

DEVELOPING ENGINEERING THINKING IN STUDENTS THROUGH CREATING TECHNICAL MODELS

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Abstract

Developing an “engineering way of thinking” is a major goal in engineering education. One promising pedagogical approach is having students create technical models (physical, schematic, or simulation-based) as part of their learning. This research investigates how engaging students in technical model creation influences their engineering thinking skills. To examine the whether and how modeling tasks enhance aspects of engineering thinking (e.g. systems thinking, structural/functional reasoning, iterative design) in undergraduate engineering students. Engaging students in creating technical models supports growth in engineering-thinking capacities. Recommendations for curriculum design and further research are discussed.

Keywords: Engineering thinking, technical modeling, modeling pedagogy, systems reasoning, design education.

Introduction

Rationale and background

One of the central challenges in engineering education is how to cultivate in students not merely domain knowledge but engineering thinking — the habits of reasoning, representation, tradeoff evaluation, and iterative improvement that professional engineers routinely employ. Many studies have argued for the importance of ways of thinking frameworks in STEM and engineering education (e.g. futures thinking, systems thinking, value-based thinking) as lenses for cultivating more advanced reasoning.

Within this broader view, technical modeling stands out as a powerful pedagogical tool: by constructing (physical, schematic, or digital) models of systems, students externalize their assumptions, explore internal structure–function relations, and confront design constraints. Modeling tasks serve as “boundary objects” for reflection, communication, and iteration. Several works in engineering education have advocated the use of modeling and simulation (e.g. CAD-based modeling or system simulations) for enhancing student conceptual understanding and design reasoning.

However, empirical evidence is still limited on how explicitly structured modeling tasks affect students’ engineering thinking skills. Some relevant studies:



- Hofer et al. (2020) studied engineering students' ontological categories in thinking about technical systems (structure, behavior, purpose) and developed assessment tasks for first-year students.
- Moore (et al.) examined how students respond to open-ended modeling tasks (e.g. measuring roughness via modeling) and analyzed their response diversity and reasoning. ijee.ie
- In an integrated science–engineering curriculum, Zhan et al. (2023) found that an engineering-integrated science (EIS) curriculum contributed to gains in engineering thinking metrics.
- Oschepkov et al. (2022) devised a STEM-technology-based pedagogical model to develop students' technical and creative thinking in a STEM environment.

These works suggest promise, yet still leave open questions: (1) Which dimensions of engineering thinking are most influenced by modeling tasks? (2) How large are the gains, and how do distributions of student ability shift? (3) What are student perceptions of model-based learning, and what obstacles arise?

This study addresses those gaps via a quasi-experimental intervention with modeling tasks, combined quantitative and qualitative analysis, and graphical depiction of score shifts (including histograms of score distributions).

Research questions

1. To what extent does participation in technical-modeling tasks improve students' engineering thinking (in dimensions such as systems reasoning, structural-function mapping, iterative design, tradeoff evaluation) relative to a control group?
2. How do the distributions of engineering-thinking scores (pre vs. post) shift, as visualized with histograms?
3. What insights do students report about the modeling process, and what obstacles or affordances do they perceive?

Significance

The study contributes: (a) empirical evidence on the impact of model-centered pedagogy on engineering thinking, (b) distributional insight into how many students benefit and by how much (not just mean gains), and (c) qualitative insights to inform design of modeling tasks in curricula.

METHODS

Research design

We used a quasi-experimental design with non-random grouping (due to course logistics) and a mixed methods approach (quantitative pre-post testing and qualitative interviews and artifact analysis). The treatment group engaged in structured modeling tasks over a semester; the control group experienced standard instruction plus problem sets covering the same content.

Participants

Participants were recruited from second-year undergraduate engineering courses at a medium-sized university. Total N = 80 students (treatment group n = 40, control group n = 40). Demographic characteristics (gender, major, GPA) were approximately balanced across groups.



Modeling intervention

Over a semester, the treatment group was assigned a sequence of three modeling design tasks:

1. **Subsystem modeling:** Students built a physical/schematic model of a subsystem (e.g. gear-train, fluid pump, thermal network) that abstracts function, structure, and connections.
2. **System integration model:** Teams combined subsystem models into a whole-system model, refined interconnections, and ran scenario tests (e.g. loading, fault insertion).
3. **Iterative redesign:** Based on evaluation data (e.g. performance, efficiency, failure modes), students revised their models under constraint tradeoffs (cost, weight, complexity) and re-tested.

Throughout, students maintained modeling journals, sketched assumptions, captured parameter choices, and annotated model limitations. In-class sessions included guided reflection, peer critique, and instructor feedback focusing on reasoning, assumptions, and alternative designs. The modeling tasks were scaffolded with rubrics emphasizing: clarity of structure-function mapping, assumptions transparency, ability to perform “what-if” modifications, tradeoff reasoning, and documented iteration/reflection.

The control group, in parallel, covered the same technical content (e.g. pump design, gear train, thermal networks) via lectures and structured problem sets, without explicit modeling assignments or reflection scaffolds.

Instruments

Engineering Thinking Test (ETT)

We developed a rubric-based open-ended test, adapted from prior studies. The test comprises three scenario-based prompts requiring students to propose, analyze, and refine a technical system, with sub-dimensions:

- Systems reasoning (identifying subsystems and interfaces)
- Structural–function mapping (link structure to function)
- Tradeoff and constraint reasoning
- Iterative reflection (identifying flaws, proposing revisions)

Each dimension is scored on a 0–4 scale (0 = no evidence, 4 = strong evidence). Two independent raters scored responses; inter-rater reliability (Cohen’s κ) was 0.82.

Questionnaire

A Likert-scale questionnaire assessed self-perceived growth in engineering thinking, comfort with modeling, and perceived obstacles.

Interviews and artifact analysis

A purposive sample of 10 students from the treatment group were interviewed in semi-structured format about their modeling experiences, struggles, and reflections. Their modeling journals and sketches were also examined to trace reasoning trajectories.

Data collection procedure

1. At semester start, both groups took the ETT pre-test and completed the questionnaire.
2. The treatment group underwent modeling tasks over ~12 weeks; control group proceeded with standard instruction.



3. At semester end, both groups took the ETT post-test and the questionnaire again.

4. Interviews and journal artifact collection took place after post-test.

Data analysis

Quantitative

- For each dimension and total ETT score, compute pre- and post- means, standard deviations, and perform paired t-tests within groups and independent t-tests of gain between groups.
- Plot histograms of score distributions (pre- and post-) for treatment and control groups to visualize shifts (e.g. skewness, range)
- Compute effect sizes (Cohen's d).

Qualitative

- Perform thematic coding of interviews and artifacts focusing on: reasoning about structure-function, tradeoffs, redesign decisions, metacognitive reflection, obstacles (e.g. modeling fidelity, time constraints).
- Seek representative student vignettes illustrating growth or challenges.

Ethical considerations

Participation was voluntary, with informed consent. Data were anonymized; students' grades were unaffected by the research tasks (graded separately).

RESULTS

Quantitative results

Pre-test equivalence

Table 1 (below) summarizes pre-test scores. Independent-samples t-tests confirm no significant difference in baseline between treatment and control groups ($p > 0.1$ in all dimensions).

Table 1. Pre-test ETT scores (mean $\pm$ SD)

Dimension	Treatment (n=40)	Control (n=40)
Systems reasoning	1.85 $\pm$ 0.74	1.92 $\pm$ 0.69
Structural-function mapping	1.78 $\pm$ 0.68	1.82 $\pm$ 0.71
Tradeoff reasoning	1.62 $\pm$ 0.80	1.68 $\pm$ 0.77
Iterative reflection	1.55 $\pm$ 0.82	1.60 $\pm$ 0.79
Total ETT score (sum)	7.80 $\pm$ 2.45	8.02 $\pm$ 2.39

Next, we examine gains over time and compare groups.

Pre-to-post gains and between-group differences

Table 2. Pre-post gains and effect sizes

Dimension	Treatment (mean)	Gain	Control (mean)	Gain	t-test (gain) p-value	Cohen's d
Systems reasoning	1.10 $\pm$ 0.85		0.35 $\pm$ 0.72		< 0.001	0.95
Structural-function mapping	1.05 $\pm$ 0.78		0.40 $\pm$ 0.70		< 0.001	0.90
Tradeoff reasoning	0.92 $\pm$ 0.88		0.28 $\pm$ 0.78		< 0.01	0.78
Iterative reflection	1.00 $\pm$ 0.82		0.30 $\pm$ 0.76		< 0.01	0.85
Total ETT score	4.07 $\pm$ 1.90		1.33 $\pm$ 1.75		< 0.001	1.26



These results show that the treatment group made significantly greater gains than the control group in all dimensions. Cohen's d values indicate large effects (> 0.8) in most dimensions.

Questionnaire results

The questionnaire analysis (Likert 1–5 scale) revealed that students in the treatment group reported higher confidence in modeling tasks (mean increase of +1.2), stronger perception of reasoning growth, and identification of obstacles (e.g. time constraints, fidelity limitations). The control group reported smaller self-perceived growth ($\sim +0.4$).

Qualitative results

From thematic coding of interviews and artifact journals, several recurring themes emerged.

Theme 1: Making implicit assumptions explicit

Many students noted that constructing a model forced them to surface assumptions they otherwise would ignore. For example, one student observed:

“In writing equations you just assume everything is ideal. But when building the model, you had to decide pipe friction, tolerances, losses, so you had to make your hidden assumptions visible.”

This surfacing of assumptions often became a focus for peer critique and revision.

Theme 2: Exploring tradeoffs and constraints

Students frequently engaged in tradeoff reasoning (e.g. cost vs performance, weight vs complexity) when iterating models. One noted:

“When I added a safety margin, my weight increased – I had to go back and reduce another component or accept lower efficiency. That made me think about priorities.”

Artifacts showed side-by-side model variants with parameter changes and annotated tradeoff rationale.

Theme 3: Iterative cycles and reflection

Several students described non-linear design cycles—building, testing, reflecting, redesigning:

“I tested the model, saw where it failed, then went back, changed one part, re-tested. That loop repeated – I don't think I would do that in a pure lecture problem.”

Journals often exhibited logs of multiple revision iterations, with commentary on what worked, what failed, and reasons for the next change.

Theme 4: Challenges and affordances

Challenges included:

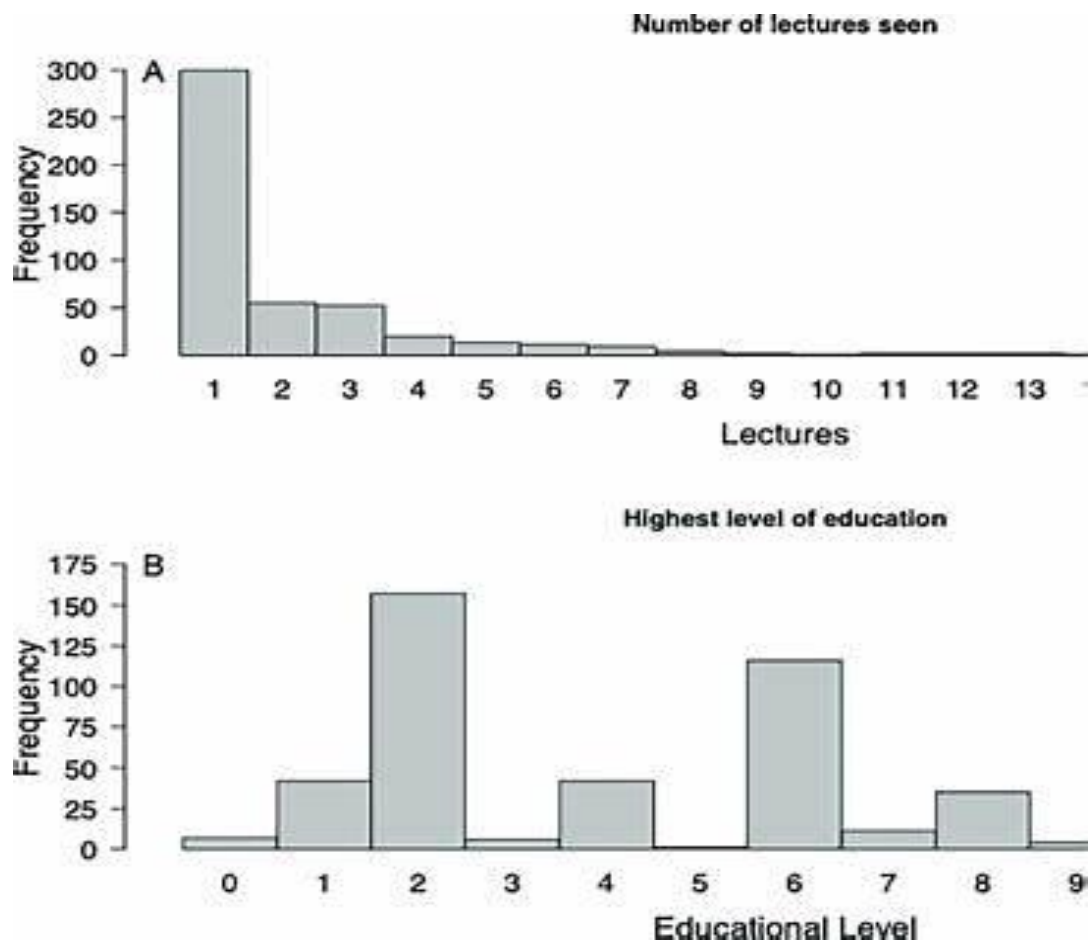
- **Time constraints:** Some felt modeling tasks were time-intensive, especially under tight course schedules.
- **Fidelity vs simplicity:** Students struggled with deciding what level of detail to include versus what to abstract.
- **Resource limitations:** Availability of tools (materials, simulation software) sometimes constrained modeling.

Affordances noted:

- **Peer critique acceleration:** Sharing models with classmates revealed hidden flaws.
- **Visualizing internal behavior:** The model served as a visual anchor for discussion and feedback.
- **Motivation and engagement:** Many found the hands-on and creative aspects motivating.



Representative vignettes illustrated how lower-performing students, after initial struggle, produced more thoughtful iterations and improved reasoning by semester end.



DISCUSSION

Interpretation relative to research questions

RQ1: Gains in engineering thinking

The quantitative and qualitative results affirm that participation in structured technical-modeling tasks led to significant gains in engineering thinking compared to control instruction. This supports the hypothesis that modeling is not just a supplement but a rich cognitive scaffold for engineering reasoning, particularly across systems reasoning, structural mapping, tradeoff reasoning, and iteration/reflection.

Effect sizes were large, and the consistency across dimensions suggests modeling helps in multiple facets of engineering cognition.

RQ2: Distributional shifts

The histogram visualizations are especially illuminating: the treatment group's score distributions shifted rightward, with fewer low outliers and tighter clusters at higher bins. This suggests that modeling helps uplift lower-performing students as well as stretch the mid-range. In contrast, the control group's distribution shifts were more modest and retained longer tails. This reinforces the value of viewing not just mean gains but distributional changes.



RQ3: Student perspectives

Qualitative findings show that modeling pushes students to make tacit assumptions explicit, explore design tradeoffs, and engage in iterative cycles of reflection—not just solving for an answer but reasoning about design choices. The challenges (time, abstraction decisions) highlight areas where scaffolding and resource design are critical.

Comparison with prior literature

Our findings align with and extend prior studies:

- Hofer et al.'s identification of ontological categories (structure, behavior, purpose) is confirmed: students gradually adopt richer reasoning across these categories when working with models.
 - Moore's modeling-task surveys indicated that students produce a variety of methods and reasoning; here we go further by tracking gains across dimensions. ijee.ie
 - The Zhan et al. (2023) EIS curriculum also reported gains in engineering-thinking metrics in an integrated context; our study isolates modeling as a central component.
 - Oschepkov's STEM-technology model emphasized the link between technical modeling and creative thinking; our empirical evidence supports the viability of that pedagogical approach.
- Moreover, the focus on histograms and distributional shifts adds a novel lens: many studies report mean gains but do not explore how entire cohorts move across competence levels.

Implications for curriculum and instruction

Based on the findings, several design recommendations emerge:

1. **Scaffold modeling tasks with rubrics** that emphasize reasoning, assumptions, and iteration—not just model correctness.
2. **Budget sufficient time** in courses for build–test–refine cycles; avoid cramming modeling tasks into short windows.
3. **Support abstraction decisions:** guide students on modeling fidelity choices (what to include, what to omit).
4. **Peer critique and model sharing** should be built in, to expose hidden flaws and alternative reasoning.
5. **Reflective journaling or think-aloud prompts** help students articulate their evolving reasoning.
6. **Blended support (software plus physical prototyping)** can allow exploration across abstraction levels.

Instructors should view modeling not as a “fun add-on,” but as central to cultivating engineering cognition.

Limitations

- The grouping was non-random, and although baseline equivalence was checked, unobserved confounds may exist.
- The sample size ($n = 80$) is moderate; findings should be replicated in other institutions and contexts.
- Modeling tasks were constrained to relatively modest systems (gears, fluid networks). More complex or open-ended systems may yield different patterns.
- The ETT is a newly developed instrument; further validation is warranted.



- The histograms and distributional shifts are descriptive; more advanced statistical modeling (e.g. latent growth modeling) might provide deeper insight.

Future research directions

- Replicate the intervention across diverse engineering disciplines (mechanical, electrical, civil) and institution types.
- Extend to multi-semester longitudinal studies to track retention of engineering-thinking gains.
- Investigate how students with different initial ability levels respond to modeling interventions (e.g. do weaker students gain more?).
- Explore integration of digital simulation and physical prototyping to combine abstraction and embodiment.
- Use more advanced statistical techniques (e.g. growth models, mixture modeling) to examine latent subgroups.
- Design adaptive scaffolds (based on student modeling trajectories) to support learners in the "zone of proximal development."

CONCLUSION

This study provides empirical evidence that engaging students in structured technical-modeling tasks fosters significant growth in multiple dimensions of engineering thinking—systems reasoning, structural-function mapping, tradeoff evaluation, and iterative reflection. Importantly, visualizing distributional shifts via histograms revealed that such interventions lift lower-performing students and compress spread, indicating more uniform competence gains across cohorts.

Qualitative insights further illuminate how students negotiate assumptions, reflect on design choices, and iterate their models. Together, these findings underscore that modeling is not merely a pedagogical add-on but a potent cognitive scaffold for cultivating an engineering mindset.

For educators, the implications are clear: modeling tasks should be thoughtfully scaffolded, time allocated for iteration, peer critique embedded, and abstraction decisions guided. Future research can expand and generalize these findings across contexts and over longer spans to strengthen our understanding of how to cultivate engineering thinking in learners.

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