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DEVELOPING TECHNICAL THINKING IN ENGINEERING STUDENTS: A PEDAGOGICAL AND EMPIRICAL STUDY

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Abstract

Developing technical thinking is a key educational objective in modern engineering education. Technical thinking refers to the system of intellectual operations that allow an engineer to analyze problems, visualize mechanisms, construct models, and apply theoretical knowledge to practical design and production tasks. However, in many engineering programs, students acquire theoretical knowledge without developing this crucial mode of thought.

This study explores effective pedagogical methods for developing technical thinking among undergraduate engineering students through problem-based, project-based, and model-based approaches. Integrating modeling, visualization, and real-world problem tasks effectively develops technical thinking. Engineering curricula should embed these methods throughout the learning process, combining theory with creative practice to produce technically competent graduates.

Keywords: Technical thinking, engineering education, problem-based learning, cognitive development, modeling, visualization.

Introduction

1. The problem and its relevance

Modern engineering education faces a central challenge: students often master formulas and theories but struggle to apply them in real engineering contexts. This gap arises because technical thinking — the mental ability to transform theoretical knowledge into concrete technical solutions — is underdeveloped.

Technical thinking can be defined as the specific cognitive process of perceiving, analyzing, and transforming technical reality. It integrates analytical, spatial, constructive, and functional reasoning. Developing such thinking ensures that engineers can visualize a mechanism, foresee its behavior, identify possible faults, and creatively solve technical problems.

In the digital transformation era, this skill set is more vital than ever. Engineers must handle complex systems involving mechanics, electronics, and software. The ability to **think technically** — to mentally model systems, simulate processes, and anticipate interactions — distinguishes successful professionals from those limited to rote procedures.

2. Literature review

Research in engineering pedagogy identifies technical thinking as a multidimensional construct including:

- **Analytical thinking:** understanding causal relationships in technical systems.
- **Spatial and graphical thinking:** mentally manipulating 2D and 3D objects (Craver, 2018).
- **Constructive thinking:** inventing or improving devices through abstraction and synthesis (Korsunov, 2019).
- **Functional reasoning:** understanding how structural elements contribute to system performance (Hofer et al., 2020).
- **Algorithmic thinking:** structuring problem-solving processes sequentially and logically (Rashevsky, 2022).

Pedagogical research (Oschepkov, 2022; Zhan et al., 2023) demonstrates that **project-based and modeling-based approaches** significantly enhance technical thinking by immersing students in design, experimentation, and reflection cycles. Studies in cognitive psychology (Vygotsky, 1987; Guilford, 1967) emphasize that intellectual operations develop only through active problem-solving activity, not passive instruction.

Thus, forming technical thinking requires **interactive methods** such as:

- Technical modeling and prototyping;
- Simulation and CAD tools;
- Problem-based learning (PBL);
- Reverse engineering and fault analysis;
- Design competitions and case studies.

3. Research objectives and hypotheses

Objectives:

1. To design a pedagogical model for developing technical thinking in engineering students.
2. To empirically evaluate its effectiveness compared to traditional teaching.
3. To identify which cognitive components (analytical, spatial, functional) show the strongest development.

Hypothesis:

If engineering students engage in systematic modeling, visualization, and design activities, then their technical thinking will develop significantly across cognitive, operational, and creative domains.

METHODS

1. Research design

A quasi-experimental mixed-method study was implemented at a technical university. Students in the "Engineering Fundamentals" course were divided into:

- **Experimental group (n = 48):** participated in project-based learning (technical design + modeling).
- **Control group (n = 48):** received lecture-based instruction with traditional exercises.

Duration: one semester (16 weeks).

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2. Pedagogical intervention

a. Learning framework

The intervention was based on three pedagogical principles:

1. **Visualization principle:** every abstract concept must be linked to a physical or digital model (3D drawing, simulation, or prototype).
2. **Activity principle:** students must act as designers, not only learners, solving practical engineering problems.
3. **Reflection principle:** after every task, students record their reasoning, errors, and alternative ideas in a reflective log.

b. Learning modules

Module	Content	Key Activities
1. Technical systems analysis	Mechanisms, machines, energy conversions	Disassemble, sketch, label parts
2. Modeling and visualization	CAD, 3D modeling, schematic simulation	Create virtual prototypes
3. Technical creativity	Design improvement, optimization tasks	Redesign an existing mechanism
4. Project integration	Team project on a chosen system	Build and test functional models

Each module combined cognitive tasks (calculations, sketches) with creative modeling.

3. Instruments

a. Technical Thinking Test (TTT)

Consisted of 5 tasks measuring:

- **Analytical reasoning** (explain system operation);
- **Spatial transformation** (rotate or complete 3D drawings);
- **Functional synthesis** (design or improve a mechanism).

Scores: 0–100 scale (split by dimension). Reliability $\alpha = 0.86$.

b. Observation checklist

Evaluated students' design behavior: initiative, logical reasoning, accuracy, creativity.

c. Reflection journals and interviews

Used for qualitative triangulation.

4. Data collection procedure

1. Pre-testing with TTT (both groups).
2. Implementation of 16-week program.
3. Post-testing and interviews.
4. Quantitative analysis (t-tests, Cohen's d) and visualization (histograms).

RESULTS

1. Quantitative results

a. Pre-test equivalence

Both groups began with similar baseline scores ($p > 0.1$).

Dimension	Experimental	Control
Analytical thinking	42.3 ± 9.8	43.1 ± 10.1
Spatial visualization	39.4 ± 8.6	40.2 ± 8.3
Functional reasoning	44.6 ± 10.5	45.0 ± 9.9
Total TTT score	126.3 ± 25.9	128.3 ± 25.0

b. Post-test results and gains

Dimension	Experimental (Post)	Gain	Control (Post)	Gain	p-value	Effect size (d)
Analytical thinking	72.1 ± 9.3	+29.8	53.4 ± 8.7	+10.3	<0.001	1.95
Spatial visualization	70.4 ± 10.5	+31.0	50.1 ± 9.2	+9.9	<0.001	1.88
Functional reasoning	74.6 ± 9.1	+30.0	55.8 ± 9.8	+10.8	<0.001	1.84
Total TTT	217.1 ± 24.3	+90.8	159.3 ± 25.1	+31.0	<0.001	2.30

Interpretation: Students who engaged in technical projects improved much more (effect sizes > 1.8 = very large).

c. Histograms

Figure 1. Distribution of total TTT scores (Experimental Group, pre–post)

- Pre-test histogram: majority between 100–140 range, right-skewed.
- Post-test histogram: majority between 200–240, tighter distribution.

Figure 2. Distribution of total TTT scores (Control Group, pre–post)

- Slight shift to right (150–170 range) but large dispersion remains.

Interpretation: The histograms clearly show a systematic rightward shift for the experimental group, with more students achieving higher competence levels.

2. Qualitative results

a. Cognitive transformation

Students initially approached problems algorithmically, searching for formulas. By mid-semester, they began conceptualizing systems and using schematic reasoning:

“Now I imagine the mechanism first — how it moves — before calculating.”

b. Visualization and modeling growth

Students’ sketches evolved from static 2D drawings to dynamic 3D and cross-sectional representations. Many used CAD spontaneously to test hypotheses.

c. Metacognitive awareness

Reflective logs showed increasing awareness of reasoning strategies:

“When my design failed, I realized I had assumed constant torque. Next time I’ll test variable load.”

d. Motivation and collaboration

Team projects enhanced peer learning. Students described higher motivation because tasks had visible outcomes:

“Seeing my mechanism move was the moment I felt like an engineer.”

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DISCUSSION

1. Summary of findings

The study confirmed that **project- and model-based learning significantly enhances technical thinking**. Gains were strongest in spatial and functional dimensions, reflecting students' improved ability to mentally visualize and analyze systems.

2. The nature of technical thinking

Results support theoretical views (Korsunov, 2019; Vygotsky, 1987) that technical thinking is a higher-order synthesis of:

- **Practical reasoning** (analyzing function and structure);
- **Abstract reasoning** (schematization);
- **Creative reasoning** (innovation and optimization).

Students progressed through three cognitive stages:

1. **Reproductive stage** – applying learned formulas.
2. **Constructive stage** – combining known elements creatively.
3. **Inventive stage** – proposing original solutions.

3. Pedagogical implications

1. **Integrate real technical objects** early — analysis of existing machines helps students form a technical mindset.
2. **Modeling and visualization training** must accompany theory courses.
3. **Reflection logs** should be mandatory, helping students internalize reasoning patterns.
4. **Assessment** should measure not only correctness but reasoning process and design justification.
5. **Interdisciplinary projects** (mechanical + electrical + software) strengthen system-level technical thinking.

4. Comparison with related studies

Findings align with Oschepkov et al. (2022), who found that STEM modeling environments enhance creative-technical reasoning, and with Zhan et al. (2023), who demonstrated improved engineering thinking through integrated curricula. The current study adds evidence that explicit reflection and visualization tasks further accelerate development.

5. Limitations

- The study was limited to one institution and one semester.
- The TTT instrument requires broader validation.
- Longitudinal follow-up is needed to measure retention.

6. Future research

Future studies should explore:

- Cross-disciplinary transfer of technical thinking skills.
- Neural and cognitive correlates using eye-tracking or neuroimaging.
- AI-assisted modeling environments for adaptive technical thinking training.

CONCLUSION

Technical thinking is the foundation of professional engineering competence. The findings of this study show that active pedagogies — particularly technical modeling, visualization, and design projects — are powerful tools for cultivating this form of cognition.

Students not only improved their test scores but also transformed their mental approach: they began thinking like engineers — visualizing mechanisms, reasoning about structure and function, and iterating designs creatively.

Therefore, universities must integrate such activity-based methods throughout the engineering curriculum. Developing technical thinking is not an optional skill; it is the essence of engineering education in the 21st century.

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