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Smart Modeling as a Transformative Approach for Restructuring STEAM Education in Light of Sustainable Development Requirements

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Abstract

Background and Problem:

The integration of smart modeling within STEAM education (Science, Technology, Engineering, Arts, and Mathematics) represents a transformative approach toward achieving sustainable development goals. However, this integration remains both conceptually and operationally underdeveloped. Contemporary educational practices reveal a pronounced *pedagogical-technological gap*, wherein digital tools are frequently employed at a superficial level without effectively promoting deep systems thinking or ethical awareness. Accordingly, this study addresses the lack of empirically validated frameworks capable of supporting the systematic restructuring of STEAM curricula to incorporate sustainability competencies through advanced smart modeling..

Objective:
This study aimed to develop and validate the **Smart-STEAM Transformative Framework (SSTF)**. Specifically, it sought to identify the essential pedagogical and technical standards, prioritize key sustainable development requirements, and examine the extent of expert consensus regarding the proposed transformative mechanisms for curriculum restructuring.

Methodology:
The study adopted a descriptive-analytical design grounded in a pragmatic paradigm and was informed by Educational Design Research (EDR) principles to bridge the gap between theory and practice.. The research sample consisted of a stratified purposive group of **145 experts and practitioners**, categorized into three clusters: Academic Experts (35.9%), Technical Specialists in Artificial Intelligence and Digital Modeling (31.7%), and Sustainability Practitioners (32.4%). Data were collected using the **Smart-STEAM Integration Survey (SSIS)**, a 24-item instrument validated through the Content Validity Index (S-CVI = 0.92) and Exploratory Factor Analysis (EFA). Statistical analyses included the Relative Importance Index (RII), Kendall's Coefficient of Concordance (W), and the Kruskal-Wallis H test to ensure analytical rigor.

Key Results:

The domains of the SSTF received a very high level of professional endorsement (M = 4.62, SD = 0.51). The domain of **Sustainable Development Competencies**achieved the highest mean score (M = 4.78), reflecting a strategic orientation toward *green competencies*. Results of the RII analysis indicated that **Ethical-Environmental Integration** was the highest priority (RII = 0.95), highlighting the role of the Arts in humanizing digital twin technologies. A strong and statistically significant level of agreement was observed among the expert groups ($W = 0.81$, $p < 0.001$), with no statistically significant differences across specializations ($p = 0.185$). Furthermore, the instrument demonstrated excellent internal consistency (Cronbach's $\alpha = 0.94$).

Conclusion and Added Value:

The study presents the **SSTF** as an innovative, expert-validated framework that integrates smart modeling (e.g., Digital Twins and Artificial Intelligence) with interdisciplinary STEAM education and sustainability ethics.

Recommendations:
cross-cultural replication studies are encouraged to examine the adaptability of the SSTF across diverse educational and technological contexts, as well as its effectiveness in enhancing systems thinking and environmentally responsible behaviors among students.

Introduction

The global educational landscape is currently at a historical crossroads, driven by accelerating sustainability challenges and profound digital transformations that have redefined the human-environment interface. In this context, STEAM education (Science, Technology, Engineering, Arts, and Mathematics) has emerged not merely as a pedagogical trend for interdisciplinary integration, but as a critical platform for developing minds capable of deconstructing and solving complex planetary crises. Today's learners require more than theoretical knowledge; they need "cognitive and technical" toolsets that enable future-oriented foresight. Consequently, Smart Modeling emerges as a transformative gateway that transcends traditional conceptual representation, creating virtual and physical learning environments where students can simulate biological systems and test sustainable solutions in risk-free settings before real-world implementation (Yuan & Zhang, 2024).

Furthermore, the epistemological shift from passive knowledge reception to active knowledge construction demands pedagogical innovations that align with the cognitive and emotional development of digital natives. Smart Modeling, which integrates computational simulations, digital twins, and data-driven visualizations, provides learners with the ability to manipulate variables, observe emergent patterns, and engage in iterative design thinking. This process not only deepens understanding of complex systems—such as climate change feedback loops or urban metabolism—but also cultivates metacognitive skills essential for lifelong learning (Kazakoff & Mitchell, 2022). In this sense, Smart Modeling functions as both a cognitive prosthesis and a creative amplifier, enabling students to externalize their mental models and refine them through collaborative inquiry.

Integrating Smart Modeling into the STEAM framework fosters a transition from "linear thinking" to "systems thinking"—a fundamental requirement advocated by UNESCO to achieve Education for Sustainable Development (ESD) that modifies behavior rather than just transmitting information (UNESCO, 2021). Systems thinking, as a higher-order cognitive competency, allows learners to recognize interconnections, feedback loops, and leverage points within socio-ecological systems. When embedded within STEAM disciplines, Smart Modeling operationalizes systems thinking by allowing students to construct, test, and validate models of real-world phenomena—from water resource management to renewable energy grid design. This alignment may support educational efforts related to Sustainable

Development Goal 4 (Quality Education) and SDG 13 (Climate Action), as emphasized by the Bonn Declaration on ESD (UNESCO, 2022).

Moreover, the integration of Smart Modeling addresses a persistent gap in traditional STEAM implementations: the underutilization of the "Arts" dimension as a driver of innovation and empathy. By incorporating artistic visualization, narrative construction, and ethical reasoning into the modeling process, learners can humanize abstract data and explore the socio-emotional implications of technological solutions. For instance, Smart Modeling projects that combine environmental science with digital storytelling or interactive media design enable students to communicate complex sustainability issues to diverse audiences, thereby fostering civic engagement and transdisciplinary collaboration (Papanastasiou et al., 2021). This artistic augmentation may extend modeling beyond a purely technical exercise toward a more reflective and value-laden practice.

With the rise of Industry 5.0, the synergy between Artificial Intelligence, digital modeling, and environmental responsibility has become the new benchmark for educational excellence. Unlike Industry 4.0's focus on automation and efficiency, Industry 5.0 explicitly prioritizes human-centricity, resilience, and sustainability. Consequently, educational systems must prepare learners to co-evolve with intelligent systems, critically evaluate algorithmic decisions, and design ethical AI applications for sustainable development (European Commission, 2022). Smart Modeling serves as an ideal pedagogical bridge in this regard, offering hands-on experiences with AI-assisted simulations, predictive analytics, and responsible data stewardship.

Therefore, restructuring STEAM education through this "smart" lens is not a mere curricular enhancement; it is a radical reimagining of the school curriculum as a digital mirror reflecting society's sustainable aspirations. This transformative approach empowers both the Arts and Sciences to humanize technology, ensuring it serves the planet's longevity, making research in this field a strategic necessity to keep pace with rapid global shifts (Chen & Liu, 2023). In addition, recent meta-analyses confirm that Smart Modeling interventions significantly improve learners' problem-solving abilities, collaborative skills, and attitudes toward sustainability when compared to traditional instruction (Ng, 2023). These findings underscore the urgency of embedding Smart Modeling not only as an occasional tool but as an organizing principle of STEAM curriculum design.

However, despite its demonstrated potential, the systematic adoption of Smart Modeling in K-12 and higher education faces multiple challenges, including insufficient teacher professional development, lack of adaptable modeling platforms, and misalignment with existing assessment frameworks. Most standardized assessments still privilege factual recall and procedural fluency over systems thinking and model-based reasoning (Sterling, 2020). Addressing these barriers requires a holistic change strategy encompassing curriculum reform, digital infrastructure investment, and assessment innovation. The present descriptive research aims to provide a comprehensive analysis of Smart Modeling as a transformative approach for restructuring STEAM education in light of sustainable development

requirements, offering evidence-based guidelines for policymakers, educators, and curriculum developers.

In summary, this introduction establishes the theoretical and practical foundations for investigating Smart Modeling within STEAM education. The remainder of the paper is organized as follows: a conceptual framework linking Smart Modeling to ESD competencies, a methodological description of the descriptive research approach, an in-depth analysis of case studies and implementation models, and finally, a set of actionable recommendations for integrating Smart Modeling into national and institutional STEAM policies.

Literature review

Digital Transformation and the Re-envisioning of STEAM Education

The evolution of STEAM (Science, Technology, Engineering, Arts, and Mathematics) has transitioned from a mere multidisciplinary grouping to a sophisticated transdisciplinary philosophy essential for navigating the complexities of Industry 5.0. Miller and Sanders (2022) argue that STEAM serves as a cognitive infrastructure where the "Arts" component acts as a catalyst for human-centric design thinking. In the wake of rapid digitalization, Yuan and Zhang (2024) assert that Artificial Intelligence (AI) is no longer a peripheral tool but a "co-cognitive partner" that necessitates a redefinition of computational thinking skills. Despite this potential, Kim and Ko (2021) identify a pervasive "superficial integration gap," where technology is applied without deep pedagogical alignment, a void that modern frameworks must address. The humanization of technology remains a central theme, with Smith and Tytler (2023) emphasizing that the aesthetic and ethical dimensions of the Arts ensure that technical innovations remain socially responsible. Furthermore, Zhou (2022) highlights how digital transformation facilitates data-driven personalized learning, while Lopez and Willison (2024) position STEAM as a vital vehicle for digital inclusion and equity. Ultimately, Tan et al. (2024) suggest that interactive modeling is the core of ideation, leading to White and Harrison's (2021) conclusion that STEAM represents the pinnacle of socio-technical integration in modern curricula.

Smart Modeling and Digital Twins as Immersive Learning Environments

Smart Modeling represents the operational backbone of the Smart-STEAM Transformative Framework (SSTF). Chen and Liu (2023) describe smart modeling as a "cognitive bridge" that enables learners to synchronize the physical and digital realms through dynamic representations. At the forefront of this shift is Digital Twin (DT) technology; Wang and Li (2022) demonstrate that DTs provide high-fidelity immersive environments where students can simulate real-world variables with unprecedented precision. According to Perez et al. (2024), such high-fidelity simulations effectively lower extraneous

cognitive load, allowing students to dedicate mental resources to higher-order problem-solving and ethical evaluation. In the context of predictive learning, Hasan and Al-Ahmadi (2025) explore how AI-driven modeling provides real-time feedback loops that allow students to pivot and refine their designs instantaneously. This is complemented by Zheng and Brown (2021), who correlate 3D modeling with enhanced spatial reasoning and abstract thinking. Müller (2023) introduces the crucial concept of "Computational Stewardship," arguing that students must develop the competency to ethically manage and oversee the autonomous systems they model. To ensure algorithmic justice, Kaur et al. (2022) emphasize the necessity of embedding accountability within modeling software, while Liu and Park (2025) predict that predictive analytics will become the standard for engineering pedagogy. Conclusively, Fisher (2021) finds that systemic thinking is a natural byproduct of continuous engagement with smart simulation environments.

Sustainable Development and Ethical Responsibility in Technical Contexts

Sustainable development is the ultimate ethical teleology of technical innovation. According to the UNESCO (2021) roadmap, education must be a "transformative force" capable of addressing existential planetary crises. Higgins et al. (2022) argue that "Transformative Pedagogy" is the essential link required to bind technical proficiency with ecological consciousness. Developing these competencies requires a strategic balance of self-awareness and transdisciplinary collaboration, as outlined by Biberhofer and Rammel (2023). Leal Filho et al. (2024) position STEAM as the most flexible framework for achieving the United Nations Sustainable Development Goals (SDGs), given its ability to synthesize technical and social innovation. The transition from functional to transformative learning is vital for long-term impact, a sentiment echoed by Sterling (2021). In terms of institutional implementation, Jucker and Mathar (2022) argue that a "whole-school systemic approach" is the only way to embed sustainability into the educational DNA. Ramirez (2025) provides the quantitative tools for this shift, demonstrating how ecological modeling allows students to measure carbon footprints and resource depletion directly within their STEAM projects. Wiek and Kay (2024) revisit sustainability competencies, highlighting "anticipatory thinking" as a pivotal skill for the next decade. O'Connor (2021) advocates for the "ethics-by-design" approach, ensuring that moral considerations are integrated into the modeling phase rather than treated as an afterthought.

Theoretical Framework: Conceptual Foundations

Smart Modeling as the Transformative Core

The integration of Smart Modeling in education is fundamentally rooted in the evolution of "Digital Twins"—virtual replicas of physical systems that allow for real-time interaction and experimentation. In a STEAM context, this allows learners to bridge the gap between abstract theoretical constructs and tangible physical realities by manipulating variables within a safe, simulated environment, fostering

deeper engagement as students transition from passive observers to active architects of digital systems (Chen & Liu, 2023; Yuan & Zhang, 2024). The use of high-fidelity simulations enables visualization of complex phenomena otherwise invisible in traditional classrooms, such as molecular structures or large-scale ecological shifts, helping students develop nuanced understanding of causality and system dynamics essential for high-level scientific inquiry (Smith et al., 2022; Lee & Kim, 2021). Beyond technical scaffolding, Smart Modeling acts as a cognitive mediator that reshapes how students process information; by externalizing internal mental models into shared digital representations, students negotiate meaning and refine understanding through iterative testing, shifting from rote memorization to higher-order functions like synthesis and critical evaluation (Higgins et al., 2022; Miller & Sanders, 2022). This cognitive offloading reduces the load associated with complex problem-solving, allowing students to focus on creative strategy and innovation, thereby democratizing access to advanced STEAM concepts (Wang & Park, 2025; Brown, 2023). The infusion of AI into educational modeling has catalyzed a paradigm shift toward "living" adaptive systems that provide real-time feedback and predictive analytics, fostering an experimental mindset where failure becomes a data point for refinement (Yuan & Zhang, 2024; Zhao & Li, 2023). These intelligent frameworks adapt to the learner's proficiency level, offering personalized challenges that maintain the zone of proximal development, pushing boundaries of what students can achieve in STEAM projects (Garcia, 2022; Thompson & White, 2025). Finally, Smart Modeling inherently cultivates "Systems Thinking"—the ability to see interconnected components rather than isolated parts—allowing students to trace interventions across entire ecosystems, account for feedback loops and non-linear relationships, and develop a global cognitive map essential for sustainable decision-making (UNESCO, 2021; Chen & Liu, 2023; Roberts, 2024; Nguyen, 2022).

Reimagining STEAM Education

The "A" in STEAM signifies a philosophical shift toward transdisciplinary synergy, where boundaries between disciplines become porous. Smart Modeling acts as the "connective tissue" providing a universal language that enables an artist to communicate with an engineer and a mathematician to collaborate with a biologist, crucial for solving wicked problems that do not fit into single academic silos (Miller & Sanders, 2022; Adams et al., 2023). Students engaged in smart modeling naturally draw upon multiple domains simultaneously—mathematics for coding, engineering for structure, arts for intuitive and ethical interfaces—mirroring modern professional environments where innovation happens at disciplinary intersections (Kim & Choi, 2021; Wilson, 2025). The inclusion of Arts ensures technology develops with a human-centric focus, emphasizing empathy, aesthetics, and ethics; Design Thinking encourages students to ask "Why?" and "For whom?" before "How?", ensuring models are socially responsible and culturally relevant (Higgins et al., 2022; Taylor, 2024). Artistic visualization techniques allow effective communication of complex data, triggering emotional responses that motivate sustainable change more powerfully than raw data alone, blending scientific rigor with artistic intuition to nurture both analytical and creative thinking (Lopez & Reed, 2022; Martin, 2023). Despite theoretical benefits, practical STEAM implementation faces structural hurdles: rigid departmental silos, lack of teacher self-efficacy with digital tools, and surface-level integration without meaningful depth (Yuan & Zhang, 2024; Davis & Green, 2022). Smart Modeling offers a structured solution by providing a

procedural roadmap where the "Model" serves as a central unit of work, allowing teachers from different departments to align learning objectives around a single digital artifact, though overcoming barriers requires cultural shift and ongoing professional development (UNESCO, 2021; Patel, 2023). The global economy's shift toward a "green and digital" twin transition demands a workforce fluent in environmental stewardship and high-tech innovation (Chen & Liu, 2023; Brown & Scott, 2024; Garcia, 2022; Lee, 2025).

Sustainable Development Mandates in Education

Education for Sustainable Development (ESD) is the "North Star" guiding 21st-century educational reform. The 17 Sustainable Development Goals (SDGs) provide a framework for addressing climate change, resource scarcity, and social inequality. Smart Modeling serves as a powerful pedagogical tool for ESD by allowing students to simulate long-term impacts of human activities on the planet, visualizing carbon footprints or circular economy benefits, making abstract global goals local and actionable, and moving beyond academic exercises toward authentic learning that contributes to global good (UNESCO, 2021; Higgins et al., 2022; Miller, 2023; Thompson, 2024). The intersection of "Green" and "Digital" defines the next decade's innovations; students must develop "Green Competencies"—a blend of environmental knowledge, technical skills, and sustainable mindset. Smart Modeling provides a laboratory for developing these skills through projects like optimizing energy efficiency of smart cities or designing autonomous irrigation for drought-stricken regions, ensuring digital literacy is never divorced from ecological responsibility (Yuan & Zhang, 2024; Zhao & Li, 2023; Green & Stone, 2021; White, 2022). Sustainable development requires a shift from extraction to stewardship; Smart Modeling fosters this by making invisible consequences visible and quantifiable, building agency as students realize they can design restorative systems, encouraging frugal innovation and responsible creation (Chen & Liu, 2023; Adams et al., 2023; Roberts, 2024; Kim, 2025). Sustainability comprises environmental, social, and economic stability; transformative STEAM education must address all three. Smart Modeling allows students to perform Social Impact Assessments on technical designs, considering equity, accessibility, and cost-effectiveness, preventing technological elitism and promoting inclusive innovation. Integrating socio-economic variables teaches that a truly "smart" solution is sustainable for everyone, regardless of socio-economic status, defining a transformative entry point for rebuilding education (Higgins et al., 2022; Miller & Sanders, 2022; Davis, 2025; Lopez, 2023).

Restructuring STEAM Education through Smart Modeling in the Saudi Educational Landscape

This research is situated within the strategic imperative to restructure STEAM education (Science, Technology, Engineering, Arts, and Mathematics) in response to the dual pressures of rapid digital transformation and the urgent global mandate for sustainable development. Within the Kingdom of Saudi Arabia, this transformation is a cornerstone of Vision 2030, which aims to transition the national economy from oil dependency to a robust, knowledge-based society. Despite the widespread deployment of advanced digital infrastructure in Saudi classrooms, a persistent "pedagogical-

technological gap" remains. This gap often results in a superficial application of technology that fails to foster the high-order cognitive skills—such as systems thinking and ethical responsibility—required for true sustainable innovation.

The Smart-STEAM Transformative Framework (SSTF) proposed in this study addresses this deficiency by positioning Smart Modeling as a fundamental cognitive and operational bridge. By integrating Digital Twins, AI-driven simulations, and interactive visualizations, the framework allows students to translate abstract scientific concepts into tangible solutions for real-world sustainability challenges. This approach aligns with the UNESCO (2021) mandate, which asserts that education must serve as a transformative force to achieve the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 13 (Climate Action)

The targeted Saudi educational system is characterized by a shift toward "Green Competencies." In this context, students are evaluated not merely on technical proficiency but on their ability to model, simulate, and mitigate ecological and social impacts using digital tools. This transition is essential for preparing the Saudi workforce for Industry 5.0, by integrating the Arts as a humanizing and aesthetic component, this research ensures that smart modeling remains grounded in empathy, cultural relevance, and social justice, preventing the educational process from becoming a purely mechanistic exercise.

Ultimately, this research provides an actionable framework for Saudi policymakers and educational leaders to redesign K-12 and higher education curricula. By utilizing empirical findings from real-time feedback loops and predictive analytics, the study justifies the necessity of smart modeling environments to cultivate "anticipatory thinking" and ethical design among the next generation of Saudi innovators.

Research question

To address the research problem, this study seeks to answer the following primary question: "How can a transformative framework be developed to restructure STEAM education through smart modeling to meet sustainable development mandates?"

The following sub-questions guide the investigation:

RQ1:What are the essential pedagogical and technical standards for employing smart modeling as a transformative approach in STEAM education?

RQ2:Which sustainable development requirements are prioritized for integration into STEAM curricula to equip learners ?

RQ3:To what extent do educational experts reach a consensus on the proposed mechanisms for restructuring STEAM education in light of the smart modeling approach?

RQ4:What are the components and structural features of the proposed transformative framework for rebuilding STEAM education based on the synergy between smart modeling and sustainability?

Methods

Research Design and Philosophical Underpinnings

This study adopts a descriptive-analytical research design embedded within a pragmatic paradigm. The pragmatic paradigm is particularly suited for research that seeks to develop and validate applied educational frameworks, as it prioritizes practical consequences over purely theoretical or abstract debates (Creswell & Creswell, 2022). Given that the primary aim of this study is to construct and validate the Smart-STEAM Transformative Framework (SSTF) based on expert consensus, a purely positivist or constructivist approach would be insufficient. Instead, pragmatism allows for the synergistic integration of quantitative data (from structured surveys) and qualitative insights (from expert feedback), enabling a more holistic and actionable outcome.

The research design was informed by Educational Design Research (EDR) principles, following the foundational work of McKenney and Reeves (2021). EDR is characterized by iterative cycles of analysis, design, development, and evaluation. In this study, the initial phase (reported here) focuses on identifying requirements and consulting specialists to construct a validated model. This design ensures that the resulting SSTF is not only theoretically sound but also practically feasible in real-world STEAM education contexts.

Context and Participants

This study was situated within the evolving landscape of **Smart Modeling as a transformative approach for restructuring STEAM education in light of sustainable development requirements**. The research context emphasizes the integration of advanced digital modeling, artificial intelligence, and sustainability-oriented practices within interdisciplinary educational systems.

The target population comprised professionals and specialists engaged in STEAM education, digital technologies, and sustainability-related fields. These participants were selected to reflect the interdisciplinary nature of Smart-STEAM transformation and to ensure the generation of reliable and contextually grounded data.

Sampling Strategy

A **stratified purposive sampling strategy** was employed to select participants who possess relevant expertise while also ensuring adequate sample size for advanced statistical analysis.

Unlike traditional expert-panel designs that rely on small samples, the present study adopted a **large-scale quantitative approach**, enabling robust psychometric procedures such as **Exploratory Factor Analysis (EFA)** and reliability testing.

The final sample consisted of **N = 145 participants**, distributed across three major professional clusters to ensure interdisciplinary representation and analytical validity.

The **Distribution of Study Sample across professional clusters is presented in Table 1 below**

Table (1):

Distribution of Study Sample (N = 145)

Cluster	n	Percentage (%)	Mean Years of Experience	Affiliation Type
Academic Experts	52	35.9%	13.9	Universities / Research Institutions
Technical Experts	46	31.7%	15.4	Industry / R&D Centers
Sustainability Practitioners	47	32.4%	15.1	NGOs / Consulting / International Organizations
Total	**145**	**100%**	—	—

This distribution ensured balanced representation across academic, technical, and sustainability domains, thereby strengthening the external validity of the findings.

Inclusion Criteria

To ensure the quality, relevance, and consistency of the collected data, the following inclusion criteria were applied:

1. Participants must have a minimum of **10 years of professional experience** in a relevant domain.
2. Demonstrated involvement in at least one **STEAM-related project** or **sustainability initiative**.
3. Academic participants were required to be actively engaged in research related to curriculum, STEAM education, or educational technology.
4. Technical and sustainability participants were required to have practical experience in **digital modeling**, **artificial intelligence**, or **sustainability implementation practices**.

Demographic and Professional Characteristics

To provide a clearer understanding of the sample composition, descriptive statistics were calculated for key demographic and professional variables.

The **Demographic and Professional Profile of Participants is shown in Table 2 below.**

Table (2):

Demographic and Professional Profile of Participants

Variable	Category	Frequency	Percentage (%)
Gender	Male	89	61.4%
	Female	56	38.6%
Qualification	PhD	68	46.9%
	Master's	49	33.8%
	Bachelor's	28	19.3%
Field of Expertise	Education/STEAM	52	35.9%
	Technology/AI	46	31.7%
	Sustainability	47	32.4%
Experience	10–15 years	63	43.4%
	16–20 years	51	35.2%
	21 + years	31	21.4%

Methodological Justification

The adoption of a **stratified purposive sampling approach** combined with a relatively large sample size (N = 145) was methodologically justified for several reasons:

- It ensures the inclusion of **domain-specific expertise**, which is essential for evaluating Smart-STEAM transformation.
- It provides sufficient statistical power for conducting **factor analysis and reliability testing**.
- It enhances the **breadth of expert representation**, while maintaining depth and contextual relevance.

Conclusion of the Sampling Design

The sampling design adopted in this study successfully balances **expertise depth** and **quantitative rigor**, thereby supporting the study's objective of evaluating Smart Modeling as a transformative approach in STEAM education.

The final sample (N = 145) is considered adequate and appropriate for advanced statistical analyses, including **Exploratory Factor Analysis**, and provides a strong empirical foundation for subsequent results and discussion sections.

Instrumentation and Validation Procedures

The present study required the systematic development of a rigorously constructed measurement instrument capable of capturing the multidimensional transition toward Smart-STEAM education within

the educational system of the **Kingdom of Saudi Arabia**. This development process was carefully aligned with the strategic objectives of **Vision 2030**, particularly those associated with educational innovation, digital transformation, and sustainable human capacity development.

The following section provides a comprehensive account of the procedures undertaken in designing, adapting, and validating the research instrument to ensure its methodological robustness and contextual relevance.

1. Development of the Smart-STEAM Integration Survey (SSIS)

The principal data collection tool employed in this study is the **Smart-STEAM Integration Survey (SSIS)**, which was specifically designed as a structured, self-administered questionnaire. The instrument was constructed to quantitatively assess the extent to which Smart-STEAM principles are integrated into educational practices.

In its finalized version, the SSIS comprises **24 items**, each measured using a **five-point Likert scale**, ranging from (1 = Strongly Disagree) to (5 = Strongly Agree). The items were systematically distributed across **four theoretically grounded domains**, derived from the Smart-STEAM Transformative Framework (SSTF). Each domain reflects a critical dimension of Smart-STEAM integration, ensuring comprehensive coverage of the construct.

The Distribution of the **24 items across the four domains is shown in** Table 3 **below .**

Table 3
Distribution of SSIS Items Across Theoretical Domains

Domain	Description	Number of Items	Item Range
A. Technical Modeling Standards	Measures the application of advanced digital technologies such as digital twins, artificial intelligence feedback systems, and simulation precision	6	1–6
B. Interdisciplinary Integration	Assesses the degree of integration among STEAM disciplines, with emphasis on the role of arts and design thinking in fostering innovation	6	7–12
C. Sustainable Competencies	Evaluates learners' acquisition of sustainability-oriented skills, including systems thinking, ecological awareness, and ethical responsibility	6	13–18
D. Transformative Implementation	Examines institutional readiness, technological infrastructure, and teacher professional development within the Saudi educational context	6	19–24
Total	—	**24 Items**	—

This structured distribution ensures both conceptual balance and psychometric integrity, allowing each domain to contribute equally to the overall construct measurement.

2. Strategic Local Adaptation of the Instrument

To enhance the ecological validity and contextual appropriateness of the SSIS within the Saudi educational environment, a comprehensive localization process was undertaken. This process involved both linguistic refinement and conceptual alignment.

First, **contextual alignment** was ensured by adapting the terminology of the instrument to reflect the official discourse used by the Saudi Ministry of Education. Particular attention was given to aligning item phrasing with the objectives of the **Human Capability Development Program**, a central initiative under Vision 2030.

Second, **cultural sensitivity considerations** were incorporated during the adaptation process. Concepts such as “Arts integration” and “social empathy” were carefully reformulated to align with Saudi cultural norms and values, while maintaining their scientific and pedagogical integrity. This ensured that the instrument remained globally relevant yet locally meaningful.

3. Content Validity Assessment (CVI)

To establish content validity, the SSIS was subjected to a rigorous expert evaluation process. A panel of **five independent specialists** in curriculum design, educational technology, and psychometrics reviewed the instrument.

Each expert evaluated the relevance, clarity, and representativeness of each item using a **four-point ordinal scale** (1 = Not Relevant to 4 = Highly Relevant). Based on their feedback, items were either retained, revised, or eliminated.

The results of the Content Validity analysis for each domain are presented in Table 4 blow.

Table 4
Content Validity Index (CVI) Results (n = 5)

Domain	Initial Items	Eliminated/Modified Items	Final Items	Average I-CVI	S-CVI/Ave
A. Technical Modeling Standards	8	2	**6**	0.90	0.92
B. Interdisciplinary Integration	8	2	**6**	0.89	0.92
C. Sustainable Competencies	9	3	**6**	0.93	0.92
D. Transformative Implementation	8	2	**6**	0.92	0.92
Overall Scale	**33**	**9**	**24**	**0.91**	**0.92**

Interpretation:

The Scale-Level Content Validity Index (S-CVI/Ave) of **0.92** indicates an **excellent level of content validity**, significantly exceeding the commonly accepted threshold of **0.78**, thereby confirming that the instrument items are both relevant and representative of the construct.

4. Exploratory Factor Analysis (EFA)

To examine the internal structure and construct validity of the SSIS, an **Exploratory Factor Analysis (EFA)** was conducted using **Principal Component Analysis (PCA)** with **Varimax orthogonal rotation**. This analysis was performed on data collected from the target sample within the Saudi educational context.

THE Key statistical indicators from the EFA are summarized Table 5 **below.**

Table 5
Summary of Exploratory Factor Analysis Results

Statistical Indicator	Value	Interpretation
Kaiser-Meyer-Olkin (KMO) Measure	0.84	Indicates strong sampling adequacy
Bartlett's Test of Sphericity	1245.3 ($p < 0.001$)	Statistically significant; suitable for factor analysis
Total Variance Explained	68.4%	Demonstrates strong explanatory capacity of extracted factors
Factor Loading Range	0.52–0.88	All items exceeded the acceptable threshold (≥ 0.40)

The EFA results confirmed the extraction of four distinct factors, consistent with the theoretical structure of the SSTF. All 24 items loaded significantly onto their respective domains, with no cross-loading issues of concern. This provides strong empirical support for the factorial validity of the instrument.

5. Reliability Analysis

To ensure the internal consistency and reliability of the SSIS, Cronbach's Alpha coefficient was calculated for each domain as well as for the overall scale.

The Reliability Coefficients for each domain and the overall scale are presented in Table 6 below.

Table 6
Reliability Coefficients (Cronbach's Alpha)

Domain	Number of Items	Cronbach's Alpha (α)	Reliability Interpretation
A. Technical Modeling Standards	6	0.92	High Reliability
B. Interdisciplinary Integration	6	0.89	High Reliability
C. Sustainable Competencies	6	0.94	Very High Reliability
D. Transformative Implementation	6	0.90	High Reliability
Overall Instrument	**24**	**0.94**	**Excellent Reliability**

The overall Cronbach's Alpha value of **0.94** indicates a **high level of internal consistency**, confirming that the SSIS is a reliable instrument suitable for measuring Smart-STEAM integration in educational settings.

Overall Methodological Conclusion

The comprehensive development and validation procedures undertaken in this study demonstrate that the **Smart-STEAM Integration Survey (SSIS)** possesses strong psychometric properties, including **high content validity, robust construct validity, and excellent reliability**.

Accordingly, the instrument can be confidently utilized in empirical investigations aimed at assessing and advancing Smart-STEAM educational practices within the Saudi context and comparable educational systems.

Data Analysis

To ensure empirical rigor and to address the multifaceted research questions, this study adopts an integrated quantitative-qualitative analytical strategy. Quantitative data are analyzed using **IBM SPSS Statistics (Version 28.0)**, whereas qualitative data are managed using **NVivo 14**, enabling a comprehensive understanding of the transformative drivers within the Saudi STEAM context.

1. Quantitative Statistical Strategy

A multi-layered statistical approach is employed to validate the Smart-STEAM Transformative Framework (SSTF):

- **Descriptive Statistics:** Means (M) and standard deviations (SD) are computed for each item and domain to determine baseline perceptions of smart modeling standards among Saudi educators

and experts.

- **Relative Importance Index (RII):** The RII is utilized to prioritize sustainable development requirements. It is calculated using the formula RII = ∑w / (A × N), allowing for the quantification of the relative weight of each variable and the identification of the most critical competencies for the Saudi knowledge economy.
- **Kendall's Coefficient of Concordance (W):** To ensure consistency in expert perspectives, Kendall's W is applied to measure the level of agreement among three expert groups (academics, technical experts, and sustainability practitioners). A statistically significant value ($p < .05$) indicates agreement regarding the framework's structural priorities.
- **Kruskal-Wallis H Test:** Due to the potential non-normal distribution of data in expert samples, this non-parametric test is used to examine differences based on professional specialization. When significant differences are detected, post-hoc pairwise comparisons with Bonferroni correction are conducted.
- **Post-hoc Reliability:** Internal consistency is reassessed following full implementation, resulting in a Cronbach's Alpha value of $\alpha = 0.94$, which reflects a high level of instrument reliability.

2. Qualitative Thematic Analysis

Qualitative data derived from open-ended responses are analyzed using the thematic analysis approach proposed by Braun and Clarke (2006):

- **Inductive Coding:** Data are imported into **NVivo 14**, where inductive coding is applied to identify recurring patterns and extract key "transformative drivers" relevant to the Saudi cultural and institutional context.
- **Intercoder Reliability:** To ensure the validity of interpretation, multiple independent coders analyze a portion of the data. The resulting Cohen's κ value of 0.84 indicates a substantial level of agreement.
- **Contextual Integration:** The qualitative findings are triangulated with the quantitative results to refine the SSTF components, particularly in relation to the humanizing function of the Arts.

3. Ethical Considerations

Ethical standards are strictly upheld in accordance with international research guidelines:

- **Institutional Review Board (IRB) Exemption: The study was exempt from formal Institutional Review Board (IRB) approval because it relied on an anonymous voluntary survey of adult participants and did not involve medical interventions, biological samples, or sensitive personal data.**
- **Informed Consent:** All participants provided written informed consent after being fully informed about the study's objectives, potential risks, and their right to withdraw at any stage without penalty.
- **Anonymity and Data Security:** Participant confidentiality is maintained through the use of unique alphanumeric identifiers. All data are encrypted and securely stored on a university server, and

findings are reported only in aggregated form to ensure complete anonymity.

Results

This section details the empirical findings derived from the deployment of the Smart-STEAM Integration Survey (SSIS) to a sample of **145** educators and experts in the Kingdom of Saudi Arabia. The analysis focuses on the validation of the Smart-STEAM Transformative Framework (SSTF) and the prioritization of its core components.

Expert Evaluation of SSTF Domains

The quantitative evaluation indicated a robust professional endorsement for the four theoretical domains of the SSTF. The overall mean score for the framework was **4.62** (SD = 0.51) on a 5-point Likert scale.

The mean scores and standard deviations for each domain are presented in t Table 7 below

Table 7: *Statistical Evaluation of SSTF Domains* (N = 145)

Domain	Mean (M)	Std. Deviation (SD)	Endorsement Level
C. Sustainable Competencies	**4.78**	**0.42**	**Very High**
B. Interdisciplinary Integration	4.65	0.48	Very High
A. Technical Modeling Standards	4.59	0.53	Very High
D. Transformative Implementation	4.46	0.61	Very High

Relative Importance Index (RII) for Sustainability Requirements

The RII was employed to rank the core requirements for integrating sustainable development within the STEAM curriculum. "Ethical-Environmental Integration" was identified as the highest priority.

The ranking of the requirements based on the RII is shown in table 8 below

Table 8: *Prioritization of Sustainability Requirements (N = 145)*

Rank	Requirement	RII	Importance Level
1	**Ethical-Environmental Integration**	**0.95**	**Very High**
2	Systems Thinking in Socio-Ecological Systems	0.91	Very High
3	Anticipatory Thinking	0.88	High
4	Computational Stewardship	0.86	High

Structural Integrity and Expert Consensus

- **Inter-group Consensus:** Kendall's Coefficient of Concordance (W) was calculated at **0.81** ($p < 0.001$), reflecting a strong and statistically significant agreement among the expert clusters regarding the proposed mechanisms.
- **Comparative Analysis:** The **Kruskal-Wallis H test** confirmed that no significant differences existed between specializations ($H = 3.45$, $p = 0.185$), suggesting a unified vision across the sample/

The results of the statistical tests comparing expert groups are shown in Table 9 below

Table 9: *Tests of Differences Among Expert Groups (N = 145)*

Statistical Test	Test Value	Degrees of Freedom	p-value	Significance
ANOVA (F)	2.94	2	0.068	Not significant
Kruskal-Wallis (H)	3.45	2	0.185	Not significant

Post-hoc Reliability Analysis

After full deployment, the internal consistency for the overall SSIS was verified. The resulting Cronbach's alpha was **0.94**, indicating excellent reliability.

Discussion

The findings from the **145** participants provide robust empirical evidence supporting the SSTF as a transformative bridge between digital infrastructure and deep pedagogical outcomes in the Saudi educational context.

1. The Paradigm Shift toward "Green Competencies"

The highest endorsement for **Sustainable Competencies** (M = 4.78) signifies a strategic shift in the Saudi educational paradigm. This suggests that the "Functional Digital Literacy" of the past is being replaced by a demand for "Green Competencies"—the ability to use digital twins and AI-driven simulations to model and mitigate real-world ecological impacts. This finding is particularly significant within **Saudi Vision 2030**, which emphasizes developing human capabilities that are globally competitive yet ecologically responsible. The results indicate that Saudi educators perceive smart modeling not just as a technical skill, but as a cognitive necessity for sustainable development.

2. Reclaiming the "A" in STEAM: Humanizing the Digital Twin

The prioritization of **Ethical-Environmental Integration** (RII = 0.95) highlights the critical role of the **Arts** in the SSTF. The consensus among the 145 participants suggests that technical proficiency, while necessary, is insufficient without an ethical and aesthetic anchor. In the Saudi context, integrating the arts ensures that Industry 5.0 technologies, such as digital twins, remain grounded in empathy and cultural relevance. This result challenges mechanistic views of STEM, advocating for a "Smart-STEAM" approach where students act as "Computational Stewards" rather than passive technology users.

3. Unified Vision as a Driver for Reform

The strong agreement indicated by Kendall's W (0.81) and the lack of variance across specializations ($p > 0.05$) provide a powerful justification for systemic reform. This consistent evaluation across academics, technical experts, and practitioners suggests that the SSTF addresses a universal need in the Saudi educational sector. This unified vision is crucial for the "Transformative Implementation" domain (M = 4.46), offering policymakers a validated framework to redesign curricula that link technical proficiency with ecological consciousness.

4. Bridging the Pedagogical-Technological Gap

The study's results directly address the "superficial use" gap identified in the research context. By achieving high reliability ($\alpha = 0.94$) and structural validity, the SSTF demonstrates that **Smart Modeling**—utilizing real-time feedback loops and predictive analytics—can transform classrooms into dynamic laboratories for sustainability. The findings suggest that when students engage in predictive modeling of socio-ecological systems, they transition from digital consumers to systemic innovators, fulfilling the **UNESCO (2021)** mandate for transformative education.:

Implications of the Results

The findings derived from the responses of **145** experts and educators yield several critical implications for the integration of the Smart-STEAM Transformative Framework (SSTF) within the educational

landscape:

- **For Curriculum Designers:** Restructuring efforts must prioritize the development of systems thinking and ethical competence as foundational prerequisites before the introduction of advanced technical tools.
- **For Policymakers:** There is a strategic need to invest in national educational standards that explicitly incorporate "Computational Stewardship". Furthermore, assessment models should be rebalanced to reflect a weighted authentic approach: 40% for technical proficiency, 40% for sustainability integration, and 20% for creative synthesis.
- **For Teacher Educators:** Both pre-service and in-service training programmes should be redesigned to foster a dual-competency model, equipping teachers with both smart modelling capabilities and transformative sustainability pedagogical skills.

Limitations

Despite the rigorous validation of the Smart-STEAM Transformative Framework (SSTF) by a robust sample, several limitations must be acknowledged to provide a balanced interpretation of the results :

- First: The study relies on professional consensus from a sample of 145 experts and educators regarding the framework's theoretical and methodological validity. While this is a vital foundational step, it does not substitute for empirical classroom implementation to fully verify the framework's scalability and effectiveness in real-world settings.
- Second: Although the sample size (N=145) is statistically sufficient for both parametric and non-parametric analyses, the use of purposive sampling to target specific expertise may limit the universal generalizability of the findings across more diverse educational populations.
- Third: This research is cross-sectional, capturing expert perceptions at a single point in time. Given the rapid evolution of generative AI, digital technologies, and sustainability targets, the framework will require periodic updates to maintain its alignment with emerging global priorities.
- Fourth: The study was conducted within a specific cultural and educational context. The perceived importance of components such as "Ethical-Environmental Integration" may vary across different national curricula and digital infrastructures, necessitating cross-cultural replication studies.
- Fifth: While the SSIS instrument demonstrated excellent internal consistency (alpha = 0.94) and content validity, it has not yet been correlated with observable student outcomes, such as the quality of smart modelling artifacts produced in actual STEAM classrooms.
- Finally: The SSTF currently serves as a comprehensive theoretical architecture. Its practical success depends on the subsequent development of detailed implementation toolkits, particularly for educators with varying levels of digital literacy or those operating in under-resourced environments.

In summary, while the SSTF provides an expert-validated foundation for educational reform, its ultimate value will be determined through iterative classroom-based research and longitudinal assessment of its

impact on systemic change.

Conclusion

This study successfully developed and validated the **Smart-STEAM Transformative Framework (SSTF)**, providing a systematic response to the identified research gap regarding empirically grounded architectures for restructuring STEAM curricula. By leveraging smart modeling as a core pedagogical driver, the framework aligns interdisciplinary education with the urgent mandates of sustainable development.

Added Value and Innovation

The SSTF introduces a novel, expert-validated architecture that synergizes three critical dimensions:

- **Smart Modeling Integration:** Utilizing digital twins, AI-driven simulations, and interactive visualizations to bridge the gap between theory and practice.
- **Humanized STEAM:** Positioning the **"Arts"** as a vital component for aesthetic and ethical reasoning, ensuring technology remains human-centric.
- **Sustainability Teleology:** Embedding sustainability ethics as the ultimate goal of technical innovation.

Key Operational Contributions include:

- A **five-stage procedural model** for implementing smart modeling within STEAM projects.
- The conceptualization of **“Computational Stewardship”** as a foundational competency for the digital-green transition.
- A **weighted authentic assessment rubric** designed to evaluate learners across three pillars: technical proficiency (40%), sustainability impact (40%), and creative synthesis (20%).

Final Synthesis

The findings confirm that restructuring STEAM through smart modeling transcends mere curricular enhancement; it represents a **radical reimagining** of the educational landscape as a digital reflection of society’s sustainable aspirations. The SSTF serves as a robust roadmap for curriculum designers and policymakers to transform STEAM education into a primary engine for sustainable development and Industry 5.0 readiness.

Declarations

Availability of Data and Materials

The datasets generated during the current study are available from the corresponding author upon reasonable request. Due to confidentiality concerns regarding the expert participants involved, the data are not publicly archived. However, anonymized datasets can be shared with qualified researchers for academic purposes, subject to appropriate ethical review and a formal request.

Ethics Approval and Consent to Participate

All procedures involving human participants aligned with the ethical standards of relevant institutional and national regulations, as well as the 1964 Declaration of Helsinki and its subsequent amendments. This study strictly complied with the research regulations applicable in the Kingdom of Saudi Arabia. Prior to enrollment, written informed consent was obtained from all participants. They were fully briefed on the study's objective, procedures, the voluntary nature of their participation, data confidentiality, and their right to withdraw at any point without penalty.

Because the study did not include any participants under the age of 16, informed consent from parents or legally authorized representatives was not required.

Institutional Review Board (IRB)

This study was exempt from formal Institutional Review Board (IRB) approval in accordance with the regulations of King Khalid University, Saudi Arabia. The research relied entirely on an anonymous, voluntary survey completed by adult participants, involving no medical interventions or collection of biological samples. Under institutional guidelines, this type of survey-based educational research qualifies for an exemption.

Declarations and Administrative Sections

Funding Statement

This study was entirely self-funded by the authors. No external financial support, grants, or sponsorships were received from any funding agencies in the public, commercial, or non-profit sectors. The absence of external funding ensured the independence and objectivity of the research process.

Ethical Compliance

The authors affirm that all procedures performed in this study were conducted in full compliance with established ethical standards governing academic research.

Comprehensive measures were implemented to safeguard participants’ rights, ensure the confidentiality and anonymity of their data, and uphold the integrity and objectivity of the research process.

The authors further declare that there are no financial or non-financial conflicts of interest that could have influenced the results, interpretations, or conclusions of this study. The self-funded nature of the research further ensured complete independence in data analysis and reporting.

Informed Consent

Written informed consent was obtained from all participants (N = 145) prior to their involvement in the study. Participation was entirely voluntary.

All participants—comprising academic experts, artificial intelligence specialists were fully informed about the study's objectives, procedures.

Participants were explicitly assured of their right to withdraw from the study at any stage without any consequences. Furthermore, all collected data were treated with strict confidentiality and were used solely for academic and scientific research purposes.

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