous access by multiple students.

Trained Instructors: Few educators possessed both computing qualifications and integrated STEM pedagogical training necessary to facilitate educational technology activities connecting multiple disciplines. Professional development opportunities in integrated STEM pedagogy and educational technology facilitation were essentially non-existent in the region.

B. Socio-Cultural Factors

Beyond infrastructure, significant socio-cultural barriers impeded integrated STEM engagement: lack of role models (particularly for girls [11]), gender stereotypes positioning computing as a masculine domain [12], economic constraints prioritizing immediate needs over educational investments, scepticism about technology education relevance, and limited awareness of STEM career opportunities. These contextual realities necessitated intervention approaches fundamentally different from Western educational technology models, requiring offline capable, minimal infrastructure solutions while maintaining pedagogical

benefits of authentic engineering-based integration [13].

III. THE CREDOVILLE MODEL

A. Educational Technology Design Principles

The Credoville model operationalizes five educational technology design principles that emerged iteratively

through implementation, enabling authentic STEM integration despite severe infrastructure constraints. Fig. 1 illustrates our five-component framework, showing how design principles form the foundation for implementation components, community engagement, and sustained outcomes.

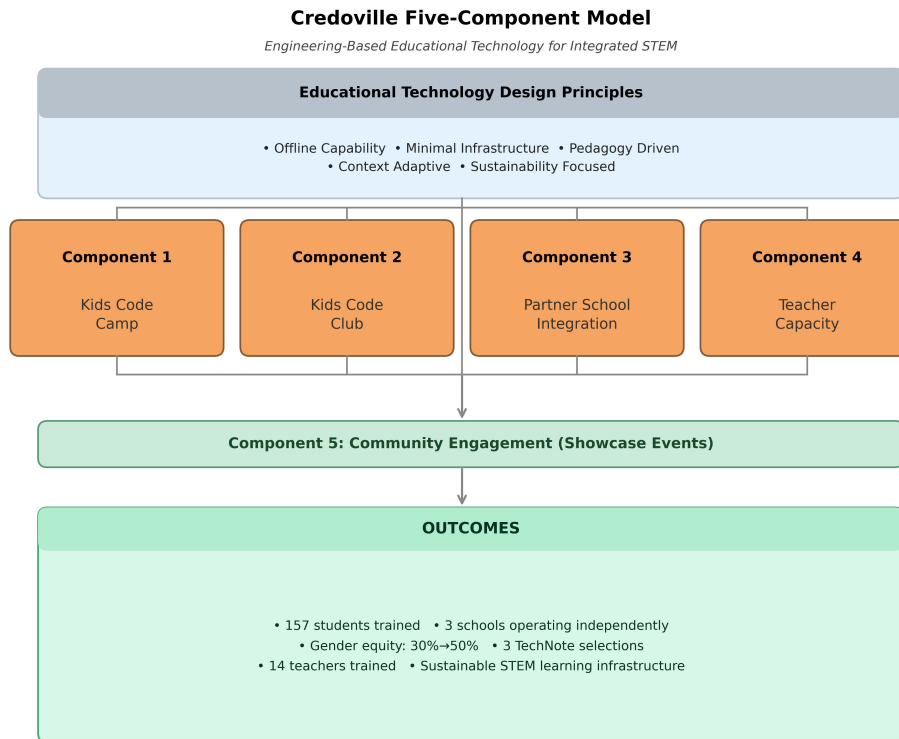


Fig. 1. The Credoville five component model for engineering-based educational technology in integrated STEM learning.

1) Offline-capability as primary design constraint

Intermittent electricity and unreliable internet necessitated selecting educational technologies that function effectively offline. Scratch operates entirely offline after initial installation. Python similarly requires no connectivity. Even IoT sensor programming employed local microcontroller development. Offline-first design proves beneficial even in connected contexts, reducing cognitive load from internet distractions and ensuring learning continuity regardless of network variability.

2) Minimal infrastructure requirements

Technology selection prioritized minimal hardware requirements. Scratch and Python run effectively on computers from 2005–2010 with 2–4 GB RAM. IoT activities used Arduino-compatible microcontrollers (\$3–5 per unit) rather than expensive robotics kits (\$200–500). Sensors employed affordable components (\$1–3 each). Minimal infrastructure requirements democratize access, enabling programs to scale affordably and sustainably.

3) Pedagogically-driven technology selection

Educational technologies were selected based on pedagogical affordances for engineering-based integrated STEM learning, not technological impressiveness.

Scratch was selected because visual block-based programming makes algorithmic thinking visible and manipulable. Python was chosen because its syntax emphasizes readability, and versatility enables authentic problem solving. We deliberately avoided ‘educational games’ that gamify isolated skills without authentic integration. Instead, students used Scratch to create educational games for partner schools, authentically integrating programming, mathematics, logic, and design.

4) Context adaptive implementation

Effective educational technology implementation requires deep contextual adaptation. ‘Power failure backup plans’ developed for every technology dependent lesson. Programming challenges were framed around locally relevant problems (agricultural water management, local transportation optimization) rather than imported scenarios with limited local resonance.

5) Sustainability focused architecture

Educational technology interventions were designed for eventual independence from external support. We trained local teachers in pedagogical approaches transferable across technologies. Teachers learned engineering-based integration methodology, not specific software operation, enabling them to adapt to technology changes or failures. Selected technologies require

minimal updates, no subscription fees, and function effectively with aging hardware.

B. Component 1: Kids Code Camp (2019)

We launched Abia State's first structured computing summer Programme, providing intensive three-week sessions combining foundational programming concepts with hands-on engineering projects. The curriculum deliberately integrated multiple disciplines through authentic engineering challenges using carefully selected educational technologies. Scratch programming introduced computational thinking as engineering design students decomposed problems, identified patterns, created abstractions, and developed algorithms. Web development integrated mathematical concepts (responsive grid layouts), design principles (visual hierarchy), and programming. Engineering challenges used paper-based computational thinking exercises framed as authentic community problems: water distribution system design, transportation route planning, waste collection optimization. These offline activities proved that integrated STEM learning occurs through engineering thinking methodology, not technology access.

C. Component 2: Kids Code Club (2020–2021)

Recognizing that intensive summer sessions alone proved insufficient, we established bi-weekly after-school programming throughout the academic year (72 sessions over two years, 216 total contact hours per cohort). This continuous engagement enabled progressive skill development through long-term educational technology projects, sustained mentorship modelling how professional engineers integrate multiple disciplines, collaborative engineering in persistent teams, and reduced participation barriers through zero cost. Without access to cloud-based learning management systems, we developed offline-first approaches using local storage, physical portfolios, and structured peer review sessions.

D. Component 3: School Partnerships

Rather than operating as an external intervention, we collaborated with local schools to establish sustainable digital learning labs and co-develop contextually appropriate integrated STEM curricula employing offline capable educational technologies. Partner school programs included IoT integration projects (environmental monitoring systems integrating sensor design, data analysis, and microcontroller programming), robotics challenges (requiring mechanical design, motion calculations, sensor programming, and iterative testing), and Python programming for authentic community needs. Three partner schools received equipment, trained instructor placement, offline-accessible curriculum materials, and ongoing technical support. Three partner schools continue operating these integrated STEM programs as of 2024 without Credoville's direct involvement, demonstrating genuine sustainability in educational technology implementation.

E. Component 4: Teacher Capacity Building

Sustainability required developing local educator

capacity in integrated STEM pedagogy and educational technology facilitation. We conducted intensive workshops (40 h initial training plus 20 h ongoing professional development), upskilling 17 teachers in: integrated STEM pedagogy (designing activities where mathematics, science, and technology naturally emerge from engineering challenges), engineering design thinking facilitation, offline-first teaching methods (maintaining pedagogical quality despite technology failures), curriculum adaptation (identifying local problems as authentic engineering challenges), assessment of integration (portfolio-based evaluation), and educational technology selection (choosing tools based on pedagogical affordances). Teachers developed 'power failure lesson plans'-backup activities maintaining learning objectives when technology is unavailable. Trained teachers became multipliers, extending reach beyond Credoville's direct capacity.

F. Component 5: Community Engagement

Addressing socio-cultural barriers required community buy-in. We organized quarterly public technology showcases where students demonstrated integrated projects solving real problems. These showcase events (8 events over 5 years, 600+ community attendees total) transformed perceptions by making visible how educational technology enables integrated STEM learning. Parents witnessed children explaining how they used mathematics to calculate robot movements, applied scientific principles to sensor behavior, and implemented solutions technologically. Seeing children from their community succeeding as young engineers fundamentally altered what families believed possible, particularly for girls [14]. Enrolment increased 40% following each showcase event. Female enrolment grew progressively from initial 30% (2018) to a sustained 50%+ (2022–2023) across cohorts (Fig. 2) following showcases featuring successful female students.

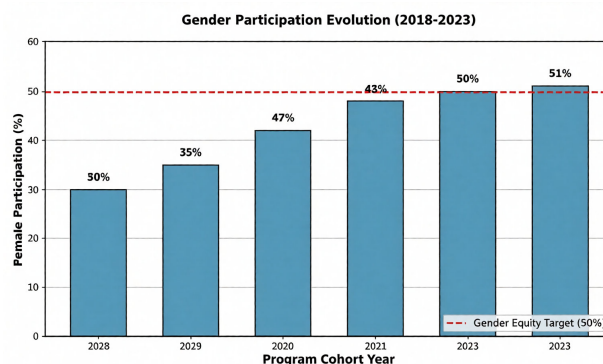


Fig. 2. Female participation evolution across program cohorts (2018–2023), demonstrating sustained gender equity achievement.

G. Integration through Engineering-Based Educational Technology

The Credoville model emphasizes that authentic STEM integration occurs through engineering-based educational technology activities, not merely teaching

multiple subjects simultaneously. We frame computational thinking and programming not as isolated technology skills but as engineering design processes facilitated through strategic educational technology selection. When students develop a program to calculate optimal routes, they engage in problem decomposition (engineering systems thinking), mathematical modelling, algorithmic design, and technological implementation. The integration is authentic because engineering naturally requires multiple disciplines working in concert. Educational technology serves as the enabling tool for this integration, not the primary focus. Resource limitations paradoxically strengthened integration. Without expensive physical sensors, students designed paper-based sensor simulations requiring deeper understanding of underlying scientific principles. These findings challenge technology-centric approaches to educational technology, suggesting pedagogical design matters more than infrastructure abundance [15].

IV. PRELIMINARY OUTCOMES

A. Quantitative Metrics

Implementation across five years (2018–2023) produced measurable outcomes: 157 students trained across seven cohorts; 3 partner schools with sustained independent programs continuing 12–18 months post intervention; 17 teachers trained in educational technology facilitation with 8 continuing active facilitation; 2 former students selected for U.S. State Department TechGirls Programme (111 selected globally from 37 countries) in the 2024 and 2025 program cohorts; gender participation increased from 30% female (2018–2019) to sustained 50% female (2021–2023); 78% retention rate.

B. Qualitative Impact

1) Sustained educational technology infrastructure

Digital labs and trained instructors continue operating integrated STEM programs beyond Credoville's direct involvement, demonstrating genuine sustainability. Critically, teachers maintain an engineering-based integration approach rather than reverting to isolated subject teaching.

2) Student outcomes

Students progressed from zero computing exposure to representing Nigeria at international STEM programs. TechGirls coordinators reported: 'These students approach problems by naturally integrating multiple disciplines. They do not ask, "Is this a math problem or a science problem?" They ask, "What do I need to solve this problem?" That is sophisticated engineering thinking.'

3) Learning processes development

Student surveys (89 students, 2020–2023) revealed significant development in integrated problem solving (Fig. 3): 68% agreed 'I am good at solving problems using science and math' (post-program) versus 23% (pre-program); 72% indicated interest in STEM careers

(post) versus 31% (pre); 81% reported confidence using technology to solve real problems (post) versus 19% (pre). This indicates educational technology facilitated fundamental shifts in problem solving approaches.

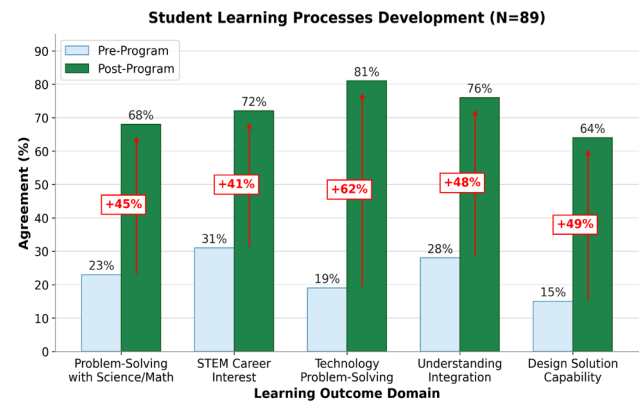


Fig. 3. Student learning processes development showing pre-program and post-program agreement on key competency indicators (N = 89).

C. Five Lessons for Practitioners

1) Integration through engineering pedagogy, not technology

Success requires recognizing that authentic STEM integration occurs through engineering-based problem-solving approaches facilitated by strategically selected educational technologies, not through expensive technology itself. Our offline capable curriculum integrated STEM as effectively as technology rich programs because integration happened in the pedagogical framing. Practitioners in resource constrained environments can achieve integrated STEM through engineering thinking regardless of infrastructure [16].

2) Context-specific engineering challenges

Success requires adapting engineering challenges and educational technology implementation to local contexts. Problems relevant to students' lived experiences proved more engaging through educational technology and demonstrated STEM integration's practical value more effectively than imported challenges [17].

3) Mentorship in integrated thinking

Students demonstrating greatest success developed integrated STEM identity. Sustained mentorship relationships where mentors modeled integrated thinking fundamentally changed students' self-perception and problem-solving approaches. Mentorship extended beyond technical guidance to include growth mindset cultivation, STEM identity affirmation, and career awareness [18].

4) Representation transforms participation

When students see individuals from similar backgrounds succeeding as engineers, engagement and persistence dramatically increase. Female student enrolment and persistence increased dramatically (30% to 50%) following visibility of successful female students.

This suggests representation affects not just student belief but also parent/community permission and support [19].

5) Sustainability through pedagogical capacity

Programs succeeded long-term when local educators internalized integrated STEM pedagogy and educational technology facilitation. Training focused on pedagogical approaches rather than technology ensured programs sustained the integration approach even as tools evolved. This pedagogical capacity, not infrastructure, determined program longevity [20].

V. DISCUSSION

A. Implications for Educational Technology

This implementation research demonstrates that authentic integrated STEM education through engineering-based educational technology is achievable in resource constrained environments without infrastructure parity with developed nations. The core finding: STEM integration occurs in the pedagogical approach facilitated by strategically selected educational technologies, not in the technologies' sophistication. Current discussions of STEM education equity often center on providing technology access. While access matters, our findings suggest pedagogical approaches in educational technology design may be more determinative of integrated STEM outcomes than infrastructure. This reframes the challenge: the gap is not primarily technological but pedagogical and capacity building in educational technology facilitation.

B. Contribution to Educational Technology Theory

This research extends educational technology theory in three ways: (1) Demonstrating Context Aware TPACK showing that technological knowledge must encompass infrastructure constraints, offline capability requirements, and sustainability considerations; (2) Establishing offline first as a design principle with pedagogical benefits beyond necessity; (3) Challenging technology deterministic approaches by empirically demonstrating that pedagogical design quality determines integration effectiveness more than technology sophistication.

C. Limitations and Future Work

As implementation research from a single case study context, this work acknowledges several limitations: modest sample size (157 students); incomplete long-term tracking; absence of a formal control group; single context findings requiring empirical validation for transferability. Future research includes longitudinal assessment of alumni integrated STEM competency development using validated instruments; comparative effectiveness studies; quantitative evaluation of teacher development trajectories; replication studies examining model adaptation across diverse contexts; and cost-effectiveness analysis [21].

VI. CONCLUSION

This implementation research demonstrates that

integrated STEM education through engineering-based educational technology is achievable in resource constrained environments through contextually adapted, community centered interventions employing offline first design principles. The Credoville five component model produced measurable and sustained outcomes: 157 students trained, sustainable infrastructure with three partner schools operating independently, and international recognition (two TechGirls selections, a highly competitive program with 111 participants selected globally from 37 countries, 2024 and 2025 cohorts).

The core empirical contribution to educational technology research: demonstrating that authentic STEM integration occurs through engineering-based pedagogical approaches facilitated by strategically selected educational technologies, rather than through technology sophistication or abundance. Critical insights for educational technology practitioners emerged across five implementation years (detailed in Section IV), demonstrating that pedagogical design quality and educator capacity determine integration effectiveness more than infrastructure sophistication.

The Credoville model contributes to growing evidence that the global STEM education equity challenge is fundamentally pedagogical and about educational technology design quality, not technological abundance. Engineering-based pedagogies authentically integrating multiple disciplines through authentic problem solving, facilitated by offline first educational technologies, can be implemented anywhere, by trained educators, addressing locally relevant challenges, with minimal infrastructure. This finding offers hope for democratizing integrated STEM education globally: the pathway through strategic educational technology design is achievable, replicable, and within reach of resource constrained communities worldwide.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Nnamdi P. Nwachukwu and Tochukwu A. Uwakeme co-founded and co-directed the Credoville Initiative; both authors designed the five-component intervention model; Nnamdi P. Nwachukwu led data collection and analysis; Tochukwu A. Uwakeme led curriculum development and teacher training; both authors contributed to writing and revising the manuscript; all authors approved the final version.

ACKNOWLEDGMENT

The authors acknowledge the students, families, and community members of Aba, Abia State who participated in and supported Credoville programs. We thank partner schools and trained teachers whose continued dedication ensures program sustainability and whose commitment to integrated STEM pedagogy and educational technology facilitation demonstrates that engineering-based

approaches can transform education even in challenging contexts. Special thanks to the TechGirls program coordinators for insights on student competencies.

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