ACTA SCIENTIAE

ISSN: 2178-7727
DOI: 10.64856/acta.scientiae.8391

Interdisciplinary Mathematics Education in Engineering: Evaluating the Impact of the STEAM Approach in Technical and Technological Programs

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ABSTRACT

Background: Mathematical education in technical and technological engineering programs faces challenges stemming from the disconnect between abstract theory and practical applications, affecting student motivation and performance. The STEAM approach emerges as a pedagogical alternative to promote contextualised and interdisciplinary learning. **Objectives**: To evaluate the impact of the STEAM approach on the development of mathematical competencies and the perception of learning in engineering students in preparatory cycles at a higher education institution in Barranquilla, Colombia. **Design**: A qualitative instrumental case study. **Setting and Participants**: Eight engineering students (mechatronics, telematics, and industrial) in preparatory cycles at a higher education institution in Barranquilla, Colombia, selected through intentional sampling with maximum variation. **Data collection and analysis**: Structured questionnaires, semi-structured interviews, and document analysis were used; the data were analysed using thematic coding and methodological triangulation. **Results**: All participants perceived the STEAM approach as facilitating applied mathematical understanding, and 75% reported improvements in creativity and problem solving. Three emerging categories were identified: connecting theory and practice through technology, developing creative thinking through interdisciplinary projects, and strengthening collaborative skills. Barriers related to technological resources (37.5%) and teacher education (50%) persist. **Conclusions**: The STEAM approach contributes significantly to interdisciplinary mathematical education in engineering, promoting meaningful learning and 21st-century competencies. Strengthening the technological infrastructure and developing specific teacher education programs are needed to consolidate its effective implementation.

Keywords: STEAM education; mathematical learning; engineering; interdisciplinarity; creative thinking; technical and technological education.

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Educación matemática interdisciplinaria en ingeniería: evaluación del impacto del enfoque STEAM en programas técnicos y tecnológicos

RESUMEN

Contexto: La formación matemática en programas técnicos y tecnológicos de ingeniería enfrenta desafíos derivados de la desconexión entre teoría abstracta y aplicaciones prácticas, afectando motivación y rendimiento estudiantil. El enfoque STEAM emerge como alternativa pedagógica para promover aprendizajes contextualizados e interdisciplinarios. **Objetivos**: Evaluar el impacto del enfoque STEAM en el desarrollo de competencias matemáticas y la percepción de aprendizaje en estudiantes de ingeniería en ciclos propedéuticos de una institución de educación superior en Barranquilla, Colombia. **Diseño**: Estudio de caso cualitativo instrumental. **Ambiente y participantes**: Ocho estudiantes de ingeniería (mecatrónica, telemática e industrial) en ciclos propedéuticos de una institución de educación superior en Barranquilla, Colombia, seleccionados intencionalmente con criterio de máxima variación. **Recolección y análisis de datos**: Se utilizaron cuestionarios estructurados, entrevistas semiestructuradas y análisis documental; los datos se analizaron mediante codificación temática y triangulación metodológica. **Resultados**: El 100% de los participantes percibe el enfoque STEAM como facilitador de la comprensión matemática aplicada y el 75% reporta mejoras en creatividad y resolución de problemas. Se identificaron tres categorías emergentes: conexión teoría-práctica mediante tecnología, desarrollo de pensamiento creativo a través de proyectos interdisciplinarios y fortalecimiento de habilidades colaborativas. Persisten barreras relacionadas con recursos tecnológicos (37.5%) y capacitación docente (50%). **Conclusiones**: El enfoque STEAM contribuye significativamente a la formación matemática interdisciplinaria en ingeniería, promoviendo aprendizajes significativos y competencias del siglo XXI. Se requiere fortalecer la infraestructura tecnológica y desarrollar programas específicos de formación docente para consolidar su implementación efectiva.

Palabras clave: educación STEAM; aprendizaje matemático; ingeniería; interdisciplinariedad; pensamiento creativo; educación técnica y tecnológica.

INTRODUCTION

Mathematical education in technical and technological engineering programs constitutes a fundamental component for the development of professional competencies in the current context. However, recent studies show that the traditional teaching of mathematics, focused on the transmission of decontextualised algorithms and procedures, poses significant difficulties for students’ conceptual understanding and motivation (Hernández-Suárez et al., 2021; Papadakis et al., 2021).

This problem is exacerbated in the propaedeutic cycles, where students with heterogeneous prior education and diverse expectations regarding their academic and professional trajectories converge (García-Peñalvo & Conde, 2022). Specialised literature indicates that around 40% of first-year engineering students have deficits in basic mathematical skills, which negatively impact their academic performance and retention rates (Freeman et al., 2020).

In this scenario, the STEAM approach (acronym for science, technology, engineering, arts, and mathematics) emerges as an innovative pedagogical proposal that seeks to integrate these five disciplines in an articulated and contextualised way (Thibaut et al., 2018). Unlike the traditional STEM approach, STEAM incorporates the arts as a catalyst for creativity and design, promoting more holistic and meaningful learning experiences (Ge et al., 2023).

Previous research has documented positive effects of STEAM in various educational contexts. Conradty and Bogner (2020) identified significant improvements in creativity and systems thinking in high school students. On the other hand, Belbase et al. (2022) reported increases in intrinsic motivation and mathematical self-efficacy among higher education students. However, gaps remain in understanding how this approach specifically operates in engineering, technical, and technological programs in Latin America.

The Colombian context presents particularities that are relevant to this study. The propaedeutic cycle programs, established by Decree 1295 of 2010, constitute a flexible strategy that allows students to obtain certifications at the technical, technological, and university professional levels sequentially (Ministerio de Educación Nacional, 2010). This modality has experienced sustained growth, currently accounting for 32% of higher education enrollment (SNIES, 2023).

Despite their quantitative relevance, there is little research on effective pedagogical practices in these programs, particularly in mathematics. Existing studies have predominantly focused on traditional university programs (Caratozzolo et al., 2022; Rodríguez-Nieto et al., 2023), creating an empirical and conceptual gap regarding how to promote meaningful learning among students in technical and technological education.

Faced with this problem, this study aims to evaluate the impact of the STEAM approach on the development of mathematical skills and on perceptions of learning among engineering students in preparatory cycles. Specifically, we seek to answer the following research question: How does the implementation of the STEAM approach influence the understanding of mathematical concepts, creative thinking and the motivation of engineering students in technical and technological education?

The findings of this research will contribute to the field of mathematical education in engineering from three perspectives: (1) they will provide empirical evidence on the effectiveness of STEAM in a poorly studied context, (2) they will identify facilitating factors and barriers to its implementation, and (3) they will generate specific recommendations for teachers and educational institutions of technical and technological education.

THEORETICAL FRAMEWORK

STEAM education: conceptual foundations and empirical evidence

The STEAM approach is an evolution of the STEM (science, technology, engineering, mathematics) model that incorporates the arts as a fifth integrating component. Its conceptual foundation is based on three complementary theoretical pillars: (1) Lave and Wenger's (1991) theory of situated learning, emphasising the importance of context in the construction of knowledge; (2) Piaget's and Vygotsky's constructivist pedagogy, which highlights the active role of the student in their formative process; and (3) contemporary theories on design thinking, which promote the creative resolution of complex problems (Resnick, 2020).

Thibaut et al. (2018) identified five defining characteristics of authentic STEAM experiences: (1) genuine integration of multiple disciplines, (2) focus on real or authentic problems, (3) promotion of design thinking, (4) inquiry-based learning, and (5) promotion of 21st-century skills. This characterisation has subsequently been refined by research that emphasises the need for balance between the different disciplines, avoiding the subordination of one to the other (Couso, 2021).

Empirical evidence on the effectiveness of STEAM has grown exponentially over the last decade. A systematic review by Perignat and Katz-Buonincontro (2019) analysed 84 studies published between 2007 and 2017, identifying positive effects in four dimensions: (1) academic performance in mathematics and science, (2) attitudes towards STEM disciplines, (3) development of critical and creative thinking skills, and (4) interest in scientific-technological careers.

More recent research has explored specific mechanisms by which STEAM operates. Ge et al. (2023) used structural equation methodology to demonstrate that the STEAM approach improves mathematical performance through two mediating pathways: increased academic self-efficacy and reduced mathematical anxiety. On the other hand, Belbase et al. (2022) documented that well-designed STEAM projects strengthen metacognition and systems thinking in engineering students.

Math learning in engineering: challenges and opportunities

Mathematical education in engineering faces particular epistemological and didactic tensions. On the one hand, it requires developing solid conceptual foundations to understand theoretical foundations; on the other, it must promote modelling and application skills in specific engineering contexts (Gainsburg, 2021). This duality frequently generates a gap between the mathematics taught and the mathematics used in professional practice.

Freeman et al. (2020) identified three recurrent problems in mathematical teaching for engineering: (1) predominance of expository methodologies that limit the active participation of the student, (2) little connection between mathematical content and real engineering applications, and (3) evaluations focused on the reproduction of algorithms rather than on conceptual understanding. These problems are exacerbated in technical and technological programs, where students frequently exhibit nonlinear academic trajectories and expectations of immediate applicability of knowledge (García-Peñalvo & Conde, 2022).

The active learning approach emerges as an alternative to address these issues. Recent meta-analyses show that active methodologies significantly reduce failure and dropout rates in initial mathematics courses for engineering (Theobald et al., 2020). However, its implementation requires profound transformations in teaching conceptions, institutional infrastructure, and evaluative culture (Borrego et al., 2021).

In this context, STEAM offers a coherent conceptual and methodological framework to articulate active learning with mathematical content applied to engineering. The integration of digital technologies, interdisciplinary projects, and artistic-creative components can constitute an effective bridge between mathematical abstraction and engineering application (Rodríguez-Nieto et al., 2023).

Creative thinking and problem solving in STEAM contexts

Creativity constitutes a fundamental transversal competence in the education of 21st-century engineers (World Economic Forum, 2020). However, its development requires specifically designed learning environments that promote divergent thinking, tolerance of ambiguity, and willingness to experiment (Cropley, 2020).

The creativity model in mathematics proposed by Leikin (2021) distinguishes between fluency (number of solutions generated), flexibility (diversity of strategies used) and originality (novelty of the approaches). Empirical research suggests that well-structured STEAM experiences can enhance these three dimensions by integrating arts and design into traditionally algorithmic mathematical activities (Conradty & Bogner, 2020).

The theoretical framework of design thinking, widely adopted in STEAM contexts, emphasises iterative processes of empathy, problem definition, ideation, prototyping, and testing (Brown, 2008). This approach is particularly relevant for mathematical education in engineering, as it promotes nonlinear and experimental approaches to complex problems, contrasting with the rigid, sequential nature of traditional methodologies (Ruthven, 2021).

STEAM research in Latin America

Research on STEAM in Latin America has experienced recent growth, although it remains concentrated in certain countries and educational levels. A review by Rocha and González (2022) identified 47 studies published between 2015 and 2021, with Brazil (32%), Mexico (23%), and Colombia (19%) as the predominant countries. 68% of these studies focused on primary and secondary school levels, revealing a gap in research on higher education and technical-technological education.

In Colombia, prior research has explored STEAM mainly in three contexts: (1) primary basic education with an emphasis on educational robotics (López & Andrade, 2021), (2) technical secondary education linked to teacher education (Martínez-Bernal & Villamizar, 2022), and (3) university degree programs in education (Conde-Carmona et al., 2024). Notably, there is little evidence on the implementation of STEAM in engineering technical and technological programs, despite its quantitative relevance in the national education system.

Existing Latin American studies identify common barriers to effective STEAM implementation: limitations in technological infrastructure, poor specialised teacher education, curriculum rigidity, and resistance to methodological changes (Santos & Silva, 2023). These findings suggest the need to investigate not only the effectiveness of STEAM, but also institutional and pedagogical conditions that facilitate or hinder its adoption.

METHODOLOGY

Design and methodological approach

This research adopted a qualitative design based on an instrumental case study (Stake, 1995) to provide an in-depth understanding of engineering students' experiences and perceptions of the STEAM approach in their mathematics education. The case study is particularly appropriate for answering "how" and "why" questions about contemporary phenomena in real-world contexts (Yin, 2018).

The interpretative paradigm that underpins this design assumes that social reality is constructed through shared interactions and meanings, requiring methodological approaches that capture the complexity and particularity of human experiences (Creswell & Poth, 2018). This epistemological positioning contrasts with positivist approaches that seek universal generalisations, privileging instead situated, contextualised understanding of educational phenomena.

Background and participants

The study was conducted at a higher education institution in Barranquilla, Colombia, that offers preparatory cycle programs across various engineering disciplines. The institution serves approximately 3,500 students, mostly from socioeconomic strata 2 and 3 of the Colombian Caribbean region.

The sample consisted of eight students selected through intentional sampling with the maximum variation criterion (Patton, 2015). The inclusion criteria were: (1) to be enrolled in mechatronic, telematic, or industrial engineering programs, (2) to have completed at least one academic semester, (3) to have participated in activities with a STEAM approach during the previous academic period, and (4) to express voluntary willingness to participate in the study.

The composition of the sample reflected diversity in terms of gender (25% women, 75% men), age (75% between 20-25 years, 25% between 25-30 years), schooling (37.5% professional technician, 62.5% technological) and academic program (50% mechatronics, 25% telematics, 25% industrial). This intentional heterogeneity enabled the capture of diverse perspectives on the phenomenon under study.

Data collection instruments and techniques

Three complementary data collection techniques were used, responding to the principle of methodological triangulation (Denzin, 2017):

(1) Structured questionnaire: Designed specifically for this study, it consisted of 15 items organised into five dimensions: prior knowledge about STEAM, perception of disciplinary integration, development of creative thinking, theory-practice connection, and global assessment of the approach. The instrument was validated by three experts in mathematics education and STEAM, yielding a content validity coefficient (CVC) of 0.87.

(2) Semi-structured interviews: Conducted individually with each participant, with an average duration of 45 minutes. The interview protocol included open-ended questions about specific experiences in STEAM activities, perceptions of mathematical learning, identification of strengths, and barriers to focus. The interviews were recorded in audio with prior authorisation and literally transcribed for further analysis.

(3) Documentation analysis: Products developed by the students during STEAM activities (projects, reports, presentations) were reviewed, as well as institutional documents related to curriculum design and teaching planning. This analysis allowed for a contrast between reported perceptions and concrete evidence of student work.

Investigation procedure

The research process was carried out in four successive phases during the second half of 2023:

Phase 1 — Preparation and ethical approval (weeks 1-3): The research protocol was prepared and evaluated by the Institutional Ethics Committee, which approved it under code IEC-2023-087. Data collection instruments were designed and validated through pilot testing with non-participating students in the final sample.

Phase 2 — Selection of participants and informed consent (weeks 4-5): Potential participants were identified according to established inclusion criteria. Informative meetings were held in which the nature, purposes, and procedures of the study were explained. All participants signed informed consent guaranteeing confidentiality, anonymity, and the right to withdraw at any time without academic consequences.

Phase 3 — Data collection (weeks 6-12): The structured questionnaire was administered in digital format. Subsequently, individual interviews were held in spaces and at times agreed upon with each participant. Relevant documents were collected and analysed simultaneously. All data were encoded using pseudonyms to protect participants' identities.

Phase 4 — Data analysis and validation (weeks 13-16): Interviews were transcribed, and the information collected was organised. Thematic analysis was conducted according to the procedures described in the next section. The preliminary findings were shared with participants for communicative validation (member checking), allowing them to verify interpretations and enrich analysis with their perspectives.

Data analysis

Qualitative data analysis followed the thematic coding approach proposed by Braun and Clarke (2006), widely used in qualitative educational research. The process comprised six iterative phases: (1) familiarisation with the data; (2) generation of initial codes; (3) theme search; (4) review of topics; (5) definition and naming of topics; and (6) report production, integrating topics into a coherent analytical narrative illustrated with empirical evidence.

The coding process was carried out independently by two researchers, yielding an inter-coder agreement index (Cohen's kappa) of 0.82, considered substantial according to the criteria of Landis and Koch (1977). The discrepancies were resolved through discussion until consensus was reached.

NVivo 12 software was used to manage and analyse qualitative data, facilitating the systematic organisation of codes, topics, and evidence. The descriptive quantitative analysis of the questionnaire data was conducted in Excel, calculating frequencies and percentages for each item.

Rigour and ethical considerations

The quality and rigour of the study were ensured by specific criteria for qualitative research proposed by Lincoln and Guba (1985): credibility (through triangulation of sources and methods, communicative validation with participants), transferability (through dense description of the context), dependability (through systematic documentation of methodological decisions), and confirmability (through analytical process audit).

Ethical considerations were governed by principles of the Declaration of Helsinki and Colombian regulations (Resolution 8430 of 1993). The protocol was approved by the Institutional Ethics Committee (code IEC-2023-087).

Interested students were guaranteed: (1) voluntary participation based on informed consent, (2) confidentiality and anonymity through the use of pseudonyms, (3) right to withdraw without consequences, (4) minimisation of psychological or academic risks, and (5) return of results to participants and institution.

RESULTS AND ANALYSIS

Characterisation of participants

The sample consisted of 8 engineering students in preparatory cycles, whose socio-demographic and academic characteristics are presented in Table 1.

Table 1

Socio-Demographic and Academic Characteristics of Participants

Characteristic	Category	n	%
Gender	Male	6	75.0
	Female	2	25.0
Age range	20–25 years old	6	75.0
	25–30 years old	2	25.0
Academic program	Eng. Mechatronics	4	50.0
	Eng. Telematics	2	25.0
	Eng. Industrial	2	25.0
Schooling level	Vocational-technical	3	37.5
	Technology	5	62.5

Note. n = absolute frequency; % = percentage. Source: By the authors.

The distribution by gender shows a male predominance (75%), consistent with national enrollment patterns in engineering, where women represent approximately 30% (SNIES, 2023). The average age of 22.8 years (SD = 2.4) aligns with the typical profile of students in preparatory cycles, who often enter higher education after nonlinear work or educational experiences.

The concentration of participants in mechatronic engineering (50%) reflects the demand for this program at the regional level, driven by the development of the industrial and logistics sectors in the metropolitan area of Barranquilla. The telematics and industrial programs, with equivalent participation (25% each), complete a representative panorama of the institutional offer in technical and technological education.

Understanding and valuing the STEAM approach

The analysis revealed that 100% of participants (n=8) had had prior contact with the term STEAM, although with differentiated levels of conceptual understanding. Three participants (37.5%) demonstrated deep understanding, explicitly articulating the five components and their interdisciplinary integration. Five participants (62.5%) showed partial understanding, correctly identifying the subjects but having difficulty explaining specific integration mechanisms.

The testimonies illustrate this conceptual diversity. A mechatronics student (Participant 3) explained, "STEAM is like an ecosystem where math is not isolated… you need to program (technology), understand physical principles (science), design solutions (engineering), and think creatively (art) to solve real-world problems." In contrast, another participant (Participant 7) offered a more operational definition: "It is using several subjects together to make projects, not just studying books."

Regarding the approach, 100% of participants reported that STEAM contributes positively to their engineering formative process. The justifications emphasised three aspects: (1) connection with professional reality (mentioned by 7 participants, 87.5%), (2) development of soft skills such as teamwork (6 participants, 75%), and (3) increased motivation towards mathematics (5 participants, 62.5%).

Technological integration and development of creative thinking

One significant finding relates to the role of technology as a mediator of mathematical learning. 87.5% of participants (n=7) reported frequent use of specialised software in academic activities. The tools mentioned included Python and TypeScript (programming), AutoCAD and SolidWorks (CAD), MATLAB (numerical computation), and ISPSoft (industrial automation).

This finding contrasts with previous research in traditional mathematics education, where the use of technology is usually limited to calculators or generic software (Drijvers et al., 2021). Participants particularly valued the authenticity of these tools: "We do not use school programs; we use the same ones companies use" (Participant 5).

Regarding creative thinking, 62.5% of participants (n=5) reported that STEAM activities promote creativity without excessive restrictions. However, 37.5% (n=3) noted persistence of theoretical emphasis that limits creative expression. One participant explained, “Sometimes we feel like we could come up with different solutions, but teachers expect us to follow specific steps” (Participant 2).

The documentary analysis of student projects partially corroborated these perceptions. Evidence of creativity was identified in five of eight projects (62.5%), manifested in the proposal of unconventional solutions, the innovative integration of disciplines, and the aesthetics of the presentation of results. The remaining three projects showed more algorithmic and conventional approaches.

Perception of theory-practice connection

The connection between theoretical mathematical concepts and practical applications is a critical dimension of engineering education. 75% of participants (n=6) perceived that STEAM activities significantly strengthen this connection, while 25% (n=2) think that important gaps persist.

Participants who positively valued this connection emphasised the applied nature of STEAM projects. An industrial engineering student said, “Before, derivatives were just abstract formulas. Now we use them to optimise real processes, calculate minimum costs, analyse efficiency” (Participant 8). This perception is consistent with theoretical frameworks on mathematical modelling that emphasise the importance of authentic contexts (Blum, 2015).

Critical participants pointed out two limitations: (1) insufficient emphasis on rigorous mathematical foundations, privileging superficial applications, and (2) excessive dependence on software that hides underlying mathematical processes. One participant posed, “Sometimes we use Python to solve systems of equations without really understanding what the algorithm does” (Participant 4).

This finding reveals an inherent tension in STEAM education: the balance between deep conceptual understanding and competence with technological tools. Recent research suggests that this balance requires intentional pedagogical design that promotes metacognitive reflection on automated processes (Drijvers, 2019).

Collaborative learning and social skills

100% of participants reported that STEAM activities involve frequent or very frequent collaborative work. This characteristic was positively valued by 87.5% (n=7), who identified benefits in three dimensions: (1) development of communication skills, (2) exposure to diverse perspectives, and (3) preparation for professional work in multidisciplinary teams.

Participants described collaborative dynamics that transcend simple task division, involving the negotiation of meanings and the collective construction of solutions. An illustrative testimony: “In my group there was someone very good in mathematics but with difficulties in programming, and I was the other way around. We had to explain each other, not just do separate parts” (Participant 6).

However, one participant (12.5%) reported negative experiences with collaborative work due to unequal distribution of responsibilities. This finding aligns with the literature on collaborative learning, which identifies the “stowaway effect” as a risk when there are no individual accountability mechanisms (Johnson & Johnson, 2019).

The analysis of the interviews allowed us to identify teaching practices that facilitate effective collaboration: (1) formation of intentionally heterogeneous groups, (2) assignment of rotating roles, (3) differentiated assessment of individual and group contributions, and (4) inclusion of metacognitive reflection on collaborative processes.

Barriers and challenges to effective implementation

Despite the mostly positive assessment of the STEAM approach, participants identified significant barriers to its full implementation. Table 2 summarises the main reported limitations.

Table 2

Barriers to the Effective Implementation of the STEAM Approach

Type of barrier	Specific description	n	%
Technological infrastructure	Limited access to specialised software	3	37.5
	Insufficient/outdated computer equipment	2	25.0
Teacher education	Resistance to innovative methodologies	4	50.0
	Insufficient mastery of technological tools	3	37.5
Structural	Curriculum rigidity	5	62.5

Type of barrier	Specific description	n	%
	Pressure for content coverage	4	50.0
Students	Poor previous math education	3	37.5

Note. n = frequency of mentions (participants were able to identify multiple barriers); % = percentage of total participants (n=8). Source: By the authors, based on interviews.

The most frequently mentioned barrier refers to curriculum rigidity (62.5%), manifested in compartmentalised study programs that hinder genuine disciplinary integration. One participant expressed, "Teachers want to do integrative projects, but each subject has its curriculum, and there is no official time to coordinate" (Participant 1).

Teaching resistance to innovative methodologies, mentioned by half of the participants (50%), constitutes another critical barrier. Students described situations in which STEAM project proposals were rejected in favour of traditional assessments. This finding is consistent with research on educational innovation that identifies teacher beliefs and institutional culture as determinants of pedagogical change (Borrego et al., 2021).

Technological limitations, although less frequent (37.5% for software, 25% for hardware), were particularly critical in mechatronics and telematics, where specialised software is fundamental. One student related, "We have to take turns using the few computers with AutoCAD; sometimes we queue for an hour" (Participant 3).

Poor prior mathematical education, reported by 37.5% of participants, is a differential barrier in preparatory cycles. Middle school students with weaknesses in algebra and geometry face additional difficulties in STEAM activities that assume certain prerequisites. This problem suggests the need for remedial strategies or specific levelling in technical and technological programs.

DISCUSSION

The findings of this study provide empirical evidence on the implementation of the STEAM approach in a poorly researched context: engineering technical and technological programs in Colombia. The results are discussed below in dialogue with the theoretical framework and the specialised literature, highlighting contributions, limitations, and implications of the study.

STEAM as a facilitator of theoretical-practical connections in mathematics

The finding that 75% of participants perceive the strengthening of theoretical-practical connections through STEAM is consistent with previous research in university contexts (Belbase et al., 2022; Caratozzolo et al., 2022). However, this study offers important nuances, showing that this perception is neither uniform nor uncritical.

Student testimonials reveal that STEAM's effectiveness in promoting theory-practice connections critically depends on how activities are designed and implemented. Projects that involve authentic modelling of engineering problems, the reflective use of technology, and metacognition about mathematical processes generate more positive perceptions than activities in which technology hides processes or applications are superficial.

This finding aligns with the theoretical framework of mathematical modelling proposed by Blum (2015), which distinguishes between "decorative applications" (where mathematical concepts are artificially linked to contexts) and "authentic modelling" (where they genuinely emerge from needs to understand or solve real problems). Participants seem to intuitively discriminate between these two types of activities, valuing those that involve authentic modelling more positively.

The reported tension between conceptual understanding and competence in the use of technological tools deserves particular attention. While research emphasises the potential of technology to enhance mathematical learning (Drijvers et al., 2021), this study suggests that this potential does not materialise automatically. It requires intentional pedagogical design that promotes "instrumentalisation" (conceptual appropriation of the tool) rather than mere "instrumentation" (technical mastery without understanding) (Artigue, 2020).

Creative thinking: persistent progress and limitations

The finding that 62.5% of participants perceive STEAM as promoting creative thinking, while 37.5% point to persistent restrictions, reflects partial implementation of the approach. Research on creativity in mathematics (Leikin, 2021; Cropley, 2020) suggests that its development requires environments that promote divergent thinking, tolerance of ambiguity, and valuation of multiple solutions.

The testimonies of participants suggest the coexistence of contradictory pedagogical practices: on the one hand, open projects that allow creative exploration; on the other, teaching expectations of predetermined "correct solutions" that inhibit creativity. This tension is consistent with literature on pedagogical change, which documents individual and institutional resistance to profound transformations in conceptions of teaching and learning (Borrego et al., 2021).

The documentational analysis of student projects provides tangible evidence of creativity in 62.5% of cases analysed, partially corroborating the reported perceptions. This methodological triangulation strengthens the credibility of the findings, suggesting that student perceptions do not constitute mere subjective opinions but correspond to observable evidence in academic products.

The integration of the arts into STEAM, emphasised in the theoretical foundations of the approach (Ge et al., 2023), appears to be implemented only to a limited extent in the context studied. Participants identified components of science, technology, engineering, and mathematics, but made little mention of artistic-creative aspects. This observation suggests that in engineering programs, STEAM may operate more like traditional STEM, with marginal additions of creativity, rather than the genuine integration of design and aesthetics proposed by authors such as Resnick (2020).

Structural barriers: beyond individual limitations

The identification of structural barriers (curriculum rigidity, pressure for content coverage) as the most frequently mentioned (62.5% and 50%, respectively) makes a significant contribution to the field. While previous literature has extensively documented barriers in teacher education and technological resources (Santos & Silva, 2023), this study shows that institutional and systemic factors may be equally or more determinative.

This observation is consistent with theoretical frameworks of educational innovation that conceptualise change as a systemic rather than an individual phenomenon (Fullan, 2020). From this perspective, the effective implementation of STEAM would require not only teacher education or investment in technology, but profound transformations in curriculum structures, assessment systems, and institutional culture.

The mention of poor previous mathematical education as a barrier (37.5%) is particularly relevant in the context of preparatory cycles. Unlike traditional university programs with rigorous selection processes, technical and technological programs frequently admit students with heterogeneous academic profiles. This characteristic implies that effective pedagogical strategies in traditional higher education may require significant adaptations.

The finding suggests the need to design specific “mathematical scaffolds” that enable students with diverse prior backgrounds to participate effectively in STEAM activities. Research on pedagogical differentiation in higher education (Tomlinson et al., 2021) offers conceptual frameworks and practical strategies that could inform pedagogical designs in propaedeutic cycles.

Collaborative learning: potential and risks

The mostly positive assessment of collaborative learning (87.5%) confirms one of the pillars of the STEAM approach. However, a participant’s identification of the “stowaway effect” underscores the importance of deliberately structuring collaborative experiences. Literature on cooperative learning (Johnson & Johnson, 2019) emphasises five essential elements: positive interdependence, individual responsibility, promoting interaction, social skills, and group processing.

The analysis of facilitating teaching practices identified in this study (heterogeneous group formation, rotating roles, differentiated assessment, metacognitive reflection) substantially coincides with these essential elements. This finding suggests that teachers participating in the study have developed, perhaps intuitively or through prior education, specific pedagogical competencies to facilitate effective collaboration.

However, the systematicity and universality of these practices cannot be assumed. Although negative experiences of collaboration are a minority, they show variability in the quality of implementation. This variability reinforces arguments for specific teacher education in facilitating collaborative learning (Borrego et al., 2021).

Study contributions to the field

This study makes three main contributions to the field of mathematical education in engineering:

First, it provides empirical evidence on STEAM in a poorly researched context: technical and technological programs in Latin America. Most previous research has focused on basic/secondary education or traditional university programs (Rocha & González, 2022). The findings reveal particularities of this context (heterogeneity of prior formations, expectations of immediate applicability, specific structural barriers) that warrant consideration in the design and implementation of STEAM.

Second, the study adopts a rigorous methodological approach that combines multiple sources (questionnaires, interviews, documentational analysis) and perspectives (students, academic products, institutional documents). This methodological triangulation strengthens the credibility of the findings and offers a more nuanced understanding than studies based exclusively on one source.

Third, the findings have direct practical implications for institutions, teachers, and curriculum designers seeking to implement STEAM in technical and technological programs. The identification of facilitating factors (the use of authentic technology, interdisciplinary projects, structured collaborative learning) and barriers (curriculum rigidity, teacher resistance, prior mathematical shortcomings) provides specific guidance for pedagogical innovation processes.

Study limitations

This study has limitations that should be considered when interpreting findings:

The case study design with a small sample (n=8) privileges depth over breadth. While it allows for nuanced understanding of experiences and perceptions, it limits transferability of findings to other contexts. Future research with mixed-method designs that combine in-depth case studies with larger-scale surveys could strengthen evidence.

The study is based mainly on student perceptions and testimonials. While these are valuable sources of information, they may not fully correspond to effective learning as measured by standardised instruments. Complementary studies that evaluate mathematical and creative competencies through pre- and post-tests would strengthen the chain of evidence for the effectiveness of STEAM.

The specific institutional context (a medium-sized urban institution in the Colombian Caribbean region) may present characteristics that limit the transferability of findings to other contexts. Multi-site comparative studies would enable the identification of generalisable patterns and contextual specificities.

The research captures student perspectives but does not systematically incorporate faculty voices or institutional directives. These additional perspectives could enrich understanding of factors that facilitate or hinder STEAM implementation.

CONCLUSIONS AND IMPLICATIONS

This study explored the implementation of the STEAM approach in technical and technological engineering programs, seeking to understand its impact on the development of mathematical competencies and perception of learning. The findings show that STEAM constitutes a valuable pedagogical alternative in this context, promoting theoretical-practical connections, creative thinking, and collaborative skills. However, its effective implementation faces significant barriers that require systematic institutional attention.

In response to the research question, the STEAM approach positively influences understanding of mathematical concepts, creative thinking, and student motivation. However, this influence is modulated by factors such as specific pedagogical design, teacher education, availability of technological resources, and institutional curriculum structures. There is, therefore, no automatic or uniform effect of STEAM, but rather a potential that materialises under specific conditions.

The practical implications of this study are organised into three levels:

At the institutional level, it is necessary to address structural barriers through: (1) curriculum flexibility that allows genuine disciplinary integration, (2) investment in adequate technological infrastructure, (3) development of assessment policies that value creativity and divergent thinking, and (4) generation of spaces for interdisciplinary teaching coordination. These transformations involve institutional policy decisions that transcend teachers' individual wills.

At the teacher level, specific formative needs are identified in: (1) design of authentic STEAM experiences that promote rigorous mathematical modelling, (2) pedagogical use of technology that strengthens (not replaces) conceptual understanding, (3) facilitation of effective collaborative learning, and (4) assessment of creative thinking and complex competencies. Teacher professional development programs should systematically incorporate these components.

At the level of pedagogical design, guiding principles emerge for effective STEAM activities: (1) starting from authentic engineering problems that genuinely require disciplinary integration, (2) promoting the reflective use of technology with an emphasis on understanding underlying processes, (3) structuring collaborative experiences with positive interdependence and individual responsibility, (4) valuing multiple solutions and creative approaches, and (5) incorporating metacognitive reflection on learning processes.

Future directions of research include: (1) longitudinal studies that evaluate the impact of STEAM on academic and professional trajectories of students, (2) experimental or quasi-experimental research that compares the effectiveness of STEAM versus traditional methodologies through standardised measures, (3) multi-site comparative studies that identify contextual factors that modulate the effectiveness of the approach, (4) collaborative action research with teachers to co-design and evaluate pedagogical innovations, and (5) studies that incorporate employer perspectives on competencies developed through STEAM.

In summary, the STEAM approach offers a promising conceptual and methodological framework to transform mathematics education into technical and technological engineering programs. Its effective implementation, however, requires a systemic approach that involves transformations across multiple levels: institutional structures, pedagogical practices, teacher education, and evaluative culture. The findings of this study contribute to understanding the potentialities and challenges of this transformative process in the particular context of Latin America.

AUTHORS' CONTRIBUTIONS STATEMENTS

RJCC was responsible for the conception and design of the research, the bibliographic review, the analysis of the data and the writing of the preliminary version of the manuscript. MFCV contributed to the literature review, the systematisation of the information, and the critical analysis of the results. EGCL participated in the collection and organisation of bibliographic sources, the discussion of the findings, and the methodological review. All authors participated in the critical review of the intellectual content, in the final writing of the text and in the approval of the version to be published, and agree to be responsible for all aspects of the work.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article, as it is based on publicly available literature. No new primary data were created or analysed in this study; the information underlying the discussions and conclusions was obtained from publicly accessible bibliographic sources, duly referenced in the text.

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