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A steam-based pedagogical model for developing technical thinking in primary school students

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Abstract

In the context of global technological transformation and the implementation of technological modernization strategies in Kazakhstan, the development of design and technical thinking (DTT) in primary school students becomes a critically important task. The aim of this study was to develop and test a pedagogical model based on an interdisciplinary STEAM approach (science, technology, engineering, arts, mathematics) and adapted to the specifics of the Kazakhstani education system. The model was developed through a theoretical synthesis of current research in STEAM education and psychological–pedagogical theories and comprises four interrelated stages: Motivational–Orientation, Project–Research, Experimentation–Analysis, and Reflective–Presentation. A school-based approbation in Shymkent (172 learners in Grades 1–4; 4 teachers) employed classroom observation, class-embedded diagnostic tasks, and brief self-reports to monitor feasibility and acceptability. Aggregated monitoring indicated 20–30% gains on indicators of independent problem formulation and stepwise solution planning; the share of learners at the "high" level rose from 26% to 43% for algorithmic (procedural) thinking and from 18% to 36% for divergent thinking. These findings are feasibility signals rather than causal estimates, suggesting practical implementability under routine conditions and motivating a subsequent controlled evaluation and scaling across diverse educational contexts in Kazakhstan.

Keywords: Design and technical thinking, Interdisciplinary approach, Kazakhstan, Pedagogical model, Primary school, STEAM education.

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1. Introduction

The development of design and technical thinking (DTT) among primary school students in Kazakhstan is influenced by global and national factors. Rapid technological transformation (Industry 4.0/5.0, digitalization) and heightened competition for innovation competencies require a revision of approaches to human capital formation [1] and intensify global competition for innovation competencies [2]. These factors necessitate a fundamental reassessment of strategies for developing human capital.

Kazakhstan, which is implementing ambitious technological development strategies [3], recognizes the critical importance of equipping the younger generation with the key competencies of the 21st century [4], such as creativity, critical and systems thinking, complex problem-solving skills, engineering and technical literacy, and, especially, interdisciplinary skills that ensure adaptability to changing conditions.

In this context, the development of an effective pedagogical model for fostering design and technical thinking in primary school students based on an interdisciplinary STEAM (Science, Technology, Engineering, Arts, Mathematics) approach [5] is particularly relevant for the Kazakhstani educational system.

This relevance is supported by several interconnected factors such as the following.

Response to national initiatives: Technological modernization strategies require the proactive preparation of engineering and technical professionals, making the development of engineering culture and DTT foundations in primary schools a strategic investment [6].

Overcoming the limitations of the traditional system: Persistent issues include fragmented knowledge, reproductive teaching methods, insufficient resources, and weak connections between knowledge and practice [7].

The potential of the STEAM approach: As a recognized tool for educational reform, it ensures interdisciplinary integration, practice-oriented learning, and the development of creativity through the "Arts" component [8].

Importance of an early start: Developing DTT in children in Grades 1–4 (ages 6–10) lays the groundwork for an engineering worldview and creates a foundation for mastering STEM disciplines.

1.1. Alignment with Current Global Trends and National Specificity

In recent years, STEAM education has rapidly developed. Systematic reviews and empirical studies from 2024–2025 highlight new directions, such as integrating metacognitive and curiosity-driven approaches (pilot workshops with primary schoolers showing improved question-asking and reflection skills) [9, 10], synthesizing student perspectives on STEAM emphasizing empathy-driven engagement and meaning-making [11], and broader bibliometric analyses revealing exponential growth in STEAM research, especially in the US and UK, but also significant gaps in studies from developing countries and longitudinal designs [12]. Additional systematic reviews emphasize the positive impact of STEAM on learning achievement, affective factors, and developmental skills [13], alongside challenges related to teacher readiness, resource constraints, and curriculum rigidity.

Kazakhstan's educational landscape presents distinctive conditions for STEAM implementation. Regional infrastructure inequality (urban vs. rural) and uneven access to material and digital tools remain key barriers [14]. The shortage of teachers trained to integrate both technical and artistic methodologies limits the effective adoption of STEAM pedagogies. Simultaneously, national strategic initiatives, such as Digital Kazakhstan and educational modernization efforts, stress the early development of engineering culture and human capital. However, the operational mechanisms for these policies at the primary level are still underdeveloped, particularly in terms of teacher training and providing localized project contexts.

Hence, adapting global findings to the Kazakhstani primary education system necessitates culturally responsive modifications, such as embedding STEAM tasks within familiar socio-cultural themes (e.g., traditional crafts, local architecture), aligning with resource realities, and integrating comprehensive interdisciplinary teacher preparation. This ensures that the STEAM educational model is both globally informed and locally situated.

1.2. Research Problem

Despite ongoing educational reforms in Kazakhstan focusing on a competency-based approach and updated curriculum content, primary schools face significant challenges in purposefully developing DTT in younger students. These challenges manifest in the continuing fragmentation of knowledge due to subject isolation, which hinders the development of a holistic understanding of technical systems; the dominance of reproductive teaching methods with a lack of age-appropriate project-based and research methods; insufficient material and methodological resources (such as limited access to construction kits, equipment, digital tools, and programs that support DTT components); and weak links between theoretical knowledge and practical, creative activity, which reduces students' motivation.

Existing approaches do not effectively address the systematic development of DTT as a key interdisciplinary competency at the primary school level.

Aim and Article Type. This article presents the design of a STEAM-based pedagogical model for developing technical thinking in primary school learners. The work follows a design-and-development (model) genre; a school-based approbation served to assess feasibility and acceptability, not to establish effectiveness.

Objectives. We aim to:

1. specify the four-stage lesson cycle and role/artifact structure (I–IV);
2. embed diagnostic checkpoints … appropriate to Grades 1–4 (ages 6–10);
3. document feasibility/acceptability under routine classroom conditions to inform subsequent confirmatory studies.

Contributions.

- Theoretical: integration of arts-integrated STEAM with an embedded diagnostic layer for technical thinking in early grades.
- Methodological: **a** replicable four-stage lesson design with rubrics and artifact prompts enabling classroom implementation and monitoring.
- Practical: low-cost adaptations and teacher-ready materials suitable for resource-constrained settings; signals of feasibility in a school-based approbation.

Article Structure. Section II outlines the theoretical basis; Section III describes the design-and-development methodology; Section IV details the model; Section V reports approbation findings (feasibility & acceptability); Sections VI–VIII present the discussion, limitations and future work, and the conclusion, followed by ethical, funding, and reference information.

2. Background and Theoretical Basis

Integrating the arts into STEM expands the design space, strengthens aesthetic–motivational engagement, and aligns schooling with twenty-first-century competencies such as creativity, critical and systems thinking, and collaboration [8, 15]. Contemporary competence frameworks for STEAM educators argue that impact depends less on "mixing subjects" and more on coherent didactics: problem–project cycles, structured reflection, and cross-disciplinary assessment [13, 16]. At the system level, international diagnostics frame STEAM as a lever for innovation and human-capital development—an orientation echoed in Kazakhstan's policy discourse [1, 2, 4, 6, 7].

In early grades, integrative STEAM projects that require specification, prototyping and iterative testing consistently foster creativity, metacognition and nascent engineering thinking [17, 18]. Recent syntheses report positive effects but emphasize variability of implementation and the centrality of pedagogical orchestration [11, 12, 19, 20].

For design-and-technical thinking (DTT), 2D/3D tasks externalize mental operations (composition/decomposition, mental rotation, drawing-to-solid correspondence) and make engineering cycles visible to young learners. Studies with 3D technology and graphics report gains in spatial imagination, planning and solution variability [21, 22]. In Kazakhstan-connected cohorts, quasi-experimental work with plane/solid modelling in didactic games improved spatial representations and algorithmic planning; recent publications extend this to STEAM thinking [23, 24].

Short, classroom-embedded robotics units yield motivational and cognitive gains when tasks are authentic and feedback cycles explicit [25, 26]. Augmented reality (AR) supports representational transitions critical for engineering drawing and design literacy, strengthening transfer between 2D schematics and 3D mental models [27, 28]. These technology-enhanced approaches complement makerspace evidence and broaden multimodal pathways into early engineering practice [21, 29].

Inclusion-oriented reviews highlight the role of multimodal (visual, tactile, embodied) resources for early engagement, including in remote formats [30, 31]. Targeted interventions show that STEAM can enhance computational thinking among diverse learners (e.g., deaf students) when tasks are adapted to sensory–linguistic profiles [32].

Across studies, the teacher acts as a designer–facilitator who plans cross-domain tasks, orchestrates interaction and reflection, and assesses interdisciplinary outcomes [16, 33]. In Kazakhstan, analyses of teacher-education models argue for embedding STEAM principles into pre- and in-service preparation to avoid "islands of innovation" [34]. Regional work also highlights students' "internal reserves" (self-regulation, flexible strategies) as mediators of problem solving—constructs directly trained by well-sequenced STEAM tasks [35].

Primary students describe STEAM as meaningful when tasks connect with interests and social purposes, supporting agency, reflection and empathic design [11, 36]. Parallel strands link STEAM to soft-skills growth (communication, collaboration, adaptability), particularly in need-based scenarios and with deliberate training [20, 37].

Two trends reshape the landscape: computational thinking (CT) as a transversal habit of mind that complements engineering design, and AI entering K-12 as both content and tool [38, 39]. Reviews document diffusion of AR/VR, fabrication and analytics into STEAM while cautioning about uneven access and teacher upskilling needs [29, 39].

Recent systematic reviews synthesize cross-national findings: frequent positive effects on achievement, attitudes and transversal competencies, yet methodological limitations persist (small samples, short durations, fidelity issues) and longitudinal designs remain scarce, especially in developing contexts [12, 14, 19]. Kazakhstani reports recognize constraints (resource disparities, curriculum rigidity) and underscore the need for locally adapted models aligned with primary-level realities [6, 7].

3. Design and Development Methodology

This work adheres to a design-and-development (model) genre focused on specifying, refining, and documenting a STEAM-based pedagogical model. The context comprises routine classroom conditions (Grades 1–4) with two 40-minute sessions per week. Development was guided by constructivist and engineering-design principles, with iterative refinement informed by teacher logs, learner artifacts, and brief classroom observations. The subsequent school-based approbation assessed feasibility and acceptability only; no hypothesis testing was planned.

Data sources (non-identifying): teacher lesson logs; anonymized learner artifacts (sketches, prototypes, reflection notes); brief teacher surveys on feasibility/acceptability; aggregated feasibility monitoring (share at predefined thresholds).

The development of the proposed STEAM-based pedagogical model for fostering design and technical thinking (DTT) in primary school students was conducted through a multi-phase research design, combining theoretical synthesis and practical piloting. The methodological approach consisted of the following key stages:

Theoretical Analysis and Synthesis: A comprehensive review of international and Kazakhstani literature on STEAM education, cognitive development theories [40, 41], problem-based learning [42], and constructivism was conducted. This analysis aimed to identify effective pedagogical principles, existing model structures (e.g., EDP, 5E, PBL), and core competencies essential for DTT. The synthesis of these elements formed the theoretical foundation and initial framework of the model.

Model Design and Component Specification: Based on the theoretical findings, the pedagogical model was systematically constructed. This involved:

Defining the Goal: To develop DTT as a key interdisciplinary competence in students in Grades 1–4 (ages 6–10).

Structuring the Process: Designing the four-stage cyclical structure (Motivational–Orientation, Project–Research, Experimentation–Analysis, Reflective–Presentation) to mirror an authentic engineering design process.

Integrating the STEAM Approach: Ensuring deep and explicit integration of the Arts component alongside Science, Technology, Engineering, and Mathematics as a driver of creativity and design thinking, rather than an optional add-on.

Developing Assessment Criteria: Creating a detailed system of criteria and indicators to evaluate cognitive and design-technical abilities, tailored to the target age group and the model's objectives.

Contextual Adaptation: The model was specifically adapted to the realities of the Kazakhstani educational context. This involved considering factors such as infrastructure inequality, resource constraints, and national strategic initiatives (Digital Kazakhstan). Strategies for using low-cost materials and embedding projects within familiar socio-cultural themes (e.g., local crafts, architecture) were incorporated to enhance feasibility and relevance.

Pilot implementation (approbation environment): The try-out monitored feasibility and acceptability under routine classroom conditions. All inferential claims are out of scope; the approbation aimed at operational feedback for refinement, not at hypothesis testing or causal inference.

Participants: The pilot involved 172 students (Grades 1–4; ages 6–10) and 4 teachers from two primary schools in Shymkent, Kazakhstan.

Procedure: Over one academic year, students participated in twice-weekly, 40-minute sessions based on the model's stages, utilizing 2D and 3D modeling materials. Teachers received methodological briefing and adapted provided project templates.

Data Collection Tools: A multi-method approach was employed to gather feedback and monitoring signals:

Note. All assessments were class-embedded, age-adapted probes; no standardized scores were computed and no between-group comparisons were planned at this stage.

Observation checklists to monitor student engagement, problem-solving behavior, and the application of new skills.

Short diagnostic tasks (adaptations of Bennett Mechanical Comprehension Test, Raven's Colored Progressive Matrices, spatial imagination tasks) administered pre- and post-intervention to gauge development in specific cognitive areas.

Student self-assessment cards to capture perceived growth in creative and technical confidence.

Teacher feedback forms to evaluate the model's practicality, identify implementation challenges, and assess observed student outcomes.

This methodological approach ensured that the developed pedagogical model was not only theoretically robust and aligned with global best practices but also grounded, adaptable, and responsive to the specific needs and constraints of the primary education system in Kazakhstan. The pilot study provided crucial initial insights for refining the model before proposing it for larger-scale experimental validation.

4. Description of the Pedagogical Model

The developed pedagogical model represents a scientific product of research conducted within the framework of the project 'Developing Design and Technical STEAM Thinking in Primary School Students through 2D and 3D Modeling.' This model addresses the fragmentation of technical and creative components in education by providing a systematic tool for fostering key competencies through interdisciplinary practice. Its implementation will facilitate the theoretical and methodological renewal of the educational process while offering concrete methodological solutions for teachers focused on the early engineering and technical training of students.

The pedagogical model represents a structured framework for developing spatial imagination, cognitive orientation, and engineering-technical thinking in primary school children in the context of interdisciplinary STEAM education. The model is organized into four interconnected and iterative stages, emphasizing cyclical improvement based on feedback and problem solving. At each stage, specific cognitive skills are purposefully developed while simultaneously fostering student autonomy and the teacher's role as a facilitator. The conceptual structure of the proposed STEAM-based pedagogical model is illustrated in Figure 1.

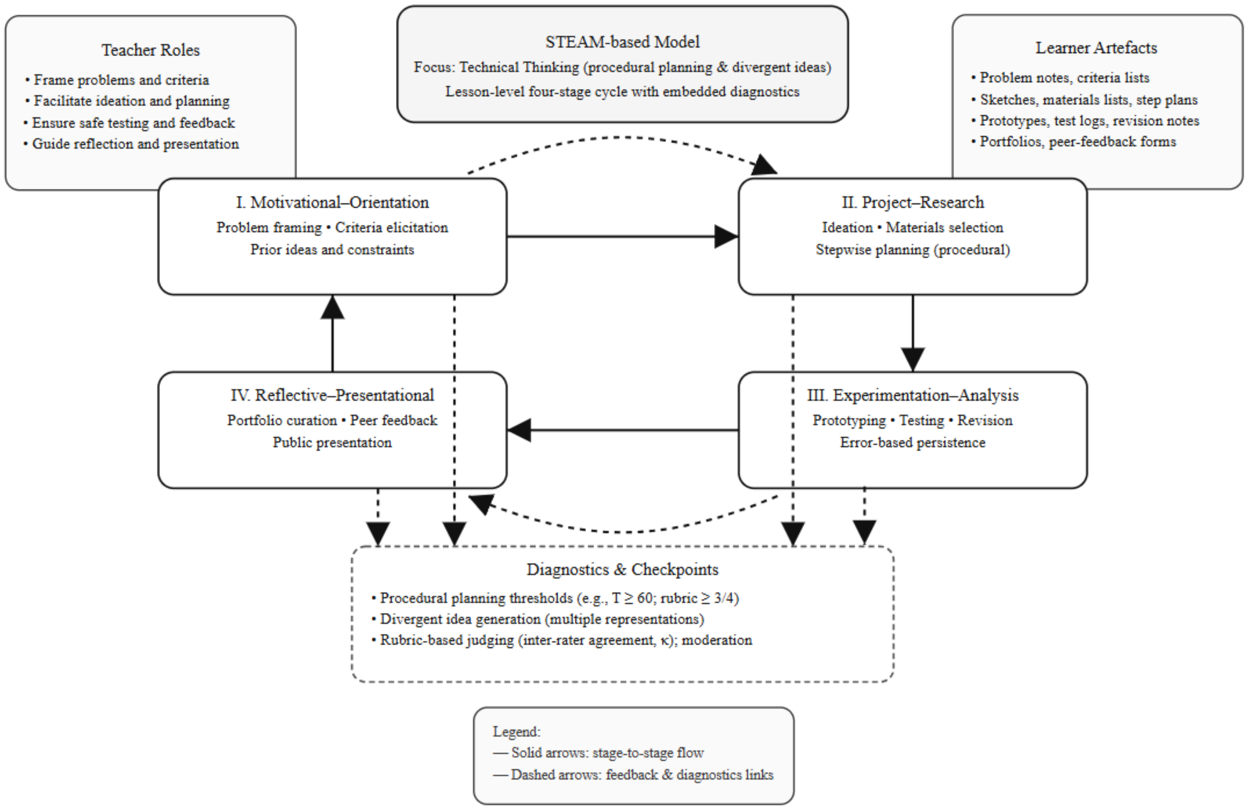

Figure 1.
Conceptual architecture of the STEAM-based pedagogical model (stages I–IV, roles of teachers and learners, diagnostic checkpoints, feedback loops).

General structure and principles: The model includes four key stages: 1) Motivational–Orientation, 2) Project–Research, 3) Experimentation–Analysis, 4) Reflective–Presentation. Its structure is cyclical and iterative, allowing a return to previous stages based on testing results and reflection, which mirrors an authentic engineering process.

Stage I: Motivational–Orientation stage. Goal: To foster cognitive motivation, contextualize the problem within a real-life situation, and set clear project objectives. The teacher acts as a facilitator by presenting the problem and moderating the discussion. Students actively formulate problems, define goals, and plan their work accordingly. The following skills were developed: cognitive motivation, problem-oriented thinking, goal setting, and basic algorithmic thinking.

Stage II: Project–Research stage. Goal: To develop research, solution design, and prototyping skills. The teacher guides requirements analysis and idea generation. Students analyze tasks, propose solutions, and create prototypes. The following skills were developed: analytical thinking (problem deconstruction), divergent thinking (solution generation), and engineering thinking (design and modeling).

Stage III: Experimentation–Analysis stage. Goal: To empirically test the prototype's functionality, analyze the results, identify shortcomings, and make corrections to the prototype. The teacher organizes testing and error analysis. Students test the prototype, record data, identify weak points, and refine the solution. The following skills were developed: critical thinking (evaluating results), analytical thinking (error diagnostics), and reflective thinking (linking actions and outcomes).

Stage IV: Reflective–Presentation stage. Goal: To effectively present results, critically reflect on the learning process and project outcomes, and assess personal contributions and growth. The teacher organizes presentations and facilitates reflection. Students present the final solution, justify their choices, conduct self-assessments, formulate conclusions and set new objectives. Skills developed: communication skills, reflective thinking (metacognitive processes), and interdisciplinary thinking (self-assessment and transferable skills) (Figure 2).

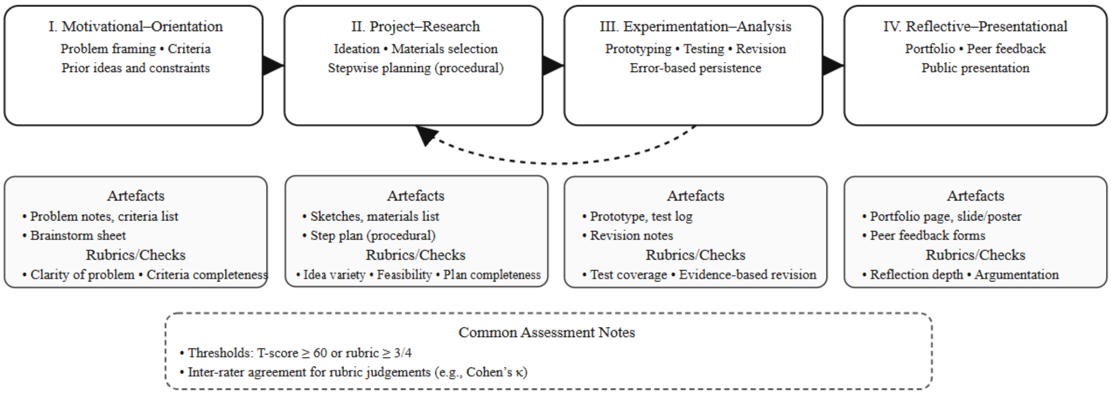

Figure 2.
Lesson-level flow of the model with artifacts, rubrics and checkpoints (stages I–IV).

4.1. Theoretical Foundations of the Model

The model is based on synthesizing key theoretical principles.

Engineering thinking: Considered a complex cognitive ability aimed at solving practical tasks involving the creation, improvement, or optimization of technical systems and processes. It includes components such as problematization, analysis, systems thinking, algorithmization, balancing divergent and convergent thinking, criticality, reflection, and practical orientation.

Project-based activity: Serves as the main pedagogical tool for developing Design and Technical Thinking (DTT). It is understood as a purposeful student activity focused on solving a significant practical problem that culminates in creating a real product. The standard cycle includes idea generation, planning, implementation, presentation, and reflection. This approach fosters interdisciplinary competencies, critical thinking, and independent learning abilities [42].

STEAM approach: Provides an integrative context for implementing the model. Its essence lies in overcoming subject isolation by integrating knowledge and methods from the natural sciences, technology, engineering, arts/design, and mathematics to solve complex problems. The "Arts" component is critically important for developing creativity, design thinking, aesthetics and visualization. Project-based activities are a natural way to organize STEAM education.

The teacher's role: The teacher's role is transformed compared with the traditional approach. The educator serves as a facilitator, mentor, organizer of the learning environment, and consultant, which requires developing new competencies.

Activity-based approach [41, 43, 44]: Forms the psychological and pedagogical foundation of the model. It posits that psychological development (including thinking) occurs during the process of active and socially mediated activity. The development of DTT is only possible by engaging students in specially organized activities that model the stages of real engineering and technical creativity in an integrated STEAM context.

The development of criteria for assessing the cognitive and design-technical abilities of younger schoolchildren in the context of the STEAM approach requires not only reliance on level-based diagnostics but also on the actual observed manifestations of these abilities in project activities. A system of criteria is proposed below, distributed by types of abilities, levels of their manifestation, and possible indicators for evaluation. The assessment criteria for the cognitive and technical abilities of primary school students are summarized in Table 1.

Table 1.
Assessment criteria for cognitive and design-technical abilities in primary school (Grades 1–4; ages 6–10).

I. Cognitive abilities

Ability	**Evaluation criteria**	**Levels of manifestation**	**Indicators of manifestation**
Problem formulation	Ability to identify and formulate a problem	Low: adopts ready-made wording Medium: formulates with the help of questions High: independently sees the problem and argues it	- Asks clarifying questions - Reformulates the problem - Draws conclusions
Analytical thinking	Ability to identify the essential conditions of the task and analyze the situation	Low: superficial analysis Medium: highlights some of the conditions High: establishes cause-and-effect relationships	- Compares examples - Detects patterns - Predicts the result
Divergent thinking	Generation of various ideas and solutions	Low: Offers one solution Medium: 2-3 options High: original and non-standard solutions	- Uses different materials - Combines unrelated objects - Not afraid of "wrong" ideas
Algorithmic Thinking	Ability to plan and follow a step-by-step plan	Low: does not build a plan Medium: with a hint, builds a sequence High: makes a step-by-step plan on their own	- Describes the sequence - Uses schemas or tables - Checks actions for consistency
Critical thinking	Ability to evaluate the result and notice mistakes	Low: does not notice mistakes Medium: responds to comments High: Offers corrections and justifications	- Adjusts the model - Argues for corrections - Compares to the benchmark
Reflective thinking	Ability to reflect on and learn from experience	Low: Can't evaluate the process Medium: answers questions High: independently draws conclusions and evaluates the contribution	- Answers the questions "What did I learn?" - Conducts self-assessment - Formulates suggestions for improvement

II. Design and technical skills

Ability	**Evaluation criteria**	**Levels of manifestation**	**Indicators of manifestation**
Engineering Thinking	Ability to create prototypes, use technical details	Low: Executes according to a template Medium: adapts ready-made solutions High: Combines components on its own	- Uses parts for their intended purpose - Applies physical principles - Creates sustainable structures
Technical Imagination	Imaginary transformation of an object and its functions	Low: Only relies on the sample Medium: offers minor changes High: Invents new forms and applications	- Draws a diagram of the future model - Comes up with “what if…” scenarios - Sees the object "from the inside"
Technological ingenuity	Ability to find non-standard technical solutions	Low: Copies the solution Medium: combines well-known techniques High: creates a new mechanism, method, structure	- Uses unexpected materials - Eliminates technical errors creatively - Demonstrates initiative
Handicraft/Assembly Skills	Ability to work with construction sets, materials, tools	Low: Needs help Medium: performs according to the instructions High: works neatly, independently	- Assembles stable structures - Handles tools safely - Produces drawings and assembles accordingly
Software and technical	Ability to program	Low: Does not use programming	- Configures sensors;

skills	simple actions of models or robots	Medium: Edits the finished code High: Writes simple scripts/algorithms	- Uses programming blocks; - Conducts self-assessment.

Additionally: Assessment formats and methods
- Checklist monitoring
- Project portfolio (photos, descriptions, video demonstrations)
- Diagnostic tasks before and after STEAM sessions
- Self- and peer assessment (at the Reflective–Presentation stage)
- Assessment by levels (beginner – basic – advanced)

Flexible scale for generalized assessment
Flexible scale for generalized assessment. We use a three-level scale for rubric judgments: beginner–basic–advanced

Level	Characteristic
Elementary	Works according to the pattern, requires the support of a teacher
Basic	Participates in planning, uses the suggested tools
Advanced	Initiates, suggests, combines, analyzes, reflects

4.2. Scientific Novelty and Practical Significance of the Model

The scientific novelty of the model lies in the following aspects:

Targeted systematization of project activity stages: A clear structure adapted for the development of DTT with detailed stages and specific tasks.

Clear correlation of process elements: Transparent connections between stage objectives, teacher/student activities, and the cognitive components being developed serve as an explicit structural foundation.

Deep integration of the STEAM approach: Positioning interdisciplinary synthesis as an organic and essential environment for the development of DTT, where art is included not as an addition but as an integral part.

Focus on iteration and reflection: The cyclical nature with logical returns based on testing and reflection mirrors the real engineering process, and reflection is a continuous element in this process.

The practical significance of this study is derived from the theoretical advantages of the model.

A concrete tool for educators: Provides a clearly structured algorithm for organizing project-based activities in technical creativity and engineering.

Clear activity guidelines: Details the roles and actions of teachers and students at each stage, allowing for purposeful and structured interaction.

Targeted development of engineering thinking components: The explicit correlation between stages and the development of cognitive skills allows for the conscious cultivation of specific aspects of thinking.

Broad applicability: The model's flexibility allows its implementation in various formats (classes, extracurricular activities, Quantoriums, and STEM/STEAM laboratories).

The comparative matrix highlights three distinctive features of the proposed model: (i) explicit integration of the Arts component as a driver of design thinking and metacognition; (ii) built-in diagnostic architecture (rubrics with levels/indicators) tailored to Grades 1–4 (ages 6–10); and (iii) contextual alignment with Kazakhstan's educational environment and resource constraints. Although EDP, 5E, and PBL offer strong procedural scaffolds, they do not, in their canonical form, combine age-specific diagnostics, explicit art-engineering synthesis, and national-context alignment within a single cyclical framework. A comparative positioning of the proposed model and established educational frameworks is presented in Table 2.

Table 2.
Comparative positioning of the proposed STEAM-based pedagogical model versus established frameworks (EDP, 5E, PBL, generic STEAM integration).

Criteria / Models	Proposed STEAM Model	Engineering Design Process (EDP)	5E Model	Project-Based Learning (PBL)	Generic STEAM Integration
Explicit interdisciplinary integration	✓	✓	~	~	✓
Explicit ART component (design/aesthetics)	✓	~	—	~	~
Cyclic & iterative with feedback loops	✓	✓	✓	~	~
Built-in diagnostics & rubrics (levels/indicators)	✓	—	—	~	—
Age adaptation (Grades 1–4)	✓	—	—	—	—
Teacher role: facilitator/mentor	✓	~	~	~	~
Resource adaptability (low-cost variants)	✓	~	—	~	~
Explicit criteria & indicators for DTT	✓	—	—	—	—
Alignment with national context (Kazakhstan)	✓	—	—	—	—

Note: Legend: ✓ - explicit; ~ - partial/implicit; — - not explicit. Sources: classic EDP, 5E, PBL frameworks; article's proposed model.

4.3. Benchmark Frameworks for Comparative Analysis

To position the proposed STEAM-based pedagogical model within the broader landscape of educational design frameworks, four well-established approaches were selected for comparative analysis: the Engineering Design Process (EDP), the 5E Instructional Model, Project-Based Learning (PBL), and a generalized “Generic STEAM Integration” approach. These frameworks were chosen because they are widely recognized in international STEM/STEAM education and collectively represent the main modes of structuring interdisciplinary project-oriented learning.

The Engineering Design Process (EDP) is a classic problem-solving cycle in engineering education, typically comprising the stages of problem identification, idea generation, planning, prototyping, and iterative improvement. In STEM and STEAM contexts, EDP is valued for its procedural clarity and alignment with authentic engineering practices. However, in its canonical form, it lacks an explicit arts/design component, age-specific adaptation for early primary grades, and detailed diagnostic tools for assessing design and technical thinking skills.

The 5E Instructional Model (Engage, Explore, Explain, Elaborate, Evaluate) is a structured inquiry-based learning framework originating in science education. It is frequently used in STEM/STEAM classrooms to scaffold conceptual understanding and to conduct exploratory activities. Although it can be adapted to include engineering and artistic tasks, the arts component is not intrinsic, and assessment tends to focus on general learning outcomes rather than specific engineering or technical skills.

Project-Based Learning (PBL) organizes instruction around extended projects that address meaningful problems and culminate in a tangible product or presentation. PBL naturally supports interdisciplinary integration and can incorporate artistic design. However, it does not prescribe a specific engineering cycle, nor does it typically provide structured diagnostics for design and technical thinking in younger students.

Generic STEAM Integration refers to flexible, teacher-driven combinations of Science, Technology, Engineering, Arts, and Mathematics without adherence to a single, codified framework. Such integration can be highly creative and contextually responsive but may lack systemic structure, consistent implementation, and robust evaluation criteria.

The comparative positioning of these frameworks alongside the proposed model is **summarized in Table 2**. It highlights three distinctive features of the model: (i) the explicit integration of an arts component as a driver of creativity and metacognition; (ii) embedded, age-appropriate diagnostic rubrics for Grades 1–4 (procedural planning and divergent idea generation); and (iii) pragmatic adaptation to Kazakhstan’s curricular requirements and resource constraints, enabling routine classroom implementation.

4.4. Methodological Aspects of the STEAM-Oriented Pedagogical Model

This study adopts a design-and-development logic: the model was specified, iteratively refined, and documented for classroom replication. Its methodological core combines a four-stage lesson cycle with role-explicit teacher mediation and learner artifacts, anchored by class-embedded**,** age-adapted diagnostic checkpoints. Evidence reported here concerns feasibility and acceptability under routine conditions; no standardized scores or between-group contrasts were used, and causal inference was not attempted. Replicability is supported by rubrics, artifact prompts, and low-cost materials; adaptability is ensured through alignment with Grades 1–4 curricular constraints and resource realities. The approach is compatible with EDP/5E/PBL yet distinct in its integrated arts component and embedded diagnostics. Subsequent work should evaluate effectiveness via controlled or quasi-experimental designs and examine long-term transfer [30].

5. Approbation Findings (Feasibility & Acceptability)

This section reports feasibility and acceptability signals observed under routine classroom conditions. The aim is not to infer causal effects but to inform subsequent confirmatory evaluation.

Feasibility: the model was delivered within the standard timetable (two 40-minute sessions per week, Grades 1–4), with teachers reporting manageable preparation and clear stage transitions.

Acceptability: teacher-reported engagement and persistence increased notably during Stages III–IV, with learners more willing to revise after errors.

Indicative monitoring signals: aggregated feasibility monitoring suggested a larger share of learners reaching predefined thresholds in procedural planning and divergent idea generation (e.g., an indicative rise in the proportion at the “High” level). These signals warrant confirmatory testing in controlled or quasi-experimental designs.

Practicality: teachers highlighted the usefulness of artifact-based rubrics and the practicality of low-cost materials; learners’ self-reports pointed to improved confidence and interest.

Key Findings: The monitoring yielded the following signals:

Engagement and Behavior: Teacher reports and observations indicated a marked increase in student engagement, particularly during the experimental-analytical stage, where learners demonstrated greater persistence in identifying and correcting design flaws.

Cognitive Skills: Observation data indicated a 20–30% increase in indicators of independent problem formulation and solution planning across the participating classes.

Diagnostic indicators: Class-embedded diagnostic tasks (age-adapted) indicated that the share of learners at the "high" level increased from 26% to 43% (algorithmic thinking) and from 18% to 36% (divergent thinking).

Self-Perception: Students' self-assessments highlighted improved confidence in performing technical tasks and expressed greater interest in future STEAM-related activities.

6. Discussion for Practitioners and Researchers

The pilot study provides preliminary feasibility evidence; any effectiveness remains to be tested in controlled or quasi-experimental designs.

Interpretation of Results: The observed improvements in problem formulation, algorithmic, and divergent thinking align with the model's theoretical foundation, which emphasizes active, project-based, and iterative learning. The increase in engagement and persistence, especially during the testing and refinement phase (Stage III), suggests that the model successfully replicates authentic engineering challenges, fostering motivation and resilience. The growth in self-confidence reported by students underscores the model's value in affecting not only cognitive but also affective domains, which is crucial for long-term interest in STEM fields.

Theoretical Alignment: These findings resonate with the constructivist and activity-based theories underpinning the model (Vygotsky, Dewey). The structured progression through the four stages appears to effectively scaffold the development of complex thinking skills by providing a clear framework for inquiry, creation, and reflection. The explicit integration of the "Arts" component, as reported by teachers, likely contributed to the increase in divergent thinking by encouraging creative exploration and multiple solution pathways.

Limitations of the Pilot: While promising, these findings must be interpreted with caution due to several limitations of the pilot study. Its scale was limited to two schools and a single academic year, restricting the generalizability of the results. The absence of a control group makes it difficult to attribute the improvements solely to the intervention, as other factors could have contributed. Furthermore, the reliance on teachers' adaptation of projects, despite briefing, introduces a variable in the fidelity of implementation.

Conclusion from Pilot: Despite these limitations, the pilot study successfully demonstrates that the model is implementable in real-world primary school settings and is associated with positive trends in key DTT competencies. The results provide a strong rationale and valuable insights for designing a more rigorous, large-scale experimental study to test the model’s effectiveness, control for confounding variables, and measure its long-term impact.

7. Limitations and Future Research Directions

While the proposed STEAM-based pedagogical model demonstrates theoretical robustness and preliminary feasibility, it has several limitations. First, the model has undergone only limited pilot testing in a small number of schools, which restricts the generalizability of these findings. Large-scale implementation across diverse educational contexts, including rural schools, schools with limited access to digital infrastructure, and institutions with varying levels of teacher preparedness, may reveal additional challenges not addressed in the initial design.

Second, the model presupposes a certain level of teacher competence in interdisciplinary project facilitation, technical creativity and digital tool integration. Without comprehensive and sustained professional development programs, there is a risk that implementation will become fragmented or revert to traditional, reproductive methods.

Third, reliance on specific materials and equipment (e.g., 3D modeling kits, construction sets, and software) may limit their applicability in resource-constrained environments. Although the model allows for adaptation to locally available materials, this flexibility has yet to be systematically tested.

Finally, the model has not yet been evaluated for long-term impact, particularly regarding the retention of technical thinking skills, transferability to other STEM domains, and influence on students' career orientation.

Therefore, future research should focus on conducting longitudinal, multi-site experimental studies to evaluate the model's effectiveness under varying conditions, develop scalable teacher training programs, explore low-cost adaptations for under-resourced schools, and assess the model's impact on broader cognitive and socio-emotional competencies.

7.1. Potential Evaluation Instruments

To ensure a rigorous assessment of the effectiveness of the proposed STEAM-based pedagogical model, a set of evaluation tools should be envisaged for future experimental and longitudinal studies. These tools are designed to capture both cognitive and non-cognitive outcomes, reflecting the model's interdisciplinary nature.

7.1.1. Standardized Cognitive Diagnostics

Bennett Mechanical Comprehension Test (age-adapted forms for Grades 1–4) — to measure the development of mechanical-technical reasoning.

Raven's Colored Progressive Matrices — for assessing nonverbal analytical reasoning.

Spatial Representation Test (method) — to evaluate spatial thinking and mental rotation skills.

Performance-based rubrics: Custom-designed Design and Technical Thinking Rubrics aligned with the model's diagnostic component, assessing problem identification, divergent and algorithmic thinking, engineering creativity, and reflective practices.

7.1.2. Process Monitoring Tools

Observation checklists for teacher–student interaction patterns, use of interdisciplinary connections, and integration of the arts component.

Video analysis of project stages to identify patterns in problem-solving behavior and collaboration.

7.1.3. Affective And Motivational Measures

Likert-scale questionnaires (pictogram-adapted for younger learners) assessing interest in STEAM activities, self-confidence in technical tasks, and perceived value of interdisciplinary learning.

Peer and self-assessment forms to be used at the Reflective–Presentation stage of the model.

7.1.4. Longitudinal Tracking

Follow-up assessments at 6–12 months to examine the retention and transfer of design and technical thinking skills to other academic domains (e.g., mathematics and science).

The integration of these tools will allow for the triangulation of data sources, enhancing the validity of the findings and enabling a fine-grained analysis of how the model influences students' competencies over time.

8. Conclusion

Thus, in the context of Kazakhstan's active educational reforms aimed at enhancing the quality and competitiveness of education in line with global trends and national strategic tasks, there is an urgent need for scientifically grounded pedagogical models. These models should purposefully develop engineering-technical thinking as a key interdisciplinary competence for future innovators from the earliest stages of learning, effectively utilizing the integrative potential and practice-oriented methodology of the STEAM approach. The proposed model is intended to address this pressing need in the education system in Kazakhstan.

The four-stage pedagogical model presented in this study offers a systematic approach to developing engineering thinking among younger schoolchildren. It organically aligns with contemporary trends, implementing the principles of the STEAM approach (integration of science, technology, engineering, art, and mathematics), project-based learning (cyclicity and iterativeness), and the competency-based approach (focus on developing problem-solving, analytical, divergent, engineering, critical, and reflective thinking skills). Its practice-oriented nature, clear guidelines for teacher and student activities, and flexibility for implementation in various formats make the model a valuable tool for improving the quality of technical education in the country. The formation of engineering thinking as a key competence for the future, which is necessary for adapting to and transforming the world, begins in primary school. The proposed model, which integrates modern educational approaches, contributes to training an innovatively minded generation.

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